Variability of Intra-D Ring Azimuthal Magnetic Field Profiles Observed on Cassini’s Proximal Periapsis Passes

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Three significant points -

Azimuthal magnetic fields observed on Saturn’s intra-D ring (IDR) field lines exhibit a range of profiles on the 23 Cassini proximal passes.

One, two or three near-symmetrical positive peaks ~10-40 nT are typical, but two passes have ~20-30 nT negative peaks, and two <10 nT fields.

Variable IDR field signatures are not organized by periapsis radius, local time, planetary period oscillation phase, or D68 ringlet phase.

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Abstract  We overview the properties of the azimuthal magnetic fields observed during the periapsis passes of the final 23 orbits of the Cassini spacecraft, including the partial orbit at end of mission, on near equatorial field lines passing inside of Saturn’s D ring. The signatures are variable in form and amplitude, though generally approximately symmetric about the point where the spacecraft trajectory lies tangent to a flux shell, corresponding to where the ionospheric field line feet map closest to the equator, consistent with the effect of interhemispheric field-aligned currents. The perturbations usually begin and end near-symmetrically at some point on field lines threading the D ring, and extend into the interior region, but in no case do they clearly extend outward onto field lines passing through the C ring. About 35% of cases display a ~20-40 nT single positive central field peak indicative of southward field-aligned current flow, while a further ~30% display two or three weaker ~10-20 nT positive peaks indicative of multiple sheets of northward and southward current. Significant smaller-scale >5 nT peak-to-peak field fluctuations are commonly superposed. A further ~20% of cases exhibit unique profiles within the data set, including two with ~20-30 nT negative fields, and two with only <10 nT fluctuating fields. The variable nature of the signatures is not connected with the pass altitude, local time, planetary period oscillation phase, or D68 ringlet phase, but may relate to variable structured thermospheric winds and/or ionospheric conductivities that suggest a significant dynamical role for D ring-atmosphere interactions.
1. Introduction

During the Grand Finale phase of the Cassini mission, the spacecraft made 22 highly inclined periapsis passes through the near-noon equatorial plane between the inner edge of Saturn’s ring system and the upper atmosphere/ionosphere of the planet, before being destroyed in the atmosphere on spacecraft revolution (Rev) 293 on 15 September 2017. A striking and unanticipated feature of the magnetic field data obtained on these close passes is the presence of structured perturbations in the azimuthal component, peaking typically at a few tens of nT, occurring in and confined to the region of field lines passing through and inside of the innermost ring of Saturn’s ring system, the tenuous D ring (Dougherty et al., 2018). These fields we term the intra-D ring azimuthal field perturbations.

The nature of these perturbations, usually directed in the positive azimuthal sense (the sense of planetary rotation) and approximately symmetrical about the equatorial crossing, suggests the presence of interhemispheric current flow along the field lines crossed by the spacecraft, generally directed from north to south. Such currents, estimated to be ~0.25-1.5 MA per radian of azimuth by Dougherty et al. (2018), are thus comparable in magnitude with those flowing on auroral field lines (Hunt et al., 2014, 2015, 2018a; Bradley et al., 2018). Such field-aligned currents must close south to north in a region lying below the spacecraft, presumably principally in the Pedersen conducting layer of the planetary ionosphere. A simple model field and current system was constructed on this basis by Khurana et al. (2018), employing a current of 1.15 MA rad\(^{-1}\). These authors also suggested that the system was generated by differential azimuthal neutral atmospheric winds flowing in the ionosphere at the two ends of these inner field lines.

While the papers by Dougherty et al. (2018) and Khurana et al. (2018) discuss the data from 9 initial passes, corresponding to Revs 271-280, omitting Rev 277, here we overview the azimuthal fields observed on all 23 proximal periapsis passes (including the final partial pass.
on Rev 293), and demonstrate the considerable variability of the azimuthal field profiles observed from pass to pass, indicative of related variations in the field-aligned and ionospheric current flow. We also examine and discuss a number of factors that might relate to the observed variability.

2. Cassini Trajectory and Regimes Traversed on Proximal Periapsis Passes

We first discuss the nature of the spacecraft trajectory on proximal Revs 271-293, conducted between April and September 2017, and the consequences for the nature of the magnetic field data obtained. On these Revs the spacecraft orbit was inclined at ~62° to Saturn’s equatorial plane, with apoapsis slightly north of the equator near midnight and periapsis slightly south of the equator near noon. The apoapsis distance was ~21 RS, near to Titan’s orbit, while periapsis was placed such that the spacecraft crossed the equator inside Saturn’s innermost D ring but above the denser atmosphere, varying non-monotonically on Revs 271-292 between radial distances of 1.064 and 1.026 RS. (RS is Saturn’s equatorial 1 bar radius of 60,268 km.) The orbital period was ~6.5 days. On Rev 293, however, periapsis was targeted below 1.022 RS, with the spacecraft then being destroyed in the denser atmosphere. For comparison with these periapsis distances, the inner and outer boundaries of the D ring are located at equatorial radii of 1.110 and 1.236 RS, respectively, while the outer boundary of the outermost main ring, the A ring, is located at 2.269 RS, with the narrow F ring at 2.326 RS. During these passes the inbound spacecraft traversed the morning sector at high northerly latitudes to reach periapsis ~5° to ~7° latitude south of the equator near noon, before passing outbound at high southerly latitudes in the afternoon sector. More precisely, periapsis was located at 13.1 h local time (LT) at the start of the proximal orbits, decreasing with time to 11.4 h LT at the end of mission. The near-periapsis proximal data thus span a modest but finite range of LTs centered near the noon meridian.
In Figure 1a we show the periapsis trajectories of Revs 276 (blue) and 292 (red) projected into a meridian plane in cylindrical \((\rho, z)\) coordinates, where \(\rho\) is perpendicular distance from Saturn’s spin/magnetic axis, and \(z\) is distance northward of the equatorial plane along that axis. These Revs are representative of those with the largest and smallest periapsis radii, respectively (see Table 1 to be introduced below), prior to final partial Rev 293, thus illustrating the modest differences in trajectories occurring over the proximal orbit ensemble, leading to modest differences in the spacecraft traversal of relevant physical regions. The outer boundary of the planet (orange spheroid) in Figure 1 specifically shows the location of the main Pedersen conducting layer of the ionosphere, taken for simplicity to be 1000 km above the 1 bar reference spheroid (Galand et al., 2011), thus with equatorial and polar radii of 61,268 and 55,364 km. The arrowed black lines outside the planet show model magnetospheric field lines, taken to consist of the principal first three terms (dipole, quadrupole, and octupole) of the axisymmetric internal planetary field model of Dougherty et al. (2018) (their Table 1), together with a typical ring current field given by the Bunce et al. (2007) model for a typical subsolar magnetopause radius of 22 \(R_S\). The evident field asymmetry about the equator (central black dotted line) is due to the quadrupole term of the internal field. For simplicity, this model is used to map field lines between the equator, spacecraft, and ionosphere throughout this paper.

The region colored darker blue in Figure 1a corresponds to field lines which thread the equatorial plane in the main ring region, spanning from the outer edge of the A ring to the inner edge of the C ring. These field lines map to the ionosphere (as shown) in the northern hemisphere between northern colatitudes (with respect to the northern pole) of \(\sim 35^\circ\) and \(\sim 57^\circ\), and in the southern hemisphere between southern colatitudes (with respect to the southern pole) of \(\sim 40^\circ\) and \(\sim 65^\circ\). The region colored lighter blue corresponds to field lines that thread the equatorial plane in the D ring region, mapping to the ionosphere in the
northern hemisphere between northern colatitudes of ~57° and ~65°, and in the southern hemisphere between southern colatitudes of ~65° and ~74°. As indicated in section 1, the spacecraft trajectories passed directly across the field lines mapping through Saturn’s main ring system both north and south, also across D ring field lines, and crossed the equator in the ‘gap’ between the inner boundary of the D ring and the main conducting layer of the planetary ionosphere.

The solid circles plotted on the trajectories just north of the equatorial plane show where the spacecraft track in the meridian lies tangent to the field lines, corresponding to the point where the field-mapped ionospheric colatitudes of the spacecraft attain their largest values, corresponding to ~70° in the northern hemisphere and ~80° in the southern hemisphere for Rev 276, and ~76° in the northern hemisphere and ~86° in the southern hemisphere for Rev 292. For simplicity these points will later be somewhat loosely referred to as the “field parallel” points on the trajectories (bearing in mind the additional but smaller azimuthal motion of the spacecraft), more accurately the points where the trajectories lie tangent to the axisymmetric model flux shell on which they are located. These points are located at radii of 1.069 R_S for Rev 276 and 1.033 R_S for Rev 292, corresponding to altitudes of ~4150 and ~2010 km above 1 bar, respectively. The open circles plotted on the trajectories just south of the equator in Figure 1a show the periapsis points on these trajectories, at radii of 1.064 R_S for Rev 276 and 1.027 R_S for Rev 292, corresponding to altitudes of ~3910 and ~1710 km above 1 bar, respectively.

Figure 1b shows a central region of Figure 1a on an expanded scale, illustrating the nature of the current system (green lines) discussed by Dougherty et al. (2018) and Khurana et al. (2018), as indicated in section 1. In the case shown, a latitudinally variable meridional current J_m flows northward in the ionosphere at low latitudes, closing via continuous
southward field-aligned currents $j_i$ on and inside D ring field lines. The associated intra-D ring azimuthal perturbation field $B_\phi$ in this case is positive, directed into the plane of the diagram as shown by the circled cross. As we will demonstrate and discuss below, however, on some passes fields and currents with reversed directions were observed.

3. Intra-D Ring Field Perturbations Observed on Cassini Revs 276 and 292

We now illustrate the nature of the magnetic field observations obtained on the proximal periapsis passes by presenting the data from two passes, specifically Revs 276 and 292 whose trajectories in the meridian are shown in Figure 1a. We note that although these Revs were employed in Figure 1a to illustrate the trajectories with the larger (Rev 276) and smaller (Rev 292) periapsis distances, we will show in section 5 that this has no bearing on the physical nature of the field profiles observed.

3.1. Field Perturbations on Rev 276

The field data obtained on Rev 276 are shown in Figure 2, where the interval corresponds to ±35 min centered on the field parallel point (see section 2), which occurred at 14:21.8 (h:min) UT on DoY 148 (28 May) 2017. This interval contains the full crossing of the field lines passing through the ring region in the equatorial plane both north and south of the equator. The north and south crossings of the field lines passing through the outer boundary of the A ring are shown by the red solid vertical lines near the start and end of the interval, where the outer red dashed lines also mark the crossings of the field line passing through the narrow F ring. The blue solid and dashed lines show the crossings of the field lines passing through the outer and inner boundaries of the D ring, respectively, such that the spacecraft was located on D ring field lines between the solid and dashed blue lines for ~6 min intervals on either side of periapsis, while lying on field lines in the gap inside the ring system in the interval between the blue dashed lines for a central ~14 min interval (see Figure 1a). The entire
crossing of the intra-D ring region, consisting of the D ring field lines and the region interior thereto, thus occupied ~26 min. The black dotted vertical line marks the central field parallel point (time zero in the plot), about which the azimuthal field profile should be approximately symmetric given the current system proposed by Khurana et al. (2018) illustrated in Figure 1b. Periapsis on this pass occurred ~4.5 min later.

Figures 2a-2c show the three spherical polar components of the magnetic field referenced to the planet’s northern spin/magnetic axis. The radial component in Figure 2a and the colatitudinal component in Figure 2b are the residual fields following subtraction of the degree 11 axisymmetric internal field model of Dougherty et al. (2018), together with the Bunce et al. (2007) model ring current field for a subsolar magnetopause radius of 22 Rs. Since these model fields consist only of poloidal components with no azimuthal field, the azimuthal component in Figure 2c is as directly measured. All of the field data in Figure 2 (and throughout the paper) were obtained using the ±44,000 nT high-field range of the Cassini fluxgate magnetometer not employed since Earth swing-by in 1999, thus requiring an intensive program of in-orbit recalibration (Dougherty et al., 2018). The calibration achieved is believed to be robust to the level of instrument digitization, which for this highest range of the fluxgate magnetometer is 5.4 nT (Dougherty et al. 2004). The data employed here have been averaged to 10 s temporal resolution, with remaining digitization noise at the few-nT level evident in the figure. The panels beneath the field data show positional information, specifically the radial distance $R$ (solid) and the perpendicular radial distance $\rho$ (dashed) in Figure 2d, the northward displacement $z$ from the equatorial plane in Figure 2e, the colatitude in Figure 2f, the LT in Figure 2g, the northern mapped ionospheric colatitude $\theta_{iN}$ in Figure 2h, and the corresponding southern mapped ionospheric colatitude $\theta_{iS}$ in Figure 2i. In the
latter two panels, the lines switch from solid to dashed at the central field parallel point where $\theta_{N,S}$ maximize.

Examination of the data in Figure 2c shows that the azimuthal field has small and slowly varying negative values in the region mapping to the main ring system, between the red and blue solid vertical lines on either side of the field parallel point, but shows large and sharply varying positive perturbations in the central region interior to the outer boundary of the D ring, of the form discussed by Dougherty et al. (2018) and modeled by Khurana et al. (2018). These perturbations begin and end on D ring field lines between the blue solid and dashed vertical lines, nearer to the inner than the outer boundaries in this case, located approximately symmetrically on either side. They then grow across two sharp field features located just inside the inner D ring boundary, indicative of an intense southward interhemispheric current flow, to peak above ~20 nT in the central region. Significant field fluctuations of ~3 min duration (~0.09 $R_S$ north-south along the spacecraft track) and ~10 nT peak to peak amplitude are also superposed on the otherwise flat-topped field maximum, giving the overall appearance of a four-peaked structure with a central local minimum. These fluctuations are also approximately symmetric about the field parallel point, indicative of spatial structures associated with intense alternating northward and southward current flows.

While these data well define the nature of the field and current structure in the meridian, they evidently provide much less information about variations in azimuth, equivalent to LT. We note, however, that the spacecraft moved eastward through ~0.9 h of LT within the region of perturbed azimuthal field, from ~12.0 inbound to ~12.9 h outbound, such that given the observed near-symmetrical form of the perturbation field, the azimuthal spatial scale of variation must be larger than this.
Comparison with the residual poloidal field components plotted using the same field scale (though with modified ranges) in Figures 2a and 2b shows very different behavior. These components vary slowly in the inbound outer main ring region, but exhibit low amplitude variations in the central region and on the outbound pass. It is thus notable that the poloidal components contain no structures on a scale or with a form that appear to relate to the central azimuthal field structure. This observation also suggests that the azimuthal field is contained within a structure which is somewhat elongated azimuthally around the planet.

3.2. Field Perturbations on Rev 292

Figure 3 similarly shows field and spacecraft position data for Rev 292 in the same format as Figure 2. In this case, however, due to the lower altitude of periapsis (Figure 1a), the intra-D ring interval is expanded somewhat to a duration of ~28 min, now comprising ~5 min on D ring field lines on either side, and ~18 min on field lines inside the D ring. The azimuthal field in Figure 3c is again seen to be weak and smoothly varying on main ring field lines, but exhibits large and highly structured variations on and inside D ring field lines. The perturbations are very different in form to those occurring on Rev 276, however, initially rising from small values close to the outer boundary of D ring field lines to peak at ~15 nT at and inside the inner D ring boundary, indicative of southward current flow, before falling to strongly negative values peaking at ~30 nT near the center point, indicative of a northward current flow. The inner northward field-aligned current flow must be approximately three times the outer southward current flow in order first to reduce the outer field perturbations to near zero values, and then to produce peak negative fields of twice the magnitude. A significant few-minute several-nT fluctuation is also observed on the inbound pass, which is only weakly mirrored outbound, likely indicative of either temporal variation during the ~10 min interval between, or to azimuthal variation in the structure over ~0.5 h of LT between ~10.9 h inbound and ~11.4 h outbound. The near-symmetrical perturbations overall,
however, span ~1.7 h LT from ~10.3 to ~12.0 h LT along the spacecraft track, indicating a structure of comparable or larger azimuthal extent.

By comparison, the residual poloidal components in Figures 3a and 3b show very similar overall behavior to that observed on Rev 276, though with outbound variations of slightly larger amplitude and with some offsets. However, there again appears to be no connection between the variations observed in the poloidal and azimuthal field components, and no essential difference in the form of the residual poloidal fields despite the major differences in the azimuthal field profile. Examination confirms that similar conclusions apply to the proximal data set as a whole (see Dougherty et al. (2018) concerning the initial set of proximal orbits), these findings thus supporting the conclusions of Dougherty et al. (2018) and Khurana et al. (2018) that the intra-D ring azimuthal field represents a locally quasi-axisymmetric structure that spans the noon sector between at least ~10.3 h (Rev 292) and ~13.7 h (Rev 271) LT.

3.3. Current Estimates

If the intra-D ring field structure can be treated as locally axisymmetric to a first approximation, as indicated by the evidence discussed above, it is possible to make simple estimates of the current flows in the meridian by applying Ampère’s circuital law to the current system shown in Figure 1b. Following the discussion of Hunt et al. (2014), their Appendix B, the (positive northward) meridional ionospheric current per radian of azimuth flowing in both northern and southern hemispheres at the feet of the field line passing through the spacecraft is given directly by

\[ I_m \approx \rho B_\phi / \mu_0, \]

where \( B_\phi \) is the measured azimuthal field, \( \rho \) is the perpendicular distance from the planetary spin/magnetic axis (as in Figure 1), and \( \mu_0 \) is the permeability of free space. By current
continuity, this is evidently also the total field-aligned current flowing on field lines between
the outer boundary of the field structure and the point of measurement. Since the
perpendicular distance \( \rho \) is almost constant at \( \sim 1 \) \( R_S \) on relevant data segments as shown in
Figures 1a, 2d, and 3d, a simple estimate of the current can be obtained from

\[
I_m \approx 0.048 B_\rho (\text{nT}) \text{ MA rad}^{-1},
\]  

with the field-aligned currents being given by the changes in \( I_m \) along the spacecraft track.

For example, the \( \sim 20 \) nT increase in \( B_\rho \) observed on Rev 276 in Figure 2c implies a total
interhemispheric southward field-aligned current of \( \sim 1 \) MA rad\(^{-1}\) flowing in the region
spanning across the inner D ring boundary into the interior region. Similarly, the \( \sim 16 \) nT
positive perturbations observed on and just inside the D ring field lines on Rev 292 implies a
total southward current of \( \sim 0.8 \) MA rad\(^{-1}\) flowing in this region, inside of which a current of
\( \sim 2 \) MA rad\(^{-1}\) flows northward to reverse the azimuthal field to \( \sim 30 \) nT as observed at the
spacecraft. In this exceptional case, therefore, the corresponding meridional currents in the
ionosphere reverse from northward at higher northern and southern latitudes, to southward
nearer to the equator on either side (this configuration is depicted, together with other cases,
in Figure 12 introduced below in section 4.5).

4. Overview and Categorization of Intra-D Ring Azimuthal Field Profiles

The data examples discussed in section 3 illustrate two important points. The first is that the
intra-D ring azimuthal field perturbations exhibit a range of signatures, though generally
approximately symmetric about the field parallel point, consistent with the effect of
interhemispheric field-aligned current flow of related variability. The second is that the
perturbations in the residual poloidal fields show no corresponding structures or variability,
being similar in form from pass to pass, thus appearing to be unrelated to the structured intra-
D ring field seen in the azimuthal component. Here we therefore concentrate on the
azimuthal component, taken to a first approximation to relate to an at least locally quasi-axisymmetric field structure associated with interhemispheric field-aligned currents and return ionospheric meridional currents such as that illustrated in Figure 1b.

In this section we thus overview, categorize, and display the azimuthal field profiles observed on all 23 proximal passes. Although we have emphasized above the previously undiscussed variability in the profiles, examination shows that two thirds of the passes can be divided into two broad categories of near-equal frequency, depending mainly on the number of principal positive peaks in the azimuthal field profile, related to corresponding variations in the sense of the field-aligned current flow. We note from the outset, however, that overall the profiles exhibit more a continuum of behaviors that can nevertheless be usefully categorized, rather than absolutely clearly distinct types. In addition to these two types of behavior, however, a further fifth of the passes exhibit profiles that are unique within the proximal orbit data set.

We now describe and display each of these categories in turn, including the unique examples.

4.1. Category A Passes

On category A passes the azimuthal field rises inbound at some point on D ring field lines from the generally weak slowly varying azimuthal fields in the main ring region to a single principal peak centered near the field parallel point, before declining near-symmetrically back to the main ring region baseline outbound. This behavior corresponds to the basic descriptions given by Dougherty et al. (2018) and modeled by Khurana et al. (2018), one example of which has already been provided in Figure 2 for Rev 276. Overall, 8 examples out of the 23 proximal passes show this type of behavior, thus comprising ~35% of the data set.

A gallery of the azimuthal field data from these passes is shown in Figure 4, corresponding to Revs 271, 272, 276, 281, 285, 287, and 291, as marked in each panel (Figures 4a-4g),
together with final Rev 293 (Figure 4h) to the extent that this can be discerned from the partial inbound data. The format of each panel is related to Figures 2 and 3, in that we plot ±35 min of 10 s resolution data either side of the field parallel point in each case, marked by the vertical black dotted line. The crossings of the outer and inner D ring field line boundaries are again indicated by vertical blue solid and dashed lines, respectively, while the crossings of the outer A ring field line boundary and the F ring field line are indicated by red solid and dashed lines, respectively. Temporal and positional data for each of these passes is given in the Table 1. Specifically, in columns 2-5 from left to right we give the 2017 day of year (DOY) and UT times of the field parallel points (corresponding to \( t = 0 \) in Figure 4 and subsequent related figures), the radial distance in \( R_S \) and equivalently the altitude above 1 bar at this time, the mapped northern and southern ionospheric colatitudes at this time (the maximum values of each on the pass), and the intra-D ring LT range (for the interval between the blue solid lines in the figures). Tabulated information on the properties of the azimuthal field profiles is also provided as outlined below.

Figures 4a-4h display the azimuthal field as measured on these 8 Revs, showing the emergence of the central intra-D ring field perturbation from the weaker and more slowly varying main ring region fields on either side. We have fitted a fourth order polynomial curve to the ±40 min perturbation fields on either side, omitting the data obtained inside the outer boundary of the D ring field lines (between the blue solid vertical lines), shown by the blue curves in Figures 4a-4h. These curves generally provide a good fit to the data outside of the D ring region on both sides, and form a simple interpolated baseline for the central region. An exception to this procedure occurs for final partial Rev 293 for which we only have inbound data, in which case the data outside of the D ring region has been extrapolated into the intra-D ring region using a simple linear fit (blue line in Figure 4h). We have then subtracted these baseline values from the observed azimuthal field to form an estimate of the
intra-D ring field alone within the central region, shown in a similar format using the same scale but with a modified range in Figures 5a-5h. We note that although the focus of the present paper is mainly on the intra-D ring field component, the nature and origin of the baseline azimuthal fields on which they are superposed are at present uncertain and subject to future study.

Examination of Figures 4 and 5 shows that the azimuthal field on these passes generally rises at some point on D ring field lines to peak at positive values ~20-40 nT above baseline, corresponding to currents from equation (2) of ~1.0-1.9 MA rad\(^{-1}\), representing the largest overall azimuthal fields within the data set. The perturbations may start and end in an approximately symmetric manner either near the outer D ring field line boundary, or near the inner D ring boundary, or at a middle point between. We note that although the inbound profile relative to the baseline for Rev 281 in Figure 5d may exceptionally suggest that the field perturbations began on inner C ring field lines, this remains unclear in the field profile as measured in Figure 4d, which suggests that the effect may result instead from uncertainties in the fitted baseline.

Inside the D ring field line region the azimuthal field values typically rise quite steadily on either side to a relatively flat-topped maximum value, though in a number of cases (e.g., Revs 276, 285, and 291 in Figures 5c, 5e, and 5g, respectively) the profiles include sharper field gradients inside the inner D ring boundary indicative of more intense field-aligned current densities. Several-nT few-minute fluctuations are often superposed on these profiles, reaching up to ~10 nT peak-to-peak amplitude, though still somewhat smaller than the overall ~30 nT peak field values. These fluctuations are particularly evident over the interval of the flat-topped maxima, though being more prominent in some examples (e.g., Revs 271, 276, and 285 in Figures 5a, 5c, and 5e), than in others (e.g., Revs 272 and 291 in Figures 5b and 5g). A tabular overview is given for each pass in columns 6-9 of Table 1. Specifically from
left to right we give the category identifier, where the perturbations and/or fluctuations start and end on each inbound and outbound pass relative to the D ring field line boundaries (outer boundary OB, inner boundary IB, and middle region MR), the peak (positive and/or negative) azimuthal field from the estimated baseline on each pass computed from 6 point (1 min) running averages in order to smooth the effect of short-term field fluctuations, and the number of primary and secondary (positive or negative) peaks, where the secondary peaks have been taken to refer to few-minute field fluctuations of least ~5 nT peak-to-peak amplitude (thus significantly larger amplitude than the few-nT digitization noise in the data mentioned in section 3.1).

4.2. Category B Passes

On category B passes the inbound azimuthal field rises from the baseline at some point on D ring field lines to peak at positive values near or inside the inner boundary of the D ring field region, before falling again to lower positive values in the inner region. With roughly symmetrical behavior in reversed order occurring outbound, this gives rise to two well-separated perturbation field peaks near to or just inside the crossings of the D ring inner boundary. This behavior implies the existence of a southward directed field-aligned current flowing in the outer part of the structure, followed by a generally smaller reversed northward current flowing inside it. In the central region between these peaks the azimuthal field may exhibit a variety of behaviors, including a well-defined central peak of comparable amplitude giving three principal peaks in total, implying further southward current flow, or smaller-scale fluctuations (similar to those observed in the central region on category A passes) of comparable or smaller peak values giving rise to multiple peaks, thus implying multiple sheets of southward and northward current. We have not sought to further subdivide the data according to these differing behaviors, however, due to the relatively small number of passes
available for study. Overall, 7 examples out of the 23 proximal passes show the above type of behavior, comprising ~30% of the data set.

The azimuthal field profiles on these 7 passes, corresponding to Revs 273, 274, 277, 278, 280, 284, and 288, are shown as measured in Figures 6a-6g in the same format as Figure 4, and with fourth order baseline subtracted in Figures 7a-7g in the same format as Figure 5. It can be seen that the maximum field in the two outer peaks is typically ~10-20 nT above baseline (~0.5-1.0 MA rad⁻¹) as recorded in Table 1, thus typically being smaller than the peak values on category A passes. The field reduction inside the peak is generally to values smaller by a factor of at least two, implying a northward current flow of at least half of the outer southward current flow. Central peaks of comparable amplitude are observed in two cases, on Revs 273 and 278 (Figures 7a and 7d), implying comparable resumed southward current, while Rev 280 (Figure 7e) shows a somewhat less distinct central peak. The remaining cases show generally weaker fields in the central region with superposed fluctuations that are usually not symmetrical, indicative of either time dependence during the ~10 min passage through the central region, or small-scale (fraction of 1 h) LT dependency. Several-nT few-minute fluctuations are particularly prominent on Rev 274 (Figures 6b and 7b). We note that this profile shares much in common with that for Rev 276 in Figure 5c, though the large relative amplitudes of the outer peaks and their location directly adjacent to the inner D ring boundary preferentially places Rev 276 in category B as described above. However, this comparison illustrates the point made at the start of this section that these profiles do not form sets of absolutely clearly distinct types, but more a continuum of behaviors.

4.3. Category C Passes

In a small sub-category of three passes, corresponding to ~15% of the data set, the azimuthal perturbation field exhibits a ~10-20 nT (~0.5-1.0 MA rad⁻¹) rather irregular central positive
peak in the region well inside of the inner D ring boundary, though smaller perturbations again generally start and end on the D ring field lines themselves. The profiles on these 3 passes, corresponding to Revs 275, 283, and 289, are shown in Figures 8a-8c and 9a-9c in the same format as Figures 4-7. It can be seen that asymmetry about the field parallel point is a significant feature, though Rev 289 (Figures 8c and 9c) exhibits an approximately symmetrical bifurcation of the central peak. Other smaller-scale field fluctuations are again present, particularly prominent on Rev 275 (Figures 8a and 9a), which are generally not even approximately symmetrical about the field parallel point, again indicative either of rapid temporal or LT variations. In particular we note that on Rev 275 a significant peak centered on the inner D ring boundary was observed outbound, similar to category B passes, but not inbound, while on Rev 289 (Figures 8c and 9c) a sharp positive spike was observed at this boundary outbound, but with negative field perturbations being observed at this boundary inbound.

4.4. Unique Passes

While the three broad categories described above encompass 18 out of the 23 proximal orbit profiles, the remaining 5 passes (~20% of cases), corresponding to Revs 279, 282, 286, 290, and 292, exhibit features that are unique within the data set, indicated as category U in Table 1. These cases are shown as measured in Figures 10a-10e and with baseline subtracted in Figures 11a-11e, in the same format as Figures 4-9, and will now be briefly discussed. We note, however, the modified field data range (but not scale) employed to contain the data in Figure 10e compared with previous like figures, and similarly in Figures 11b, 11c, and 11e.

On Rev 279 (Figures 10a and 11a) the perturbations in the outer parts of the system are essentially those of category A profiles, with positive azimuthal perturbation fields starting centrally within the region of D ring field lines which grow steadily in magnitude into the interior region, reaching peak amplitudes of ~27 nT (~1.3 MA rad\(^{-1}\)), comparable to category
A profiles (Table 1). However, rather than peaking near the center of the pass as generally
the case for category A passes, the profile displays a relatively smooth and symmetrical
minimum at ~19 nT at the center of the pass, indicative of a reversal in the sense of the field-
aligned current from southward in the outer part to northward in the inner (the northward
current traversed on the inner field lines being ~0.4 MA rad^{-1}). Few-minute fluctuations at
typical several-nT amplitudes are evident in the outer part of the profile, near the inner D ring
boundary field lines.

We may compare this profile with that observed on Rev 292 (Figures 10e and 11e), already
discussed in section 3 (Figure 3), which in its outer regions resembles one of the higher
amplitude category B cases (e.g., Rev 288 in Figures 6g and 7g), with perturbation fields that
rise from background at the outer D ring boundary to form a fluctuating peak at ~15 nT (~0.7
MA rad^{-1}) just inside the inner D ring boundary, before falling in value in the inner region.
However, in this case the perturbation field falls not just to smaller positive values as on Rev
279 (Figure 11a) and in several category B profiles (e.g., Figures 7c, 7f, and 7g), but to the
strongest negative perturbation field relative to the baseline observed during any of the
proximal passes, ~22 nT (~1.1 MA rad^{-1}), peaking close to the field parallel point. This
behavior again indicates the presence of southward field-aligned current flow (~0.7 MA rad^{-1})
in the outer part of the structure on D ring field lines, reversing to northward current flow in
the interior. In this case, however, the total northward field-aligned current is sufficiently
large (~1.8 MA rad^{-1}) that it reverses the sense of the azimuthal field to negative in the central
region, with corresponding southward meridional currents in the ionosphere. Fluctuations are
also observed in the outer parts of the negative field region both inbound and outbound, as
noted in section 3, very prominently on the inbound pass.

Clear observations of strong negative perturbation fields are not confined to Rev 292,
however, but were also observed on Rev 286 (Figures 10c and 11c). Here the profile is
entirely different to Rev 292, however, taking the form of twin negative peaks centered near the two inner D ring boundary crossings, similar to a reversed category B profile. The fields peak at $\sim 11 \text{ nT} \ (\sim 0.5 \text{ MA rad}^{-1})$ inbound and $\sim 17 \text{ nT} \ (\sim 0.8 \text{ MA rad}^{-1})$ outbound, indicating a measure of asymmetry. Between these negative peaks the field exhibits few-minute positive fluctuations peaking at $\sim 5 \text{ nT}$ that are somewhat asymmetric, but suggestive of a near-zero local minimum near the field parallel point. The form of the outer perturbations indicates the presence of nearly equal and opposite northward then southward field-aligned current flow, opposite to all other passes, though stronger outbound than inbound.

Two final cases, in which the field perturbations throughout were much weaker than usual, Revs 282 and 290, are shown in Figures 10b and 11b, and Figures 10d and 11d, respectively. On the first of these passes the perturbations are predominantly negative, with peak values of only $\sim 8 \text{ nT} \ (\sim 0.4 \text{ MA rad}^{-1})$, while on the second they are predominantly positive, peaking at $\sim 7 \text{ nT} \ (\sim 0.3 \text{ MA rad}^{-1})$. The data on these passes thus demonstrate that the excitation mechanism is not always active at the $\sim 15-40 \text{ nT}$ peak levels generally present on other passes. On Rev 282 (Figures 10b and 11b) negative deflections are associated with the inner boundary of the D ring, with a short-lived negative feature occurring just inside the inner boundary inbound and a broader negative feature straddling the boundary outbound, together with a broad flat-topped negative peak located across the center. This pass is thus akin to a reversed sign version of category B Rev 278 (Figures 6d and 7d). On Rev 290 (Figures 10d and 11d) the weak fluctuating positive perturbations start and end in the middle of the D ring region and straddle the inner D ring boundary inbound and outbound, before falling again to smaller fluctuating values in the central region. This pass might therefore alternatively be considered as a very low amplitude version of a category B profile.
4.5. Overview of Field Perturbations and Related Currents

In Figure 12 we provide a visual overview of the variable form of the principal azimuthal perturbation field patterns and associated currents observed during the proximal orbit passes. Specifically we show meridian sections in the dayside equatorial region in a format following Figure 1b, where the curve on the left of each diagram indicates the principal conducting ionospheric layer 1000 km above the 1 bar spheroid, the black dotted line shows the planetary equatorial plane, and the black arrowed lines the field lines mapping to the inner and outer boundaries of the D ring. The strength of the azimuthal field is indicated by the colored shading within the intra-D ring region, red for positive (into the plane of the diagram), and blue for negative (out of the plane of the diagram). The green lines indicate the sense of the field-aligned and ionospheric current flows in the meridian, related to the spatial gradients in the azimuthal field.

Figure 12a corresponds to category A passes, specifically, for example, to Revs 271 (Figure 5a) and 287 (Figure 5f), in which positive perturbations begin close to the outer boundary of D ring field lines, and grow in strength to peak at the field parallel point inside the D ring field region just north of the equator. The corresponding field-aligned current flow is consistently southward throughout the intra-D ring region, and closes northward in the ionosphere. The ionospheric current thus maximizes in the equatorial region as indicated by the large green arrow, and declines monotonically on either side as indicated by the smaller green arrows, to zero at the outer boundary of the D ring field lines. The field and current structure of all category A passes are similar, though the perturbations begin inside of the outer D ring boundary in other cases such as Rev 276 (Figures 2 and 5c) and 291 (Figure 5g).

Of course, due to the finite altitude of the spacecraft at the field parallel point, ~3200 km above 1 bar for Revs 271 and 287 (Table 1), the innermost region of equatorial field lines depicted remains unobserved on these passes, mapping in the ionosphere between ~72° north
colatitude and ~82° south colatitude for these Revs (Table 1), such that the picture shown is to that extent conjectural. The diagram also does not represent the smaller cross-field scale structures associated with the few-minute several-nT field fluctuations observed on many of the passes, which involve narrow layers of essentially equal and opposite southward and northward current flow superposed on the larger-scale structures depicted here.

Figure 12b corresponds to category B passes, specifically to Revs 273 (Figure 7a) and 280 (Figure 7e), for which positive perturbations again begin near to the outer boundary of D ring field lines, grow in strength to peak values close to or just inside the inner boundary of D ring field lines and then decline again to significantly smaller values in the interior region. In the above passes positive perturbations then grow again to peak near the field parallel point. The field-aligned current is then again directed southward on D ring field lines as the positive azimuthal field increases inwards, but then reverses to northward current flow inside the inner D ring boundary as the perturbation field declines. The field-aligned current then reverses back southward once more in the innermost region observed, associated with the central peak in the azimuthal field. The consistently northward-directed ionospheric current correspondingly has three comparable maxima (given comparable strengths in the perturbation field peaks), one near the equator (with the same caveat as indicated above), and two near to or just inside of the feet of the field lines mapping to the inner D ring field boundary in each hemisphere. The patterns of all category B passes show similar features, though the perturbation fields on many of them begin inside of the outer D ring boundary such as for Rev 278 (Figure 7d), and also often differ in the innermost region. While exhibiting the outer field maximum near the inner D ring boundary and subsequent reversal of the field-aligned current to northward, some passes do not exhibit a subsidiary inner maximum such as Rev 277 (Figure 7c), and some only larger amplitude smaller scale
structures with relative minima near the field parallel point such as Revs 274 (Figure 7b) and 288 (Figure 7g).

Figure 12c illustrates the structures associated with the singular category U profile observed on Rev 292 (Figures 3 and 11e). In this case the field and currents in the outer region are similar to the category B system illustrated in Figure 12b, in that positive perturbations grow throughout the D ring field region to peak just inside the inner D ring boundary, associated with a southward directed field-aligned current, before falling in the interior region associated with a reversal of the field-aligned current flow to northward. In this case, however, the field-aligned current remains strong and northward in the innermost region sampled, associated with a reversal in the sense of the azimuthal field to negative, peaking in the innermost region observed. The ionospheric current then has two northward-directed peaks at or just inside of the inner D ring boundary, one in each hemisphere, while reversing to southward between in the region of negative perturbations, peaking (with the above caveat) in the equatorial region.

Figure 12d depicts the reversed current signatures observed on singular category U Rev 286 (Figure 11c). In this case negative perturbation fields begin on central D ring field lines, increasing to peak in strength near the inner D ring boundary. The field-aligned currents in this case are consequently directed uniquely northward within the inner part of the D ring region, reversing to southward as the negative field declines sharply inside the inner D ring boundary and then returns to weakly positive values. In the innermost region sampled the latter field also appears to return to small values, associated with resumed northward field-aligned current flow. The ionospheric currents in this case thus have two southward-directed peaks located close to the inner boundary of D ring field lines, one in each hemisphere, with two lower latitude peaks of weaker northward current flow either side of the equator.
5. Possible Origins of Intra-D Ring Azimuthal Field Variability

We now consider some possible factors that may be related to the variability in intra-D ring azimuthal field profiles. It is first evident that variations in the radial distance of the proximal passes, or equivalently the altitude above 1 bar, is not germane to this issue. As mentioned in section 2 and quantified in Table 1 in terms of the radius and altitude at the field parallel point, the radius varied non-monotonically in a set of Rev groups between ~1.069 and ~1.032 Rs prior to final part-Rev 293, corresponding to altitudes between ~4200 and ~1900 km. However, comparison of these radii/altitudes in Table 1 with the corresponding pass category and peak fields as discussed in section 4 reveals no correspondence. It is in any case evident that a profile of one sort, such as category B, could not in general be formed by a differing radial sampling of a profile of another category, such as category A.

It is also clear that the nature of the profiles is not organized by LT, as also quantified in Table 1 by the LT range spanned within the intra-D ring field region on each pass, since the LT region spanned on all passes is almost completely overlapping. That is to say, the intra-D ring region on the last full pass spanned LTs in the range ~10.3-12.0 h, while that on the first pass spanned the immediately adjacent range ~12.1-13.7 h (Table 1), a full range of ~3.4 h. Furthermore, as previously pointed out in section 3, the usually near-symmetric form of the perturbations observed on these passes indicates that only weak azimuthal spatial variations are present in the currents on the ~1.6 h LT ranges spanned on each pass, indicating significant extension of the structures on either side of the LT range actually spanned. These findings do not, of course, rule out the possibility of significant variations in the intra-D ring fields and currents occurring over larger ranges of LT into the dusk, midnight, and dawn sectors not explored on the proximal orbits. It is, however, clear that the variable nature of the noon-sector events reported here is not ordered by LT, in that all category types were observed from pass to pass over the full range of LTs spanned by these observations.
A further possibility is that the variability relates to the Saturn planetary period oscillation (PPO) phenomenon, which is found to modulate a wide range of magnetospheric field, plasma, wave, and auroral data (e.g., Provan et al. (2018), and references therein). Two rotating modulation systems are generally present, one generated from the northern polar hemisphere and the other from the southern, having variable and slightly different rotation periods near to the planetary rotation period, and variable relative amplitudes. During the proximal orbit interval considered here, the two periods were near constant at ~10.79 h for the northern system and ~10.68 h for the southern system, with the northern system being dominant, but only by a factor of ~1.3-1.4 in equatorial magnetic perturbation field amplitude (Hunt et al., 2018a, 2018b; Provan et al., 2018).

To examine whether the rotational phases of these perturbation systems play a role in the intra-D ring field variability we have divided the passes into four quadrants of northern (N) and southern (S) PPO phase given by

\[ \Psi_{N,S}(t) = \Phi_{N,S}(t) - \varphi , \]

where \( \Phi_{N,S}(t) \) gives the empirically-determined azimuth with respect to noon of the principal meridians of the northern and southern modulation systems at any time \( t \), and \( \varphi \) is the azimuth of the spacecraft observation point also with respect to noon (see Provan et al. (2018) for further details). Results for the dominant northern PPO system are shown in Figures 13a-13d for \( \pm 45^\circ \) intervals of phase centered on \( 0^\circ, 90^\circ, 180^\circ, \) and \( 270^\circ \), respectively, as marked in the figure. In dividing the profiles we specifically consider the phase at the field parallel point, though the change in phase taking place during each \(~27\) min intra-D ring pass is small (\(~15^\circ\)). We show the azimuthal perturbation field with baseline removed versus time for each Rev falling within the above phase ranges (omitting final partial Rev 293), in a similar format to Figures 5, 7, 9, and 11, but now color-coded as shown at the top of each figure panel. The results show that a full range of profile behaviors is observed in each phase.
quadrant, thus providing no indication that the phase of the dominant PPO northern system organizes the main variations observed in these data.

In Figure 14 we show corresponding results obtained by similarly dividing the passes according to the southern PPO system phase. In this case it is seen that the data are very unevenly distributed in southern phase, with most of the passes being evenly distributed in the 90° intervals centered on 0° and 180°, and relatively few in the intervals centered on 90° and 270°. This distribution follows from the accidental fact that the orbit period during the proximal orbit interval (~6.46 days) was close to an integral number of half-periods of the southern PPO system, such that the phase changed by ~180° from one pass to the next. Even so, as for the northern PPO phase, there is no indication in these results for a significant role of the southern PPO phase in the organization of these data.

We recall from section 1, however, that Khurana et al. (2018) have suggested that the intra-D ring perturbation field is produced by differential azimuthal neutral wind drag at the two ends of the field lines in the northern and southern ionospheres, noting that near-symmetric field perturbations across the equator indicative of interhemispheric current flow implies interhemispheric angular momentum transfer. In terms of this picture, the observed variability must then reflect related pass-to-pass variability in the latitude profiles of the zonal thermospheric winds and/or ionospheric Pedersen conductivities, as we now briefly discuss. Assuming approximate axisymmetry, we show in the Appendix that the steady-state meridional ionospheric current per radian of azimuth (positive northwards) flowing at both northern and southern feet of a field line is in general given by

\[ I_m = \frac{\sum_{PS} \sum_{PN} (\Omega_{nS} - \Omega_{nN})}{\sum_{PS} \frac{|\beta_{iS}|}{\rho_{iS} B_{S}^{2}} + \sum_{PS} \frac{|\beta_{iN}|}{\rho_{iN} B_{N}^{2}}} \]  

(4)
were $\Sigma_{PN, S}$ are the height-integrated Pedersen conductivities at the northern ($N$) and southern ($S$) field line feet, $\Omega_{nN, S}$ are the corresponding angular velocities of the neutral atmosphere within the Pedersen layers, $\rho_{iN, S}$ are the perpendicular ionospheric distances from the planetary spin/magnetic axis, $B_{iN, S}$ are the magnitudes of the ionospheric fields, and $|b_{iN, S}|$ are the magnitudes of the field components normal to the ionospheric layer. The related expression given by Khurana et al. (2018) (their equation (3)) was derived under simplified conditions of, e.g., equal ionospheric conductivities at the two ends of the field line. Assuming near-equal field and geometrical conditions at either end of the field line, i.e., $B_{iN} \simeq B_{iS} = B_i$, $|b_{iN}| \simeq |b_{iS}| = |b_i|$, and $\rho_{iN} \simeq \rho_{iS} = \rho_i$, as will generally approximately be the case, we then have

$$I_m \approx \frac{\Sigma'_P B^2 \left( \Omega_{nS} - \Omega_{nN} \right)}{|b_i|},$$

where the effective conductivity parameter is $\Sigma'_P \approx \Sigma_{PN} \Sigma_{PS} / (\Sigma_{PN} + \Sigma_{PS})$, i.e., the square of the geometric mean of the northern and southern conductivities divided by the arithmetic sum. If the two conductivities are equal, $\Sigma_{PN} = \Sigma_{PS} = \Sigma_p$, the effective conductivity is, $\Sigma'_P \approx \Sigma_p / 2$, while if one conductivity is much larger than the other, $\Sigma_{plarge} \gg \Sigma_{psmall}$ then $\Sigma'_P \approx \Sigma_{psmall}$, i.e., the governing conductivity is the smaller of the two (the steady state plasma angular velocity then being close to the neutral angular velocity in the high conductivity hemisphere (equation (A7))). We recall from equation (1) that in the axisymmetric approximation the meridional current at the field line feet is directly related to the azimuthal perturbations on the field line by $I_m \approx \rho B_i / \mu_i$, thus allowing empirical estimates from the observed field values of order $\sim 1$ MA rad$^{-1}$ as, e.g., in section 3.3. Then if in equation (5) we take, for example, $\Sigma'_P \sim 2$ mho (Moore et al., 2010), $\Delta V_n = \rho_i \left( \Omega_{nS} - \Omega_{nN} \right) \sim 300$ m s$^{-1}$ (corotation on the equator is $\sim 10$ km s$^{-1}$), equatorial
\( B_i \approx 20,000 \text{nT}, \ |\vec{b}_i| \approx 2B_i \sin \lambda \) (approximately the radial component) with latitude, e.g. \( \lambda \approx 20^\circ \), near the inner edge of the D ring, and \( \rho_i \approx R_s \approx 60,000 \text{ km} \), we estimate \( I_m \approx 1 \text{MA rad}^{-1} \). Thus, as indicated by Khurana et al. (2018), the mechanism provides reasonable current and perturbation field values when using reasonable input parameters.

It can then be seen from equations (4) and (5) that the variable structures in the intra-D ring azimuthal field may in general be due to variations in either the north-south neutral atmospheric angular velocity shear \( \Delta \Omega_n = (\Omega_{nS} - \Omega_{nN}) \), or the effective ionospheric conductivity \( \Sigma_r \), or both. For example, the positive peaks in azimuthal field lying typically just inside the inner D ring field line boundary in category B cases imply the existence of either a latitudinally restricted region of enhanced flow shear due to an eastward jet of a few hundred m s\(^{-1}\) in the southern thermosphere and/or a similar westward jet in the northern thermosphere, or a latitudinally restricted region of modified effective conductivity \( \Sigma_r \) of several mho within a region of weaker more continuous angular velocity shear. The perturbations on category A passes imply the growth or maintenance of such conditions into the innermost field lines sampled, with superposed shorter-period fluctuations perhaps being associated with waves generated by the shears in flow. In situ Cassini measurements on the proximal passes indeed show the presence of strong variability in the upper equatorial ionospheric plasma from pass to pass, indicative of significant dynamical interactions with D ring material as well as ring shadow effects (Wahlund et al., 2018; Hadid et al., 2018). Observations on these passes also demonstrate the influx of \( \sim 10^4 \text{ kg s}^{-1} \) of volatiles and dust into the equatorial atmosphere, captured from the inner D ring by atmospheric drag (Hsu et al., 2018; Mitchell et al., 2018; Perry et al., 2018; Waite et al., 2018). Tentative evidence for rotational modulation of such influx due to azimuthally structured components of the D ring (e.g., Hedman et al., 2014), specifically from the D68 ringlet lying at a radial distance of
~67,600 km (~1.122 Rs) was also presented by Waite et al. (2018). Considering that such time dependence might conceivably relate to the variable intra-D ring fields discussed here, we have also examined whether the field signatures are organized in a phase system rotating with the D68 ringlet at a rate of 1751.7 degrees per day (equivalent to the Kepler orbit period of 4.932 h). A phase quadrant analysis was therefore undertaken similar to that described above for the PPO phases. However, the results were very similar to those in Figure 13 for the PPOs, thus providing no evidence of a link between the perturbation field signatures and the orbital phase of the D68 ringlet.

The detailed origin of these variations thus remains unclear. However, equations (4) and (5) show that the usual positive sense of the azimuthal perturbation fields directly implies larger atmospheric angular velocities in the sense of planetary rotation at the southern field line feet compared with the northern feet. Khurana et al. (2018) noted that such conditions would prevail if the atmospheric equatorial jet, by far the most prominent stable flow feature observed at tropospheric levels (e.g., García-Melendo et al., 2011), was preserved in similar measure at thermospheric heights, when combined with the net offset of the field line feet towards the north resulting from the axial quadrupole component of the internal planetary magnetic field. However, here we have presented two examples out of 23 with equally large negative field perturbations (Revs 286 and 292 in Figure 11), thus directly implying a reversed sense of thermospheric flow shear within the same region, while in two other cases only weak perturbations were observed (Revs 282 and 290 in Figure 11), indicative of much smaller interhemispheric flow shears of both signs. We also note the frequent occurrence of field signatures apparently related to D ring structures, specifically the extrema often associated with the inner boundary of D ring field lines as observed on category B (and other) passes, as well as the general confinement of the perturbations to the intra-D ring region, implying that thermospheric flow shears become much weaker outside of this region. Such
signatures point to a significant but variable dynamic role in these processes for the D ring material and its interaction with the equatorial atmosphere. Following Brice and McDonough (1973) it is further conceivable that the related variable flows thus envisaged play a role in the transport and loss of the trapped energetic charged particles also observed on intra-D ring field lines (Roussos et al., 2018).

6. Summary and Conclusions
Following initial reports by Dougherty et al. (2018) and Khurana et al. (2018) describing the magnetic field measurements during the early proximal orbits, in this paper we have made a first overview of the azimuthal field perturbations observed on intra-D ring field lines on all 23 proximal passes, including the partial pass made on final Rev 293. We have shown that the profiles are considerably variable in form and amplitude, though usually approximately symmetric about the central point of the pass where the trajectory lies parallel to a flux shell, consistent with the effect of interhemispheric field-aligned current flow. By comparison, the residual perturbations in the poloidal field components are essentially similar from pass to pass, and do not exhibit features with related form or spatial scales to the azimuthal component. This suggests that the azimuthal fields form part of an equatorial structure which is elongated in azimuth significantly beyond the ~1.6 h LT extents spanned on each pass, such that they can be treated as quasi-axisymmetric in nature, at least locally. The LT extent over which direct observations of this phenomenon were obtained spans from ~10.3 h pre-noon (Rev 292) to ~13.7 h post-noon (Rev 271), thus totaling ~3.4 h of LT, the observations thus not precluding significant variations in form in other LT sectors not explored on the proximal passes.

Despite the variability in form, we find that ~65% of the passes (15 out of 23) can be divided into two near-equally occurring categories we have termed A and B. In category A the
azimuthal field rises on D ring field lines to a single usually flat-topped central positive peak value in the interior region, typically ~20-40 nT indicative of a southward field-aligned current flow of ~1.0-1.9 MA rad\(^{-1}\). Few-minute (~0.1 R\(_S\) scale) fluctuations exceeding ~5 nT peak-to-peak, also often approximately symmetric about the field parallel point, are often superposed, indicative of short-scale variable field-aligned current flow. In category B the field rises similarly on D ring field lines to peak at typically ~10-20 nT near or just inside the inner D ring boundary before falling again to form two well-separated field peaks, indicative of a southward field-aligned current flow of ~0.5-1.0 MA rad\(^{-1}\) followed by a northward current flow of a half or more of these values. In between these peaks the field may exhibit a third central peak with comparable peak field values, or weaker values often with superposed fluctuations similar to those seen near the maxima of category A profiles. A third sub-category C containing 15\% of cases (3 out of 23) exhibits similar ~10-20 nT peak perturbations (~0.5-1.0 MA rad\(^{-1}\)) but with asymmetric irregular central positive peaks confined to the region well inside of the inner D ring boundary field line. The remaining 20\% of cases (5 out of 23) exhibit a variety of forms and consequent field-aligned current structures that are unique within the proximal data set. These include two examples with large negative peaks ~20 nT, one peaking centrally on intra-D ring field lines and the other exhibiting two peaks located approximately symmetrically near the inner D ring boundary field line. In addition, two examples occur in which only weak <10 nT field variations and fluctuations are present throughout the intra-D ring region, one predominantly positive in sign and the other predominantly negative. We note that although these field perturbations and hence currents often extend to the outer boundary of D ring field lines, in no case do they unequivocally extend onto C ring field lines.

With regard to the time scale on which the nature of the current system changes take place, we note that the occasionally significant asymmetries in profile between the inbound and
outbound passes on a given Rev (e.g., particularly category C cases) may provide evidence of temporal changes on the several minute time scales involved, although LT variations might also be responsible. Certainly, the time scale for change must generally be modest compared with the ~6.5 day orbital period time scale, given the general lack of relation between the profiles observed from pass to pass (see, e.g., Table 1). With regard to the origins of the field variability, we find that it is not connected with the altitude of the pass, the LT of the pass, the phase of the Saturn planetary period oscillations, or the rotational phase of the D68 ringlet. If, following Khurana et al. (2018), we suppose that the perturbations are due to differential zonal thermospheric wind drag acting at the two ends of these inner field lines, the results imply a related variability in the latitude profiles of either the zonal winds or the ionospheric conductivity, or both, on the ~6.5 day orbital period time scale. The form of the perturbations points to a significant dynamical role in this variability for the interaction between the material in the D ring and Saturn’s outer equatorial atmosphere, as observed directly during the proximal passes.

Appendix: Calculation of Meridional Current Due to Differential Neutral Atmospheric Drag

In this appendix we derive equation (4) for the meridional ionospheric current per radian of azimuth associated with differential wind drag under generalized conditions of differing ionospheric conductivities and magnetic field conditions at either end of the field lines. We assume axisymmetry and that steady state conditions apply. The latter condition implies that the plasma angular velocity $\omega$ is constant along each field line between the two hemispheres, taken positive in the sense of planetary rotation, so that if the neutral atmospheric angular velocities in the northern ($N$) and southern ($S$) ionospheres are $\Omega_{nN}$ and $\Omega_{nS}$, respectively, the velocities of the plasma relative to the neutral atmosphere are given by
\[ V_{n,s} = \rho_{n,s} \left( \omega - \Omega_{m,n,s} \right) \hat{\phi}, \]  
(A1)

where \( \rho_{n,s} \) are the perpendicular distances of the ionospheric layers from the planet’s spin/magnetic axis, and \( \hat{\phi} \) is the unit vector in the azimuthal (planetary rotation) direction.

The electric fields in the rest frame of the neutral gas in the two ionospheres are then

\[ E_{n,s} = -V_{n,s} \times B_{n,s} = \rho_{n,s} \left( \omega - \Omega_{m,n,s} \right) B_{n,s} \times \hat{\phi}, \]  
(A2)

where \( B_{n,s} \) are the planetary poloidal fields in the two ionospheres, such that the Pedersen current densities are given by

\[ j_{p,n,s} = \sigma_{p,n,s} E_{n,s} = \sigma_{p,n,s} \rho_{n,s} \left( \omega - \Omega_{m,n,s} \right) B_{n,s} \times \hat{\phi}, \]  
(A3)

where \( \sigma_{p,n,s} \) are the Pedersen conductivities. These currents, in the direction \( B_{n,s} \times \hat{\phi} \), will thus have components both normal and tangential to the ionospheric layer. The normal component is taken to generate a small electric polarization of the layer which drives a current along the field lines within the layer such that the total current, Pedersen plus parallel, is tangential to the layer (i.e., meridional) as required. The required parallel current density is given by

\[ j_{m,n,s} = \sigma_{p,n,s} \rho_{n,s} \left( \omega - \Omega_{m,n,s} \right) \frac{B_{n,s} \cdot \hat{m}_{n,s}}{B_{n,s} \cdot \hat{n}_{n,s}} B_{n,s}, \]  
(A4)

where \( \hat{n}_{n,s} \) is the unit vector normal to the ionospheric layer directed positive outward from the planet, and \( \hat{m}_{n,s} = \hat{n}_{n,s} \times \hat{\phi} \) is the unit vector tangential to the layer in the meridian positive northwards. Adding the Pedersen and parallel current densities given by equations (A3) and (A4), the total meridional current density, positive northwards, is given by

\[ j_{m,n,s} = \frac{\sigma_{p,n,s} \rho_{n,s} \left( \omega - \Omega_{m,n,s} \right) B_{n,s}^2}{B_{n,s} \cdot \hat{n}_{n,s}}. \]  
(A5)
Integrating with height through the ionospheric layer and in azimuth through an arc of length $\rho_{N,S}$ spanning one radian then yields the total meridional current per radian of azimuth

$$I_{mN} = \frac{\Sigma_{PN,S} \rho_{N,S}^2 (\omega - \Omega_{nN}) B_{N,S}^2}{(B_{N,S} \hat{n}_{N,S})} = \frac{-\Sigma_{PS} \rho_{S}^2 (\omega - \Omega_{nS}) B_{S}^2}{b_{N,S}},$$  \hspace{1cm} (A5)$$

where $\Sigma_{PN,S}$ are the height-integrated Pedersen conductivities, and $b_{N,S}$ are the normal field components $b_{N,S} = (B_{N,S} \hat{n}_{N,S})$, which we note given the sense of Saturn’s internally-generated field are positive at the northern end of the field line and negative at the southern end.

From current continuity we then require the meridional currents per radian to be equal at the two ends of each field line, i.e., $I_{mN} = I_{mS}$, thus implying no cross-field current on field lines above the ionosphere, corresponding to no net force on the plasma in the steady state.

Separating the northern from the southern expression in equation (A5) we then have

$$\frac{\Sigma_{PN} \rho_{N}^2 (\omega - \Omega_{nN}) B_{N}^2}{|b_{N}|} = -\frac{\Sigma_{PS} \rho_{S}^2 (\omega - \Omega_{nS}) B_{S}^2}{|b_{S}|},$$  \hspace{1cm} (A6)$$

where for clarity the $|b_{N,S}|$ indicate the magnitudes of the normal field components. Equation (A6) may then be solved for the angular velocity of the plasma, intermediate between the two neutral angular velocities, given by

$$\omega = \frac{\left(\frac{\Sigma_{PN} \rho_{N}^2 B_{N}^2}{|b_{N}|} \Omega_{nN} + \frac{\Sigma_{PS} \rho_{S}^2 B_{S}^2}{|b_{S}|} \Omega_{nS}\right)}{\left(\frac{\Sigma_{PN} \rho_{N}^2 B_{N}^2}{|b_{N}|} + \frac{\Sigma_{PS} \rho_{S}^2 B_{S}^2}{|b_{S}|}\right)},$$  \hspace{1cm} (A7)$$

where we note that if the neutral atmospheric angular velocities are equal, $\Omega_{nN} = \Omega_{nS} = \Omega_n$, then $\omega = \Omega_n$ as expected. Substituting this solution back into equation (A5) we find the common steady state meridional current in both hemispheres to be given by

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\[ I_m = I_{mN} = I_{mS} = \frac{\Sigma_{PN} \Sigma_{PS} (\Omega_{N} - \Omega_{N'})}{\Sigma_{PN} \rho_{N}^{2} B_{N}^{2} + \Sigma_{PS} \rho_{N'}^{2} B_{N'}^{2}} \] 

which is equation (4) in section 5. Again assuming axisymmetry, we note from Ampère’s law and the argument in section 3.3 that the azimuthal perturbation field at any point along the field line is \[ B_{\phi} = \mu_{0} I_{m}/\rho \], where \( \rho \) is the perpendicular distance from the spin/magnetic axis (as in equation (1)).

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Figure 1. Plots showing inner field line regimes in a meridian plane using cylindrical $(\rho, z)$ coordinates, where $\rho$ is the perpendicular distance from the planet’s spin/magnetic axis, and $z$ is the distance northward from the equator along the axis. The outer edge of the planet (orange spheroid) corresponds to the ionospheric layer 1000 km above the 1 bar reference spheroid (see text) while the arrowed black lines show model magnetic field lines consisting of the first 3 terms of the axisymmetric Dougherty et al. (2018) model (their Table 1) plus the Bunce et al. (2007) ring current model for a typical subsolar magnetopause radius of 22 $R_S$.

In Figure 1a the darker blue area corresponds to field lines that pass through the main rings in the planet’s equatorial plane (black dotted line), from the outer boundary of the A ring to the inner boundary of the C ring, while the lighter blue area corresponds to field lines passing through the tenuous inner D ring at the equator. Polar field lines are drawn at 5° colatitude intervals from the southern pole from 0° to 30°, together with their conjugate counterparts in the north, where the purple areas indicate the approximate location of the auroral currents, and the dashed lines show the field line passing through the moon Enceladus at ~3.95 $R_S$ in the equatorial plane. Cassini trajectories for Revs 276 (blue) and 292 (red) are shown.
projected into the meridian, representative of those with the largest (Rev 276) and smallest (Rev 292) periapsis distances during the proximal orbit sequence. Periapsis points are indicated by the small superposed open circles located south of the equator, while the field parallel points where the trajectory attains its maximum mapped colatitudes (minimum latitudes) in the northern and southern ionospheres are shown by the small superposed solid circles just north of the equator. Figure 1b shows the region containing the field lines passing through the D ring in the same format but on an expanded scale, displaying the current system envisaged by Dougherty et al. (2018) and Khurana et al. (2018) (arrowed green lines). These consist of a latitudinally variable meridional ionospheric current $I_m$, northward directed as shown, closed by an outer southward directed field-aligned current $j_l$, resulting in an interior positive (into the plane of the diagram) azimuthal perturbation field $B_\phi$ (circled cross).
Figure 2. Plot of magnetic field and position data for the periapsis pass of Rev 276, where we show the interval ±35 min on either side of the near-periapsis point where the spacecraft attains its largest field-mapped colatitudes in Saturn’s ionosphere (1000 km above 1 bar), marked as $t = 0$ by the central vertical black dotted line. The UT time corresponding to this point is 14:21.8 (h:min) on 2017 DoY 148 (Table 1). The vertical colored lines indicate the
crossing of field lines mapping to various planetary ring features on the inbound and outbound portions of the pass (see Figure 1a), where the dashed red lines correspond to Saturn’s narrow outer F ring, the solid red lines to the outer boundary of the outer A ring, the solid blue line to the outer boundary of the inner D ring, and the dashed lines to the inner boundary of the D ring. Figures 2a-2c show the spherical polar $r$, $\theta$, and $\phi$ field components, respectively, referenced to the planet’s northern spin/magnetic axis, from which the order 11 internal field of Dougherty et al. (2018) has been subtracted, together with Bunce et al. (2007) model ring current field for a typical subsolar magnetopause radius of 22 $R_S$. Since these model fields are axisymmetric with no azimuthal component, the azimuthal field in Figure 2c is as measured. Figure 2d shows the spacecraft planetocentric radial distance $R$ (solid) and perpendicular distance from the planetary spin axis $\rho$ (dashed) ($R_S$). Figure 2e shows the perpendicular distance $z$ from the planet’s equator (positive northward) ($R_S$). Figure 2f shows the spacecraft colatitude with respect to the north polar axis (deg). Figure 2g shows the spacecraft LT (h). Figures 2h and 2i show the field-mapped colatitudes of the spacecraft in the ionosphere in the northern and southern hemispheres, respectively, where the colatitude with respect to the northern pole is shown in Figure 2h and the colatitude with respect to the southern pole is shown in Figure 2i.
Figure 3. As for Figure 2, but for the periapsis pass of Rev 292. In this case, the time of the field parallel point (i.e., $t = 0$ in the plot) is 00:04.7 (h:min) UT on 2017 DoY 252 (Table 1).
Figure 4. Gallery of category A azimuthal field profiles as described in section 4.1, where we show the total azimuthal field as measured over a ±35 min interval about the field parallel point (taken as \( t = 0 \)), the UT times of which are given in Table 1. As in Figures 2 and 3, the blue vertical solid and dashed lines mark crossings of field lines passing through the outer
and inner boundaries of the D ring, respectively, while the red vertical solid and dashed lines mark the crossings of field lines passing through the outer boundary of the A ring and through the narrow F ring, respectively. The blue curves show fourth order polynomial fits to ±40 min data excluding the intra-D ring data between the pair of blue solid vertical lines, thus forming an interpolated baseline for the central region. An exception occurs for the partial data from final Rev 293 (Figure 4h) for which a linear fit to the inbound data has been extrapolated into the intra D ring region to form a baseline.
Figure 5. Gallery of category A azimuthal field profiles in a similar format to Figure 4, but where the blue baseline curves in Figure 4 have been subtracted from the data as measured to give an estimate of the intra-D ring field alone. Note the modified field range (but not scale) compared with Figure 4.
Figure 6. Gallery of category B azimuthal field profiles as measured, in the same format as Figure 4.
Figure 7. Gallery of category B azimuthal field profiles with baseline subtracted, in the same format as Figure 5.
Figure 8. Gallery of category C azimuthal field profiles as measured, in the same format as Figures 4 and 6.
Figure 9. Gallery of category C azimuthal field profiles with baseline subtracted, in the same format as Figures 5 and 7.
Figure 10. Gallery of category U azimuthal field profiles as measured, in the same format as Figures 4, 6, and 8. Note the revised field data range (but not scale) employed to contain the data in Figure 10e.
Figure 11. Gallery of category U azimuthal field profiles with baseline subtracted, in the same format as Figures 5, 7, and 9. Note the revised field data range (but not scale) employed to contain the data in Figures 11b, 11c, and 11e.
Figure 12. Visual overview of principal azimuthal perturbation field patterns and associated currents observed during the proximal passes, in a similar format to Figure 1b. The curve on the left side of each diagram indicates the principal conducting ionospheric layer 1000 km above the 1 bar spheroid, the black dotted line the planetary equator, and the black arrowed lines the field lines mapping to the inner and outer boundaries of the D ring. The azimuthal field strength is indicated by the colored shading, red for positive (into the plane of the diagram), and blue for negative azimuthal fields (out of the plane of the diagram). The green arrowed lines indicate the sense of the field-aligned and ionospheric current flows.
Figure 13. Superposed time series profiles of azimuthal field perturbations relative to their baselines, plotted relative to the time of their field parallel points (corresponding to $t = 0$) in a similar format to Figures 5, 7, 9, and 11, sorted into ±45° sectors of northern PPO phase centered on 0°, 90°, 180°, and 270°, as indicated at the top of each panel, and color coded as also indicated. The PPO phase considered is specifically that at the time of the field parallel point.
Figure 14. As for Figure 12, but where the time series profiles are now sorted into ±45° sectors of southern PPO phase centered on 0°, 90°, 180°, and 270°, as indicated at the top of each panel.
Table 1. Proximal orbit periapsis pass data and behavior of azimuthal field signature.

<table>
<thead>
<tr>
<th>Rev</th>
<th>UT time</th>
<th>Radius/altitude (2)</th>
<th>Maximum ionospheric colatitude N/S(3)</th>
<th>Intra-D ring region LT start/end h</th>
<th>Start/end (B_w) perturbation in/out</th>
<th>Peak (B_w) field (4) nT</th>
<th>Number peaks primary(5) / secondary(6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>271</td>
<td>116 08:59.2</td>
<td>1.053 / 3203</td>
<td>72.3 / 82.0</td>
<td>12.13/13.68</td>
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<td>33</td>
<td>1/4</td>
</tr>
<tr>
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<td>122 19:37.9</td>
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<td>72.3 / 82.1</td>
<td>12.04/13.60</td>
<td>A MR/ OB</td>
<td>41</td>
<td>1</td>
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<tr>
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<td>72.9 / 82.7</td>
<td>11.96/13.52</td>
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<td>25</td>
<td>3</td>
</tr>
<tr>
<td>274</td>
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<td>1.048 / 2902</td>
<td>73.0 / 82.9</td>
<td>11.87/13.44</td>
<td>B IB/ MR</td>
<td>16</td>
<td>2/5 NS(10)</td>
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<tr>
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<td>72.9 / 82.7</td>
<td>11.79/13.36</td>
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<td>17</td>
<td>3 NS/2 NS</td>
</tr>
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<td>70.0 / 79.6</td>
<td>11.75/13.23</td>
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<td>70.0 / 79.6</td>
<td>11.67/13.15</td>
<td>B IB/ IB</td>
<td>10</td>
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<td>71.0 / 80.7</td>
<td>11.57/13.09</td>
<td>B IB/ MR</td>
<td>14</td>
<td>3/1 NS</td>
</tr>
<tr>
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<td>167 23:51.0</td>
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<td>71.2 / 80.9</td>
<td>11.49/13.01</td>
<td>U MR/ MR</td>
<td>27</td>
<td>2</td>
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<td>70.3 / 79.9</td>
<td>11.26/12.76</td>
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<td>72.3 / 82.1</td>
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<td>72.4 / 82.3</td>
<td>11.05/12.63</td>
<td>B OB/ OB</td>
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<td>2</td>
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<tr>
<td>285</td>
<td>206 18:54.5</td>
<td>1.052 / 3111</td>
<td>72.4 / 82.2</td>
<td>10.96/12.54</td>
<td>A MR/ OB</td>
<td>24</td>
<td>1/3 NS</td>
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<td>72.1 / 81.9</td>
<td>10.88/12.46</td>
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<td>-15</td>
<td>2–/3 NS</td>
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<td>219 17:18.5</td>
<td>1.054 / 3266</td>
<td>72.0 / 81.8</td>
<td>10.80/12.38</td>
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<td>226 04:18.2</td>
<td>1.034 / 2024</td>
<td>75.7 / 85.7</td>
<td>10.66/12.35</td>
<td>B MR/ MR</td>
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<td>75.8 / 85.9</td>
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<td>75.9 / 86.0</td>
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<td>293(11)</td>
<td>258 10:31.5(12)</td>
<td>1.022 / 1508(13)</td>
<td>77.3 / 87.4(14)</td>
<td>9.94/---</td>
<td>A OB/ --</td>
<td>19</td>
<td>1/1</td>
</tr>
</tbody>
</table>

1 UT time of the field parallel point (time of mapping to minimum ionospheric colatitudes)
2 Altitude above planetary 1 bar surface
3 Colatitudes given with respect to the N/S poles, respectively
4 Maximum positive or minimum negative value relative to baseline of 6 point (1 min) running mean of 10 s data
5 Primary peaks refer to overall structures on several-minute time scales positive unless indicated
6 Secondary peaks refer to few-minute fluctuations of \(\geq 5\) nT peak-to-peak amplitude positive unless indicated
7 Outer boundary of D ring field lines
8 Middle region of D ring field lines
9 Inner boundary of D ring field lines
10 Non-symmetrical primary or secondary peaks
11 Parameters are based on partial inbound data only
12 Estimated time along spacecraft track; last data were acquired shortly prior to this time
13 Values at the time of last data