SOME PHYSICAL PROPERTIES OF
CHONDRITIC METEORITES

by

PHILIP M. MARTIN

A thesis submitted in fulfilment of
the requirements for the degree of

Doctor of Philosophy

University of Leicester

December 1979
Meteorite researchers are a dedicated band but relatively few in number and therefore they tend to work, for the most part, individually and in isolation. I feel particularly lucky, therefore, that for the duration of the work for this thesis I have been in close contact with two persons who have provided stimulation, support and advice at appropriate times. I hope I have given something in return. Of these two persons my first and sincerest thanks go to Dr. Allan Mills who has supervised the research and been of enormous help and encouragement in so many ways. He has been perhaps the greatest influence in my early research career. The second person whom I thank is Professor D.J. Barber who, although not concerned with the work for this thesis, has provided stimulation in other areas of meteoritics and encouraged the production of the thesis. I would also like to express my gratitude to the late Professor P.C. Sylvester-Bradley who instigated me to take up the challenge in the first place. A number of other colleagues have been of assistance during the course of the work. In particular, I would like to express my gratitude to Dr. R. Hutchison, Dr. D.W. Hughes and Professor A.J. Meadows. Numerous friends have, in ways they will not realise, helped me to produce this thesis. To them I also quietly express my appreciation. Finally, I should like to thank all those in the Department of Geology and Astronomy, Leicester University for all kinds of assistance over the last few years, and Mrs. M. Rickwood for the excellent undertaking of the arduous task of typing the thesis. If I have omitted anyone I apologise and express my thanks.
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A meteorite may be described as a natural space probe that was formed somewhere in the solar system sometime during the last five billion years and was recently received from outer space without human aid.

Brian Mason.
CHAPTER ONE

METEORITES AND THEIR SIGNIFICANCE

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1.1 Introduction

Meteorites have probably encountered the Earth throughout its history leaving their imprints as astroblemes and, more recently, in the records of man. Although writers of classical times considered the meteorites to be of extraterrestrial origin, this view only became widely accepted again in very recent times with the publication of Chladni's book (1794). Authenticated falls date from 1492 when a 127 Kg stone fell at Ensisheim. The stone is still preserved in the local church.

Sears (1978) has demonstrated how our knowledge of the mineralogy and chemistry of meteorites has developed since Chladni's time. Important factors in the discovery of elements in meteorites were the introduction of wet chemical analysis (c.1815), qualitative spectroscopy (c.1860), quantitative spectroscopy (c.1910) and radioactivity methods (c.1950). Mineral identification in meteorites has also progressed in a step-wise fashion as a result of the developments of thin sections (c.1860), the polarising and the reflected light microscopes (c.1875), X-ray diffraction techniques (c.1910) and, most recently (c.1960), the electron microprobe. Surprisingly, their physical properties have received considerably less attention.

As a source of extraterrestrial material, meteorites came to us free of charge. At first they were studied because of the potential information they were thought to hold as indicators of the nature of the Earth's interior since the meteorites were considered to be the remnants of a shattered planet or planets. More recent investigations have shown that the meteorites hold keys to more fundamental problems such as the origin and early evolution of solar
system material and its accretion into planets and other bodies. Indeed, the most recent discoveries of isotopic anomalies in some meteoritic components suggests that they have stored information on stellar nucleosynthetic processes during supernovae explosions.

1.2 The classification of meteorites

On a broad basis meteorites fall into four groups. Nearly six per cent of falls* are composed predominantly of iron with smaller amounts of nickel and are called the IRONS. A further one-and-a-half per cent of falls also contain large amounts of iron (and nickel) but mixed with silicate material, the so called STONY-IRONS. However, the remaining meteorites, amounting to nearly ninety-three per cent of all falls, are the STONY meteorites in which silicates are the predominant constituents. There are two types of stony meteorites, originally distinguished by the presence or absence of small, roughly spherical silicate bodies, igneous in character and embedded in the fine-grained matrix (Rose, 1865). More than nine out of ten stony meteorites contain these inclusions. Gustav Rose, when cataloguing the meteorite collection of the University of Berlin, named these meteorites "chondrites" after the ancient Greek word "chondros" meaning "grain of seed", a reference to the tiny rounded bodies which categorise these stones.

* Meteorites actually seen to fall are referred to as "falls", those which are found and recognised as meteorites are called "finds". About half of the meteorites in collections are falls. However, only a very small percentage (perhaps 1% at most) of meteorites that encounter the earth's surface every year are recovered. (Many fall into the oceans or in uninhabited regions).
The term chondrite remains in use today. The rounded bodies themselves have come to be called chondrules. The stony meteorites not containing chondrules are called "achondrites".

Many elaborate schemes have been proposed to further categorise each of the four basic meteorite groups (see Sears, 1978). In the case of the chondritic meteorites, the group with which this thesis is concerned, the classification scheme most widely adopted is the two-parameter system devised by Van Schmus and Wood (1967) in which a meteorite is classified on both a chemical and a petrologic foundation.

On the basis of the overall abundance of Fe/Si and the state of oxidation of Fe, the chondrites can be separated into five chemical groups - E, H, L, LL, and C chondrites. The H (high Fe), L (low Fe) and LL (low Fe, low metal) groups collectively comprise the ordinary chondrites, the largest group indistinguishable on plots of Al/Si, Mg/Si and Ca/Si. The E (enstatite) and C (carbonaceous) groups represent two extremes, most highly reduced and most highly oxidised respectively.

The petrologic scheme devised by Van Schmus and Wood is more arbitrary. Six types are defined from type 1 which represents material having experienced the least degree of reheating to type 6, that which has experienced the most intense reheating. It has been found necessary to add a further more highly metamorphosed group, type 7. (It is possible that the metamorphism occurred as part of the formation process of the meteorites rather than subsequent to it). It is still unclear whether the higher petrological types can have been produced by metamorphism of the lower types, or whether the types represent varying degrees of metamorphism of different starting materials. The fact that the E and C chondrites exhibit a range of Fe/Si values (which is not thought to be affected by metamorphism) suggests that for these meteorites at least the latter is the case.
The variation in Fe/Si ratio within the classes of the ordinary chondrites is, however, much less so it is less clear which of the above two possibilities was operative here.

Wasson (1974) has convincingly argued that the chief weakness of the Van Schmus and Wood classification scheme (and its forerunners) is that it places all carbonaceous chondrites in the same group. This implies that they are closely related which is not the case. Studies by Van Schmus (1969), Mason (1971) and McCarthy and Ahrens (1972) indicate that the original members of the type III should be separated into two groups. Wasson calls these CV and CO where the second letters are the first letters of the meteorites chosen by Van Schmus (1969) as type specimens, namely Vigarano and Omans. To distinguish two type III CV chondrites from other type 2 carbonaceous chondrites which have higher Fe/Mg ratio (and C and H\textsubscript{2}O contents), Wasson termed the remaining type III carbonaceous chondrites CM after Mighei his chosen type specimen.

Wasson can find no strong evidence linking the Vigarano, Omans or Mighei groups with each other, nor any of these with the type 1 carbonaceous chondrites. He therefore distinguishes the type 1 chondrites as a separate group. Choice of Orgueil, the largest and most widely studied and therefore most logical meteorite of this group, as the type specimen would result in confusion with the Omans type. Wasson therefore chooses the second most abundant representative, Ivuna, to make the symbol CI.

Table 1.1 shows the distribution of chondrites among the different petrologic types. It should be noted that only the carbonaceous chondrites populate the two lower petrologic types. The CI chondrites do not contain chondrules. It is on the basis of the similarity in volatile element abundances that they are classed along with the chondrule bearing carbonaceous meteorites. The nomenclature described above will be adopted in this thesis.
**TABLE 1.1**

Distribution of chondrite falls among the petrologic types. *

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<td>H</td>
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<td>CI</td>
<td>5</td>
<td></td>
<td></td>
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</table>

* Taken from Wasson (1974). (Recent falls have not significantly affected the overall balance of falls among the petrologic types).
1.3 The importance of the chondritic meteorites

If the present influx of meteoritic material to the earth's surface is a true reflection of the ratio of the various types in the solar system now and throughout its history, then the fact that the vast majority of this material contains chondrules is particularly significant since it indicates that the chondrule forming process(es) was widespread, at least in the regions of the solar system where the meteorites formed. (In fact it is likely that the proportion of chondritic meteorites in space is underestimated when based on terrestrial falls since it is probably that many carbonaceous chondrites do not survive passage through the atmosphere because of their more friable nature and are therefore under represented in terrestrial falls.) The formation of chondrules and their accretion into the meteorites are two of the most fundamental problems in meteorites today.

In order to obtain constraints on the chondrule-forming process(es), a great deal of research has been undertaken on the chemical, mineralogical and petrological properties of meteoritic chondrules. Surprisingly, however, their purely physical properties have been little investigated yet they also most probably hold valuable constraints for theories of chondrule origin. This thesis is primarily directed toward obtaining such constraints from some previously poorly defined physical properties of meteoritic chondrules.

1.4 Meteoritic inclusion terminology

It does not seem appropriate to discuss the characteristics of chondrules at this point. It is, however, worthwhile considering the terminology that has been applied to chondrules and related meteoritic inclusions for which there does not appear to be a standard nomenclature. This has led to a certain amount of confusion and misunderstanding, mainly because of a diversification in the use of
the term "chondrule". This has led to the introduction of more specific terms such as "droplet" and "near-spherical" as prefixes to the term chondrule. It would seem that the terminology should be defined more specifically.

Wasson (1974) suggests that the term chondrule "should be restricted to those bodies which formed as molten droplets... Spheroidal bodies which have not been molten, or which may have formed by processes other than those which formed the chondritic chondrules should be called chondrule-like objects". These definitions appear sound. Having defined chondrules so specifically the terms "droplet" and "near-spherical" may be dispensed. In the absence of any criteria other than shape it may in some cases be impossible to ascertain whether a spherical meteoritic inclusion which was once molten was indeed so or obtained its form by some other process such as abrasion. It is difficult to envisage a classification system to overcome this problem.

Some meteoritic inclusions are chondrule-sized with irregular or angular shapes and appear to be fragments of larger crystalline masses. Some have been rounded, perhaps by abrasion during tumbling. The term "lithic-fragment chondrule" has often been applied to such objects. It does not seem wise to classify such objects as chondrules at all, "lithic-fragment inclusion" seems more appropriate.

I would suggest that the most satisfactory definitions for meteoritic inclusions are :-

CHONDRULE  a spherical body which appears to have formed as a molten droplet.
CHONDRULE FRAGMENT  an obvious fragment of a chondrule.
CHONDRULE-LIKE INCLUSION  spheroidal bodies which do not show signs of having been molten, or which may have been formed by processes other than those which formed the chondritic chondrules, e.g. abrasion.
LITHIC-FRAGMENT INCLUSION - irregular or angular fragments of larger crystalline masses but not of chondrules.

The above terminology seems adequate to classify the majority of meteoritic inclusions, especially in the ordinary and enstatite chondrites. Irregular Ca, Al-rich inclusions are found in some carbonaceous chondrites (e.g. Allende), these could be termed IRREGULAR or AMOEBOID INCLUSIONS. No simple system would completely categorise every meteoritic object.

Adopting the above nomenclature in this thesis raises a problem. Later chapters deal with an investigation of the size and shape of whole, separated spherical inclusions from some chondritic meteorites. They were selected on the basis of near-spherical form and generally smooth surfaces. As this is the only criterion to suggest they were once molten, the possibility that some were rounded by other processes cannot be ruled out. Observations of thin-sections of chondritic meteorites indicated that chondrules are much more abundant than chondrule-like inclusions as defined above. There is good justification, therefore, in terming the spherical meteoritic inclusions examined in this thesis "chondrules".

* In the first publication of data presented in this thesis (Martin and Mills, 1976) the term "droplet-chondrule" was used to describe the spherical inclusions extracted. However, for the second publication (Martin and Mills, 1978) one of the referees suggested that, as there was no petrographic proof that the objects had been molten, the term "near-spherical" should be employed in preference to "droplet". This experience emphasises the confusion in terminology and the need for stricter definitions to be adopted.
1.5. Thesis outline

This thesis is concerned with obtaining information and constraints on the origin of chondrules and chondritic meteorites. To this end some of the less well understood physical properties of chondrules and chondrites have been examined. A glance at recent texts on meteorites (Wasson, 1974; Sears, 1978) demonstrates the lack of investigation into such properties when compared to the amount of research that has been conducted on the chemical, mineralogical and petrological properties of the chondritic meteorites. The physical properties which have received some attention include density (Clarke et al, 1970; Jarosewich, 1966; Keil et al, 1964; Mason, 1962, 1963, 1966; Mason and Wilk, 1961; Wasson, 1974) porosity (Alexeyeva, 1958; Engelhardt, 1963; Stacey et al, 1961), compressive strengths (Buddhue, 1942), seismic velocities (Alexeyeva, 1960), heat capacity (Alexeyeva, 1958), melting temperatures (Alexeyeva, 1958; Ivanova et al, 1968; Volarovitch and Leontieva, 1941), thermal conductivity (Alexeyeva, 1960), electrical properties (Alexeyeva and Tovarenko, 1961; Alexeyeva and Guskova, 1969; Fensler et al, 1962; Wood, 1963) and optical properties (Aronson et al, 1967; Blair and Edginton, 1968; Chapman and Salisbury, 1973; Egan et al, 1973; Gaffey, 1974; Geake and Walker, 1967; Johnson and Fanale, 1975; Sears, 1974; Sears and Mills, 1974; Veverka and Noland, 1973; Watson, 1938; Wood, 1963).

Although some of these investigations have produced data relevant to theories of the origin of chondrules and chondrites, some important physical properties which could probably provide valuable constraints appear to have been relatively neglected. It was, therefore, decided to examine some of these as the research for this thesis.
The size and shape characteristics of chondrules were thought to be able to provide valuable clues to their origin and accretion into chondrites, two fundamental, widely discussed problems in meteorite research today. These properties were examined in samples obtained by disaggregation of relatively friable meteorites. The results are presented in Chapter 4. Other investigations of meteoritic particle sizes (Dodd, 1976; King and King, 1978, 1979) have taken measurements of apparent dimensions in thin-sections. The advantages and disadvantages of this technique over disaggregation, sieving etc., and the inherent problem of conversion of apparent size-distributions to their real counterparts, are discussed in Chapter 3. The publication of the results of the analysis of the size and shape of chondrules presented in Chapter 4 (Martin and Mills, 1976, 1978) stimulated a number of others to examine the problem (Hughes, 1978a, 1978b; King and King, 1978, 1979; Gooding et al, 1978; Das Gupta et al, 1978; cf. Stakheev et al, 1973). The results of these analyses, along with a re-analysis of Hughes' (1978b) Bjurbolle sample, are discussed in Chapter 5. The following chapter, Chapter 6, deals with an attempt to try to fit chondrule mass-distribution disaggregation data to a Rosin or Weibull statistical function. These functions have been found to describe some terrestrial distributions. In the Appendix, the lunar regolith soil mass-distribution as determined from Apollo 11, 12, 14, 15 and 16 samples has been tested against Rosin's law. This law has been found to fit artificially crushed products of many kinds and sizes as well as some weathered source rocks; many lines of evidence suggest that the lunar regolith is the product of repeated impacts (crushing events) on the lunar surface.

The orientation of the long axes of chondrules in some chondritic meteorites has also been examined to look for the presence of any preferred orientation. It was thought that this might provide clues to the mode of accretion of chondrules in chondrites. The results
are presented in Chapter 7. Preferential orientation of chondrules had previously been investigated by Dodd (1965).

Various techniques have been adopted to analyse and describe the measurements presented in this thesis. Those adopted in the case of size and shape characteristics of chondrules were mainly those used in sedimentological studies. Although they have not proved entirely satisfactory, they seemed the most applicable in the light of those available. So as not to impede the course of later chapters with lengthy discussions of the techniques as they arise, it was decided to assign a separate chapter, Chapter 2, for this task.

Chapter 8, the final chapter of the thesis, draws together the results from the research presented for the thesis and discusses their significance and the constraints they place on theories for the origin of chondrules and chondrites. Other lines of evidence relevant to these problems are also discussed.

A full bibliography is given at the end of the thesis after the Appendix.

Copies of papers containing results from the research reported in the thesis published prior to the submission of the thesis are contained in an envelope at the back of the thesis.
CHAPTER TWO

TECHNIQUES ADOPTED IN THE ANALYSIS OF DATA

ON THE PHYSICAL PROPERTIES OF

METEORITIC CHONDRULES AND CHONDRITES

2.1. Introduction 27
2.2. Grade scales 28
2.3. Size analytical techniques 29
2.4. Shape analytical techniques 33
2.5. Statistical analysis of orientation data 36
2.6. Summary 37
2.1. Introduction

So as not to impede the course of future chapters with lengthy descriptions of the techniques adopted in the analysis of the data as they arise, it was decided to assign a separate chapter to this task except for the testing of the chondrule size data against the Rosin and Weibull statistical functions which occupies a complete chapter (Chapter 6). The present chapter is, therefore, concerned with outlining the techniques adopted to analyse and describe the size and shape properties of the chondrule suites from the meteorites examined and the analysis of the chondrule long axis orientation data.

The techniques adopted in later chapters of this thesis for the analysis and description of meteoritic chondrule size and shape properties are, in general, those specifically devised for and widely used in sedimentological studies. In such studies, the size distribution and shapes of particles are diagnostic in tracing the evolution and history of a sediment. However, the adoption of these techniques to the present study should not be taken to imply a direct comparison between chondritic meteorites and terrestrial sediments, rather that these sedimentological analytical techniques seem, in the light of those available, the most applicable for describing the characteristics of the chondrule size and shape data. The techniques have been widely adopted in geological (and to a lesser extent biological) studies. It is hoped, therefore, that their adoption in the present study may lead to a readier understanding of the data and its significance by those familiar with these techniques as employed elsewhere.

Despite the wide adoption of these techniques in other areas of research and their consequent documentation in many standard texts, it was nevertheless felt desirable to outline those employed in later chapters of this thesis so that the reader may be immediately aware of their former application and suitability to the present investigation.
The choice of grade scale can be significant in the analysis of size and shape data. For this reason the types and relevance of grade scales are discussed prior to the outlining of the techniques adopted in the analysis of chondrule size and shape data. Finally, the treatment of orientation data is described. A fuller description of all of these techniques may be found in Krumbein and Pettijohn (1938).

2.2 Grade Scales

The techniques adopted for the analysis and description of the size and shape properties of chondrules requires the measurement of various dimensions of each individual particle. The measurements, particularly in the case of size analyses, are then commonly arranged on some kind of size scale for convenience in conducting the analyses and in tabulating the data. The continuous scale of sizes is usually divided into a number of arbitrary divisions (or classes) - a so called grade scale is thus constructed.

If measurements are taken in, say, millimeters, each class in a grade scale is invariably of equal interval size. For example, if a series of measurements lies between zero and ten millimeters, it might be that ten classes are chosen each of one millimetre interval i.e. (10 - 9)mm, (9 - 8)mm etc. It is often the case, however, that grade scales based on equal class intervals do not always describe the properties of a distribution satisfactorily. This is particularly the case in a distribution which exhibits a large range of sizes when an interval appropriate to discriminate between particles in the lower size range of the distribution would be a negligible difference at the larger end of the size range. Conversely, in the same distribution, a grading so chosen to effectively discriminate between the largest particles would be hopelessly inadequate at the smaller size end of the distribution.

It seems, then, that a grade scale in which each grade bears a fixed size ratio to preceding and succeeding grades is often
more satisfactory in categorising a distribution. Many such grade scales have been proposed and are in common use although only one is of concern in this thesis. That is the phi ($\phi$) scale devised by Krumbein (1934) by applying a logarithmic transformation equation to Wentworth's grade scale (Wentworth, 1922) in itself a modification of Udden's grade scale (Udden, 1898). The phi scale has integers for the class limits and increases with decreasing grain size. The transformation Krumbein chose was:

$$\phi = - \log_2 d$$

where $d$ is the diameter in millimeters. The relationship between Wentworth's grades and $\phi$ units is shown in Table 2.1.

Before proceeding further, it should be stressed that, although grade scales tend to divide a distribution into a number of intervals or classes, the fact that one is generally dealing with a continuous distribution must not be forgotten.

The choice of grade scale then, is not entirely arbitrary. They serve two functions, descriptive - to place nomenclature and terminology on a uniform basis, and analytical - so that various kinds of analyses may be performed on the distribution.

2.3. Size analytical techniques

Krumbein and Pettijohn (1938) state "If all soils or sediments were composed of perfect spheres, a definition of size would be simple." Fortunately, as the shape analyses indicate (see Chapter 4), the whole segregated chondrules examined in this thesis were good approximations to spheres. Their sizes were, therefore, more readily definable.

The three principle diameters (maximum (a), intermediate (b) and shortest (c) ) of each chondrule were measured.
TABLE 2.1.

The relationship between Wentworth's grades and Phi-units

<table>
<thead>
<tr>
<th>Wentworth Grades (mm)</th>
<th>Phi (Ø)</th>
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</thead>
<tbody>
<tr>
<td>32</td>
<td>-5</td>
</tr>
<tr>
<td>16</td>
<td>-4</td>
</tr>
<tr>
<td>8</td>
<td>-3</td>
</tr>
<tr>
<td>4</td>
<td>-2</td>
</tr>
<tr>
<td>2</td>
<td>-1</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>0.5</td>
<td>1</td>
</tr>
<tr>
<td>0.25</td>
<td>2</td>
</tr>
<tr>
<td>0.125</td>
<td>3</td>
</tr>
<tr>
<td>0.0625</td>
<td>4</td>
</tr>
<tr>
<td>0.031</td>
<td>5</td>
</tr>
</tbody>
</table>
The maximum diameters were used in the analysis of the data for size properties.

The most frequently used technique for the representation of a distribution of particle sizes is the construction of a histogram. This involves the segregation of the spread of the distribution into size-ranges or classes and the number percent of particles falling into each range determined. A histogram is then plotted of number percent \( (y - \text{axis}) \) versus class range \( (x - \text{axis}) \). A vertical rectangle is drawn with a width equal to the class interval and a height proportional to the frequency in the class. Convention among sedimentologists is to plot the size scale such that values of diameter increase to the left. This procedure is adopted here.

Histograms may be constructed using both arithmetic or logarithmic (e.g. \( \varnothing \) - units) scales. In both cases it is customary for each grade to be of equal width. Therefore, if logarithmic scales are used the grades of smaller particle size represent a smaller range of sizes than the grades for larger particle sizes. For example, if intervals are of 1 \( \varnothing \) - unit, the \( +3 \) to \( +2 \varnothing \) - interval corresponds in the arithmetic scale to 0.125mm to 0.25mm, a range of only 0.125mm, whereas the \( -3 \) to \( -2 \varnothing \) - interval corresponds to an arithmetic interval from 8mm to 4mm, a range of 4mm.

A histogram then is a statistical device used to represent frequency, in this case number frequency. They give a visual display of frequency which is more readily digestible than a column of

\* Number percents are usually plotted rather than number since it allows for comparisons between distributions to be readily made.
figures. However, the choice of class interval can affect the shape of a distribution when presented in histogram form. A more accurate display of frequency may be represented by a cumulative frequency curve. This remains relatively constant regardless of the class limits adopted.

A cumulative frequency curve is constructed by plotting ordinates which represent the number frequency larger or smaller than a given diameter, resulting in the "more than" and "less than" curves respectively. The "more than" type is adopted in this thesis. As in the case of histograms, the horizontal scale may be either arithmetic or logarithmic.

It is often more difficult to visualise a distribution from an inspection of its cumulative frequency curve than from its histogram. However, cumulative curves have come into wide use because statistical values may be conveniently extracted from them. In sedimentological studies the statistical parameters of a distribution are listed to facilitate the comparison of sediment analysis and as an aid in correlation between sediment types and their environment. They are of use, therefore, in comparisons between distributions. They are used in this thesis for this purpose and, hopefully, for comparisons with chondrule size distributions obtained by others.

Inman (1952) has discussed the various statistical parameters that may be determined from a frequency size-distribution and selected five to aid in its description. The skewness and kurtosis indicate the departure of a distribution from a log-normal one. This is so since many size-distributions are found to approach normality when the logarithm of the size is used to construct the size-frequency distribution curve.

The five parameters selected by Inman were based on the percentile diameters at $Φ_5$, $Φ_{16}$, $Φ_{50}$, $Φ_{84}$, and $Φ_{95}$ extracted from the cumulative size-frequency curve plotted using sizes converted to $Φ$ units. The parameters are readily computed. They are defined in
Inman noted that in some cases it is not practicable to measure percentiles near the extremes of a distribution (i.e. $\phi_{0.00}$ and $\phi_{0.95}$) and in many cases a distribution may be adequately described by three parameters only, a measure of central tendency, a measure of dispersion, and one of skewness. It can be seen from Table 2.2 that these three primary parameters may be determined without recourse to $\phi_{0.00}$ and $\phi_{0.95}$ estimates. Although a more complete description of a distribution is furnished when all five parameters are listed, it was decided that the three primary measures would be adequate for describing the chondrule size distributions measured in this thesis.

For completeness the arithmetic mean and median diameters, standard and mean deviations for the chondrule size-distributions were also determined. For those not familiar with the calculation of these parameters, a full description is given in Krumbein and Pettijohn (1938).

2.4. **Shape analytical techniques**

Shape has often been confused with roundness. The latter is a measure of the degree of curvature of the edges and corners of a body and is, therefore, quite independent of shape. Shape is concerned with the form of a body and is, perhaps, difficult to quantify. Visual inspection of a particle may enable it to be described in broad terms such as spherical, near-spherical, disc-shaped etc. However, various systems of a quantitative nature have been devised for the description of shape for sedimentological purposes. The most relevant of these to the present study are described below. They were not found to be entirely satisfactory. There are a number of reasons for this. For example, the differences in shape among chondrules were found to be relatively small compared to variations among terrestrial sedimentary particles such as, say, pebbles in a stream. It must also be remembered
### TABLE 2.2.

Measures used in the description of a size-frequency distribution
(after Inman, 1952)

<table>
<thead>
<tr>
<th>Measure</th>
<th>Nomenclature</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central tendency</td>
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<td></td>
</tr>
<tr>
<td>Phi median diameter</td>
<td>Md$\phi$ = $\phi$ 50</td>
<td></td>
</tr>
<tr>
<td>Phi mean diameter</td>
<td>$M\phi = \frac{1}{2} (\phi_{16} + \phi_{84})$</td>
<td></td>
</tr>
<tr>
<td>Dispersion (sorting)</td>
<td>Phi deviation measure</td>
<td>$\sigma\phi = \frac{1}{2} (\phi_{84} - \phi_{16})$</td>
</tr>
<tr>
<td>Skewness</td>
<td>Phi skewness measure</td>
<td>$\alpha\phi = \frac{M\phi - Md\phi}{\sigma\phi}$</td>
</tr>
<tr>
<td></td>
<td>2nd Phi skewness measure</td>
<td>$\beta\phi = \frac{1}{2} (\phi_{95} - \phi_{5}) - \alpha\phi$</td>
</tr>
<tr>
<td>Kurtosis (Peakedness)</td>
<td>Phi Kurtosis measure</td>
<td></td>
</tr>
</tbody>
</table>
that chondrules were identified and extracted on the basis of near-spherical form and generally smooth surfaces (they were, therefore, well rounded). It is inevitable, therefore, that they would fall into limited categories in any shape analysis. It is any departure from sphericity of the chondrules that is of primary concern in the present analysis.

Most of the techniques devised for the analysis of shape involve combining and/or plotting various ratios derived from measurements of the three major axes of individual particles. This necessitates three dimensional observation of individual particles. For this reason and because of the fact that true particle size could also only be determined by such an approach, it was necessary to examine whole chondrules disaggregated from the parent meteorites.

The analyses used for shape description in this thesis are described below.

a) Zingg (1935) devised a four-class system to describe particle shape based on a comparison of the axis ratios \( b/a \) and \( c/b \). Four classes were defined as follows:

1. \( b/a > 2/3 \), \( c/b < 2/3 \) disc-shaped
2. \( b/a > 2/3 \), \( c/b > 2/3 \) spherical
3. \( b/a < 2/3 \), \( c/b < 2/3 \) bladed
4. \( b/a < 2/3 \), \( c/b > 2/3 \) rod-like

b) By plotting the ratio \( b/a \) against \( a \), Hagerman (1933) found that for some terrestrial examples he was able to utilise grain shape to mark different stratigraphic horizons, each horizon exhibiting a different field on the plot. This technique has been adopted here to compare the shape characteristics of the chondrule suites examined.
c) Wentworth (1922) has somewhat confusingly expressed the shape of a particle by a roundness and a flatness ratio. The latter he expressed as $a + b/2c$. Histograms of the flatness ratio versus frequency have been constructed from the data from the chondrule suites examined.

2.5  Statistical analysis of orientation data

The analysis of directional or oriented data often requires methods different from those used in studying conventional linear distributions. This is so for a number of reasons. For example, whereas linear observations have a reference origin defined, directions or angles are measured in terms of some completely arbitrary origin. Circular data can depend strongly on the origin selected as reference. As an instance, if $0^\circ$ is chosen as an origin and two observations are $1^\circ$ and $359^\circ$, the mean would be $180^\circ$, the opposite sense of the true direction. If $270^\circ$ is chosen as the origin, the observations will be $269^\circ$ and $271^\circ$ giving a mean of $270^\circ$ which fits the data.

In the present analysis the problem is not too severe since all that is being investigated is whether the long axes of chondrules are preferentially aligned. Clustering of data points is, therefore, being sought. Individual photographs of chondrite sections were secured to an orientometer table or thin-sections were fixed on a microscope stage and the long axis of individual chondrules aligned along a fiducial line and their nominal orientation was read. As the measurements are of the double-headed vector type, two directions may be read, one hundred and eighty degrees apart, one between $0^\circ$ and $180^\circ$ and the other between $180^\circ$ and $360^\circ$. Only that between $0^\circ$ and $180^\circ$ was taken. Results were then grouped into classes and histograms of frequency versus orientation constructed.

Mean azimuth and standard deviation have been calculated for each specimen following the method of Krumbein (1939).
This approach overcomes the problems outlined above unless there is no mode in the data and gives an indication of the degree of orientation of chondrule long-axes.

2.6. Summary

The techniques that have been adopted in this study to analyse and describe the size and shape characteristics of meteoritic chondrule suites were those designed for and employed in the study of terrestrial sediments. Although they may not, therefore, seem ideal for the present study, and they have not proved entirely satisfactory, yet they appear to be the most appropriate until more relevant techniques are developed.

Histograms have been the main statistical procedure adopted to test for preferential orientation of chondrules in chondrites.
CHAPTER THREE

AN EXAMINATION OF THE SIEVING AND THIN-SECTION TECHNIQUES IN PARTICLE SIZE-DISTRIBUTION DETERMINATION

<table>
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<tr>
<th>Section</th>
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<td>3.2. The sieving technique</td>
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<td>3.8. Conclusion</td>
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</table>
3.1 Introduction

Three techniques have in general been employed in the determination of particle sizes; measurement of whole separated particles, sieving through a series of standard apertures, and measurement of displayed dimensions in thin-section. Only the measurement of whole separated particles gives an indication of true size and has been adopted in the investigation of chondrule size-distributions in this thesis. The other two techniques, however, have the advantage of being generally quicker and easier to undertake. It will be demonstrated though that measurements from sieving and thin-sections must be approached with caution since neither technique measures true and/or maximum particle size. It is, however, worthwhile considering their effectiveness to the study of chondrule sizes especially as meteorite thin-sections are abundant since they are usually prepared as an aid in the description and classification of specimens. (The disaggregation of meteoritic material is not usually desirable because of its scarcity). Some researchers have studied the problem of chondrule size by adopting the thin-section technique. Particle shape cannot be inferred from either the sieving or thin-section techniques.

3.2 The sieving technique

Sieving is a simple, convenient, quick and widely used technique for particle size segregation in sedimentological studies. A description of the technique may be found in Krumbein and Pettijohn (1938). Briefly, particles are separated into size ranges by seeing if they pass through a series of sieves of gradually decreasing mesh size. A particle is retained on a sieve once the mesh size is smaller than the particle. However, the theory of sieving is not as simple as the practice.
Sieves sort particles not on the basis of their longest diameters, but the intermediate and shortest diameters are the deciding factors. This is so since a particle may pass through a sieve with the longest dimension perpendicular to the mesh. This is diagrammatically explained in Figure 3.1. Sieves, therefore, sort grains according to shape as well as size. However, the fact that many sands, separated into size frequency distributions by sieving, often exhibit a log-normal distribution indicates that significant data is not necessarily obscured by the process. This property of sieving though may not be a restrictive one in the case of chondrules since chondrules are, by definition, roughly spherical.

There are, however, two reasons that restrict the use of sieving to chondrule size separation. It is customary to present the frequency data obtained by sieving in terms of weight rather than numbers, though it is, of course, possible to count the number of particles in each sieve fraction. The most serious drawback to sieving in the present application is that it is not suitable for separating a distribution with a restricted range of sizes. The results presented later in this thesis demonstrate that meteoritic chondrules exhibit a very narrow range of sizes, especially when compared with many terrestrial sediments.

Friedman (1958) compared size-distributions obtained from thin-section and sieve analyses of quartz grains in individual sandstone samples (no direct measurements on disaggregated grains were made) and constructed curves to enable distributions determined from thin-section measurements to be converted to their sieve equivalents. This has often been taken to indicate conversion to true size equivalence; the arguments above indicate that this would clearly not be the case for non-spherical particles. Friedman's technique has gained wide acceptance and will be discussed more fully in the following section.
Fig. 3.1. Diagram to demonstrate how sieves sort particles on the basis of their intermediate and shortest diameters. In the lower diagram the longest dimensions of the particles A and B are perpendicular to the sieve mesh yet they may pass through the sieve. The upper diagram shows that it is the intermediate and shortest diameters of the two particles that control whether they may pass through a sieve.
3.3 The thin-section technique

Thin sections of geological materials are invariably prepared as an aid in mineralogical identification, examination of crystal relationships and relative abundances, etc. It would seem, therefore, most convenient to measure grain sizes from available thin-sections if the technique was reliable. However, if random grain diameters are measured from thin sections, the distribution of observed sections is not an indication of the grain diameters themselves. This is so since the random sections will only rarely be exactly through the centre of the grain. Invariably, therefore, the apparent size of a grain determined in thin-section will be less than its real maximum size. Grain size-frequency distributions determined from thin-section measurements will correspondingly be displaced to smaller sizes with respect to the real size frequency distribution. It is not possible to determine the real size of an individual particle from a measurement of its displayed apparent size after random slicing as in thin-section preparation.

For the reasons outlined above the feasibility of converting particle size-frequency distributions determined from thin-section measurements to true size equivalents has been extensively investigated in the past for particles of spherical and other forms and various conversion procedures developed (Chang and Dullien, 1976; Friedman, 1958; Fullman, 1953; Goldsmith, 1957; Greenman, 1951a, 1951b; Hagerman, 1924; Kellerhals et al, 1975; Kendall and Moran, 1963; Krumbein, 1935; Krumbein and Pettijohn, 1938; Nicholson and Merckx, 1969; Packham, 1955; Pelto, 1952; Reid, 1955; Roethlisberger, 1955; Rosenfield et al, 1953; Scheill, 1931; Wicksell, 1925, 1926). Only the procedures adopted for the conversion of meteoritic apparent particle-size frequency-distributions will be discussed here.
3.4 Techniques applied to meteoritic particle size data

Dodd (1976) corrected the size-distributions of meteoritic particles obtained from measurements on thin-sections of nineteen ordinary chondritic meteorites by using Friedman's conversion curves (Friedman, 1958). This method of correction was based on a comparison between the size-distributions obtained from thin-section and sieve analyses of quartz grains in individual sandstone samples. (No direct measurements on disaggregated grains were made.) In general the sieve-equivalent distribution curve was displaced to a finer range than the thin-section distribution. This result may be explained by the fact that sieves sort particles on the basis of their intermediate and shortest diameters. Friedman's technique therefore results in the corrected distribution being displaced to a finer range than exhibited by the thin-section distribution being treated. It would appear that it is not a suitable technique for conversion of thin-section particle size-distributions, (particularly of spherical particles) to real-size equivalents because real-size distributions should fall in a coarser range than their thin-section equivalents.

Hughes (1977) initially proposed the correction of thin-section distributions of chondrules by multiplying all points on the cumulative frequency curve by the common factor $\sqrt{3/2}$ but was finally convinced (Hughes, 1978) that such a technique, no matter what the value of the common factor, would never be satisfactory. This can readily be demonstrated from Fig. 3.4 where the thin-section distribution of random sections of spheres of equal size (see later) can not be brought into coincidence with its real counterpart by the multiplication of all points on the curve by any single common factor.

Hughes eventually approached the problem in a different way. After converting his determined size-frequency distribution for disaggregated Bjurbolle chondrules to a mass-frequency
distribution (in the same manner as that adopted in Chapter 6), he constructed a cumulative mass percentage curve. Hughes also constructed an expected thin section apparent size-distribution, based on his Bjurbole disaggregation data, using the technique described in Chapter 6 and converted that to a cumulative mass percentage curve. The 16th, 50th and 84th percentile values were determined from both the cumulative mass percentage curves and the ratio between the disaggregation and thin section percentile values calculated. These were found to be 1.074, 1.100 and 1.55 for the 16th, 50th and 84th percentile values respectively. Hughes considered these values to be a function of the particle size distribution, and since he concluded that the distribution also followed Rosin's law, the three values were used to correct the thin section percentiles for Bjurbole and Chainpur "droplet" chondrule and "lithic fragment" chondrule distributions. A similar approach was used to correct the mean and median thin section values for these distributions to give the "true" values expected from disaggregation.

Direct comparison can only be made between Bjurbole chondrule disaggregation and corrected thin section chondrule mean and median diameters. The mean diameter values were in fairly close agreement but the corrected thin section median diameter value was much further removed from the value obtained from the disaggregation data than was the uncorrected thin section value.

Hughes' technique may seem a relatively simple one but on closer inspection appears rather contrived. The relationship between a thin section size-distribution and its real size counterpart will become apparent later when it will be seen that Hughes' technique is not ideally applicable to other distributions than that from which it was derived. This, plus the facts that the results were not impressive and that Hughes has now decided that the relevant distributions give a poor fit to Rosin's law (see Chapter 6) suggests
that the technique is not satisfactory for the purpose of conversion of chondrule thin-section size distributions to their real counterparts.

King and King (1977, 1978, 1979) decided that no correction technique was satisfactory to convert their thin-section measurements of meteoritic particle sizes. They, therefore, presented their data untreated. Their results are discussed in Chapter 5.

It would seem, therefore, that no suitable conversion technique has been applied to the meteorite data. The problem may seem intractable. However, the advantages in deriving an accurate method made it appear worthwhile to consider the problem again. After considerable effort, a suitable technique was developed. However, it was later realised that the essentials of the technique had already been described in the literature. When Krumbein tackled the same problem (Krumbein, 1935) he also subsequently discovered that Hagerman (1924), Wicksell (1925, 1926) and Fischer (1933) had previously and independently looked for a conversion procedure. Although they had adopted different mathematical approaches, all had reached essentially the same conclusions and procedure. The explanation for these events lies in the fact that the scientists had been from different scientific backgrounds, astronomical, biological and geological. It is not surprising, therefore, that they had been unaware of the previous research and publications.

However, the procedure does not appear to have received wide application in the geological sciences despite its superiority over those more frequently used. This may be attributed to its more tedious nature — although it does appear to lend itself to computer techniques.
3.5 Random sectioning of spheres

Consider a sphere, of diameter \( d \), which is sectioned once. The plane of the section has an equal probability of cutting the sphere along any chord or the diameter. Examination of the section would reveal a circular body of (apparent) diameter \( d \). It is not possible to determine the real diameter of the original sphere from the measurement of any section of that sphere.

Now consider a monodispersed system of spheres each sectioned at random. This is diagrammatically illustrated in Figure 3.2. The problem we wish to solve is how to work backward from a distribution of two-dimensional sections to that of three-dimensional spheres.

It is a relatively straightforward matter to calculate the cumulative frequency curve that would be obtained from measurement of displayed apparent sections. This may be approached by considering the random sectioning of one sphere a number of times. Since the sphere is symmetrical we may restrict ourselves to a two-dimensional analysis with a range from 0 to \( AB \), where \( AB \) is the diameter of the sphere as demonstrated in Figure 3.3. If sectioning is parallel to the \( x \)-axis, the radius \( MN \) may be divided into a number of equal lengths, then random sectioning should result in an equal number of slices through each of the segments along \( MN \). The length of each chord separating one segment from the next is readily determined and a cumulative frequency curve of sectioned diameter computed. The curve is shown in Figure 3.4. The curve demonstrates that there is not an equal spread of apparent diameters between 0 and \( AB \) (as would be indicated by a straight line plot), but instead there is a tendency for a large proportion of the sectioned spheres to exhibit apparent diameters close to their real diameter. (More mathematical treatments of this procedure may be found in Krumbein, 1935, Hagerman, 1924, and most
Fig. 3.2. Monodispersed system of spheres if sectioned along the line AB will reveal four apparent diameters of different size.
Fig. 3.3. Sphere of diameter AB, radius MN used in the calculations in section 3.5.
Fig. 3.4. Cumulative frequency curve of apparent diameters of randomly sectioned spheres of equal size or by one sphere randomly sectioned a number of times.
texts on sedimentological analysis). From an observation of this curve it might be assumed that spheres of various sizes had been sectioned. This illustrates the general effect of sectioning and emphasizes that from observations alone it cannot be argued that an approach to the true frequency curve has been obtained. In practice, of course, the picture is even more complex since polydispersed systems are usually encountered. It is also generally the case that the particles under examination are not true spheres. However, here we are restricting the problem to spherical objects. It is also possible to consider a polydispersed system as a mixture of monodispersed systems.

It is possible to describe the derived cumulative number frequency curve of sectioned monodispersed spheres (Figure 3.4) mathematically. The fractional number, F, of diameters observed between AB and a chord, d, is:

\[ F = \frac{\sqrt{AB^2 - d^2}}{AB} \quad 3.1 \]

The fraction, F, having diameters between two chords (or apparent diameters) \( d_1 \) and \( d_2 \) where \( d_1 > d_2 \) is:

\[ F = \frac{\sqrt{AB^2 - d_2^2} - \sqrt{AB^2 - d_1^2}}{AB} \quad 3.2 \]

This relationship enables the fraction of diameters in a size range contributed by random sectioning of spheres of equal known size to be determined.
3.6 The conversion technique

The relationships outlined above for a monodispersed system of spheres may be extended to a polydispersed system and forms the basis of the correction technique.

In a polydispersed system of spheres random sectioning will likewise produce a distribution in sizes of the revealed circular sections. However, the problem is complicated by the fact that spheres with different diameters will contribute sections of the same size. If is, therefore, necessary to determine the source of each section before correction. Figure 3.5 schematically illustrates how spheres of five different sizes can, when sectioned, contribute circular sections of the same size.

In a distribution of section diameters revealed after random sectioning of a polydispersed system of spheres, as chondrules in a meteorite thin-section may be considered to be, after arrangement into class intervals or size ranges, only the sections in the largest size can unambiguously be identified, they are sections of the largest particles with diameters very close to their sectional diameters. The sections in the largest size range cannot have been produced by sectioning of particles with diameter outside the range.

If it is assumed that particles with diameters in the largest size range have a diameter equal to the mid-point of the size range it is possible, using equations 3.1 and 3.2, to calculate the fractional number of sections in each range produced by random sectioning of the largest particles. Since the sections in the largest size range are identified as belonging to the largest particles only and the number of sections (O) in this range is known, it is an easy matter to calculate the actual number of particles, N, of those observed with a diameter in the largest size range since -
Fig. 3.5. Diagram to illustrate how five spheres of different true diameters can, when sectioned, contribute apparent circular sections of equal size.
\[ N = \frac{O}{F} \]

where \( F \) is the calculated frequency.

The number of particles with diameters in this range but whose sections fall outside it may be estimated for each size range since

\[ M = N \cdot F^* \]

where \( M \) is the number in a range where the calculated frequency is \( F^* \). These 'interfering' sections must be removed from the remaining classes before proceeding further.

The next largest size class may now be treated as above and so on until the last, smallest, size range is reached. The number of sections remaining in that range after correction of all the other ranges is equal to the number of particles observed with diameters in that range.

It can be seen that each subtracted term depends on the previously calculated values. The technique is based on probability. The number of smallest particles may therefore be, to some extent, inaccurately estimated because of accumulated errors.

Despite these errors and the assumptions involved, it is possible, using the technique outlined above, to determine to a reasonable degree of accuracy the real size frequency distribution from the size frequency distribution of displayed sections after random sectioning of a polydispersed system of spherical particles.

A more mathematical approach to the whole problem and its solution along the lines described above may be found in Underwood (1970).
3.7 The technique is tested

The technique has been tested in the following manner. Known numbers of 3/16" (4.8mm) and 1/8" (3.2mm) diameter bronze spheres were mixed with bakelite chips by an independent party. The mixture was then fused under pressure in a metallurgical mounting press. No prior information on its constituents was imparted.

After sectioning, the apparent diameters of the sectioned spheres on all but the last slice were measured. (The last slice was omitted in case some of the spheres accumulated at the bottom during fusion, resulting in a non-random distribution). Apparent diameters were measured using a binocular microscope containing an eyepiece scale. These scalar readings were later converted into millimeters. In some cases the smaller parts of the bronze spheres fell out of the block during sectioning, but it was still possible to measure the surface diameter of the cavity.

The two-hundred and fifty observed apparent diameters were arranged into suitable size classes, and a size-distribution histogram constructed as shown in Figure 3.6. The histogram exhibits a spread in sizes with a peak at 3.2-2.8mm and possibly another at 4.8-4.4mm. The data was corrected using the technique described above. A new histogram was constructed, also shown in Figure 3.6. The corrected distribution shows two clearly defined peaks at the positions of the poorly defined peaks in the uncorrected distribution. The numbers outside these peaks are greatly reduced. (The correction was not, however, applied to a class when the number after removal of 'interfering' particles fell to a low or negative value). The block actually contained one-hundred of the larger spheres and two-hundred of the smaller ones. The correction technique cannot correct for unobserved particles, thus the ratio of particles in the two peaks (or the number percents) in the real and corrected samples should be in good agreement
Fig. 3.6. Dashed line - size distribution histogram of observed apparent diameters of the sectioned spheres. Continuous line - size distribution after correction using the technique described in section 3.6.
TABLE 3.1.

Results of the ratio and number percent of diameters in the peaks in the real, uncorrected sectioned and corrected sectioned distributions of two sizes of bronze spheres embedded in bakelite.

<table>
<thead>
<tr>
<th></th>
<th>Ratio</th>
<th>Number percent in</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>largest : smallest spheres*</td>
<td>largest</td>
</tr>
<tr>
<td>Real</td>
<td>1 : 2</td>
<td>33.3</td>
</tr>
<tr>
<td>Uncorrected</td>
<td>1 : 2.6</td>
<td>11.6</td>
</tr>
<tr>
<td>Corrected</td>
<td>1 : 1.8</td>
<td>35.9**</td>
</tr>
</tbody>
</table>

* Number in largest size peak normalised to 1.0

** Number outside the peaks omitted
if the technique is satisfactory. These values for the real, corrected and uncorrected distributions are shown in Table 3.1. The figures indicate that the real and corrected values are in good agreement.

The effectiveness with which the technique resolved the distribution peaks, and the close agreement between the relative numbers in the peaks in the real and corrected samples, demonstrates the validity of the method. The analysis implies that the proposed technique is suitable for many natural distributions.

3.8 Conclusion

The technique described above seems capable of correcting size frequency distributions of chondrules determined from thin-section measurements to their real size counterparts. This would enable comparisons of chondrule size distributions to be made whether the disaggregation or thin-section techniques have been employed.

It may seem strange that the technique, since it is widely described in the literature, has not already been used in this context. However, even after exhaustive searches the author was not aware of its prior existence. It would seem that the technique has not been described in the literature usually referred to by meteorite researchers. The fact that examination of the size-distribution of chondrules has only recently been investigated may also be of significance. It is hoped, however, that the technique will be used in this context in the future.
CHAPTER FOUR

SIZE AND SHAPE OF METEORITIC CHONDRULES

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4.6 Summary of results from friable meteorites 78
4.7 Attempted disaggregation of a less friable meteorite - Parnallee 78
4.1 Introduction

Considerable research has been undertaken into the chemical and mineralogical constitution of chondrules (in particular see De Gasparis et al (1975); Dodd and Walter (1973); Graham (1975); McSween (1977); Osborn and Schmitt (1971); Osborn et al (1973, 1974); Walter (1969); Walter and Dodd (1973) in order to obtain constraints on origin. In contrast their physical properties have received little attention. It would seem, though, that their size and shape characteristics might provide equally valuable insights into their formation mechanism. Perhaps the difficulty of segregating chondrules from matrix has hindered research in the field.

Despite this lack of quantitative results on the physical properties of meteoritic chondrules, most texts on meteorites give an indication of chondrule sizes and emphasize their near-spheroidal form, presumably determined from thin-section examinations. Mason (1952) states that chondrules are ".... commonly about 1mm in diameter ....". Nininger (1952) refers to ".... the vast majority being less than 2mm in diameter ....". Similarly, Wasson (1974) contends chondrules are ".... usually a few tenths of a millimeter to a few millimeters in diameter ....". Most recently Sears (1978) describes that in thin section under the microscope ".... most chondrites are seen to consist of large (say 2mm), circular chondrules ....".

Stakheev et al (1973) reported briefly on the size distribution of whole separated chondrules from the Nikolskoe, Elenovka, Saratov and Bjurbolle L-group chondritic meteorites. The data was also reported by Lang et al (1975) though in neither case did it receive its due significance - the original article was published in Russian, the later one was only an abstract.
Dodd (1976) reported on the size-distribution of metal and silicate particles (including chondrules) obtained from measurements on thin sections of nineteen unequilibrated ordinary chondrites. It was this research that stimulated the present study. However, it was decided for the present study that a more specific approach was necessary so as to obtain constraints on chondrule origin. Observations were restricted to whole separated chondrules only. The publication of the results presented in this chapter (Martin and Mills, 1976, 1978) influenced a number of others to also examine the size distribution of chondrules in particular.

Hughes (1978a, b) has conducted a disaggregation and thin-section analysis of the size of chondrules in the Bjurbole meteorite and a thin section analysis of chondrules from the Chainpur meteorite. King and King (1978, 1979) have examined the grain size in ordinary, C2 and C3 chondrites. A number of presentations at the 41st annual meeting of the Meteoritical Society (Sudbury, Ontario, Canada, August 1978) discussed the size of chondrules (Das Gupta et al, Gooding and Keil, Carl and Herr). Further discussion of the results of these investigations is reserved for the following chapter which deals with an intensive comparison of them along with those presented here.

4.2 Material

In order to measure both the size and shape of chondrules, whole, separated specimens were required. It is difficult to separate chondrules from matrix in most meteorites. In a few cases, however, the meteorites are relatively friable greatly facilitating chondrule extraction. It was decided to utilise this property for selecting material for preliminary investigation.
As their friability makes this type of meteorite unusually rare, it might be argued that chondrules from them may not be truly representative of meteoritic chondrules. On the other hand, however, this property and the generally low degree of metamorphism of these meteorites rather indicates that their chondrules are more likely to be in their primary configurations, and consequently more valuable to obtain constraints on origin. It is also very likely that friable chondrites are more abundant in space than estimates from terrestrial meteorite falls would suggest. Many would be expected to break-up during their passage through the atmosphere with a consequent low probability of recovery.

Three relatively friable meteorites were chosen for chondrule extraction - Bjurbole (L4), Chainpur (LL3) and Allegan (H4). The Bjurbole and Chainpur material was kindly supplied by Dr. Brian Mason of the Department of Mineralogy, Smithsonian Institution, Washington, U.S.A. Dr. R. Hutchison of the Department of Mineralogy, British Museum (Natural History) kindly provided the Allegan sample (Museum number BM 1920, 281).

4.3. Sampling

The Bjurbole and Chainpur material was, upon receipt, mostly disaggregated. Some gentle crushing was necessary to separate chondrules from matrix. The chondrules were extracted by hand-picking and cleaned with simple mechanical tools. During this procedure some chondrules fragmented. A microscopic examination of these fragments showed their surfaces to have a very fine, even matrix coating. However, this coating was too thin to affect the measurements significantly. No further cleaning techniques were employed.

The chondrules were distinguished from other particles on the basis of their near-spherical form and generally smooth surfaces.
Ninety-seven chondrules were extracted from the Bjurbole sample, and two hundred and forty-five from Chainpur.

The Allegan sample was somewhat different. Two fractions comprised the 10.7g of material - approximately 6.2g of angular chunks and 4.5g of finer, disaggregated material. Only the latter was used for chondrule extraction. This fraction was sieved to remove the very finest-grained material (< 0.2mm) which tended to obscure chondrules. The remainder (~2.9g) was intensively examined under a binocular microscope for chondrules which were identified, removed and cleaned as before. The < 0.2mm material was also examined for chondrules but none were found. It became increasingly more difficult with decrease in size to decide whether some particles were indeed chondrules.

4.4 Measurement

Individual chondrules from each meteorite were viewed by means of two binocular microscopes, one arranged vertically, the other horizontally. Magnifications of 16x, 25x, 40x, 62.5x and 100x were used depending upon the size of chondrule under examination. Both microscopes were equipped with identical calibrated eyepiece scales against which the maximum length (a), breadth (b) and width (c) of each chondrule were measured. The scale readings were later converted into millimeters and phi (φ) units (see Chapter 2).

4.5 Results

4.5.1 Size distribution

The maximum diameters (mm values) of the chondrules from each meteorite were arranged into classes and comparative histograms of the number in each class constructed. The size-distribution histograms for Bjurbole and Chainpur chondrules are shown in Figure 4.1, and for Allegan chondrules in Figure 4.2.
Fig. 4.2. Size distribution histogram of chondrule maximum diameters (mm) in the Allegan meteorite.
In all three cases the distributions are negatively skewed, exhibiting a rapid rise from the smallest diameter to a well-defined peak and, after a sharp drop from this peak, a more gradual fall-off in number with increase in diameter. However, the position of the peak in each distribution and the size-ranges are somewhat different. In Bjurbole, the spread of chondrule sizes was found to be from a lower limit of 0.4mm up to 2.2mm with a peak in the distribution between 0.8mm and 1.2mm. 50.7% of the chondrules from Bjurbole fall into this range, 10.4% have diameters below 0.8mm, leaving 38.9% exhibiting diameters greater than 1.2mm. The results for Chainpur chondrules are fairly similar but here the distribution spreads from the same lower limit of 0.4mm to a slightly larger upper limit of 2.4mm. The distribution peak is displaced slightly with respect to the Bjurbole peak so as to fall between 0.6mm and 1.00mm. 45% of Chainpur chondrules are contained within this peak, 9.8% have smaller diameters, and 46.9% have larger diameters.

In contrast the Allegan chondrule size distribution exhibits some notable differences. The lower limit cut-off lies at the smaller diameter of 0.15mm and the upper limit cut-off at the larger diameter of 2.75mm. The peak in the distribution is notably different to the Bjurbole and Chainpur chondrule size-distribution peaks lying between 0.35mm and 0.75mm. 66.0% of the Allegan chondrules have maximum diameters in the distribution peak, only 7.3% have smaller maximum diameter than the peak and 26.7% have larger maximum diameters. Consequently the data suggests that although Allegan chondrules exhibit a larger range in sizes than do chondrules from Bjurbole and Chainpur, the peak in the size-distribution is at a lower size range but is more well defined as it encompasses a greater percentage of chondrules. The data is emphasized in Table 4.1.
### TABLE 4.1.

Some characteristics of the size distributions of chondrules from the Bjurbole, Chainpur and Allegan meteorites.

<table>
<thead>
<tr>
<th></th>
<th>Lower limit (mm)</th>
<th>Upper limit (mm)</th>
<th>Spread (mm)</th>
<th>Distribution Peak (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bjurbole</td>
<td>0.4</td>
<td>2.2</td>
<td>1.8</td>
<td>0.8 - 1.2</td>
</tr>
<tr>
<td>Chainpur</td>
<td>0.4</td>
<td>2.4</td>
<td>2.0</td>
<td>0.6 - 1.0</td>
</tr>
<tr>
<td>Allegan</td>
<td>0.15</td>
<td>2.75</td>
<td>2.60</td>
<td>0.35 - 0.75</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Below distribution peak</th>
<th>Within distribution peak</th>
<th>Above distribution peak</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bjurbole</td>
<td>10.4</td>
<td>50.7</td>
<td>38.9</td>
</tr>
<tr>
<td>Chainpur</td>
<td>9.8</td>
<td>43.0</td>
<td>46.9</td>
</tr>
<tr>
<td>Allegan</td>
<td>7.3</td>
<td>66.0</td>
<td>26.7</td>
</tr>
</tbody>
</table>
When the phi values are used in the construction of size-distribution histograms, the distributions become more symmetrical, reflecting a log-normal distribution of chondrule sizes (see Figs 4.3 and 4.4). This is more apparent in the case of Chainpur and Allegan for Bjurbolle tends to retain a prominent peak whatever the choice of the class intervals. This is probably a result of the statistically small number of chondrules examined from Bjurbolle.

Cumulative number frequency curves of chondrule maximum diameters (\(g\) units) for the three meteorites are shown in Figs. 4.5 and 4.6. From these curves the 16th, 50th and 84th percentiles were extracted and used in the calculation of the statistical parameters following Inman (1952) (see Chapter 2). These parameters, along with those calculated from the mm-size data, are presented in Table 4.2. The differences in the distribution peaks for the three chondrule suites is reflected in different values for the calculated mean and median diameters of each distribution, whereas the overall similarity in shape of the three distribution curves is reflected by similar values for deviation and skewness measures.

4.5.2 Shape analysis

The sedimentological techniques adopted to analyse for shape have been outlined in Chapter 2 where it was pointed out that they have not proved entirely satisfactory as the differences in shape among the chondrules are relatively small compared with, say, pebbles in a stream. In the absence of any better alternatives, however, the conventions adopted seem the most appropriate.

The ratios \(b/a\) and \(c/b\) have been determined for each chondrule and the appropriate class as devised by Zingg (1935) determined. In Bjurbolle only 1 chondrule of the 97 examined falls into the class i (disc-shaped) category, the remainder (\(\sim 98\%\)) falling into the spherical class, class ii. The picture for Chainpur is very similar with 2 out of 235 class i chondrules and 243 (\(\sim 98\%\)) class ii chondrules.
Fig. 4.3. Size distribution histogram of chondrule maximum diameters (Φ-units) in the Bjurböle and Chainpur meteorites.
Fig. 4.4. Size distribution histogram of chondrule maximum diameters (Ø-units) in the Allegan meteorite.
Fig. 4.5. Cumulative frequency curves of chondrule maximum diameters (Ø-units) in the Bjurböle and Chainpur meteorites.
Fig. 4.6. Cumulative frequency curve of chondrule maximum diameters (φ-units) in the Allegan meteorite.
TABLE 4.2.

Statistical parameters for the size distribution of Bjurbole, Chainpur and Allegan chondrules.

<table>
<thead>
<tr>
<th>Parameters from major-axis data*</th>
<th>Bjurbole</th>
<th>Chainpur</th>
<th>Allegan</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arithmetic mean (mm)</td>
<td>1.18</td>
<td>1.09</td>
<td>0.57</td>
</tr>
<tr>
<td>Median (mm)</td>
<td>1.12</td>
<td>1.02</td>
<td>0.60</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>1.11</td>
<td>1.42</td>
<td>1.07</td>
</tr>
<tr>
<td>Mean deviation</td>
<td>0.28</td>
<td>0.37</td>
<td>0.23</td>
</tr>
<tr>
<td>Percentiles (φ) **</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>-0.575</td>
<td>-0.68</td>
<td>0.17</td>
</tr>
<tr>
<td>50</td>
<td>-0.14</td>
<td>0.05</td>
<td>0.75</td>
</tr>
<tr>
<td>84</td>
<td>0.20</td>
<td>0.64</td>
<td>1.28</td>
</tr>
<tr>
<td>Parameters from (φ) percentiles **</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>median diameter</td>
<td>-0.14</td>
<td>0.05</td>
<td>0.75</td>
</tr>
<tr>
<td>mean diameter</td>
<td>-0.187</td>
<td>-0.02</td>
<td>0.725</td>
</tr>
<tr>
<td>deviation measure</td>
<td>0.388</td>
<td>0.66</td>
<td>0.56</td>
</tr>
<tr>
<td>skewness measure</td>
<td>-0.12</td>
<td>-0.11</td>
<td>0.045</td>
</tr>
</tbody>
</table>

* After Krumbein and Pettijohn (1938)
** After Inman (1952)
Similarly, 99% of the Allegan chondrules fall into class ii, 0.6% into class i and 0.4% into the rod-like class, class iv. In no case did a chondrule fall into the class iii (bladed) category. The observation of 0.4% of Allegan chondrules falling into class iv whereas none were observed in this category from Bjurbole and Chainpur is perhaps not significant since 0.4% of the total number of chondrules examined represents <1 in the case of Bjurbole and \( \sim 1 \) in Chainpur. In all three cases there was found to be no preference for one of the axis ratios b/a or c/b to predominate.

Figs. 4.7 and 4.8 shows the boundaries of the distribution fields of a plot of b/a versus a for individual chondrules from each meteorite, as utilised by Hagerman (1936). In the case of Chainpur and Allegan it was found that another boundary encompassing a smaller area, yet still containing within it the majority of the chondrules, could be drawn and are shown in the figures. In the case of Allegan this is quite marked. It would seem that these more closely mark the boundaries of the chondrule distribution fields, those few specimens falling outside being anomalous. When these less extensive distribution fields for Chainpur and Allegan and that for Bjurbole are compared they are found to be remarkably similar, that for Allegan being slightly less extensive than those of Bjurbole and Chainpur.

Fig. 4.9 and 4.10 represents histograms of Wentworth's ratio \((a + b/2c)\) versus number per cent in each class for the chondrule suites. Once again, although there are small differences between the histograms they are all very similar in their major trends.

The above methods for analysing particle shape demonstrate three significant points in the case of the chondrules examined. First, the chondrules examined depart from sphericity by only small degrees; second, any such departures appear random (i.e. there is no preferential chondrule shape), and finally, the suites of
Fig. 4.7. Field boundaries of Hagerman plot of chondrules from the Bjurböle and Chainpur meteorites.
Fig. 4.8. Field boundary of Hagerman plot of chondrules from the Allegan meteorite.
Fig. 4.9. Histogram of Wentworth's ratio \((a+b/2c)\) for chondrules from the Bjurböle and Chainpur meteorites.
Fig. 4.10. Histogram of Wentworth's ratio $(a+b/2c)$ for chondrules from the Allegan meteorite.
chondrules from the three meteorites, Bjurbole, Chainpur and Allegan are extremely similar in their shape properties.

4.6 Summary of results from friable meteorites

The results on the size-distribution of chondrules from the meteorites Bjurbole, Chainpur and Allegan presented here indicate that although the shapes of the size-distributions are similar in all three cases and the actual size ranges of chondrule maximum diameters are similar, proportionally many more chondrules with maximum diameters in the smaller end of the size range (< 0.8mm) were observed in Allegan, resulting in the displacement of the distribution peak from ~1.0mm as found in Bjurbole and Chainpur to 0.75mm - 0.35mm in Allegan. Chondrule mean and median diameters were similarly affected.

On the other hand, all three chondrule suites are remarkably similar in their shape characteristics.

Further discussion of these results is reserved for the following chapter, Chapter 5, where they are compared with chondrule size-distributions determined by other researchers.

4.7 Attempted disaggregation of a less friable meteorite - Pamallee

In order to extend the analysis of chondrule size and shape it was decided to attempt to extract chondrules from a less friable meteorite than Bjurbole, Chainpur and Allegan. Dr. R. Hutchison of the British Museum (Natural History) kindly donated a sample of approximately 12 grams of Pamallee (off BH 34792). The sample was split into two approximately equal halves, one half was sent to Dr. D.W. Hughes, Sheffield University to attempt disaggregation separately.

Dr. K. Fredriksson of the National Museum of Natural History, Smithsonian Institution, Washington, D.C., U.S.A., had separated some meteoritic chondrules from surrounding material using a
gentle freeze-thaw technique. Dr. Fredriksson (personal communication) kindly supplied details of this technique and it was decided to adopt it on the remaining Parnallee split.

The sample was immersed in distilled water in a PTFE container and placed in a vacuum dessicator overnight to aid the water to seep into any cracks and pores. The assemblage was removed from the dessicator and placed in liquid nitrogen until the distilled water froze. It was then transferred to a bath of hot water to melt the distilled water ice. The procedure was repeated for a number of days. Unfortunately, the sample remained totally intact. Dr. S. Rajan of the Department of Terrestrial Magnetism, Carnegie Institute, Washington D.C., U.S.A., kindly allowed an attempt at disaggregation of the Parnallee sample using apparatus constructed by him. The technique was essentially the same except that the immersed sample was transferred from liquid nitrogen to a bath of hot water automatically at appropriate preselected intervals. The sample was thus subjected to the freeze-thaw technique for longer periods of time. At intervals the assemblage was placed in an ultrasonic bath to aid disaggregation. Once again the sample remained intact.

As a last attempt at disaggregation it was decided to subject the immersed specimen to very intense ultrasonic vibration from an ultrasonic drill. Even this proved fruitless.

Using similar techniques, Dr. D.W. Hughes also was unable to disaggregate his Parnallee split.

It was not possible, therefore, to examine the size and shape of chondrules from the Parnallee meteorite.
CHAPTER FIVE.

A COMPARATIVE SURVEY OF CHONDRULE

SIZE DISTRIBUTIONS

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<tr>
<td>5.6. Summary</td>
<td>99</td>
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</tbody>
</table>
5.1. Introduction

Other reports have been published dealing with the size distribution of meteoritic chondrules as well as the results presented in the previous chapter of this thesis. Both the disaggregation and thin-section techniques have been applied to the problem. Despite the inherent difficulties with the treatment of data obtained by the thin-section technique, as outlined in Chapter 2, it is possible and instructive to compare the available results. This is particularly so in the case of Bjurbole whose chondrules have been examined in the present study, by Hughes (1978a) and by Stakheev et al (1973). Differences between the results of Hughes and those presented in this thesis, despite similar techniques, instigated an examination of Hughes' Bjurbole material by the present author. The results are presented in this chapter.

5.2. Analyses from measurements on thin-sections

There have been four major examinations of meteoritic particle sizes adopting the thin-section approach, in the ordinary chondrites by Dodd (1976) and King and King (1979), in types 2 and 3 carbonaceous chondrites by King and King (1978), and in Bjurböle and Chainpur by Hughes (1978a).

Dodd segregated his meteoritic particle size measurements on the basis of metal or silicate particle only. He did not differentiate chondrules from other silicate particles and imposed a limit such that only particles exhibiting an apparent diameter greater than 0.1mm were measured. Dodd's results are not, therefore, ideally suitable for the comparative purposes of this chapter. They will not, therefore, be discussed at length.
In their study of the carbonaceous chondrites, King and King classified each silicate particle on which they took measurements as either, (1) fluid drop or lithic chondrule, (2) mineral, lithic or chondrule fragment, or (3) other. Only in the case of fluid drop chondrules did they measure sections less than 0.1 mm apparent diameter. Chondrule fragments were defined as being "less than one-half of whole chondrules ...". It is unfortunate, therefore, that in this analysis of chondrule size data and the construction of cumulative number percent frequency curves, chondrule fragment measurements were also included. Cumulative number frequency curves were also presented for the fluid drop chondrule data only. Their observations indicated that such particles are rare in the C2 and C3 meteorites, ranging from a minimum of 0.1 to a maximum of 3.12 volume percent in Cold Bokkeveld and Murchison respectively.

Although King and King do not disclose the number of measurements of fluid drop chondrules, it is obvious that such measurements were extremely limited. The total number of particles in their chondrule and chondrule fragment category ranged from only 13 to 82 with the exception of Murchison where 240 measurements were taken. The number of fluid drop chondrules must, therefore, be extremely low indeed. This paucity of measurements resulted in cumulative number frequency curves being constructed for only ten of the twelve meteorites they examined. These cumulative curves were far from smooth. It does not seem wise to discuss King and King's fluid drop chondrule data for the carbonaceous chondrites further.

The restricted number of measurements, the inclusion of chondrule fragment measurements and the fact that uncorrected apparent dimensions were used in the analyses, suggest that King and King's all chondrule results should be treated with caution. Nevertheless, it will be seen later that the analyses indicate some significant points.
In their study of the ordinary chondrites, King and King restricted their size measurement to fluid drop chondrules only. The measurement technique and compilation of data were identical to those adopted in their previous study of the carbonaceous chondrites. It appears that many more measurements of fluid drop chondrule size were taken in the case of the eleven ordinary chondrites examined, ranging from twenty-eight in Bishunpur to one hundred and fifty-three in Clovis. In four cases, more than one hundred measurements were taken. It is a pity, therefore, that individual cumulative number frequency curves were not shown though they all fell within a rather restricted envelope.

The size distribution of chondrules in the Bjurbole and Chainpur meteorites have been examined in thin-sections by Hughes (1978a) who classified chondrules into droplet and lithic fragment categories. Although the two sections from which measurements were taken are poorly reproduced in the relevant publication, the present author would argue with Hughes' identification of some particles in these sections as chondrules. This is borne out by the large estimated areal percentages of chondrules in the sections, 33% and 30%, 35% and 32% for droplet and lithic fragment chondrules in Bjurbole and Chainpur respectively. Arguments against Hughes' correction technique for these apparent size distributions have been presented in Chapter 3. These points plus the statistically small number of measurements, 118 in Bjurbole and 182 in Chainpur, suggest that this data obtained by Hughes should be treated with caution.

5.3 Analyses from measurements on whole separated chondrules

In his study of meteoritic chondrule size, Hughes also examined whole separated chondrules from Bjurbole. Chondrules were extracted and identified using the same technique as employed in the
disaggregation studies in this work. Extracted specimens were photographed en masse and their maximum dimensions were measured using a millimetre rule from an enlarged reproduction of the photographic negative. The data were analysed along the lines adopted in this thesis. The results are discussed in the following section.

Stakheev et al (1973) separated a large number of chondrules from the four L-group meteorites Saratov, Nikolskoe, Elenovka and Bjurbole. Measurements were grouped into 0.1mm size ranges on the basis of their median diameters. The weight of chondrules in each class was also determined. The number frequency data are given in Table 3.1. Size distribution histograms have been constructed from this data and are presented in sections 5.4 and 5.5 of this chapter. Without having seen the segregated particles or photographs of them, it is impossible to comment on their identification and classification as chondrules. However, attention is drawn to the discussion of this data in Chapter 6.

Das Gupta et al (1978) and Gooding et al (1978) have briefly reported on the results of measurements of the size of whole, separated meteoritic chondrules. The results are also discussed in section 5.5.

5.4 Size distribution of chondrules in the Bjurbole meteorite

The friability and availability of material has resulted in the investigation of the size-distribution of chondrules in the Bjurbole meteorite by a number of researchers, as outlined in the previous sections. Bjurbole chondrule size distribution histograms constructed from measurements on whole separated chondrules as determined in this study, by Hughes (1978a) and by Stakheev et al (1973), are presented in Figure 5.1. Although all three curves exhibit the same general trends, a sharp rise from a lower limit cut-off to a well defined peak followed by a more gradual fall off in number with increase in size,
<table>
<thead>
<tr>
<th>Size Range (mm)</th>
<th>Saratov number in class</th>
<th>percent in class</th>
<th>Nikolskoe number in class</th>
<th>percent in class</th>
<th>Elenovka number in class</th>
<th>percent in class</th>
<th>Bjurbolle number in class</th>
<th>percent in class</th>
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<td>0.3</td>
<td>1</td>
<td>0.1</td>
<td>1</td>
<td>0.1</td>
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Fig. 5.1. Size distribution histograms of chondrules from the Bjurbole meteorite. Thick continuous line, Hughes (1978a); thin continuous line, Stakheev et al (1973); dashed line, Chapter 4.
there are notable differences in the positions of the distribution peaks and the lower limit cut-off points. Differences in the distributions are also reflected in the values for the mean and median diameters and $\phi_{50}$ given in Table 5.2. The distributions determined by Stakheev et al and Hughes are closely similar. The displacement of the histogram of Stakheev et al's data to the smaller end of the scale may be explained by the fact that median diameter values were used in its construction, Hughes used maximum diameter values. In contrast to these two distributions, that constructed from the present study is displaced to the larger end of the size range. It was, therefore, decided to check Hughes' results.

The Bjurbolle material examined by Hughes was kindly supplied by Dr. R. Hutchison, British Museum (Natural History). The sample number was BMNH 1927, 11. The material was in two fractions - one consisted of the objects identified as chondrules by Hughes, the other contained the remaining material. The latter fraction was examined under a binocular microscope for chondrules, adopting the same identification techniques as described in Chapter 4, but none were found. Particles in the former fraction were also viewed under the binocular microscope and whole particles identified by the author as chondrules were removed. Three hundred and seventy-two such objects were distinguished compared to the nine hundred and fifty-five segregated by Hughes. The particles classified by Hughes as chondrules, but discounted by the author, were discarded on the basis of being either chondrule fragments (in some cases chondrules may have fragmented during the period between the return of the material to the British Museum (Natural History) and its receipt and examination by the author), mineral fragment or possessing an irregular surface and/or non-spherical form. No particle was observed to have a smooth surface and form other than near-spherical.
TABLE 5.2.

Mean and median diameter, \( d_{50} \) and \( \phi_{50} \) values for chondrule size distributions from the Bjurbole meteorite as determined by Martin, Hughes and Stakheev et al.

<table>
<thead>
<tr>
<th></th>
<th>Bjurbole</th>
<th></th>
<th></th>
</tr>
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<tr>
<td></td>
<td>Martin</td>
<td>Hughes</td>
<td>Stakheev et al</td>
</tr>
<tr>
<td></td>
<td>(Chapter 4)</td>
<td>(1978a)</td>
<td>(1973)</td>
</tr>
<tr>
<td>Mean diameter (mm)</td>
<td>1.18</td>
<td>0.74</td>
<td>0.51</td>
</tr>
<tr>
<td>Median diameter (mm)</td>
<td>1.12</td>
<td>0.66</td>
<td>0.41</td>
</tr>
<tr>
<td>( \phi_{50} )</td>
<td>-0.14</td>
<td>0.60</td>
<td>1.29</td>
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</table>
Particles identified as chondrules were viewed individually under a binocular microscope containing an eyepiece scale against which the maximum diameter was measured. The scalar readings were later converted into millimeters and Φ-units which were used in the construction of a size-distribution histogram and the calculation of the statistical parameters. The histogram is shown in Figure 5.2 with that constructed by Hughes for comparison. Reference to this figure shows that, despite the difference in the number of particles identified as chondrules, the two distributions are in good agreement. This similarity is reflected in the statistical parameters determined from the two distributions, presented in Table 5.3.

The weight per cent of chondrules in the Bjurbole meteorite based on the present analysis was calculated to be 10.7 compared to Hughes' estimate of 27.1 weight per cent chondrules. The value of 10.7% compares quite well with the estimate for Allegan chondrules given in Chapter 4 (13%) and the estimates from areal percent count of chondrules in CO3 (1.21% - 8.16%) and CV3 (3.54% - 21.30%) meteorites by King and King (1978).

The close agreement in the results from this dual analysis of the same material and their similarity to the results of Stakheev et al on the size distribution of Bjurbole chondrules raises the question as to why the result of the Bjurbole chondrule analysis presented in Chapter 4 is so different. There are two possible explanations:

1) Bjurbole is inhomogeneous with respect to chondrule size. It is worth mentioning that King and King have detected bedding or layers exhibiting different particle sizes and/or types, in many carbonaceous chondritic meteorites.

2) The Bjurbole chondrule size distribution presented in Chapter 4 is in error since a representative suit of chondrules
Fig. 5.2. Size distribution histograms of chondrules from the same specimen of the Bjurbolle meteorite as determined by Hughes (1978a) (continuous line) and the author (dashed line).
**TABLE 5.3.**

Statistical parameters for the size distribution of chondrules from the Bjurbolle meteorite (sample BMNH 1927,11) as determined by Martin and Hughes.

<table>
<thead>
<tr>
<th>Parameters from major-axis data *</th>
<th>Bjurbolle (BMNH 1927, 11)</th>
<th>Martin</th>
<th>Hughes (1978a)</th>
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<tr>
<td>Arithmetic mean (mm)</td>
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<td>0.74</td>
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<tr>
<td>Median (mm)</td>
<td>0.62</td>
<td>0.66</td>
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<tr>
<td>Percentiles (φ) **</td>
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<tr>
<td>16</td>
<td>1.22</td>
<td>1.29</td>
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<tr>
<td>50</td>
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<td>84</td>
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<td>-0.26</td>
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</table>

<table>
<thead>
<tr>
<th>Parameters from (φ) percentiles **</th>
<th>Bjurbolle (BMNH 1927, 11)</th>
<th>Martin</th>
<th>Hughes (1978a)</th>
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</thead>
<tbody>
<tr>
<td>Median diameter</td>
<td>0.69</td>
<td>0.60</td>
<td></td>
</tr>
<tr>
<td>Mean diameter</td>
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<td>0.515</td>
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<tr>
<td>Deviation measure</td>
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<td>Skewness measure</td>
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<td></td>
</tr>
</tbody>
</table>

* After Krumbein and Pettijohn (1938)

** After Inman (1952)
was not obtained. A re-examination of the material used in this analysis did not reveal any further chondrules. The lack of fine material in the sample (present in the Allegan and Hughes' Bjurbole samples) and its already disaggregated nature suggests that this sample may have had some fraction removed at some time.

Although the available evidence suggests the second alternative is perhaps the most likely only further examination of Bjurbole material will satisfactorily resolve the problem. Unfortunately, time did not permit this to be done during the period of research for this thesis.

5.5 Size distributions of chondrules in meteorites other than Bjurbole

Stakheev et al also measured the sizes of whole separated chondrules from the Elenovka, Saratov and Nikolskoe meteorites. Size distribution histograms have been constructed using their data and are shown in Figure 5.3. The distributions exhibit the same trends as those already described. However, the peak in chondrule size is at a slightly higher value in Elenovka than in Saratov, Nikolskoe and Bjurbole (see previous section). This is reflected in the slightly higher mean and median chondrule diameter values as set out in Table 5.4. The Saratov and Nikolskoe histograms exhibit a more well-defined peak than do the Bjurbole and Elenovka distributions. For example, in the size range 0.1 - 0.4mm are contained approximately seventy percent of the chondrules from Saratov and Nikolskoe. In comparison, only some fifty percent of chondrules from the other two meteorites fall in this size range.

A comparison of the histograms constructed from the data of Stakheev et al for chondrules from Bjurbole, Saratov and Nikolskoe with those presented in Chapter 4 and Hughes' analysis of Bjurbole chondrules shows relatively more chondrules in the size range 0.1 - 0.3mm.
Fig.5.3. Size distribution histograms of chondrules from the Saratov (continuous thick line), Nikolskoe (continuous thin line), and Elenovka (dashed line) meteorites constructed from the data of Stakheev et al (1973).
### TABLE 5.4.

Statistical parameters for the chondrule size distributions from the meteorites, Elenovka, Bjurbole, Saratov and Nikolskoe (Stakheev et al, 1973).

<table>
<thead>
<tr>
<th>Parameters from size data *</th>
<th>Elenovka</th>
<th>Bjurbole</th>
<th>Saratov</th>
<th>Nikolskoe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arithmetic mean (mm)</td>
<td>0.82</td>
<td>0.51</td>
<td>0.38</td>
<td>0.40</td>
</tr>
<tr>
<td>Arithmetic median (mm)</td>
<td>0.74</td>
<td>0.41</td>
<td>0.30</td>
<td>0.30</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Percentiles ((\phi)) **</th>
<th>16</th>
<th>50</th>
<th>84</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>1.03</td>
<td>2.32</td>
<td>2.84</td>
</tr>
<tr>
<td>50</td>
<td>0.43</td>
<td>1.29</td>
<td>1.74</td>
</tr>
<tr>
<td>84</td>
<td>-0.26</td>
<td>0.36</td>
<td>0.78</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameters from ((\phi)) percentiles **</th>
<th>0.43</th>
<th>1.29</th>
<th>1.74</th>
<th>1.74</th>
</tr>
</thead>
<tbody>
<tr>
<td>Median diameter</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean diameter</td>
<td>0.38</td>
<td>1.34</td>
<td>1.81</td>
<td>1.57</td>
</tr>
<tr>
<td>Deviation measure</td>
<td>0.65</td>
<td>-0.98</td>
<td>-1.03</td>
<td>-0.83</td>
</tr>
<tr>
<td>Skewness measure</td>
<td>-0.08</td>
<td>-0.05</td>
<td>-0.07</td>
<td>-0.20</td>
</tr>
</tbody>
</table>

* After Krumbein and Pettijohn (1938)

** After Inman (1952)
To some extent this may be explained by the fact that Stakheev et al utilised average projected chondrule diameter measures for the construction of histograms whereas, in the other investigations, maximum chondrule diameters were used. However, the results presented in Chapter 4 on the shape of chondrules showed them to be near-spherical. If chondrules were selected by Stakheev et al on the same criteria adopted in the present investigation, the above explanation would not fully account for the observation. Without seeing the particles selected by Stakheev et al, it is not possible to say whether this small effect is a real one. The general similarities in the shapes of the chondrule size-distributions constructed from the data of Stakheev et al to those presented in Chapter 4 and that obtained by Hughes for Bjurbole along with the fact that they all exhibit lower limit cut-off points is significant.

Results from a study of the size and weight of ninety-seven olivine plus pyroxene chondrules from the Chainpur meteorite by Das Gupta et al (1978) appear inconsistent. Sizes are quoted to range from 0.5mm to 3.5mm and weights from 0.3mg to 45mg. If these weights are used to calculate the densities of the largest and smallest particles (assuming the quoted dimensions are diameter values) values of \( \sim 2 \text{ gm cm}^{-3} \) and \( \sim 21 \text{ gm cm}^{-3} \) are obtained. It would seem that a mistake has occurred somewhere. It is difficult to see where this might be from the brief report where the data is given in the form of the number of particles falling in given mass ranges. In view of this discrepancy between mass and size, it seems unwise to discuss or comment upon the results so far published by Das Gupta et al. However, one point is worth noting, a preponderance of particles with smaller weights, and presumably, therefore, smaller sizes was observed.

Gooding et al (1978) separated a total of 160 chondrules from eleven type 3 H-, L- and LL- group chondrites. The size, shape, density and surface morphology of each specimen was examined.
Chondrule size measurements from each meteorite were combined and a histogram presented (Gooding et al., 1978). This procedure was obviously necessitated by the small sample number from each meteorite. It would seem unwise to adopt this practice frequently since differences in the size distribution of chondrules between meteorites might be obscured. In this instance, however, results from individual meteorites were too few to enable individual size distribution histograms to be constructed.

The mean maximum dimension of all the chondrules examined in the study was found to be 1.15 mm. Although this value compares well with those for Bjurbole and Chainpur chondrules presented in Chapter 4, it is much higher than all the others discussed. It could be, given the difficulty of segregating chondrules from matrix, the relatively small number of chondrules extracted and the requirements of the rest of the survey, that Gooding et al. biased their sampling to chondrules of larger size.

The inadequacies in the approach and presentation of the data on grain size distributions in thin-sections of carbonaceous and ordinary chondritic meteorites by King and King (1978, 1979) have already been outlined. Since no corrections were made to the apparent size measurements, and, except for the fluid drop chondrules, no particles less than 0.1 mm maximum apparent dimension were measured, it is impossible to tell from the data whether there is a natural lower limit cut-off in size in any of the particle categories as has been indicated in the case of chondrules by the research outlined above. It was not felt worthwhile correcting King and King's relevant data using the technique described in Chapter 3 since, in the case of the carbonaceous chondrites, the "all chondrule" data included measurements of chondrule fragment sizes and the "fluid drop chondrule" measurements were very few in number per meteorite. The data were also not presented in a form ideally suitable for correction. In the ordinary chondrites
insufficient data was presented to construct individual meteoritic fluid drop chondrule cumulative size frequency curves. With these limitations in mind, it seems wise to discuss the analyses of King and King in general terms only.

King and King found that the eleven ordinary chondrite fluid drop chondrule cumulative size frequency distribution curves they constructed, were generally parallel and fell within a rather restricted envelope with a narrow range. The upper and lower limits for the $d_{16}$, $d_{50}$ and $d_{84}$ values estimated from this envelope are given in Table 5.5. They observed that curves from five of the six H-group meteorites they examined occupied the fine side of the envelope, supporting the suggestion by Dodd (1976) that the H-group chondrites may have a generally finer silicate particle size than the L- and LL-groups.

Grain size distributions of all particles >0.1mm in the case of the carbonaceous chondrites maximum apparent diameter, all chondrules and fluid drop chondrules were found to be similar for the same meteorite. Overall, these distributions were similar in the CM2 and CO3 meteorites, whereas the analyses of results from the CV3 meteorites indicated a coarser, more extensive grain size distribution closer to those of the ordinary chondrites. These effects can be seen from the upper and lower limits of the $d_{16}$, $d_{50}$ and $d_{84}$ values for the three carbonaceous chondrite groups as listed in Table 5.5. Also tabulated for comparison are the same d values obtained from thin-section measurements of droplet and lithic fragment chondrules in Bjurböle and Chainpur as determined by Hughes (1978a) and those determined for silicate particles adopting the same technique by Dodd (1976).

A comparison of the results in this table shows that King and King's analyses indicate a preponderance of very fine material in the CM2 and CO3 sections examined. This observation is particularly
Summary of $d_{16}$, $d_{50}$ and $d_{84}$ values for various particle size distributions in some chondritic meteorites.

<table>
<thead>
<tr>
<th>Meteorite</th>
<th>Particle type</th>
<th>Investigator</th>
<th>$d_{16}$</th>
<th>$d_{50}$</th>
<th>$d_{84}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bjurbole</td>
<td>DC</td>
<td>Hughes (1978a)</td>
<td>1.47</td>
<td>0.98</td>
<td>0.56</td>
</tr>
<tr>
<td></td>
<td>LFC</td>
<td>Hughes (1978a)</td>
<td>1.72</td>
<td>1.21</td>
<td>0.63</td>
</tr>
<tr>
<td></td>
<td>SP</td>
<td>Dodd (1976)</td>
<td>0.54</td>
<td>0.26</td>
<td>0.06</td>
</tr>
<tr>
<td>Chainpur</td>
<td>DC</td>
<td>Hughes (1978a)</td>
<td>1.97</td>
<td>1.41</td>
<td>0.61</td>
</tr>
<tr>
<td></td>
<td>LFC</td>
<td>Hughes (1978a)</td>
<td>2.24</td>
<td>1.36</td>
<td>0.59</td>
</tr>
<tr>
<td></td>
<td>SP</td>
<td>Dodd (1976)</td>
<td>0.92</td>
<td>0.47</td>
<td>0.18</td>
</tr>
<tr>
<td>Ordinary</td>
<td>LDC</td>
<td>King and King (1979)</td>
<td>1.0-0.44</td>
<td>0.63-0.26</td>
<td>0.32-0.18</td>
</tr>
<tr>
<td>chondrites</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CM2</td>
<td>AC</td>
<td>King and King (1978)</td>
<td>0.36-0.19</td>
<td>0.18-0.12</td>
<td>0.12-0.05</td>
</tr>
<tr>
<td>CO3</td>
<td>AC</td>
<td>King (1978)</td>
<td>0.31-0.20</td>
<td>0.17-0.14</td>
<td>0.14-0.08</td>
</tr>
<tr>
<td>CV3</td>
<td>AC</td>
<td></td>
<td>1.24-0.66</td>
<td>0.46-0.23</td>
<td>0.18-0.09</td>
</tr>
</tbody>
</table>

Notes:
- DC - droplet chondrule (see Hughes, 1978a)
- LFC - lithic fragment chondrule (see Hughes, 1978a)
- SP - silicate particle (see Dodd, 1976)
- LDC - liquid droplet chondrule (see King and King, 1979)
- AC - all chondrules (see King and King, 1978)
interesting. It is not simply an artefact of the thin-section technique. It was demonstrated in Chapter 3 that the random sectioning of particles of equal size will produce a range of apparent sections in which a large proportion would be close to the true diameter. A preponderance of sections of small apparent diameter, as observed by King and King, therefore indicates a preponderance of particles with small diameters. A close examination of individual cumulative number frequency curves constructed from this data shows that in the CO2 and CM3 meteorites about 50 percent of the chondrules exhibited sections in the 0.1 - 0.2mm size range. This would seem to indicate that chondrules in these two groups of meteorites are generally smaller than chondrules in the ordinary chondrites and the CV3 meteorites.

Cumulative number frequency curves constructed for chondrules from the CV3 data of King and King indicate a larger spread in apparent diameter values with a less well-defined clustering towards the smaller sizes (0.5 - 0.2mm) when compared to the constructed CO2 and CM3 chondrule cumulative number frequency curves. The limited measurements for fluid drop chondrules appear to support these general trends.

5.6. Summary

The disaggregation data on the size-distribution of chondrules from the ordinary chondrites reviewed in this chapter indicates two important points:

1) Chondrules have a restricted size range with a pronounced lower-limit cut-off in size, probably around 0.2mm.

2) There is a preponderance of chondrules at the smaller end of the size range, usually centered around 0.5mm.

These conclusions are generally supported by the measurements of apparent diameters of chondrules from thin-section studies.
From the data so far obtained it is not possible to say whether there are any major differences in the size-distributions of chondrules from the ordinary chondritic meteorites except that perhaps the H-group meteorites have generally a smaller particle and chondrule size.

However, results obtained from thin-section measurements of apparent chondrule diameters in the carbonaceous chondrites suggest significant differences in chondrule size-distributions between the carbonaceous and ordinary chondrites. Chondrules from the carbonaceous chondrites appear to have a more restricted range of sizes and proportionally more smaller chondrules. These observations appear more strongly pronounced in the CO3 and CM2 meteorites - in which chondrule size-distributions are very similar - than in the CV3 meteorites.

The significance of the above observations to the origin of chondrules is discussed in Chapter 8.
CHAPTER SIX

THE MASS DISTRIBUTION OF CHONDRULES AND THE

ROSIN AND WEIBULL STATISTICAL FUNCTIONS

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6.1. Introduction

Generally, in the analysis of data, the relationship of a distribution to some known function is sought. Two such functions, the Rosin and Weibull, seem appropriate for testing chondrule size-distributions against. The Rosin statistical function (Rosin and Rammler, 1934) has been found to fit artificially crushed products of many kinds and sizes suggesting that data which fit the law may bear evidence of having been subjected to crushing phenomena. If chondrules were produced by impact events, which has produced the lunar regolith and has been found to obey Rosin's law (see Appendix A), it might be thought that chondrule mass-distributions should follow the law. The Weibull statistical function (Weibull, 1951) is an extended three-parameter form of Rosin's law which takes into account some of the inadequacies of Rosin's law in describing some distributions. These two functions are described more fully in later sections.

Martin and Mills (1976, 1978) argued that meteoritic chondrules did not follow Rosin's law after testing the cumulative number data for Bjurbolle, Chainpur and Allegan chondrules presented in Chapter 4. They concluded that, from this viewpoint, chondrules did not bear evidence of having been subjected to crushing phenomena and had not, therefore, been produced by impact events.

However, Hughes (1978a) tested his Bjurbolle and Chainpur chondrule cumulative number data and concluded that they did, indeed, give a fit to Rosin's law. In a later publication, after converting the Bjurbolle disaggregation chondrule cumulative number data to cumulative mass percentages, Hughes (1978b) decided that the fit to Rosin's law was "less than impressive ...". A reasonable fit could only be obtained by ignoring the 7\% by weight of material made up of particles having diameters less than 0.7\text{mm} and the 8\% by weight of the material made up of particles with diameters greater than 2.6\text{mm}. However, ignoring
15% by weight of the chondrules removed 56% by number. This included those that fell in the peak in the size distribution histogram. It seems unwise to draw any meaningful conclusions from an analysis of data treated in this manner. However, Hughes found that the complete mass frequency data obeyed with "considerable precision ..." a Weibull distribution law.

It is worth noting that Dodd (1976) found that his size data for meteoritic particles gave a reasonable fit to Rosin's law. However, it must be noted that his study was not restricted to measuring chondrules alone, all silicate particles with an apparent thin-section diameter greater than 0.1mm were measured. This result is not, therefore, directly comparable with those outlined above.

It would seem, therefore, that the results published to date are somewhat inconclusive. The Rosin and Weibull statistical functions are designed when used for the present application to test data from sieve analyses. Cumulative mass percentages should, therefore, be used as they give a more accurate fit than cumulative number analyses.

It was decided, therefore, to test as many of the available chondrule analyses, after converting number size-frequency data to mass size-frequency data where necessary, against both the Rosin and Weibull statistical functions. For this purpose the data on Bjurbole, Chainpur and Allegan chondrules presented in Chapter 4 was utilised as was the chondrule mass data determined by Stakheev et al (1973) for Bjurbole, Nikoskoe, Elensvka and Saratov. This data was kindly supplied by Dr. Bruno Lang, Department of Radiochemistry, University of Warsaw, Poland. I am grateful to Dr. Lang for supplying the data and allowing its use for the purpose of the present analyses. Hughes' disaggregated Bjurbole chondrule data was also re-tested against Rosin's law.
6.2 The chondrule data

As outlined in the previous section, both the Rosin and Weibull statistical functions should ideally be tested against cumulative mass percentages for a more accurate indication of fit. The chondrule data presented in Chapter 4 was not in this form. It is, nevertheless, possible to estimate the mass of chondrules in each size range from the presented number size-frequency data provided a suitable density value can be adopted. The procedure followed was to take the size data segregated into classes as used in the construction of the size-distribution histogram and to assume that in each class all chondrules were spherical and had a diameter at the mid-point of the range. The mean mass, \( m \), of a chondrule in a range is simply:

\[
m = \frac{4}{3} \pi r^3 \rho \quad 6.1.
\]

where \( r \) is the radius and \( \rho \) the density of the chondrule. The total mass of chondrules, \( M \), in any size range is:

\[
M = \frac{4}{3} \pi r^3 \rho N \quad 6.2.
\]

where \( N \) is the total number of chondrules in the range. Once the mass of chondrules has been calculated in this manner for each range, it is a simple matter to determine cumulative mass percentages. These have been determined for Bjurbole, Allegan and Chainpur chondrules utilising the size data presented in Chapter 4. The calculated cumulative mass percentages are presented in Table 6.1. Also tabulated is Hughes' (1978b) result for Bjurbole chondrules corrected slightly because of a miscalculation in the 0.2 - 0.3 mm size range mass determination.
The density value adopted in the above determinations was 3.258 g cm$^{-3}$. This was the mean mass of disaggregated Bjurbole chondrules as determined by Hughes (1978a). Recently, Gooding et al (1978) have quoted density values of 3.22 g cm$^{-3}$, 3.25 g cm$^{-3}$ and 3.12 g cm$^{-3}$ determined for separated chondrules from H7-Ir and LL-group ordinary chondritic meteorites respectively. The value of 3.258 g cm$^{-3}$ adopted here does not seem unreasonable.

It might be argued that since the Rosin and Weibull functions were designed to be tested against mass size frequency data obtained by sieving and as sieves sort particles on the basis of their intermediate and shortest diameters (see Chapter 3), the above mass determinations might be in error since maximum chondrule diameters were utilised in the original classification of the measurements into size classes in Chapter 4. However, it was shown in the analyses of chondrule shape, also presented in Chapter 4, that the chondrules examined were very nearly spherical. It is felt, therefore, that any discrepancies caused by the above effect would be small. Consequently, they have been neglected in the analyses.

In most cases, Stakheev et al determined the mass of chondrules in each size range for the four L-group meteorites they studied. In the few instances where this was not done, mass values have been estimated using the technique described above. The data is presented in Table 6.1 where the estimated mass fractions are bracketed. It can be seen from this table that these estimates are in the smallest size ranges. Although these classes often contain a large number of chondrules of small sizes, corresponding mass fractions are small. Any errors introduced by the adoption of an incorrect density value for the mass estimates would have a minimal effect on the cumulative masses.

It is possible, however, from the data presented by Stakheev et al to estimate average chondrule densities in each size range.
### TABLE 6.1.

Individual class masses and cumulative mass percentages of chondrules from the Saratov, Nikolskoe, Elenovka and Bjurbole meteorites examined by Stakhiev et al (1973).

<table>
<thead>
<tr>
<th>Size range (mm)</th>
<th>Saratov 1</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th>Elenovka 1</th>
<th></th>
<th></th>
<th></th>
<th>Bjurbole 1</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mass [g]</td>
<td>class weight</td>
<td>cumulative</td>
<td>mass [g]</td>
<td>class weight</td>
<td>cumulative</td>
<td>mass [g]</td>
<td>class weight</td>
<td>cumulative</td>
<td>mass [g]</td>
<td>class weight</td>
</tr>
<tr>
<td>0.1 - 0.2</td>
<td>0.0059</td>
<td>0.7</td>
<td>0.3</td>
<td>0.0022</td>
<td>0.2</td>
<td>0.2</td>
<td>(0.009)</td>
<td>0.2</td>
<td>0.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.2 - 0.3</td>
<td>0.0235</td>
<td>3.3</td>
<td>3.3</td>
<td>0.0160</td>
<td>1.3</td>
<td>3.3</td>
<td>(0.0097)</td>
<td>1.0</td>
<td>1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.3 - 0.4</td>
<td>0.0175</td>
<td>8.8</td>
<td>8.8</td>
<td>(0.0150)</td>
<td>7.8</td>
<td>7.8</td>
<td>0.0120</td>
<td>3.2</td>
<td>3.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.4 - 0.5</td>
<td>0.1007</td>
<td>20.5</td>
<td>20.5</td>
<td>0.0132</td>
<td>11.7</td>
<td>11.7</td>
<td>0.0109</td>
<td>6.9</td>
<td>6.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5 - 0.6</td>
<td>0.0744</td>
<td>29.7</td>
<td>29.7</td>
<td>0.0122</td>
<td>15.3</td>
<td>15.3</td>
<td>0.0192</td>
<td>13.3</td>
<td>13.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.6 - 0.7</td>
<td>0.0756</td>
<td>40.1</td>
<td>40.1</td>
<td>0.0135</td>
<td>19.3</td>
<td>19.3</td>
<td>0.0260</td>
<td>18.6</td>
<td>18.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.7 - 0.8</td>
<td>0.0627</td>
<td>50.6</td>
<td>50.6</td>
<td>0.0159</td>
<td>23.8</td>
<td>23.8</td>
<td>(0.0640)</td>
<td>17.6</td>
<td>17.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.8 - 0.9</td>
<td>0.0653</td>
<td>58.3</td>
<td>58.3</td>
<td>0.0234</td>
<td>29.3</td>
<td>29.3</td>
<td>0.0641</td>
<td>25.7</td>
<td>25.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.9 - 1.0</td>
<td>0.05772</td>
<td>65.0</td>
<td>65.0</td>
<td>0.0232</td>
<td>36.4</td>
<td>36.4</td>
<td>0.0583</td>
<td>33.9</td>
<td>33.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.0 - 1.1</td>
<td>0.0539</td>
<td>72.5</td>
<td>72.5</td>
<td>0.0230</td>
<td>46.3</td>
<td>46.3</td>
<td>0.0562</td>
<td>40.6</td>
<td>40.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.1 - 1.2</td>
<td>0.0529</td>
<td>78.1</td>
<td>78.1</td>
<td>0.0230</td>
<td>50.2</td>
<td>50.2</td>
<td>0.0565</td>
<td>47.5</td>
<td>47.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.2 - 1.3</td>
<td>0.0393</td>
<td>81.6</td>
<td>81.6</td>
<td>0.0223</td>
<td>56.9</td>
<td>56.9</td>
<td>0.0600</td>
<td>54.2</td>
<td>54.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.3 - 1.4</td>
<td>0.03301</td>
<td>85.5</td>
<td>85.5</td>
<td>0.0205</td>
<td>65.0</td>
<td>65.0</td>
<td>0.06688</td>
<td>61.1</td>
<td>61.1</td>
<td></td>
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1. Alabaster et al. (1973)
2. Hughes (1976) - mass fractions estimated from size frequency data
3. Chapter 4, this thesis - Mass fractions estimated from size frequency data

* Values from reference 2 and 3 have been estimated from size distribution data, see text.
using equation 6.2 rearranged thus,

\[ \rho = \frac{3M}{4 \pi \frac{r^3}{N}} \]

6.3.

This has been done and the results are presented in Table 6.2. These calculated densities exhibit an interesting, unexpected feature. In Elenovka, Bjurbole and Saratov, there is a general decrease in average chondrule density with increase in size. This is more pronounced in Elenovka and Saratov, the results for Bjurbole are a little more erratic. This general trend is also displayed by the average chondrule densities calculated for Nikolskoe except for a sudden increase in density estimates between diameters of 1.3mm and 1.7mm. If this effect is real, it is a very interesting observation. Studies of the chemical composition of individual chondrules have not revealed any correlation between composition and size. (Fredriksson et al, 1978; Das Gupta et al, 1978; Gooding and Keil, 1978b; Grossman et al, 1978).

Petrological examination of chondrules in thin sections of the ordinary chondrites reveal that the major constituents are olivine, pyroxene and glass, metal grains are rare. It is difficult to imagine from such observations what mineralogies would give rise to the extremes of chondrule density indicated by the data of Stakheev et al.

An alternative explanation is that perhaps the particles measured by Stakheev et al were irregular and as a consequence accurate volume measures would not be obtained from calculations using measured median diameters as performed above. Density estimates based on volume determinations so obtained would, therefore, be in error. This explanation does not seem entirely satisfactory, however, since in the smaller particles volume estimates would have to be underestimated and in the larger particles volume estimates would have to be overestimated to account for the departures in density estimates from an expected value of around \( 3 \text{ gm cm}^{-3} \). Further information is needed before the problem can
Estimated average chondrule densities (gm cm\(^{-3}\)) in each size range for the meteorites studied by Stakheev et al (1974).

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be resolved. For the present analyses the data of Stakheev et al must be accepted as it stands. The estimated class weights have been retained for the analyses. The results of the analyses should be regarded with the above anomaly in mind. (See section 6.8 Footnote).

6.3 Rosin's law

Rosin's law (Rosin and Rammler, 1934) has been found to fit artificially crushed products of many kinds and sizes (Moore, 1934; Bennett, 1936; Geer and Yancey, 1938) suggesting that data which fit the law may bear evidence of having been subjected to crushing phenomena. Some weathered source rocks have also been found to follow the law (Krumbein and Tisdell, 1940).

The law was originally introduced by Rosin and Rammler as a function of the type:

\[ R = 100e^{-bd^n} \]

where \( R \) is the weight percent retained on a sieve of mesh size \( d \), \( e \) is the number 2.7188 and \( b \) and \( n \) are constants for any given material. Bennett (1936) reviewed the basis for the law and showed that it could be obtained directly from probability considerations in the form:

\[ R = 100e^{-\left(\frac{d}{K}\right)^n} \]

where \( (1/K)^n \) has been substituted for \( b \). In the interpretation of the size of the crushed products it is found that \( K \) represents an average size and \( n \) a reciprocal of the spread of the curve - a concept similar to the "sorting value".

Geer and Yancey (1938) have designed a very useful special co-ordinate system such that if the cumulative weight percent of a given comminuted sample plotted on the grid system yields a straight line, then the material can be said to follow Rosin's law. Moreover, the
Rosin numbers, $k$ and $n$, may readily be determined from such a plot - $n$ is the tangent of the slope of the line and $k$ is the millimeter value at the intersection of the straight line with the 36.8% line of the vertical scale.

6.4 Chondrule mass-distributions and Rosin's law

In order to test whether chondrules follow Rosin's law, the cumulative mass percentage values presented in Table 6.1 have been plotted on the specially ruled co-ordinate system devised by Geer and Yancey (millimeter size values were converted to $\phi$-units). The resulting curves are shown in Figures 6.1 - 6.3. For comparison, the results for Bjurbole chondrules from all three sources are plotted on Figure 6.4. Examination of these plots reveals that they all display the same general trends. Most significantly, none of the distributions gives a good straight line plot on the grid system adopted. All exhibit straight line segments which generally steepen with decrease in size. The exception to this is the plot for Nikolskoe chondrules where the slope decreases slightly towards smaller particle sizes and a distinct displacement of the plot around 0 $\phi$. Reference to Figure 6.4 shows that Hughes' estimated disaggregation Bjurbole chondrule mass frequency data does not yield a straight line plot and therefore does not appear to obey Rosin's law. This data has not previously been tested against the law using the Geer and Yancey grid system.

The most reasonable conclusion to draw from these analyses is that none of the chondrule mass frequency distributions so far tested appears to give a fit to a Rosin law distribution. The Rosin numbers were consequently not determined. It might be tentatively suggested, therefore, from a comparison with terrestrial and artificial examples, that there is no evidence from the present analyses to suggest that the meteoritic chondrules examined have been subjected to or produced by crushing phenomena.
Fig. 6.1. Cumulative weight per cent plots of chondrules from the Bjurböle and Chainpur meteorites using the data from Chapter 4. Ordinate conforms to Rosin's law.
Fig. 6.2. Cumulative weight per cent plots of chondrules from the Bjurböle (Hughes, 1978b) and Allegan (Chapter 4) meteorites. Ordinate conforms to Rosin's law.
Fig. 6.3. Cumulative weight per cent plots of chondrules from the Bjurböle, Elenovka, Nikolskoe and Saratov (Stakhheev et al, 1973) meteorites. Ordinate conforms to Rosin's law.
Fig. 6.4. Cumulative weight per cent plots of chondrules from the Bjurbole meteorite. Filled circles, data from Chapter 4; squares, Hughes 1978b; crosses, Stakheev et al, 1973.
There is an explanation, as pointed out by Hughes (1978b), why chondrule mass distributions do not give a fit to Rosin's law. Rosin's law requires that the upper limit of size in a distribution be infinite and that the mass percentage values approach zero asymptotically indicating there can be no minimum chondrule size. Both these requirements are refuted by the chondrule size-distribution analyses discussed in this thesis. The second of these factors, the minimum size requirement, may be taken into account by the introduction of a third parameter into the Rosin law equation (equation 6.5). This three parameter equation is:

\[ R = 100e^{-\frac{(d - a/k)^n}{k}} \]

and represents a Weibull distribution (Weibull, 1951; Plait, 1962; Berrettoni, 1964) which has found applications in many reliability studies. In equation 6.6, \( a \) is a constant for a particular distribution. It is estimated by taking the Rosin law plot of \( \log_{10} \left( \frac{1 - R}{100} \right) \) as a function of \( \log_{10} d \) (where \( d \) = mesh size), and subtracting constant values from each \( d \) value and reploting until a straight line is obtained. When this is achieved, the constant value subtracted from all \( d \) values is equal to \( a \). This procedure is usually aided by using the special "Weibull times log 2 cycles" probability paper (for example, see Berrettoni, 1964). The parameter, \( a \), is usually referred to as the location parameter since it is directly related to the minimum value that \( d \) takes. Alteration of the location parameter changes the abscissa value of the \( R = 0 \) point. Of course, the Weibull probability function reverts to a Rosin law distribution when \( a \) is put equal to zero.

The other two parameters, \( k \) and \( n \), in equation 6.6 are the same as in the Rosin law equation, 6.5, and are referred to as the
scale and shape parameters respectively. They may be determined simply from the plots on Weibull probability paper from the principal abscissa \( \log_{10} (d - a) \) and the principal ordinate \( \log_{10} \left( - \log_e \left(1-R/100\right) \right) \), \( k \) is again the slope of the straight-line plot and \( n \) is related to an intercept value. A full description is given in Berrettoni (1964).

6.6. Chondrule mass distributions and the Weibull statistical function

As the chondrule mass frequency data presented in Table 6.1 did not give a fit to Rosin's law, probably for the reasons outlined above, it was decided to determine whether the data could be fitted to the Weibull statistical function. Cumulative mass frequency determinations for each meteorite were plotted on Weibull probability paper and are shown in Figures 6.5 - 6.10. As expected, straight line plots were not obtained. Straight line plots for each distribution were sought by subtraction of various \( \alpha \) values from each \( d \) value as described in the preceding section. Best fits are shown in the figures. Table 6.3 presents values for the three parameters, \( \alpha \), \( k \) and \( n \), determined from the best-fit plots.

Reference to Figures 6.5 - 6.10 shows that the data gives much better fits to a Weibull distribution than to a Rosin's law distribution as previously tested (Figures 6.1 - 6.4). Some of the Weibull distribution fits are more impressive than others. For example, good fits were obtained from the data for Allegan, Saratov and Bjurbole (Stakheev et al). Elenovka gave a reasonable fit to the distribution while the Bjurbole and Chainpur data determined from the results of analyses presented in Chapter 4 gave the least impressive fits. Hughes (1978b) had already found an impressive fit to a Weibull distribution with his disaggregated Bjurbole chondrule data. Nikolskoe is the exception and does not give a good fit to physically realistic values of \( \alpha \).
### TABLE 6.3.

Parameters extracted from the Weibull plots of meteoritic chondrules presented in Figures 6.5 - 6.10.

<table>
<thead>
<tr>
<th>Meteorite</th>
<th>Data Source</th>
<th>k</th>
<th>n</th>
<th>α</th>
</tr>
</thead>
<tbody>
<tr>
<td>Allegan</td>
<td>1</td>
<td>1.088</td>
<td>1.26</td>
<td>0.34</td>
</tr>
<tr>
<td>Bjurbole</td>
<td>2</td>
<td>0.471</td>
<td>1.84</td>
<td>0.32</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.707</td>
<td>1.65</td>
<td>0.23</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>0.744</td>
<td>2.30</td>
<td>0.55</td>
</tr>
<tr>
<td>Chainpur</td>
<td>1</td>
<td>0.415</td>
<td>2.66</td>
<td>0.38</td>
</tr>
<tr>
<td>Elenovka</td>
<td>3</td>
<td>0.567</td>
<td>2.14</td>
<td>0.30</td>
</tr>
<tr>
<td>Nikolskoe*</td>
<td>3</td>
<td>0.506</td>
<td>2.22</td>
<td>0.00</td>
</tr>
<tr>
<td>Saratov</td>
<td>3</td>
<td>1.671</td>
<td>1.15</td>
<td>0.28</td>
</tr>
</tbody>
</table>

1. Chapter four.

* Nikolskoe chondrule mass-distribution does not give a fit to a Weibull distribution with any realistic values of α.
Fig. 6.5. Cumulative weight per cent plots of chondrules from the Bjurbole meteorite (Chapter 4). Lower plot is a Rosin curve, upper plot is the best fit of the data to a Weibull distribution.
Fig. 6.6. Cumulative weight per cent plots of chondrules from the Chainpur meteorite (Chapter 4). Lower plot is a Rosin curve, upper plot is the best fit of the data to a Weibull distribution.
Fig. 6.7. Cumulative weight per cent plots of chondrules from the Allegan meteorite (Chapter 4). Lower plot is a Rosin curve, upper plot is the best fit of the data to a Weibull distribution.
Fig. 6.8. Cumulative weight per cent plots of chondrules from the Saratov meteorite (Stakheev et al, 1973).

Lower plot is a Rosin curve, upper plot is the best fit of the data to a Weibull distribution.
Fig. 6.9. Cumulative weight per cent plots of chondrules from the Bjurbole meteorite (Stakheev et al., 1973). Lower plot is a Rosin curve, upper plot is the best fit of the data to a Weibull distribution.
Fig. 6.10. Cumulative weight per cent plots of chondrules from the Elenovka meteorite (Stakheev et al, 1973). Lower plot is a Rosin curve, upper plot is the best fit of the data to a Weibull distribution.
The distribution yields its best fit to the Weibull function only if a negative $\alpha$ value is used. The best fit is given when a value of -2 is adopted. This is physically unrealistic. It seems reasonable to conclude that the Nikolskoe chondrule mass-frequency data does not follow a Rosin or Weibull function. It might be explained by the fact that the data showed a different trend when tested against Rosin's law to the other data tested (section 6.4). It might be that the Nikolskoe data is less reliable than the rest. Alternatively, there may be a real difference in the chondrule mass distribution in Nikolskoe when compared to mass distribution of chondrules from Bjurbolle, Chainpur, Allegan, Saratov and Elenovka.

6.7. Summary

Chondrule mass-frequency data including determinations from size frequency data, have been tested to see if they fit any recognisable category by means of the Rosin and Weibull statistical functions. While none of the mass-frequency distributions gave a fit to Rosin's law they could all, with the exception of Nikolskoe, be fitted with varying degrees of accuracy, to a Weibull function.

The inadequacies in fitting the distributions to Rosin's law suggests, by analogy with natural terrestrial and experimentally produced distributions, that meteoritic chondrules have not been subjected to or produced by crushing phenomena as has, for example, the lunar regolith soil component (see Appendix). This is significant in the light of proposed theories for the formation of chondrules, some of which invoke crushing type mechanisms such as impact events. This will be discussed more fully in Chapter 8.
Immediately prior to the submission of this thesis the author visited Dr. B. Lang, Department of Radiochemistry, Warsaw University, Poland, and was able to examine thin sections of a limited number of the particles identified as chondrules and extracted from the meteorites Bjurbolle, Elenovka, Nikolskoe and Saratov by Stakheev et al (1973). It was apparent from the sections that a large number of the particles would not have been selected as chondrules by the author. Some were obvious chondrule fragments, others had very irregular outlines. It is unlikely that these particles were produced by the break-up of chondrules during the preparation of the thin-sections. It is not possible to determine the real volume of non-spherical particles from a measure of any single one of their dimensions. Density values determined from volume estimates and measured weights as performed in section 6.2 of this chapter would, therefore, be in error if the proportion of non-spherical particles were large. It is difficult to estimate the number of such particles from the few observed in the thin-sections. The observations would suggest, however, that the proportions of non-chondrule particles were large. It would seem that the selection of non-spherical particles as chondrules by Stakheev et al is the reason for the observed variation in estimated density with size as described in section 6.2. The inclusion of particles other than chondrules in the chondrule mass frequency data will also affect the reliability of the fits of the data to the Rosin and Weibull functions as performed in sections 6.4 and 6.6 respectively. Without examining all the particles extracted as chondrules by Stakheev et al it is difficult to say more about the effect of the inclusion of the non-chondrule particles on the data. The results of the analyses and their interpretation in this chapter for the material of Stakheev et al should, therefore, be approached with the above comments in mind.
CHAPTER SEVEN

PREFERENTIAL ORIENTATION OF CHONDRULES IN CHONDRITIC METEORITES

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7.1. Introduction

It is now more than a century since oriented fabrics were first noted in chondrites by von Reichenbach (cited by Wahl, 1952) when foliation in thirteen chondrites was described. More recently, studies of the magnetic anisotropies of meteorites have suggested preferential alignment of metal grains (Stacey et al., 1961, Weaving, 1962). Whereas the study of Stacey et al. revealed only foliation, the presence of both foliation and lineation were suggested by the work of Weaving. Stacey et al. noted an increase of magnetic anisotropy with decreasing porosity in the suite of chondrites they examined and inferred that foliation was due to compaction during recrystallisation.

An extensive analysis of the orientation of the long axes of chondrules in sets of three interlocking thin-sections cut perpendicularly from twenty-two chondrites led Dodd (1965) to a different conclusion. Dodd found that most of the samples examined showed a strong foliation commonly accompanied by a subordinate lineation in the plane of foliation, only four samples were weakly foliated or unfoliated and lacked lineation. There appeared to be no systematic relationship between foliation and degree of recrystallisation. Dodd therefore concluded that the fabric element was a relict depositional feature imposed during sedimentation of the chondrules. Interestingly, Dodd tentatively suggested that the fabric data appeared to show a correlation with the abundance of chondrules relative to matrix, the chondrule-rich samples being more strongly foliated.

The question of preferential orientation in chondrites is certainly an intriguing one but has received little attention. This could be due to the fact that to detect foliation and lineation, orientations in more than one plane of each specimen must be examined. This is often difficult with meteoritic material because of its scarcity. (Dodd, 1965, has outlined the problem of detecting lineation and foliation with respect to the plane of the section).
The most important questions that need to be answered in this context are, is preferential chondrule orientation a common feature in the chondritic meteorites and, when it occurs, was it imposed during accumulation and compaction of the meteorite parent body, during later metamorphism or by some other means? The results to date appear to indicate that lineation and foliation of chondrules are common features in the chondrites though the mechanism which gave rise to this petrofabric is still not clear.

It was, therefore, decided to examine some available chondrites for the presence of preferential orientation of the long axes of chondrules in order to obtain more information for the elucidation of the questions outlined above. In particular it was decided to examine the three relatively friable meteorites Bjurbole, Chainpur and Allegan to see if there was any correlation between compaction and degree of preferential orientation. If fabric orientation was produced during compaction and metamorphism it might be argued that these three relatively friable, uncompacted, meteorites should exhibit a low degree of chondrule long-axis preferential orientation when compared to less friable specimens.

Visual examination of the Leoville type 111 carbonaceous chondrite had disclosed a strong orientation of the long axes of chondrules. This prompted an examination of the orientation fabric in Leoville and other suitable available specimens of carbonaceous chondrites. Samples of the Grosnaja, Coolidge, Vigarano and Allende meteorites were therefore studied.

7.2. Samples

As pointed out by Dodd (1965), to detect foliation and lineation orientation in three intersecting faces should ideally be examined. It was not possible to adopt such an approach in the present
analysis. However, it was possible to obtain specimens which had been sliced, revealing a relatively smooth, flat surface. A number of such specimens were chosen on which well defined chondrules were also displayed. These included six faces on specimens of the Parnallee (LL3) meteorite (British Museum, Natural History specimen number BM 34792), two faces on specimens of the Kediri (unclassified) meteorite (BM 1974, M14), and a face displayed by a specimen of the Knyahinya (L5) meteorite (Natural History Museum, Paris, specimen number A 759). Of the carbonaceous chondrites examined, chondrule orientations were measured on four separate faces of the Leoville (BM (NH) 1969, 144 and Leicester University specimen number LU 44484), three faces of the Vigarano (BM 1924, 15), two faces of the Coolidge (BM 1959, 854), one face of the Grosnaja (BM 63624) meteorites, and one face of the Allende (Natural History Museum, Vienna, specimen number L 2923) meteorites.

The friability of the Allegan, Bjurbole and Chainpur meteorites makes it difficult to obtain smooth flat surfaces when these specimens are sliced. However, it is possible to obtain reasonable thin-sections of these meteorites especially if they are impregnated with a suitable material to bind them together during the grinding and polishing processes. The disadvantage with examining thin-sections over sectioned surfaces for chondrule long axis orientation is the small area available for study with the consequent low number of the chondrules displayed. To compensate for this, however, chondrules are usually more apparent in thin-sections enabling more chondrules per unit area to be identified and, as their outlines are generally more obvious, their long axis orientations may more easily be measured and with greater precision. Thin-sections of the Allegan (BM 1920, 281a; 1920, 281b), Bjurbole (BM 1926, 494; 1927, 11) and Chainpur (BM 1915, 86) meteorites were kindly supplied by Dr. R. Hutchison, British Museum (Natural History) for the purposes of this study.
7.3. Measurement

Measurements of the orientation of chondrule long axes from cut surfaces and thin-sections of meteorites necessitated two different approaches. In the case of the sliced surfaces, each face was photographed using fine-grained monochrome film and appropriate enlargements were prepared. This avoided the problem posed by the removal and transport of actual specimens and facilitated magnification to a suitable size. Individual photographs were mounted on the table of an orientometer designed to allow movement in translation and rotation (Whitaker and Gatrall, 1967), and viewed through a binocular microscope fitted with a line reticule in one eyepiece. Individual chondrules were aligned with their long axis along this fiducial line, and their nominal orientation was read from the degree scale of the orientometer turntable. Each measured image was marked with a spot of ink to avoid confusion and possible duplication.

The meteorite thin-sections, however, were placed individually on a mechanical microscope stage and viewed under low magnification through an eyepiece containing a line reticule. All elongate chondrules in each section were oriented with their long axis along this fiducial line, and their nominal orientation was read from the degree scale of the microscope stage.

7.4. Analysis and Results

Chondrule orientations from each of the fifteen specimens were grouped into 5°, 10° or 20° classes and histograms constructed of number per cent in each class versus orientation. The resulting histograms are shown in Figures 7.1 - 7.25. Krumbein's (1939) method was used to determine the mean azimuth and standard deviation (σ) of chondrules in each specimen. This is a simple and rapid technique though it fails where
there is no mode in the data. The standard deviation may be used as a measure of the degree of orientation shown by chondrules. If all chondrules are oriented in the modal class (i.e. maximum preferential orientation) \( \sigma \) will have a value of 0°. A \( \sigma \) value of 52° indicates an equal number of chondrule orientations in all classes, and, therefore, no preferred orientation. An example of the method of calculation of the mean azimuth and standard deviation is shown in Table 7.1. Calculated values for each specimen are given in Table 7.2. The mean azimuths are also shown on the relevant histograms. \( M_1 \) and \( M_2 \), used in the determination of these two parameters, are also given in Table 7.2.

Examination of the orientation histograms and the values for the carbonaceous chondritic meteorites studied indicates that there is a wide spread in degree of preferential orientation of chondrule long axes. Chondrules in the Leoville meteorite exhibit the most striking degree of preferential long axis orientation being spread over a very limited range, the \( \sigma \) values are very close to zero emphasizing the strong orientation fabric. Since all the faces of Leoville examined possess this strong degree of preferential alignment of chondrule long axes it would seem that both foliation and lineation are present in Leoville. Grosnaja also displays a strong degree of preferential chondrule orientations, whereas the orientations in Coolidge and Allende show a wide scatter with no prominent preferential chondrule alignments. Of the three faces of the Vigarano meteorite on which measurements were taken, two exhibit a poor degree of preferential chondrule long axis alignment while one face (Vigarano 2) displayed a relatively good petrofabric. This may be explained by the fact that this latter face was cut either parallel to \( K_{\perp} \) or perpendicular to \( K_{\parallel} \). The lack of orientation in the other two faces indicates that lineation and foliation are not both present in this meteorite.

The results for the ordinary chondritic meteorites examined similarly display a wide range of degree of preferential
TABLE 7.1.

Example of calculation of mean azimuth and standard deviation for chondrule long axis orientation data using the method of Krumbein (1939). Data are for Paranalle specimen 6.

<table>
<thead>
<tr>
<th>Class</th>
<th>Midpoint</th>
<th>f</th>
<th>d</th>
<th>fd</th>
<th>d²</th>
<th>fd²</th>
</tr>
</thead>
<tbody>
<tr>
<td>140 - 160°</td>
<td>0</td>
<td>-4</td>
<td>0</td>
<td>16</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>160 - 180°</td>
<td>1</td>
<td>-3</td>
<td>-3</td>
<td>9</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>0 - 20°</td>
<td>4</td>
<td>-2</td>
<td>-8</td>
<td>4</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>20 - 40°</td>
<td>17</td>
<td>-1</td>
<td>-17</td>
<td>1</td>
<td>17</td>
<td>17</td>
</tr>
<tr>
<td>40 - 60°</td>
<td>50°</td>
<td>36</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>60 - 80°</td>
<td>19</td>
<td>1</td>
<td>19</td>
<td>1</td>
<td>19</td>
<td>19</td>
</tr>
<tr>
<td>80 - 100°</td>
<td>3</td>
<td>2</td>
<td>6</td>
<td>4</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>100 - 120°</td>
<td>0</td>
<td>3</td>
<td>0</td>
<td>9</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>120 - 140°</td>
<td>1</td>
<td>4</td>
<td>4</td>
<td>16</td>
<td>16</td>
<td>16</td>
</tr>
</tbody>
</table>

where, f is the number of chondrules in each class

\[ \text{Mode} = \text{midpoint of modal class} = 50° \]

Calculations

Let \( m_1 = \frac{\sum fd}{\sum f} = \frac{181}{81} = 0.01 \)

\[ m_2 = \frac{\sum fd^2}{\sum f} = \frac{89}{81} = 1.10 \]

\[ \text{Mean azimuth} = \text{Mode} + (m_1 \times \text{class interval}) \]

\[ = 50° + (0.01 \times 20°) \]

\[ = 50.2° \]

\[ \text{Standard deviation} (\sigma) = (\text{class interval}) \left( m_2 - m_1^2 \right)^{\frac{1}{2}} \]

\[ = (20°) \left( 1.10 - (0.01)^2 \right)^{\frac{1}{2}} \]

\[ = 21.0° \]
Fig. 7.1. Histogram of the orientations of the long axes of chondrules in the Parnalle meteorite, specimen 1. Dashed line is the calculated mean azimuth.
Fig. 7.2. Histogram of the orientations of the long axes of chondrules in the Parnalle meteorite, specimen 2. Dashed line is the calculated mean azimuth.
Fig. 7.3. Histogram of the orientations of the long axes of chondrules in the Parnallee meteorite, specimen 3. Dashed line is the calculated mean azimuth.
Fig. 7.4. Histogram of the orientations of the long axes of chondrules in the Parnalle meteorite, specimen 4. Dashed line is the calculated mean azimuth.
Fig. 7.5. Histogram of the orientations of the long axes of chondrules from the Parnallee meteorite, specimen 5. Dashed line is the calculated mean azimuth.
Fig. 7.6. Histogram of the orientations of the long axes of chondrules from the Parnallee meteorite, specimen 6. Dashed line is the calculated mean azimuth.
Fig. 7. Histogram of the orientations of the long axes of chondrules in the Chainpur meteorite. Dashed line is the calculated mean azimuth.
Fig. 7.8. Histogram of the orientations of the long axes of chondrules in the Allende meteorite. Dashed line is the calculated mean azimuth.
Fig. 7.9. Histogram of the orientations of the long axes of chondrules in the Leoville meteorite, specimen 1. Dashed line is the calculated mean azimuth.
Fig. 7.10. Histogram of the orientations of the long axes of chondrules in the Leoville meteorite, specimen 2. Dashed line is the calculated mean azimuth.
Fig. 7.11. Histogram of the orientations of the long axes of chondrules in the Leoville meteorite, specimen 3. Dashed line is the calculated mean azimuth.
Fig. 7.12. Histogram of the orientations of the long axes of chondrules in the Leoville meteorite, specimen 4. Dashed line is the calculated mean azimuth.
Fig. 7.13. Histogram of the orientations of the long axes of chondrules in the Vigarano meteorite, specimen 1. Dashed line is the calculated mean azimuth.
Fig. 7.14. Histogram of the orientations of the long axes of chondrules in the Vigarano meteorite, specimen 2. Dashed line is the calculated mean azimuth.
Fig. 7.15. Histogram of the orientations of the long axes of chondrules in the Vigarano meteorite, specimen 3. Dashed line is the calculated mean azimuth.
Fig. 7.16. Histogram of the orientations of the long axes of chondrules in the Coolidge meteorite, specimen 1. Dashed line is the calculated mean azimuth.
Fig. 7.17. Histogram of the orientations of the long axes of chondrules in the Coolidge meteorite, specimen 2. Dashed line is the calculated mean azimuth.
Fig. 7.18. Histogram of the orientations of the long axes of chondrules in the Grosnaja meteorite. Dashed line is the calculated mean azimuth.
Fig. 7.19. Histogram of the orientations of the long axes of chondrules in the Bjurbole meteorite, specimen 1926,494.
Fig. 7.20. Histogram of the orientations of the long axes of chondrules in the Bjurbole meteorite, specimen 1927,11. Dashed line is the calculated mean azimuth.
Fig. 7.21: Histogram of the orientations of the long axes of chondrules in the Knyahinya meteorite. Dashed line is the calculated mean azimuth.
Fig. 7.22. Histogram of the orientations of the long axes of chondrules in the Allegan meteorite, specimen a. Dashed line is the calculated mean azimuth.
Fig. 7.23. Histogram of the orientations of the long axes of chondrules in the Allegan meteorite, specimen b. Dashed line is the calculated mean azimuth.
Fig. 7.24. Histogram of the orientations of the long axes of chondrules in the Kediri meteorite, specimen 1. Dashed line is the calculated mean azimuth.
Fig. 7.25 Histogram of the orientations of the long axes of chondrules in the Kediri meteorite, specimen 2.
**TABLE 7.2.**

Orientation analyses of chondrule long axes in chondritic meteorites

<table>
<thead>
<tr>
<th>Sample</th>
<th>Type</th>
<th>No of chondrules examined</th>
<th>$M_1$</th>
<th>$M_2$</th>
<th>Mode Azimuth</th>
<th>Mean Azimuth</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leoville 1</td>
<td></td>
<td>200</td>
<td>0.17</td>
<td>1.11</td>
<td>175°</td>
<td>173.3°</td>
<td>9.1°</td>
</tr>
<tr>
<td>Leoville 2 CV3</td>
<td>100</td>
<td></td>
<td>0.5</td>
<td>1.00</td>
<td>95°</td>
<td>100.0°</td>
<td>8.7°</td>
</tr>
<tr>
<td>Leoville 3</td>
<td></td>
<td>100</td>
<td>0.25</td>
<td>1.27</td>
<td>172.5°</td>
<td>171.0°</td>
<td>5.6°</td>
</tr>
<tr>
<td>Leoville 4</td>
<td></td>
<td>159</td>
<td>0.16</td>
<td>1.11</td>
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orientation of chondrule long axes of the less friable meteorites.

The six Pamallee specimens exhibit a range in degree of orientation of chondrule long axes. Specimens 1 and 6 have good preferred orientation, 2 and 4 moderate and 3 and 5 weak chondrule long axis preferential alignment. It is not possible from the data to determine whether it is foliation, lineation or both that is present in Pamallee although the presence of some degree of orientation in all faces examined suggests that both foliation and lineation are present. However, the differences in degree of preferential chondrule long axis orientation observed in the six Pamallee specimens may be explained by the fact that those specimens exhibiting weakest orientation were sliced at greater angles away from the foliation and/or lineation direction than those specimens which exhibited the strongest degrees of orientation.

The degree of preferential alignment of chondrule long axes was poor in the face of Knyahinya examined indicating foliation and/or lineation to be weak.

Dodd, however, found Knyahinya to possess a good foliation and weaker lineation. This difference in results for this meteorite may be explained by the fact that the surface examined in the present study was further away from the direction of foliation than was one of those examined by Dodd.

In the case of Kediri, one face (Kediri 2) exhibited a random orientation of chondrule long axes whereas the other face (Kediri 1) displayed a good degree of preferential alignment. It would seem that Kediri 1 was sectioned either parallel to the foliation or perpendicular to the direction of lineation. As in the case of Vigarano the results would seem to indicate that foliation and lineation are not both present in Kediri.

The sections of the three friable meteorites examined, Bjurbolle, Chainpur and Allegan, all display a wide scatter of orientations
with a weak preferential direction of alignment of chondrule long axes.

In the case of Bjurbole 1926, 494, random chondrule long axis orientations were observed. Dodd’s results for Bjurbole indicated the presence of only a weak foliation and little or no lineation. The present analysis supports this. Certainly none of the carbonaceous chondrite sections studied exhibit as prominent a preferential alignment of chondrule long axes as has been observed in many of the other meteorites studied.

7.5. Discussion

The results outlined in the previous section disclose a number of important points namely:

a) Preferential orientation of chondrule long axes appears common in, and perhaps characteristic of, the chondritic meteorites. In only a few cases was no orientation fabric observed.

b) The more friable meteorites appear to display a weaker fabric orientation than the less friable meteorites.

c) There is a wide range in degree of preferential alignment of chondrule long axes.

d) There appears to be no obvious correlation between degree of chondrule long axis preferential orientation and degree of metamorphism.

d) Leoville, the meteorite comprised of a high volume percentage of chondrules, possessed the strongest foliation and lineation of the specimens examined.

These conclusions, in general, support those of Dodd (1965).

It might be argued that conclusion b) above indicates that preferential chondrule orientation is not a relict depositional feature imposed during sedimentation, as suggested by Dodd (1965), but is due to compaction during recrystallisation as inferred by Stacey et al. (1961) to explain the observed increase of magnetic anisotropy with
decreasing porosity in chondrites. On the other hand, conclusion d) above argues that preferential chondrule orientation is not related to metamorphism. It could be that magnetic anisotropy and preferential chondrule orientations in meteorites are unrelated features and that the latter was produced to varying degrees, during aggregation of the meteorite parent bodies whereas the former is the result of later metamorphic processes on these parent bodies. This latter event might also have affected the chondrule petrofabric. It would seem that the nature of the process whereby chondrule long axes became preferentially aligned is still not clear. Further discussion of the problem is given in the concluding chapter of this thesis, Chapter 8.
CHAPTER EIGHT

CONCLUSIONS - CONSTRAINTS FOR THE ORIGIN

OF CHONDRULES AND CHONDRITES

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8.1. Introduction

The analysis of some previously little investigated physical properties of meteoritic chondrules presented in this thesis have indeed provided some valuable new constraints on the origin of chondrules and their accumulation into meteoritic parent bodies. This was the main aim of the research. These constraints will be reviewed in this chapter followed by a discussion of their implications with regard to current theories of chondrule origins and the early history of meteorites.

8.2. Constraints on origins from the physical properties of meteoritic chondrules

Perhaps the most important constraints on chondrule origins imposed by the results presented in this thesis may be drawn from the size and shape analyses of chondrules presented in Chapters Four and Five. They indicate that meteoritic chondrules do not come in a variety of shapes and sizes but rather that most are roughly spherical and fall into a relatively restricted size range (≈ 0.2 - 2.5mm) with a predominance of particles with diameters falling at the smaller end of the size range (≈ 0.3 - 0.7mm), larger chondrules being less frequent. These properties appear, from the evidence available, to be characteristic of the chondritic meteorites though there is evidence to indicate that, compared to the ordinary chondrites, chondrules from the carbonaceous chondritic meteorites have a more restricted range of sizes and proportionally more very small chondrules. It would appear that these observations are more strongly pronounced in the CO3 and CM2 meteorites.

The near sphericity of meteoritic chondrules is not surprising. This was one of the features used to distinguish chondrules from other
material. As they were once molten droplets it is to be expected that a spherical form should result upon crystallisation and solidification.

When the shape of the chondrule frequency size-distribution histograms are examined closely an interesting observation may be made which sheds light on an important aspect of the early history of chondrules. The near-sphericity of chondrules (as evidenced in Chapter Four) and the presence of glass indicate that chondrules were once molten droplets. It is also generally assumed that throughout this molten period chondrules were free isolated bodies most probably in motion with respect to each other. During this time some chondrules and/or molten droplets would most likely have suffered mutual collisions. Indeed, juxtaposed chondrules are observed in meteorite thin sections and some separated chondrules exhibit bowl-shaped depressions which appear to have been produced by the impingement of one chondrule into another when one was "plastic". There is evidence, then, to indicate that collisions between chondrules did occur while some were in the "plastic" state. If, however, collisions had taken place while the chondrules were molten, complete coalescence of the colliding droplets would most probably occur (unless the relative speed of collision was so high that vaporisation took place). If this had been a common occurrence a second peak in the chondrule frequency size-distribution histograms would be expected centered on the diameter equivalent to the volume of two chondrules from the main peak, since collisions between droplets of this size-range would presumably predominate. No such feature is apparent in the chondrule frequency size-distributions presented in this thesis or elsewhere. This would seem to indicate that collisions between chondrules while in the molten state were rare. It would appear that this was also the case while chondrules were "plastic", observations indicating that at most ten per cent of chondrules exhibit (non-hypervelocity) impact pits and only four per cent of chondrules are multiple (Keil, 1979).
The above inference is interesting since it enables a further tentative constraint on chondrule early history to be drawn. By analogy with the kinetic law of gases and atomic collisions, the number of collisions, \( Z \), a chondrule is likely to encounter is equal to

\[
Z = d^2 v t n
\]

where \( d \) is the diameter of a chondrule, \( v \) is the relative velocity of the colliding chondrules, \( t \) is time, and \( n \) is the number density. It is possible using available data to place limits on some of these parameters and arrive at an approximate value for \( n \).

From the measurements presented in this thesis it would seem that a reasonable value for \( d \) would be 0.05 cm. Lange and Larimer (1973) examined an unusual chondrule in the Ngawi chondrite in which was embedded a metal grain. They calculated that the relative velocity of the collision was \( 10^5 - 10^6 \) cm sec\(^{-1}\). A reasonable upper limit for \( v \) would, therefore, appear to be \( 10^5 \) cm sec\(^{-1}\), this value will be adopted for the purposes of the present calculation. A series of experiments by Nelson et al (1972) and Keil et al (1973) produced chondrule-like objects from individual free-falling droplets of various materials, melted by a focused continuous CO\(_2\) laser beam. These objects cooled rapidly (\( \sim 1000^\circ \) C sec\(^{-1}\)). Keil (1979) has reported the results of recent more extensive experiments adopting the same techniques which indicates a slower cooling rate (\( \sim 1000^\circ \) C hr\(^{-1}\)) to give the textural properties of porphyritic chondrules. It seems appropriate, therefore, to work out equation 6.1 for two values of \( t \), \( t = 1 \) second and \( t = 3.5 \times 10^3 \) seconds. The absence of a second peak at larger diameter in the chondrule size-distribution histograms indicates that the number of mutual collisions, with coalescence, \( Z \), between chondrules was low. By analogy with the number of collisions between chondrules when in the "plastic" state estimated from observation, a reasonable value for \( Z \) would appear to be 0.1, i.e. one chondrule in ten encounters another. Inserting these values for the
parameters ($Z$, $v$, $d$, $t$) in equation 6.1 yields

\[
\begin{align*}
  n &= \frac{0.1}{(0.05)^2 \cdot 10^5 \cdot 1} \\
  n &= 1 \cdot 10^{-5} \\
  \text{and} \\
  n &= \frac{0.1}{(0.05)^2 \cdot 10^5 \cdot 3.5 \cdot 10^3} \\
  n &= 4 \cdot 10^{-12}
\end{align*}
\]

for $t$ values of 1 and $3.5 \cdot 10^3$ respectively. These figures indicate that, if the assumptions are correct, the number density of chondrules during their cooling through the liquid state was surprisingly low. In the light of present information, values adopted for the parameters $Z$, $d$, $v$ and $t$ appear reasonable — $d$ has been determined here, an increase in $v$ would most probably result in vaporisation of the colliding particles, $t$ has been estimated experimentally and $Z$ has been inferred with some support from observation. Present indications are then that the number density of chondrules during their cooling through the liquid and "plastic" states was low.

Perhaps the most important question that arises from the analysis of chondrule size-distributions is why do meteoritic chondrules exhibit a narrow range in sizes with a pronounced peak in distribution toward the lower end of the size range and a prominent lower limit cut-off in size? Dodd (1976) concluded that the narrow size-distribution of chondrules in chondrites was a result of aerodynamic sorting during accretion of the chondritic material. If chondrules had been produced with a large range in sizes and then sorted it might be expected that some chondrites would contain predominantly large chondrules and some predominantly small ones. There
is no evidence to suggest that this is the case. It might be argued that the apparently small difference in chondrule size-distributions in the CO3 and CM2 meteorites compared to other chondrites is a result of this sorting process yet why should the smaller chondrules be preferentially accreted by selected groups of the carbonaceous chondrites? There are also differences in composition between chondrules from the ordinary and these carbonaceous chondrites (McSween, 1977). It would seem that sorting of chondrules with respect to size has so far not been observed. It seems more likely that the restricted size range of meteoritic chondrules is an intrinsic property though it is not yet clear whether chondrules were produced primarily with this property or whether the chondrule forming process acted on material already possessing this characteristic. This will be discussed further in a following section.

The chondrule lower limit cut-off in size at around 0.2mm might be explained by one of two mechanisms. For example, if chondrules were produced by a high-energy event acting on already condensed material it could be that the energy of this event was such that material with a mass below a certain value was vaporised, material with mass greater than this value would, however, have been liquefied (with perhaps some vaporisation), and subsequently recrystallised forming chondrules. Alternatively, surface tension effects might explain this property. Arguments may be raised against both of these proposals. For example, in the former case it might be expected that the smaller chondrules would have suffered some loss of material by vaporisation during the high-energy event. This might result in a marked difference in composition between smaller and larger chondrules. The results of Keil's group of researchers (Keil, 1979) indicates that there is, however, no marked correlation between size and type or chemistry of chondrules. Indeed, an important finding from their work is that although the chemical composition of individual chondrules from H, L and LL group meteorites shows a wide range, it is not possible to differentiate between these groups on the basis of the range in composition of each group. Keil is of the opinion that this indicates
that the chondrules from the ordinary chondrites must have been produced from heterogeneous starting material. The similarity in chondrule chemistry in the ordinary chondrites also extends to the rare-earth abundances and to their mineral chemistry. These results suggest that the H, L and LL groups differ because of differences in their metal contents and matrix chemistries. Contrary to earlier opinion (Fredriksson, 1963, 1969; Fredriksson and Reid, 1965; Urey, 1967; Kurat et al, 1969; Whipple, 1966; Dodd, 1971; van Schmus, 1969; Schmitt et al, 1968; Walter, 1969; de Gasparis et al, 1975; Osborn et al, 1974) these results would seem to indicate that chondrules differ from their host matrix.

The argument against surface tension as the controlling factor in the lower limit of chondrule size is that once molten droplets, microchondrules, which are smaller than 0.2 mm in diameter, are found in some primitive type I carbonaceous chondrites. Small, glass spherules are also a constituent of the lunar regolith.

The restricted size-range of chondrules, the preponderance of particles at the smaller end of the size-range, the lower limit cut-off in size and the similarity in these properties among the chondritic meteorites appear to be strong constraints for theories of chondrule origin.

A further constraint is applied by the finding, presented in Chapter Six of this thesis, that chondrule mass-frequency distributions do not follow Rosin's law and are, therefore, by analogy with artificially produced samples not the product of crushing phenomena. Chondrule mass-frequency distributions can, however, be described by the Weibull statistical function.

8.3 Further constraints on the origin of meteoritic chondrules

Along with the constraints derived from the study of the physical properties of meteoritic chondrules outlined in the previous section, any theory for the origin of chondrules must also satisfactorily explain a number of other constraints imposed from investigations of other properties of
chondrules. These constraints must also be outlined before the theories of chondrule formation can be discussed.

Evidence has been presented in the previous section which indicates that chondrules formed in a dispersed medium in which coalescence or flocculation was minimised. However, when composite chondrules are observed textural relationships appear to be systematic and may, therefore, provide petrographic constraints under which hypotheses concerning chondrule origins must operate.

Members of double and triple connected chondrules appear to be always of the same petrologic type and composition (McSween, 1977). It was pointed out in the previous section that the results of the experiments by Keil’s group (Keil, 1979) suggest that the different petrologic types of chondrules were formed under different rates of cooling. In fact, Keil argues that composition and degree of supercooling are also factors which control the ultimate texture of a chondrule. McSween (1977) concludes that the close genetic relationship between multiple chondrules demonstrates that the different chondrule petrologic types did not form in close proximity. If this was indeed the case it is clear that mixing of the different types must have occurred to some extent prior to accretion. McSween (1977) has argued that, in the case of the carbonaceous chondrites, large scale mixing of chondrules and inclusions before accretion was not a pervasive process in the nebula because each meteorite class has its own distinctive population of inclusions and/or chondrules. This is not so in the ordinary chondrites where distinctions cannot be drawn on the basis of chondrule compositions and textures (Keil, 1979).

Keil’s observations on the control of chondrule textures might also be taken to imply that the different chondrule types were not formed in close proximity. However, it is not yet apparent whether any of the factors controlling the ultimate texture a chondrule will take up is dominant or not. For example, it might, given the correct conditions, be possible to produce chondrules exhibiting a wide range of textures in the same event starting from
heterogeneous starting material. It does not, however, seem difficult to envisage the production of chondrules in close proximity in a number of events under slightly varying conditions with subsequent mixing of material before accretion.

An alternative suggestion to explain the close genetic relationship between multiple chondrules is that once one member of the group had crystallised it controlled the texture adopted by its companions. It has also been suggested that, in some cases at least, multiple chondrules are the result of the extrusion of molten material from one of the members on cooling to form an adjacent chondrule(s). This would obviously explain the close similarity in composition between multiple chondrules and, since they would be subjected to the same conditions, it would be expected that similar textures would be adopted by all members of the group on crystallisation.

Finally, the measurements of the ages of meteorites and chondrules shows that chondrules are certainly not younger than their parent meteorites nor are they appreciably older. It would seem, therefore, that they did not form long before their accretion into meteorites. They are, however, amongst the oldest, unaltered, solar system material available for study. It would seem that meteoritic chondrules formed early in the history of the solar system prior to or during accretion of the meteorite parent bodies.

8.4 Constraints and the origin of meteoritic chondrules

8.4.1. Introduction

Current hypothesis for the origin of chondrules fall into two categories. The first suggests that they are primary objects formed by various means directly from the solar nebula. The other category envisages some form of high-energy event acting on pre-existing material whereby chondrules are secondary objects. The various suggested mechanisms of chondrule formation falling into both of these categories will now be discussed in the light of the constraints on chondrule origins outlined in the previous sections.
8.4.2. Primary hypotheses

Over one hundred years ago Sorby (1877) postulated that chondrules were primary liquid condensates when he described them as 'drops of a fiery rain'. Shortly after Meunier (1884) suggested that chondrules condensed from the outer turbulent gas layers of a star. More recent variations on this condensation model have removed chondrule condensation to regions of the solar nebula away from the sun or to proto-planetary atmospheres.

McSween (1977) favours chondrule and inclusion formation by direct condensation from the solar nebula since the observed continuance in chondrule and inclusion compositions in the carbonaceous chondrites might, he believes, be rationalized by a condensation path which dips at some point into the liquid stability field and gives rise to chondrules. McSween presents arguments whereby the observed textural relationships and elemental correlations would be predicted by this model. Others (Walter and Dodd, 1972; Dodd and Walter, 1972) have, however, presented chemical, textural and mineralogical arguments against chondrule formation in this way. Certainly the quench textures of chondrules would be difficult to produce during the expected slow cooling of the nebula during condensation. Blander et al (1976) have, however, determined by experiment that chondrule-like melts can undercool by as much as 750°C below their liquidus temperatures before solidification which might then have been rapid once crystal nucleation took place. Moreover, the temperature of many chondrules would increase upon crystallisation since the crystallisation of forsterite is exothermic. Textures would thus be determined not by the slow cooling rate prior to recalescence but by the magnitude of the rapid temperature rise.

There is, however, one major stumbling block to all theories of chondrule formation by direct condensation from the solar nebula and that is that liquids are not stable at the low pressures (≈10^-3 atmospheres) generally envisaged in the solar nebula. Various suggestions have been made to overcome this problem.
Direct condensation under "constrained equilibrium" is considered to have been a viable process by Blander and Katz (1967) and Nelson et al (1972). Although such a model is difficult to test contradictory evidence has been presented by Osborn et al (1973) who noted an Al - Ir correlation in chondrules from unequilibrated ordinary chondrites. The constrained equilibrium theory predicted no correlations since Ir would condense as a solid after Fe and not with Al at high temperature.

To circumvent the pressure problem the direct equilibrium condensation models have to appeal to special conditions to raise the pressure sufficiently to stabilise liquids. Wood (1963) has advocated transient high-pressure as a result of shock waves resulting from mass-ejection from the protosun during a T-Tauri phase. It seems unlikely that the necessarily high pressures for direct chondrule condensation would be achieved in this manner. An alternative model is that of Podolak and Cameron (1974) whereby chondrule liquids condense in the dense proto-planetary Jovian atmosphere. Here the removal of these objects from this environment to enable their accretion into the meteorite parent bodies would appear to be somewhat difficult to achieve.

Herndon and Suess (1977) and Wood and McSween (1977) have examined the effects on condensation of hydrogen depletion and various gas/dust mixing ratios respectively to see if liquid condensation can more readily be achieved. Wood and McSween conclude that at high dust concentrations chondrule melts can be stabilised at lower pressures. Hydrogen depletion has a similar effect. Whether these are viable physical processes in the nebula is debatable.

It is not readily apparent that any of the 'primary' models for chondrule origins should give rise to the size constraints outlined previously unless the process of direct nebula condensation is analogous to the condensation of raindrops from water vapour which produces a size uniformity (Best, 1950, 1951; Pedersen and Todsen, 1960). McSween (1977) has pointed out the difficulty of realising these models with the most recent calculations describing the conditions in the solar nebula. Whereas earlier theoretical models (e.g. Cameron and Pine, 1973) predicted that temperatures in the nebula
would have been high enough to allow the vaporisation of the interstellar
dust with subsequent cooling and condensation, the later models (Cameron, 1976)
indicate that this might not have been the case and that condensation could
not have occurred since temperatures were never sufficiently high to completely
evaporate the interstellar grains. However, vaporisation and condensation
is allowed in the hot interior atmospheres of giant gaseous protoplanets in
the newer models which also predict vigorous turbulence. If this was so
gas/dust fractionation via gravitational settling to the midplane could not
have taken place. It is postulated that gas/dust fractionation may have been
possible in the giant gaseous protoplanets.

It would appear that to produce chondrules by any of the proposed
primary hypotheses requires specialised conditions for equilibrium
condensation or "constrained equilibrium" to stabilise liquids. This seems,
to a large extent, to negate the foremost reasons for invoking the formation
of chondrules in a 'primary' fashion.

8.4.3. Secondary hypotheses

Perhaps the oldest secondary hypothesis for the formation of
chondrules is that of volcanism first proposed by Tschermak (1875) and later
revived by Merrill (1920), Wahl (1952), Ringwood (1961) and Fredriksson and
Ringwood (1963). However, terrestrial volcanoes do not produce chondrules
or chondrule-like objects and, unlike meteoritic chondrules, volcanic ejecta
is poorly sorted (Fisher, 1964).

Whipple (1966) and Cameron (1966) have discussed the possibility
of melting condensed dust grains or aggregated dust balls by lightning
discharges in space. If, as discussed in the previous section, vaporisation
and condensation of interstellar dust did not take place in the solar nebula,
dust agglomerates might be expected. A number of arguments may be levelled
against this proposal. Separation of charge and the generation of
electrostatic potentials as a result of the movement and dispersion of
finely-divided material has been confirmed by laboratory studies (Harper,1967).
A spark discharge - such as volcanic lightning (Anderson, 1965) - generally equilibrates the charge at atmospheric pressure. However, at reduced pressures, charge equalisation occurs via a glow discharge (Llewellyn Jones, 1966). If this were the mechanism by which electrostatic potentials were dissipated in the solar nebula it is unlikely that melting of material would take place via this process. If, however, melting was accomplished by lightning it has been suggested (Podolak and Cameron, 1974) that, in some cases at least, melting by lightning would result in vaporisation of the surface layers of the solids without internal liquifaction. Chondritic meteorites are not known to contain chondrules with unmelted cores or partially melted dust balls. Finally the micron sized nature of interplanetary dust (Brownlee et al, 1977) suggests that the number of particles needed to aggregate to produce chondrule-sized objects would be so large that the resulting chondrules would vary little in bulk composition (Dodd and Walter, 1972) which is not the case (see section 8.2).

At the present time perhaps the most popular model for the formation of chondrules is production by impact melting. Two impact models have been advocated, namely impacts between small objects in space (Whipple, 1972; Wasson, 1972; Cameron, 1973; Lange and Larimer, 1973; Kieffer, 1975; Kerridge and Kieffer, 1977) or impacts into the surface regolith of a parent body. (Fredriksson, 1963; Kurat, 1967; Urey, 1967, Wlotzka, 1969; Dodd, 1971; King et al, 1972; Keil, 1979).

Of the former type, Kieffer (1975) suggested that high velocity collisions between relatively small (millimeter to centimeter sized) particles in space might produce melts by extrusion from the intersection of obliquely colliding surfaces, a process termed jetting, which would most probably produce liquids intermediate in composition between the colliding objects. However, the carbonaceous chondrites contain irregular (Ca, Al-rich) inclusions different in composition to their (Fe, Mg-rich) chondrules. Such inclusions are just as likely to have suffered collisions with chondrule precursors producing chondrules with intermediate composition (unless the chondrules and
inclusions were formed in different regions of the nebula and subsequently brought together prior to accretion into meteorite parent bodies). Chondrules with such an intermediate composition have not been observed suggesting that pre-existing material did not form chondrules by this type of impact melting mechanism (Grossman and Clark, 1973). It has also been shown in an earlier section that collisions between chondrules while molten or "plastic" were probably rare events. It would seem unlikely, therefore, by extrapolation that impacts would have been more common immediately prior to the time chondrules were in these states.

Wood and McSween (1977) have argued that gas drag in the solar nebula would have kept particles in low-inclination, circular orbits such that collisions would not be of sufficient velocity to produce melting and jetting of material.

Concerning the second group of impact models, the presence of glassy and devitrified spherules undoubtedly of impact origin in the lunar regolith soil breccias (Fredriksson et al, 1970, 1971; Kurat et al, 1971, 1972; Keil et al, 1972; King et al, 1972; Nelen et al, 1972; Christophe – Michel – Levy et al, 1972) and at one terrestrial impact site (Fredriksson et al, 1973) has lent strong support in the eyes of many to the theory of chondrule production by impacts in an 'extended' regolith. A number of serious objections may be raised against this model, however. The chondrule-like objects observed in the lunar material and at the Lonar impact site are rare indicating melts so produced are insignificant (<1% efficiency, O'Keefe and Ahrens, 1975). A process of concentration would be required to produce the observed abundance of chondrules in meteorites if they were produced by this mechanism. The chondrule-like spherules also have bulk compositions which reflect that of the target rocks. It has been shown that meteoritic chondrules and surrounding matrix do not exhibit quite such a compositional correspondence. Glass fragments and glass spherules along with a very few chondrules which have compositions similar to the bulk rock have been observed in the Malvern (Jerome and Christophe – Michel – Levy, 1971) and Bununu (Noonan, 1974;
Jerome and Desnoyers, 1974) howardites. Such meteorites have been interpreted as soil breccias (i.e. regolith material) (Reid, 1974; Bunch, 1975; Dymok et al, 1976) and should, therefore, be expected to contain abundant chondrules if impact melting was the process of formation of chondrules yet they do not. The brecciated debris and agglutinates, characteristic of regolith samples, are also largely absent in chondrites (Kerridge and Kieffer, 1977).

Although the studies of Christophe - Michel - Levy et al (1972), King et al (1972), Kurat et al (1972) and Nelen et al (1972) have demonstrated that chondrules can be formed on parent-body surfaces by impact, large impacts would be necessary to achieve the devitrification observed in many meteoritic chondrules. Wasson (1974) has shown that for a 300Km parent-body the escape velocity is much lower than the minimum impact velocity required to produce melts. By this means chondrule formation would be a very inefficient process as most would be lost to space. Finally, the mass-distribution of chondrules does not follow Rosin's law to which many artificially crushed products may be fitted. The lunar regolith on the other hand, the product of repeated impacts (i.e. crushing events) does follow this function. Meteoritic accumulation also appears to have been a gentle process (see section 8.5).

Thus, although some meteoritic chondrules were probably produced by impact in a regolith, the chemical variability of meteoritic chondrules and their concentrations in meteorites point to a different explanation for the production of the majority of them.

Indeed, the origin of chondrules by either of the impact melting models necessitates concentration of the melted products because of the inefficiency of the processes. This thesis has shown that meteoritic chondrules have a narrow size-distribution yet impacts generally produce droplets of widely varying sizes. Aerodynamic sorting of chondrules has been proposed by Dodd (1976) to explain the restricted size range of chondrules and to produce the observed lineation and foliation. Such a process would have excluded from accretion any fine-grained material such as the matrix of the carbonaceous chondrites. Other objections to this proposal have been made in section 8.2.
8.4.4. Summary

In summary it appears that, although a few meteoritic chondrules are probably the products of impacts into regolith material, the mechanism(s) whereby the majority of chondrules were formed cannot, as yet, be ascertained with any certainty since the constraints on chondrule origins imposed by the size and shape analyses presented in this thesis, along with those from other lines of research, do not enable any of the proposed models to be entirely rejected or affirmed. It is likely that this state of affairs arises from the lack of specific predictions of the properties of chondrules produced by the models which in turn is due to the lack of understanding of the physical and chemical processes in the events proposed. Only when these are more fully understood can the constraints be applied on a more specific basis.

It is worthwhile stressing again the importance of the elucidation of the major chondrule-forming process(es). If the present influx of meteoritic material to the earth is representative of the proportions of the meteorite types in the solar system then the chondrule-forming process was a widespread one, at least in some regions of the solar system and perhaps throughout large regions. It could be that chondrule production was the rule rather than the exception in the formation of early solar system material. A fuller understanding of the process(es) involved in the formation of meteoritic chondrules might, therefore, shed light on conditions and processes in the solar nebula around the time of planetary formation.

From the evidence so far available, the author would suggest that the most likely interpretation is that the chondrule-forming process acted on heterogeneous, rather dispersed material already possessing a narrow range of sizes (or masses). Nebula dust ball agglomerates would, therefore, seem the most likely chondrule precursors. The nature of the high-energy event(s) which melted these agglomerates is still not clear. It would appear that the chondrule-forming process either occurred before larger (millimetre sized) dust-balls could accumulate or some process in the nebula hindered the aggregation of dust-balls of large size.
Perhaps the most serious objection that can be raised against this type of model is the argument that chondrules formed from nebula dust-ball agglomerates should have a narrow range of compositions because of the large number of grains constituting each aggregate yet chondrule compositions vary widely. However, it is possible to envisage differences in composition of nebula dust-ball agglomerates since particles would sink to the mid-plane of the nebula at varying rates depending upon their size and density.

8.5. The accumulation and early history of meteoritic material

The friable nature (i.e. lack of compaction) of some of the meteorites (Bjurbole, Chainpur, Allegan) studied in the present research and the presence in some carbonaceous chondrites of fine-grained friable, irregular inclusions with intricate mossy-like margins against surrounding matrix suggests that accumulation of meteoritic material must have been a gentle process. Reaction rims around many meteoritic inclusions at the contact with the matrix indicates that the material was hot during accretion. Recently Hutchison et al (1979) have concluded, after examining compositional and textural relationships in the Tieschitz meteorite, that it effectively accreted at $(800^\circ \pm 100)^{\circ}C$. Such a high temperature of accretion has significant implications on previous ideas for the accretion of meteorite parent bodies whereby the two component model (Larimer and Anders, 1967) has been widely accepted. It seems unlikely that the carbonaceous meteorites could have accreted at such a high temperature.

It was shown in Chapter Seven that most meteorites exhibit a non-random orientation of elongate particles. It is not yet clear whether this petrofabric was imposed during accretion when particles, already elongate, would tend to come to rest with their long axis parallel to the surface of deposition or whether the particles attained their elongate form and oriented nature during metamorphic reheating and squeezing of the meteoritic material by overburden pressure. As there appears to be no correlation between amount of metamorphism and degree of orientation in the meteorites it has been argued
that the petrofabric was therefore more probably imposed during accretion and compaction. Later metamorphism may, however, in some cases have affected the petrofabric whilst in others it had little or no effect. However, it is generally assumed that degree of metamorphism is related to depth of burial and, therefore, to overburden in which case a correlation between degree of metamorphism and degree of preferential orientation would be expected. This may not necessarily be so, however, in which case chondrule long-axis preferential orientation may have been produced during metamorphism.

It must be concluded that the nature of formation of the petrofabric in most chondritic meteorites is not yet fully understood.

8.6. Conclusion

It was not considered at the outset of the present research that the problems of the origin of chondrules and the accumulation and early history of the chondritic meteorites would be solved, rather that new and important relevant information could be obtained that would allow further constraints to be added to those already deduced from other lines of research. To a large extent this has been achieved. Before these problems can be elucidated more information is required not only on the nature of chondrules and chondrites but also on the processes and conditions prevailing in the solar nebula some 4.5 billion years ago.
APPENDIX

DOES THE LUNAR REGOLITH FOLLOW

ROSIN'S LAW?

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<th>Description</th>
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<td>A.3</td>
<td>Results and conclusion</td>
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</tbody>
</table>
A.1 Introduction

In Chapter 6 it was pointed out that Rosin's law (Rosin and Rammler, 1933) had been found to fit artificially crushed products of many kinds and sizes as had some weathered source rocks. It might be expected, then, that material produced by impact(s) should follow Rosin's law. One type of theory for chondrule origin implies formation by impact mechanism, consequently the chondrule size distributions presented in this thesis were tested against the law. It was concluded that these distributions did not follow Rosin's law (Chapter 6).

Many lines of evidence suggest that the lunar surface layer, now termed 'regolith' with the finest component (less than 1mm) referred to as 'soil', is the product of repeated impacts on the lunar surface. Such evidence includes the small mean particle size of the regolith, the incorporation of fragments of underlying basalt, the presence of shock features and glass spatter from shock-melting, meteoritic debris, and microcraters on rock fragments and glass sphere surfaces (Short, 1975). At first it was thought that repetitive impacts on the lunar surface would cause both comminution and progressive turnover of the regolith. This view has, however, been re-evaluated in the light of data from the later Apollo missions. It now appears that deposition of successive layers of ejecta (millimeters to centimeters thick) by base-surges etc. associated with the formation of the larger craters is the major mode of deposition of the regolith.

It, therefore, seems appropriate to examine whether the lunar regolith particle-size distribution follows Rosin's law.
A.2 Measurements and technique

The regolith particle-size distribution data (less than 1mm) has been taken from a series of papers - Apollos 11 and 12, King et al (1971); Apollos 14 and 15, King et al (1972); Apollo 16, Butler et al (1973). All these analyses were performed using the technique of dry sieving with an Allen-Bradley sonic sifter and precision sieves. U.S. standard sieves (woven mesh, square aperture) were used for the size range 841 - 37\(\mu\mu\); for particle sizes smaller than this electroformed square aperture sieves were used. From the reported size-fraction weights cumulated weight per cent values were calculated and the sieve sizes converted to \(\phi\)-units. The resulting data were plotted on the specially ruled grid devised by Geer and Yancey (1938). Representative samples from each Apollo mission are shown in Figures A.1 - A.4 (Apollos 11 and 12 - Figure A.1; Apollo 14 - Figure A.2; Apollo 15 - Figure A.3; Apollo 16 - Figure A.4). The Rosin numbers for these samples were determined from the plots and are given in Table A.1.

A.3 Results and conclusion

Examination of the lunar regolith soil cumulative particle-size frequency distribution plots in Figures A.1 - A.4 shows them all to be markedly similar. The samples are poorly sorted and exhibit relatively good straight line plots from the largest particle sizes down to 4.76 \(\phi\) (37 \(\mu\)). Plots of particle-sizes smaller than this are characterised by a change in slope of the frequency curve, usually accompanied by a displacement of the line. It should be noted that this is true not only for the samples presented here but for all those tested in this manner.
Fig. A.1. Cumulative weight per cent plots of Apollos 11 and 12 lunar regolith soil samples. Ordinate conforms to Rosin's law.
Fig.A.2. Cumulative weight per cent plots of Apollo 14 lunar regolith soil samples. Ordinate conforms to Rosin's law.
Fig. A.3. Cumulative weight per cent plots of Apollo 15 lunar regolith soil samples. Ordinate conforms to Rosin's law.
Fig. A.4. Cumulative weight per cent plots of Apollo 16 lunar regolith soil samples. Ordinate conforms to Rosin's law.
As there are more data points for particle sizes larger than 4.76\(\phi\) than for smaller sizes, plus the fact that the smaller particles tend to clump together (thereby, possibly, giving rise to larger errors in the size analysis of small particles), the slope of the straight line plot from the largest particle sizes down to 4.76\(\phi\) was used to determine \(n\). In all cases \(k\) could be determined from this region of the plot also. It should be pointed out, however, that, in general, 40 - 50\% of particles by weight were smaller than 4.76\(\phi\).

The Rosin numbers for the representative samples, shown in Table A.1, reflect the overall similarity in their cumulative weight per cent plots. Although there is a spread in the \(k\) values, the values for \(n\) represent a restricted range in slopes from 28.5° to 39.5°.

Since in each sample the cumulative weight per cent plots for lunar regolith soil particle sizes down to 4.76\(\phi\) lie on straight lines on the specially devised grid system used (as, in general, do plots of smaller particle sizes where more than two size fractions were determined), it would seem that the lunar regolith soil component as sampled by Apollos 11, 12, 14, 15 and 16 conforms to Rosin's law. This would suggest further evidence for the origin of the lunar regolith by impact. Obviously, it was not necessary to test the lunar regolith soil data against a Weibull distribution.

The chondrule size data presented earlier in this thesis (Chapter 4) along with other chondrule size data were found not to fit Rosin's law (Chapter 6). This would seem to suggest different modes of origin for meteoritic chondrules and the lunar regolith. Further arguments against an impact origin for chondrules were presented in Chapter 8.
Value of the Rosin numbers, n and K extracted from the samples of Apollo regolith soils in Figures A.1 - A.4.

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PUBLISHED PAPERS

Copies of papers reporting results from this thesis and published before submission of the thesis are contained in the envelope at the back of the thesis.
SOME PHYSICAL PROPERTIES OF CHONDRITIC METEORITES

by Philip M. Martin

Meteorites appear to be the most primitive objects in the solar system and, therefore, contain valuable information on the early history of solar system material. The most abundant meteorites, the chondrites, are characterised by the presence of small spherical silicate inclusions, chondrules. Although the chemical, mineralogical and petrological properties of chondrules have been investigated their purely physical properties have received little attention. The present thesis therefore examined the size, shape and orientation of long axes of chondrules and tested the fit of chondrule mass distribution to known statistical functions in order to obtain constraints on the origin of chondrules and the accumulation and early history of meteorites.

The size range of chondrule diameters was found to be rather limited from a pronounced lower limit cut-off around 0.2mm up to a few millimeters. A preponderance of particles of smaller diameter (≈ 0.3 - 0.7mm) was observed. Although there appeared to be no marked difference in chondrule size distributions in the ordinary chondrites, those in the carbonaceous chondrites are more restricted with a greater preponderance of smaller particles. Departures from sphericity of chondrules were found to be small and random. Chondrule mass-frequency distributions could be fitted to the Weibull statistical function (except for Nikolskoe) but were found not to obey Rosin's law suggesting, by analogy, that chondrules were not produced by crushing phenomena.

Most chondrites were found to exhibit some degree of preferential orientation of chondrule long axes which was less marked in relatively friable meteorites and appeared unrelated to degree of metamorphism.

It was concluded that the observations suggest that chondrules are most probably secondary objects formed by a high-energy event acting on material with a restricted mass range. Accumulation of meteoritic material was a gentle process with the petrofabric most likely being imposed during this period.
DOES THE LUNAR REGOLITH FOLLOW ROSIN'S LAW?

PHILIP M. MARTIN and A. A. MILLS
Departments of Geology and Astronomy, The University, Leicester, U.K.

(Received 27 September, 1976)

Abstract. Results from particle-size distribution analyses of the lunar regolith (less than 1 mm) as sampled by Apollos 11, 12, 14, 15 and 16 have been tested to see if they conform to Rosin’s law, which has been found to describe crushed products of many kinds and sizes. In all the lunar examples the law appears to be followed closely. It is concluded that the lunar regolith is probably the result of crushing forces, most likely impacts on the lunar surface.

1. Introduction

The lunar surface layer is now termed ‘regolith’, with the finest component (less than 1 mm) referred to as ‘soil’. The small mean particle size of the regolith, the incorporation of fragments of underlying basalt, the presence of shock features and glass spatter from shock-melting, meteoritic debris, and microcraters on rock fragments and glass sphere surfaces seem to indicate that impact on the lunar surface has been the prime agent in producing the regolith (Short, 1975). At first it was thought that these repetitive impacts would cause both comminution and progressive turnover of the regolith. This view has, however, been re-evaluated in the light of data from the later Apollo missions. It now appears that deposition of successive layers of ejecta (millimeters to centimeters thick) by base-surges etc. associated with the formation of the larger craters is the major mode of deposition of the regolith.

If the lunar regolith is, indeed, the product of repeated impacts on the lunar surface, we might expect the regolith particle-size distribution to follow Rosin’s law (Rosin and Rammler, 1934) since artificially crushed products of many kinds and sizes have been found to fit this function (Moore, 1934; Bennett, 1936; Geer and Yancey, 1938) as have some weathered source rocks (Krumbein and Tisdel, 1940).

The law is usually expressed in the form (after Bennett, 1936):

\[ R = 100 e^{-\frac{x}{k}} \]

where \( R \) is the weight per cent retained on a sieve of mesh \( x \), \( k \) represents an average size and \( n \) is the reciprocal of the spread of the distribution curve.

Geer and Yancey (1938) have designed a special co-ordinate system such that if the cumulative weight per cent plot of a given comminuted sample yields a straight line, then that material can be said to follow Rosin’s law. Moreover, the Rosin numbers, \( n \) and \( k \), are readily determined – \( n \) is the tangent of the slope of the line and \( k \) is the millimetre value at the intersection of the straight line with the 36.8% line of the vertical scale.

We report here on tests to see whether the lunar regolith soil, as sampled by Apollos 11, 12, 14, 15 and 16, follows Rosin’s law.

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2. Measurements and Technique

The regolith particle-size distribution data (less than 1 mm) has been taken from a series of papers – Apollos 11 and 12, King et al. (1971); Apollos 14 and 15, King et al. (1972); Apollo 16, Butler et al. (1973). All these analyses were performed using the technique of dry sieving with an Allen-Bradley sonic sifter and precision sieves. U.S. standard sieves (woven mesh, square aperture) were used for the size range 841 – 37 μ; for particle sizes smaller than this electro formed square aperture sieves were used. From the reported size fraction weights we have calculated cumulative weight per cent values and converted the sieve sizes to phi (ϕ) units (−log₂ diameter (mm)) – after Krumbein, 1934).

Resulting data were plotted on the specially ruled grid devised by Geer and Yancey (1938). Representative samples from each Apollo mission are shown in Figures 1 - 4 (Apollos 11 and 12 – Figure 1; Apollo 14 – Figure 2; Apollo 15 – Figure 3; Apollo 16 – Figure 4.). The Rosin numbers for these samples were determined from the plots and are given in Table I.

TABLE I

<table>
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<th>Specimen number</th>
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<th>k in mm.</th>
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3. Results and Conclusion

Examination of the lunar regolith soil cumulative particle-size frequency distribution plots in Figures 1–4 shows them all to be markedly similar. All samples are poorly sorted and exhibit relatively good straight line plots from the largest particle sizes down to 4.76 ϕ (37 μ). Particles smaller than this are characterised by a change in slope of the plot, usually accompanied by a displacement of the line. We should point out that this is true not just for the samples presented here but for all the regolith samples we have tested. We feel it unlikely to be coincidence that this alteration in slope occurs at the point where the change from woven mesh to electroformed sieves was undertaken in the original particle-size analyses. As there are more data points for particle sizes larger than 4.76 ϕ than for smaller sizes, plus
Fig. 1. Cumulative weight per cent plots of Apollo 11 and 12 lunar regolith soil samples. Ordinate conforms to Rosin's law.

Fig. 2. Cumulative weight per cent plots of Apollo 14 lunar regolith soil samples. Ordinate conforms to Rosin's law.
Fig. 3. Cumulative weight per cent plots of Apollo 15 lunar regolith soil samples. Ordinate conforms to Rosin’s law.

Fig. 4. Cumulative weight per cent plots of Apollo 16 lunar regolith soil samples. Ordinate conforms to Rosin’s law.
the fact that the smaller particles tend to clump together (thereby, possibly, giving rise to larger errors in the size analysis of small particles), we have used the slope of the straight line plot from the largest particle sizes down to 4.76 $\phi$ to determine $n$. In all cases $k$ could be determined from this part of the plot also. We should point out however that, in general, 40–50% of particles by weight were smaller than 4.76 $\phi$.

The Rosin numbers for the representative samples (Table I) reflect the overall similarity in their cumulative weight per cent plots. Although there is a spread in the $k$ values, the values for $n$ represent a restricted range in slopes from 28.5° to 39.5°.

Since in each sample the cumulative weight per cent plots for lunar regolith soil particle sizes down to 4.76 $\phi$ lie on straight lines (as, in general, do plots of smaller particles where more than two size fractions were determined) we conclude that the lunar regolith as sampled by Apollos 11, 12, 14, 15 and 16 conforms to Rosin's law. We believe that here we have further evidence for the origin of the lunar regolith by impact.

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SIZE AND SHAPE OF NEAR-SPHERICAL ALLEGAN CHONDRULES

PHILIP M. MARTIN * and A. A. MILLS

Departments of Geology and Astronomy, University of Leicester, Leicester LE1 7RH (U.K.)

Received September 3, 1977
Revised version received October 12, 1977

Chondrules were extracted from a disaggregated sample of the Allegan meteorite. Individual chondrules were examined with apparatus incorporating two orthogonal binocular microscopes, and their three major axes measured. Maximum chondrule diameters ranged from 0.15 to 2.75 mm with a peak in distribution between 0.35 and 0.75 mm. The chondrule size distribution was found not to conform to Rosin's law. The chondrules were found to depart from sphericity by only small amounts. The authors still believe that the melting of nebula dust-ball agglomerates by some high-energy event was the most probable mechanism for the formation of chondrules.

1. Introduction

We have previously reported on the size and shape of near-spherical chondrules separates from the Bjurböle and Chainpur chondritic meteorites [1]. Hughes [2] has also investigated the size distribution of chondrules from these two meteorites. Here we report on similar properties for chondrules from the Allegan (H4) chondrite as part of our continuing investigation to elucidate constraints on chondrule origin from their purely physical properties.

Allegan is similar to Bjurböle and Chainpur in being relatively friable thereby greatly facilitating chondrule extraction. Once again, we believe that this characteristic and the low degree of metamorphism in Allegan indicate that its chondrules are more likely to be in their primary configuration and, consequently, more valuable for obtaining constraints on origin.

2. Material, sampling and measurement

The material was kindly supplied by Dr. R. Hutchison of the Department of Mineralogy, British Museum (Natural History). The 10.7-g sample (Museum number BM 1920,281) consisted of two fractions — approximately 6.2 g of angular chunks and 4.5 g of finer, disaggregated material. The disaggregated fraction was sieved to remove the very finest-grained material (<0.2 mm) which tended to obscure chondrules. The remainder of this fraction (~2.9 g) was intensively examined under a binocular microscope for chondrules which were extracted by handpicking and, where necessary, cleaned using simple mechanical tools. Microscopic examination of a number of broken chondrules revealed negligible surface matrix coating. The <0.2-mm material was also examined for chondrules but none was found.

The 1256 chondrules we extracted were distinguished from other particles by their near-spherical form and generally smooth surfaces. It became, however, increasingly more difficult with decrease in size to decide whether some particles were indeed chondrules.

The chondrules were weighted and found to comprise 15% by weight of the fraction examined.

Individual chondrules were viewed using two orthogonal binocular microscopes. Magnifications of 16X, 25X, 40X, 62.5X and 100X were used depending upon the size of chondrule under examination. Both microscopes were equipped with identical eyepiece
scales against which the maximum length \((a)\), breadth \((b)\) and width \((c)\) of each chondrule were measured. The scale readings were later converted into millimetres and phi \((\phi)\) units \((-\log_2\text{ diameter (mm)}, \text{after Krumbein [3]})\).

### 3. Results

#### 3.1. Size distribution

The histogram in Fig. 1 displays the range of chondrule maximum diameters from the lower limit of 0.15 mm up to the maximum of 2.75 mm, the spread in \(a\) diameters being 2.6 mm. The shape of the size distribution is negatively skewed, with a rapid rise from the smallest diameters to a well-defined peak. After a sharp drop in numbers from this peak, there is a more gradual fall-off in number with increase in diameter. In Allegan, the peak in the size distribution of chondrule maximum-diameters lies between 0.35 mm and 0.75 mm, into which range 66.0% of all chondrules fall. Only 7.3% of chondrules have maximum diameters below 0.35 mm, while 26.7% have \(a\) larger than 0.75 mm.
These results contrast with the size distributions we have previously obtained for separated chondrules from the Bjurböle and Chainpur meteorites [1]. In both of these cases, although the shapes of the distribution curves were similar to that obtained from Allegan chondrules, the distribution peak occurred at larger diameters (~1.0 mm) and there was a lower limit cut-off of chondrule maximum diameter at 0.4 mm. This is discussed along with Hughes’ [2] investigation later.

When the Allegan phi values for \( a \) are used in the construction of a size distribution histogram, as shown in Fig. 2, the distribution becomes more symmetrical, indicating a log-normal distribution of chondrule sizes in Allegan. Fig. 3 is a cumulative number frequency of chondrule maximum diameter phi values for Allegan. From this curve the 16th, 50th and 84th percentiles were extracted. These percentiles were used in the calculation of the statistical parameters (following Inman [4]). These parameters, along with those calculated from the millimetre-size data (after Krumbein and Pettijohn [5]) are presented in Table 1.

We have tested the Allegan chondrule size distribution data to see if it conforms to Rosin’s law which has been found to fit artificially crushed products of many kinds and sizes [6]. If the law is followed a straight-line plot of the cumulative weight percent values should be obtained when plotted on the specially ruled grid devised by Geer and Yancey [7]. Such a plot for Allegan chondrules is presented in Fig. 4. As can be seen, a straight-line plot was not obtained. We have previously found that this was also the case for Bjurböle and Chainpur chondrules.

### 3.2. Shape analysis

We have subjected the Allegan measurements to the same shape analyses as were performed on our previous chondrule samples [1]. We found that 99% of Allegan chondrules fall into the class ii (spherical) category as devised by Zingg [8]. A further 0.6% fall into Zingg’s class i (disc-shaped), whereas the remaining 0.4% fall into the rod-like class iv. None was found to fit the class iii (bladed) category. We had previously determined that the majority of the chondrules (~98%) we had extracted from Bjurböle and Chainpur fell into the class ii category. No class iv chondrules were observed from them. However, 0.4% of the total number of chondrules examined is

---

**TABLE 1**

Statistical parameters of the size distribution of Allegan chondrules

<table>
<thead>
<tr>
<th>Parameters from major-axis data *</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Arithmetic (mean (mm))</td>
<td>0.57</td>
</tr>
<tr>
<td>Median (mm)</td>
<td>0.60</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>1.07</td>
</tr>
<tr>
<td>Mean deviation</td>
<td>0.23</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Percentiles (( \phi )) **</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>0.17</td>
</tr>
<tr>
<td>50</td>
<td>0.75</td>
</tr>
<tr>
<td>84</td>
<td>1.28</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameters from ( \phi ) percentiles **</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>( \phi ) median diameter</td>
<td>0.75</td>
</tr>
<tr>
<td>( \phi ) mean diameter</td>
<td>0.725</td>
</tr>
<tr>
<td>( \phi ) deviation measure</td>
<td>0.56</td>
</tr>
<tr>
<td>( \phi ) skewness measure</td>
<td>-0.045</td>
</tr>
</tbody>
</table>

* After Krumbein and Pettijohn [5].

** After Inman [4].
<1 in the case of Bjurböle and ~1 in Chainpur.

The boundary of the distribution field of a plot of $b/a$ against $a$, as devised by Hagerman [9], for the chondrules we have examined from Allegan is illustrated in Fig. 5 by the continuous line. When the individual plots are examined, however, another boundary enclosing a smaller area, yet still containing within it the majority of the chondrules, can be drawn. This is represented by the dashed line in the figure. Ninety-six percent of the chondrules are contained in this smaller area. Apart from an extension of the distribution field to lower values of $a$, the Allegan boundary is very similar in extent to those we found for Bjurböle and Chainpur chondrules.

Fig. 6 is a histogram of Wentworth's [10] roundness ratio ($a + b/2c$) vs. the number percent of Allegan chondrules with that ratio in each class. Once again there is close agreement in this result with Wentworth’s roundness ratio histograms of Bjurböle and Chainpur chondrules. Allegan does tend to have a greater percentage of chondrules in the ratio range $1.0–1.1$ suggesting more of its chondrules approach sphericity than do chondrules from the other meteorites we previously examined.

3.3. Summary

Although the size distribution of Allegan droplet chondrules differs significantly from the size distributions previously obtained for Bjurböle and Chainpur chondrules, the shape properties of all three droplet chondrule suites are remarkably similar.

4. Discussion

R.T. Dodd (personal communication) has expressed concern that our previous paper [1] may have misled some into thinking the data presented there was directly comparable with some of his own in a prior publication [11]. This is not so. Whereas we measured the size distribution of whole separated droplet chondrules from two meteorites, Dodd measured the maximum diameters of all silicate particles (droplet, irregular and fragmented chondrules, and matrix particles) in thin sections of the meteorites he examined. It is not surprising, therefore, that the two sets of data differ. It was because of this difference in approach that we did not discuss Dodd’s results more fully. We apologise that our previous publication may have confused some on this point.

When comparing the data presented here on the dimensions and shape of near-spherical chondrules from Allegan with those we have previously published [1] for Bjurböle and Chainpur chondrules, we find the shape properties of the three chondrule suites to be extremely similar though this may, in part, be due to the selection procedure adopted. However, the chondrule size distributions exhibit noticeable differences. Although the actual size range of chondrule maximum diameters varies only slightly in Allegan compared to Bjurböle and Chainpur, proportionally many more chondrules with smaller maximum diameters (~0.8 mm) were observed in Allegan, resulting in the displacement of the distribution peak from
Fig. 7. Comparison of size distribution of Allegan chondrules presented here with that of Bjurböle chondrules as determined by Hughes [2] and by Martin and Mills [1].

Hughes [2] has investigated the size and mass distribution of droplet chondrules from Bjurböle and Chainpur. He obtained size data from this section studies of both meteorites and, after a disaggregation of Bjurböle by gentle crushing, from measurements on an enlarged photograph of the whole near-spherical chondrules he extracted. We are not entirely happy with Hughes’ treatment of his thin section measurements and discuss the matter of size distribution determination from thin section measurements elsewhere [12]. However, we believe the size distribution of disaggregated Bjurböle chondrules obtained by ourselves and by Hughes are comparable.

Hughes found a continuous size range from 0.2 to 2.6 mm plus a few chondrules with diameters greater than this. The Bjurböle size distribution histogram he obtained was negatively skewed with a rapid rise in number density from 0.2 mm to a peak between 0.4 and 0.6 mm. This was followed by a gradual decline in numbers with increase of diameter. Mean and median diameter were calculated at 0.750 mm and 0.688 mm, respectively. Although the shape of the size distribution of Bjurböle chondrule maximum diameters obtained by Hughes is, therefore, similar to that previously obtained by us, Hughes’ distribution is displaced to smaller diameters. In fact, Hughes’ results for Bjurböle more closely resemble those of Allegan chondrules presented here. This can be easily seen when the two distribution histograms are compared, as is shown in Fig. 7. The agreement is very good. We hope to re-examine the size distribution of chondrules from the Bjurböle and Chainpur meteorites.

Hughes also found that a greater weight percentage of the Bjurböle he disaggregated was in the form of chondrules — 27% — than have we here for Allegan — 15%. This could be due to the fact that we are comparing results from two different meteorites; Bjurböle may actually be comprised of more chondrules than is Allegan. However, part of the difference may have arisen as a result of the different disaggregation techniques adopted (our Allegan material from which the chondrules were extracted was, essentially, already disaggregated) and in the identification and classification of objects as chondrules between Hughes and ourselves.

We differ from Hughes on a further point. Hughes has tested his size distribution data to see if it conforms to Rosin’s law and believes his data points fall sensibly on a straight line. We have found that our data for Bjurböle, Chainpur and Allegan does not conform to the law as we have not obtained straight-line plots.

We therefore conclude that near-spherical chondrules are not the products of crushing forces (cf. impact events). It is interesting to note that we have also tested the lunar regolith particle size distribution (less than 1 mm), which appears to have been subjected to repeated impacts, against Rosin’s law [13]. An excellent fit with the law was found. A far better fit, in fact, than Hughes’ chondrule data.

In our previous publication [1] we discussed the proposed mechanisms for the formation of chondrules. The physical properties of Allegan chondrules we have reported on here do not lead us to alter our view that the most likely of these mechanisms is the melting of nebula dust-ball agglomerates by some high-energy event.
Acknowledgements

We are grateful to Dr. R. Hutchison of the British Museum (Natural History) for the loan of the meteorite sample (BM No. 1920,281) and for comments on the manuscript.

References

SIZE AND SHAPE OF CHONDRULES IN THE BJURBÖLE AND CHAINPUR METEORITES

PHILIP M. MARTIN and A. A. MILLS

Departments of Geology and Astronomy, Leicester University, Leicester, LE1 7RH (Great Britain)

Received July 21, 1976
Revised version received September 15, 1976

Chondrules were extracted from the Bjurböle and Chainpur chondritic meteorites by gentle crushing and hand-picking. Individual chondrules were examined with apparatus incorporating two orthogonal binocular microscopes, and their three major axes measured. Various statistical methods were used to analyse size distribution and shape. These parameters were found to be very similar in chondrules from both meteorites. Maximum chondrule diameters ranged from 0.4 to 2.4 mm, with prominent peaks in distribution at about 1.0 mm. No chondrules with maximum diameters less than 0.4 mm were observed, even after assiduous search. The chondrules departed from sphericity by only small amounts and in a random fashion.

These results are discussed in relation to proposed theories for the origin of chondrules and suggest to the authors that the melting of nebula dust-ball agglomerates by some high-energy event was the most probable chondrule-forming process.

1. Introduction

It is almost a century since Sorby [1] first suggested that chondrules — those roughly spherical crystalline bodies abundant in most stony meteorites [2] — are igneous in texture, being once hot droplets of molten rock. However, his conclusion that conditions on the surface of the sun seemed exactly right to produce a fiery rain of chondrules has long since been discarded, more recent theories being developments of two main hypotheses. The first suggests that chondrules are primary nebula, and later accumulated into meteorite parent-bodies [3–6]. The second group of hypotheses considers chondrules to be formed as secondary objects from pre-existing material, by processes such as volcanism [7–11], melting of dust by shock [12], impact [13–18], or lightning discharge [19].

Attempts to elucidate the chondrule-forming process have resulted in many papers on the chemical and mineralogical constitution of chondrules [20–26] but surprisingly little has been done to determine constraints from their purely physical properties.

We report here on the size distribution and shape of chondrules from the Bjurböle and Chainpur chondritic meteorites. Stakhheev et al. [27] and Lang et al. [28] have reported briefly on the size distribution of chondrules from the Nikolskoe, Elenovka, Saratov and Bjurböle L-group chondrites. More recently Dodd [29] has examined the size distribution of silicate and metal particles in thin sections from nineteen unequilibrated ordinary chondrites, including the two meteorites we consider here.

2. Material

It seems likely that the analysis of chondrule shape and size has been hindered by the difficulty of segregating chondrules from their matrix. Some chondrites, however, are relatively friable, greatly facilitating chondrule extraction. Bjurböle and Chainpur are two such meteorites, and so were chosen for preliminary investigations. Bjurböle is classified as an L4 and Chainpur an LL3 chondrite in the Van Schmus and Wood [30] classification scheme.

As their friability makes this type of meteorite un-
usually rare, it might be argued that chondrules from them may not be truly representative of meteoritic chondrules. We believe, however, that this property and the low degree of metamorphism of Bjurböle and Chainpur indicate that the chondrules that we have examined are more likely to be in their primary configuration, and consequently more valuable to obtain constraints on origin. It is also quite likely that friable chondrites are more abundant in space than estimated from terrestrial meteorite falls, as many would be expected to break-up during their passage through the atmosphere, with a consequent low probability of recovery. We do, of course, recognise the desirability of examining chondrules separated from “ordinary” chondrites, and plan to extend our work to include them. Experiments on disaggregation techniques are being made for this purpose.

3. Sampling and measurement

Material was kindly supplied by Dr. Brian Mason, Smithsonian Institution, Washington, U.S.A. After gentle crushing of each specimen, chondrules were extracted by hand-picking and cleaned with simple mechanical tools. During this procedure some chondrules fragmented. A microscope examination of these fragments showed their original surfaces to have a very fine, even matrix coating. However, this coating was too thin to affect our measurements significantly and no further cleaning techniques were employed. Representative chondrules from each specimen are shown in Fig. 1.

Ninety-seven chondrules from Bjurböle and two hundred and forty-five from Chainpur were viewed individually by means of two binocular microscopes, one arranged vertically, the other horizontally. Magnifications of 40X, 62.5X and 100X were used depending upon the size of chondrule under examination. Both microscopes were equipped with identical eyepiece scales with which the maximum length (a), breadth (b) and width (c) of each chondrule were measured. The scale readings were later converted into millimetres and phi (\(\phi\)) units \([-\log_2 \text{diameter (mm)}\], after Krumbein [31]).

4. Statistical examination

4.1. Size distribution

The maximum diameters (mm values) of the chondrules from each specimen were arranged into classes and comparative histograms of the number in each class drawn. The histograms are shown in Fig. 2 and demonstrate that the range of chondrule maximum diameters in both meteorites are remarkably similar. The values range from a lower limit of 0.4 mm, common to both specimens, up to 2.2 mm in Bjurböle and 2.4 mm in Chainpur. There is, therefore, a spread in maximum chondrule diameters of about 2.0 mm. We
believe this lower limit of 0.4 mm to be real and not an artifact arising from the method of preparation since the smallest chondrules were readily observable in, and extractable from, both meteorite specimens. Examination of thin sections is not a reliable guide to minimum sizes: this point is discussed later.

The similarity in the data also extends to the shape of their size-distribution curves. In both cases they are negatively skewed, with a rapid rise from the smallest diameters to a well-defined peak and, after a sharp drop from this peak, a gradual fall-off in number with increase in diameter. In Bjurböle the distribution peak lies between 0.8 and 1.2 mm, into which 50.7% of the chondrules fall. Only 10.4% of chondrules have diameters below 0.8 mm, leaving 38.9% with diameters greater than 1.2 mm. The results for Chainpur are very similar, but in this specimen the distribution peak is displaced slightly with respect to the Bjurböle peak so as to fall at 0.6–1.0 mm. Forty-three percent of Chainpur chondrules are contained within this size range; 9.8% have smaller diameters and 46.9% are larger.

When the phi values are used in the construction of size-distribution histograms (Fig. 3) the distribution becomes more symmetrical, indicating a log-normal distribution of chondrule sizes. This is more apparent in the case of Chainpur, for Bjurböle tends to retain a prominent peak whatever the choice of the class intervals.

Cumulative number frequency curves of the chondrule maximum diameters (φ-units) for the two meteorites are shown in Fig. 4. From these curves the 16th, 50th and 84th percentiles were obtained and used in the calculations of the statistical parameters, following Inman [32]. (The 5th and 95th percentiles are better representatives of the extremes of a distribution but are difficult to measure accurately in the chondrites. The 16th and 84th percentiles give a satisfactory practical compromise.) These parameters, along with those calculated from the mm-size data are given in Table 1. The displacement of the peak in Bjurböle chondrule maximum diameters to a slightly larger size is reflected in marginally greater values of the calculated mean and median diameters for chondrules from Bjurböle, whereas the overall similarity in shape of the two size-distribution curves is reflected in similar values for deviation and skewness measures.

To see if the size distribution of the chondrules fits

Fig. 2. Histograms of chondrule maximum diameters (mm) in the Bjurböle and Chainpur meteorites.

Fig. 3. Histograms of chondrule maximum diameters (φ-units) in the Bjurböle and Chainpur meteorites.
into any recognisable category, the data was tested by means of Rosin’s law. This has been found to fit artificially crushed products of many kinds and sizes, suggesting that data which fit the law may bear evidence of crushing phenomena [33]. Geer and Yancey [34] have developed a simple test of whether a sample obeys Rosin’s law by using a specially ruled grid. A cumulative weight percent plot on this grid yields a straight line if the law is obeyed. Cumulative number frequency data for the Bjurbøle and Chainpur chondrules are plotted in Fig. 5. In both cases the data depart from a straight-line plot, there being a noticeable change in directions at about 1.5 mm, more noticeable in Chainpur. This suggests that the size distributions of chondrules from the two meteorites is not a result of crushing forces.

TABLE 1
Size distribution data of chondrules from the Bjurbøle and Chainpur meteorites

<table>
<thead>
<tr>
<th>Parameters from major-axis data *</th>
<th>Bjurbøle</th>
<th>Chainpur</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of chondrules examined</td>
<td>97</td>
<td>245</td>
</tr>
<tr>
<td>Arithmetic mean (mm)</td>
<td>1.18</td>
<td>1.09</td>
</tr>
<tr>
<td>Median (mm)</td>
<td>1.12</td>
<td>1.02</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>1.11</td>
<td>1.42</td>
</tr>
<tr>
<td>Mean deviation</td>
<td>0.28</td>
<td>0.37</td>
</tr>
<tr>
<td>Percentiles (p) **</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>-0.575</td>
<td>-0.68</td>
</tr>
<tr>
<td>50</td>
<td>-0.14</td>
<td>0.05</td>
</tr>
<tr>
<td>84</td>
<td>0.20</td>
<td>0.64</td>
</tr>
<tr>
<td>Parameters from (p) percentiles</td>
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<td></td>
</tr>
<tr>
<td>median diameter</td>
<td>-0.14</td>
<td>0.05</td>
</tr>
<tr>
<td>mean diameter</td>
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</tr>
<tr>
<td>deviation measure</td>
<td>0.775</td>
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</tr>
<tr>
<td>skewness measure</td>
<td>-0.061</td>
<td>-0.054</td>
</tr>
</tbody>
</table>

* After Krumbein and Pettijohn [35].
** After Inman [32].

4.2. Shape analysis

Shape must not be confused with roundness, the latter being a measure of the degree of curvature of the edges and corners of a body and, therefore, quite independent of shape. Fig. 1 shows the chondrules from Bjurbøle and Chainpur to be well rounded and roughly spherical. It is their departure from sphericity that we are most concerned with here.

In our analysis of chondrule shape we have used the conventions adopted in sedimentological studies [35]. This has involved combining and plotting various ratios derived from the three major-axis measurements. This has not proved entirely satisfactory since the differences in shape among the chondrules are relatively small compared with, say, pebbles in a stream.

Zingg [36] has devised a four-class system to describe particle shape based on a comparison of the axis ratios $b/a$ and $c/b$. The four classes are defined as follows:

(i) $b/a > 2/3$  $c/b < 2/3$  disc-shaped
(ii) $b/a > 2/3$  $c/b > 2/3$  spherical
(iii) $b/a < 2/3$  $c/b < 2/3$  bladed
(iv) $b/a < 2/3$  $c/b > 2/3$  rod-like
Fig. 5. Size-frequency data for chondrules from Bjurböle and Chainpur meteorites. Ordinate conforms to Rosin's law.

We have determined these ratios and classified the results accordingly. We find that, in Bjurböle, only one chondrule falls into the class i (disc-shaped) category and the remainder (~98%) fall into the spherical class, class ii. The picture for Chainpur is very similar with two class i chondrules and 239 (~98%) class ii. We also find no preference in either meteorite for one of the axis ratios to predominate, there being roughly equal numbers of chondrules in which $b/a > c/b$ as vice versa.

By plotting the ratio $b/a$ against $a$, Hagerman [37] found that for some terrestrial examples he was able to utilise grain shape to mark different stratigraphic horizons, each horizon exhibiting a different distribution field on the plot. We have used this technique for the chondrules from our meteorite specimens. The boundaries of their distribution fields are shown in Fig. 6. The two distribution fields are very similar, especially below $a = 1.5$ mm. For values of $a$ greater than 1.5 mm the Chainpur distribution field is more extensive than that of Bjurböle. However, this appears to be due to two anomalous chondrules, because if these are ignored and the Chainpur field boundary redrawn (dotted line, Fig. 6), the distribution fields of chondrules from both meteorites become almost identical for all values of $a$.

Wentworth [38] has defined a roundness ratio which is simply $a + b/2c$. This factor has been calculated for our chondrules and histograms of this ratio versus number percent in each class for Bjurböle and Chainpur are shown in Fig. 7. Bjurböle tends to have a greater percentage of chondrules with ratios of between 1.3

Fig. 6. Field boundaries of Hagerman plot of chondrules from the Bjurböle and Chainpur meteorites.
Fig. 7. Histogram of Wentworth's roundness ratios of chondrules from the Bjurböle and Chainpur meteorites.

and 1.7 than Chainpur, though in both cases the vast majority of chondrules have roundness values below 1.3. There also appear to be fewer Bjurböle chondrules in the 1.0–1.1 class than in the following class, unlike Chainpur. We are not sure if this is real or due to insufficient sampling.

The above methods for analysing particle shape demonstrate three significant points. First, the chondrules we have examined depart from sphericity by only small degrees; second, any such departures appear random (i.e., there is no preferential chondrule shape); and finally, the suites of chondrules from both the Bjurböle and Chainpur meteorites are extremely similar in their shape properties.

4.3. Summary

Perhaps the most important observation to be made from the results presented here is the remarkable similarity in the shape and size distribution of suites of chondrules from the two meteorites Bjurböle and Chainpur.

5. Discussion

Of the sixteen chondrites examined by Dodd [29] he concluded that all but Bjurböle had similar - essentially log-normal - silicate particle size distributions. Our results do not support this as we find the particle size distribution in Bjurböle to be extremely similar to that in Chainpur, a chondrite also studied by Dodd. It is unlikely that this is due to inhomogeneity in the Bjurböle meteorite since, as Dodd points out, the chondrites are texturally uniform. Our median particle diameter and calculated statistical parameters also differ significantly from Dodd’s. This is no doubt due to the fact that Dodd’s measurements were taken from thin sections of meteorites whereas we have examined whole chondrules. In the former case one is only rarely measuring maximum diameters as chondrules will be sliced at random.

It is obvious that even a relatively large chondrule would appear to be amongst the smallest observed in a thin section if the plane of the section only just grazed it. This fact would explain why chondrules with (apparent) diameters of less than 0.4 mm are observed in meteorite thin sections, yet we could find none in our samples of separated chondrules in spite of assiduous search.

Dodd’s results appear to indicate a general decrease in chondrule median diameter from LL- to L- to H-group chondrites. Although we only report on two chondrites our analyses tend to oppose this trend since we find the Bjurböle (L4) chondrules median diameter (which Dodd found to be the smallest of the L-group chondrites he examined) to be slightly larger than that for Chainpur (LL3) chondrules.

We conclude from our size-distribution data that the chondrules from Bjurböle and Chainpur are very similar. They are also extraordinarily similar in shape. We have found that although very few are perfectly spherical, the majority depart from sphericity by only small amounts, and in a random fashion.

There is good evidence that the chondrules we have examined have retained their primary configuration. As previously mentioned both Chainpur and
Bjurböle are relatively friable, suggesting their chondrules have undergone little compaction and deformation. The random nature of their small departures from sphericity would seem to indicate this. It also appears that, in the case of Bjurböle, the chondrules accumulated with random orientations since an absence of preferential orientation of their long-axes has been noted [39]. (This property has not been examined in Chainpur.) If chondrule shape had been modified by such processes as overburden pressure, etc., after accumulation preferential chondrule orientation and flattened elliptical shapes would be expected. These properties were not observed.

The absence of one feature in the size-distribution curves is of interest. The near-sphericity of the chondrules as evidenced here, along with a consideration of their internal structures and in some cases the presence of glass, indicates that the chondrules were once molten. There is evidence that collisions between chondrules occurred while some were "plastic" [40]. If collisions had taken place while the chondrules were molten, complete coalescence of the colliding droplets would most probably occur. If this had been a frequent event we might expect to see a second peak in the size-distribution curves at the diameter equivalent to the volume of two chondrules from the main peak, since collisions between chondrules of this size-range would predominate. In the case of Bjurböle this would lie at about 1.40–1.25 mm and about 1.14–1.01 mm for Chainpur. There is no evidence for such secondary peaks in our data. This would seem to indicate that collisions between chondrules were rare. This is substantiated to some extent by visual examination of thin sections or cut faces of meteorites, where juxtaposed chondrules are only rarely seen. Of course, this only indicates that such events were rare while chondrules were cooling from the liquid to the solid state.

The above inference is interesting in that we can tentatively estimate some constraints regarding chondrule history. By analogy with the kinetic law of gases and atomic collisions, we find that the number of collisions, $Z$, a chondrule is likely to encounter is equal to:

$$n \pi d^2 v t n$$

where $d$ = diameter of chondrule, $v$ = velocity (relative),

$t$ = time, and $n$ = number density.

We can estimate some of these parameters and arrive at an approximate value for $n$.

From our data we may assume for the purpose of the present calculation that $d = 0.1$ cm. Lange and Larimer [41] examined an unusual chondrule in the Ngawi chondrite in which was embedded a metal grain. They calculated that the relative velocity of the collision was $10^5–10^6$ cm/sec. If we assume this value to be typical of chondrule relative velocities we can put $v = 10^5$ cm/sec. A series of experiments by Nelson et al. [42] and Keil et al. [43] produced chondrule-like objects from individual free-falling droplets of various materials, melted by a focused continuous CO$_2$ laser beam. These objects cooled and crystallised rapidly – in about one second. We will therefore adopt this value for $t$ in the above equation. Our data and visual observation indicate $Z$ to be very low. Let us say that 1 in 100 chondrules suffer a collision, thereby $Z = 0.01$. Inserting these values for the parameters ($Z, d, v, t$) we find:

$$n = 0.01/\left[\pi(0.01)^2 \times 10^5 \times 1\right]$$

$$n \sim 3 \times 10^{-6}$$

This result indicates the number density of chondrules during their cooling through the liquid state to have been surprisingly low, if our assumptions are correct. The only parameter we might be able to alter significantly is $t$, the chondrule liquid-state time, since only limited experimental work has been performed. It might be that much longer cooling rates also give rise to chondrules. Of the other parameters $d$ has been determined here and is satisfactory, an increase in $v$ would most likely result in vapourisation of colliding bodies, and $Z$ would need to be increased to increase $n$ – which seems unlikely as any significant increase in $Z$ would be apparent in our data. So, unless the chondrules were in the molten state for appreciably longer than estimated we must conclude that the number density of chondrules during this part of their history was very low.

Dodd [29] concluded that the narrow size distribution of chondrules in chondrites is a result of aerodynamic sorting during accretion of the chondritic material. It is our opinion, however, that this was not the major process responsible for the chondrules narrow size distribution, but rather that the restricted size range is a result of the chondrule-forming process. If chondrules had been produced with a large
range in sizes and then sorted we would surely expect to find some chondrites with predominantly large chondrules and some with predominantly small ones. This does not appear to be the case, the differences in size distributions between chondrites being much more subtle. There is also some evidence to suggest that chondrules are often genetically related within but not between chondrites [13-24], although more recent data demonstrate that this may not always be so [25]. It is our tentative conclusion from the limited data so far obtained that chondrules were produced as near-spherical bodies with a narrow size range and, possibly, of a low number density. We hope to show later, though, that this may not have been entirely due to the chondrule-forming process itself, but simply that this process acted on material already possessing some of these characteristics.

The similarity in the physical properties we have examined of the chondrules from Bjurböle and Chainpur leads us to believe that — even if these chondrules had not been produced in the same high-energy event — they are the products of identical or very similar events. We will now examine the proposed mechanisms for chondrule production in the light of this argument.

Of the proposed secondary chondrule-forming processes, impact splattering [13-18] would tend to yield particles of widely varying sizes, as evidenced by studies of the lunar soils [44-47]. These studies have also shown that repeated impacts tend to narrow the size distribution but do not result in such textural homogeneity as in the chondrites [48]. Impact-produced chondrule-like bodies have been found in lunar samples [49-55] and from one terrestrial impact site [56] but are rare. Kurat et al. [55] estimate that such bodies amount to a few volume percent in rock 14318 — in which they are more abundant than in any other Apollo 14 sample so far studied. Our results from the Rosin’s law plots would also seem to indicate that chondrules are not the products of crushing (e.g., by low-velocity collisions).

Keiffer [57] has suggested that chondrules are the products of particle-to-particle collisions between bodies from 0.5 mm to 20 cm in size. This process produced jetting of molten material from which the chondrules condensed with a chemical composition a mixture of the two colliding particles. It is difficult to see how such a process would give rise to chondrules of two distinct chemical compositions (Fe-, Mg-rich and Ca-, Al-rich) as are actually observed in the Allende meteorite [18], and none with intermediate compositions.

Volcanism is another proposed process for chondrule formation [7-11] yet the ejecta from terrestrial volcanoes are poorly sorted [58] and they do not produce chondrule-like objects.

Direct condensation of droplets from the nebula gas — a primary hypothesis [3-6] — might produce a narrow size range of bodies if this process is analogous with the condensation of atmospheric water droplets [59-61]. There are, though, chemical, textural, mineralogical and petrological arguments against chondrule production in this way [62,63]. However, if nebula condensation produced dust-ball agglomerates (not droplets) in a narrow size range, which were later melted by some high-energy event, we might be able to explain the physical and chemical properties of chondrules. Indeed Whipple [19] has suggested that lightning discharges might have been common in the solar nebula, and have been the energy source for the melting of already-condensed material to produce chondrules. Wood [12] had already suggested this may have occurred by shock melting. Although we would not like to say which of these two processes (or any other which melted nebula condensates) is the most likely, such a procedure appears the most reasonable from these proposed to produce chondrules in the narrow size range observed, if sorting was not the dominant factor in achieving this.

The above is only a tentative conclusion: much more data of the sort presented here is needed before firm conclusions can be reached. We are currently working on this problem.

Acknowledgements

Dr. B. Mason of the Smithsonian Institution kindly supplied the specimens for which we are very grateful. The help and advice of Drs. B. Lang and J.H.McD. Whitaker was much appreciated. The research was sponsored by the Natural Environment Research Council.

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Preferential orientation in four C3 chondritic meteorites

It is more than a century since oriented fabrics were first noted in chondrites (see ref. 1). but since then little work has been done on the topic2-6, the most extensive being that by Dodd7. He found that most of his H-and L-group chondrites possessed foliation, together with lineation in the most strongly foliated specimens. The preferential orientation of elongated olivine phenocrysts in porphyritic chondrules has also been observed8.

A visual examination of the Leoville C3 chondrite disclosed a strong orientation of the long axes of the chondrules. This prompted us to compare the orientation of the long axis of the chondrites in this meteorite with three other Type 3 carbonaceous chondrules: Grosnaja, Coolidge, and Vigarano. We were unable to obtain specimens, the most extensive being that by Dodd7. The preferential orientation of elongated olivine phenocrysts in porphyritic chondrules has also been observed8.

We thus decided to photograph each available face using fine-grained monochrome film, and then to prepare appropriate enlargements. This avoided the problem posed by the removal and transport of actual specimens and facilitated magnification to a suitable size. Individual photographs were mounted on the table of an orientometer designed to allow movement in translation and rotation9, and were viewed through a binocular microscope fitted with a line reticule in one eyepiece. Chondrules were aligned with their long axis along this fiducial line, and their nominal orientation was read from the degree scale of the orientometer turntable. Each measured image was marked with a spot of ink to avoid confusion and possible duplication. The measurements are of the double-headed vector type10, so only the direction between 0° and 180° was taken.

Chondrule orientations for each specimen were grouped into 5°, 10° or 20° classes according to the number of measurements and their scatter, and the resulting histograms are shown in Fig. 1. The mean vector direction and its magnitude are also shown, complete orientation being expressed as 100% and a random distribution by 0% (ref. 7).

Histograms give a good visual idea of the presence and degree of any orientation and our measurements indicate a high degree of orientation of the long axes of chondrules from all specimens of the Leoville chondrite, in the Grosnaja specimen, and on face b of the Vigarano specimen (Fig. 1 a, b, c, e and g). The other two faces of Vigarano (Fig. 1 d and f) exhibit a much lower degree of chondrule orientation, and the Coolidge specimens (Fig. 1 h and i) show a wide scatter. These qualitative impressions are borne out by the calculated vector magnitude.

From these results it seems that the orientations of the long axes of chondrites are strong in Leoville and Grosnaja chondrules, moderate in one plane of the Vigarano specimen, and very weak or nonexistent in the Coolidge specimens. Dodd7 could find no preferred orientation in the last-named meteorite. The wide range of degrees of orientation between the four C3 chondrites examined also supports Dodd’s conclusion that there is no correlation between orientation and degree of metamorphism.

The identification of the mechanisms which produced asphericity and alignment of the chondrules in some chondrites is not an easy matter. Are these phenomena related to the primary chondrule-forming process, to effects occurring during aggregation, or are they a result of secondary processes in the meteorite parent body? Are the two phenomena related? More data are needed before these questions can be resolved.

For this reason we are at present examining the orientations of the long axes of chondrules in more detail, along with such factors as shape and size distribution, density, friability, and so on. It is hoped that these studies will enable us to draw conclusions concerning the formation of chondrules and the genesis of meteorites.

We thank Dr. R. Hutchison, J. H. McD. Whitaker and M. A. Khan for their advice.

Philip M. Martin
A. A. Mills
Elaine Walker

Departments of Astronomy and Geology,
University of Leicester,
Leicester LE1 7RH, UK

Received June 25; accepted July 22, 1975.


Printed in Great Britain by Henry Ling Ltd., at the Dorset Press, Dorchester, Dorset.