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Star formation in the GC: observational constraints and theory

Sergei Nayakshin
Dept. of Physics & Astronomy, University of Leicester, LE1 7RH, UK

Abstract. We review some observational aspects and theoretical models for the formation of the young massive stars in the central parsec of our Galaxy. It is concluded that an in-situ star formation model provides the best description of the data. One possible guess for the initial gas configuration is one circular and another eccentric gas discs, not necessarily coeval during their short lifetimes. The circular disc probably resulted from a mass deposition event long compared with the local orbital time, whereas the eccentric disc should have formed more dynamically. Based on X-ray observations of the GC, we argue that the initial mass function (IMF) of stars formed in these discs is top-heavy. Such top-heavy IMF is most likely a result of inefficiency with which these optically thick discs fragment, and thus may be a generic result for star-forming AGN discs. We also present preliminary results of numerical simulations of star forming discs, showing that stars with a top-heavy IMF can be formed in both circular and eccentric discs. However, the inner arcsecond "S-stars", and the massive star cluster IRS13E, do not naturally form in these star-forming discs, and still lack explanation.

1. Introduction

Young massive "He-I" stars dominate the power output of the central parsec [13] of our Galaxy. Many of these stars are now resolved to be located in a very well defined and rather thin stellar disc that rotates clockwise as seen on the sky [15, 5, 27]. The rest of the stars can be arguably classified as a second more diffuse disc or a feature that rotates counter clock-wise [5, 27]. Stars appear to be on more eccentric orbits in that disc [27, 17]. Such bright massive stars seem to be excluded from the central arcsecond ($1'' \approx 0.04$ pc), which instead contains a dozen less massive but still quite young B-type stars [7, 8, 3]. In this paper we will not discuss these latter stars except to say they are clearly important but we do not yet have a good model for these.

"Standard" models of star formation are not easily applicable here due to a huge tidal field of the central object at $R = 0.1$ pc distances from Sgr A*. The required gas density is $n_H > 10^{11}\mathrm{cm}^{-3}(R/0.1\mathrm{pc})^{-3}$.

Two models seem most promising. [6] suggested that the stars may have been formed at a distance of tens of parsecs, thus avoiding the need for the excessive gas density prior to star formation, in a massive star cluster. The cluster's orbit would then decay through dynamical friction with the background stars. Further detailed models showed that the cluster needs to be very massive ($M \sim 10^6\,\mathrm{M}_\odot$), very compact, and also contain an intermediate mass black hole [11, 12, 10]. In the other model, stars are formed in situ out of a massive cold and self-gravitating disc [15, 21]. This process has been predicted by theorists [26, 9] but has not yet been observationally verified.

Below we review some of the evidence for in-situ formation of the young stars near Sgr A*, and top-heavy nature of their IMF. We also discuss models of a gaseous star-forming disc.

2. Evidence for in-situ star formation

[27] find a well defined outer edge of about $\simeq 0.5$ parsec to the observed distribution of young massive stars in the GC. This is difficult to understand if stars migrated into the inner parsec from outside. In the massive young cluster disruption model [6], the cluster is disrupted gradually as it sinks closer in, first loosing stars most loosely bound to it. Detailed models of this process [10] show that stars are distributed anywhere between the cluster's place of birth to the disruption radius. If the "pre-maturely" lost stars were massive stars, then the NIR observations of [27] should have detected them.

In principle, there remains a possibility that the cluster was very strongly mass-segregated, i.e., that massive stars were present only in its core, and the rest of it was made up of low mass stars, $M \sim \mathrm{M}_\odot$. In that case, perhaps, all high mass stars could be transported within the inner parsec. This model seems to be challenged by X-ray data. Recent calibration of X-ray properties of T Tauri stars by [28] revealed that they are very bright in X-rays, i.e. some three orders of magnitude brighter than they are on the main sequence. Their spectra have both a soft and a hard component. The latter is observable even at high extinction regions such as the GC. These young stars also display giant X-ray flares, with some becoming as bright as $\sim 10^{33}$ erg s^{-1}. Importantly, the bulk of X-ray emission clearly comes from magnetic flares on the stellar surface, proving that the emission is due to internal relaxation processes of young stars and is thus independent of the large scale star formation environment.

[24] used these new X-ray results for young stars, and observations of the GC reported in [33], to show that the inner ~ 10 parsec could not be hiding more than 10^4 or so young low mass stars. This is insufficient: some $10^5 - 10^6\,\mathrm{M}_\odot$ of young stellar mass is needed to make the cluster heavy enough for it to sink in during the short lifetime of the young massive stars.

3. Top-heavy (or bottom-light) IMF of stellar discs

Because Sgr A* is so dim in X-rays, it turned out possible to push the X-ray constraints further. [1] described the properties of the unresolved X-ray emission near Sgr A* in detail. [24] used these results to deduce that the area most densely populated by massive young stars, i.e., the inner $R \leq 0.2$ parsec could contain no more than $\sim 10^3\,\mathrm{M}_\odot$ of low-mass YSO ($M < 3\,\mathrm{M}_\odot$). This is interesting since a factor of 10 or so more would be expected if the IMF were the "normal" galactic one, such as [18]. [31] reported adaptive optics NIR observations of the Arches cluster that show a "bottom-light" IMF for the inner parts of the cluster. [32], using *Chandra* X-ray data, also finds a deficiency of low mass stars for both Arches and the Quintuplet clusters.

While this similarity in deficiency of low mass stars between the three young star clusters is suggestive and intriguing, the interpretation is not yet clear. For the central star cluster, due to high velocity dispersions there, the relaxation time is around $\sim 10^9$ years. Hence any low mass stars, if born there on orbits similar to those of "He-I" stars, would still be present now. The present day MF for these low mass stars should thus be the same as their IMF. On the other hand, for Arches and Quintuplet clusters the relaxation times are comparable to their age estimates. It is possible that these clusters had a more normal IMF as low mass stars were evaporated off the clusters.

4. Constraints on total stellar masses from orbital modelling

Suppose that the two stellar systems were created infinitely thin and flat, as they would be in the simplest self-gravitating disc scenario. With time, an isolated stellar disc will thicken due to internal N-body heating, and two stellar discs will warp each other due to their non-spherical gravitational potentials [22, 21]. Both of these effects are stronger the more massive the stellar discs are. Now, if the initial systems were not thin and flat, then the thickening and warping will be even quicker (see [25]). Therefore, demanding that the model orbital configuration fits two stellar planes no worse than the real stars do at the present moment, we can arrive at a constraint on the total mass of these discs. This is useful as it is independent of X-ray and NIR constraints, and could potentially uncover "dark matter" in these discs.

The simplest constraint comes from the small height to radius ratio of the innermost clockwise system [27], $H/R \sim 0.1$. This by itself requires the disc mass to be less than $\sim 10^5\,\mathrm{M}_\odot$ [21]. To test disc warping constraints, [25] set up the initial stellar discs as two infinitely thin systems of $N-$body particles on circular orbits and then evolved them for 3 million years. The disc angular momentum vectors were assumed to be given by the best fits to the observed stellar discs [27].

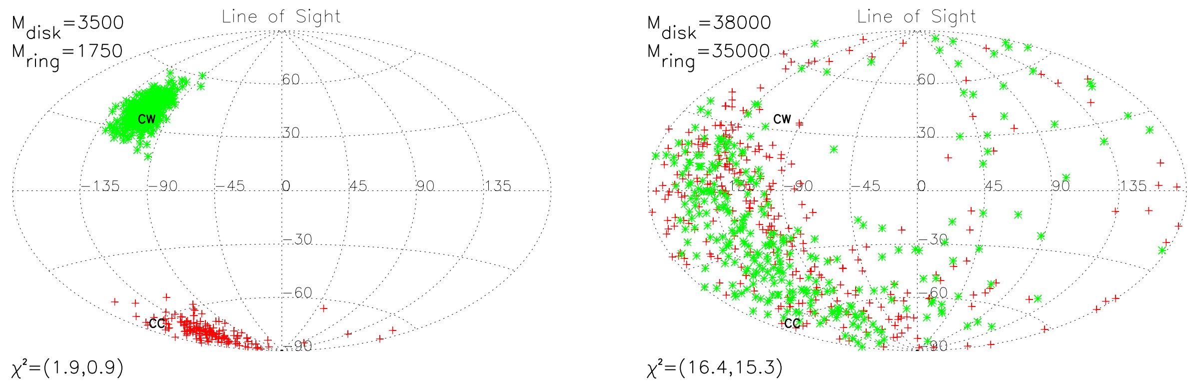

Figure 1. The projections of the angular momentum vectors of individual stars for two different tests from [25]. The positions of the clockwise and counter-clockwise systems from [27] are shown with symbols CW and CC, respectively. Total disc and ring masses are labelled at the upper left corner. The values of the minimum reduced χ^2 fits to the (ring, disc) systems are displayed in the lower left corner of the Figure. The test on left easily passes comparison with the data, whereas the one on the right is strongly ruled out.

Figure 1 shows two such calculations, one with low discs masses, and another with high (the values of disc masses are shown in the upper left corner of each panel). In the low mass case, hardly any orbital precession took place, and hence the systems remain to be very well defined nearly flat stellar discs. The χ^2 fit to these configurations yields small values of χ^2 (see the lower left corner of the panels). The right hand figure shows a very strongly disturbed system. The values of χ^2 from the observations [5, 27] yield limits of around $10^4\,\mathrm{M}_\odot$ for the total masses of each of the stellar discs. We believe these are robust lower limits, however one calls or models the second stellar disc/feature, as eccentric or thickened stellar systems are even more vulnerable to warping [25].

5. A basic self-gravitating gaseous disc model

From a theoretical perspective, the most conveniently studied disc model is one which is just on the brink of gravitational collapse. For this to be the case, the disc has to be both massive enough and be able to cool fast enough: Toomre parameter $Q = 1$, and $t_{\rm cool} \lesssim 3\Omega^{-1}$ [26, 4], where $\Omega = \sqrt{GM_{\rm BH}/R^3}$. This theoretical construction, which most properly called a marginally star-forming disc, may be quite relevant to real AGN discs. Indeed, if the disc came into existence through a gradual mass accumulation from larger scales (see §8), it is quite likely that the disc mass was increasing very slowly compared to the local dynamical time, $1/\Omega$. In that case, the disc will always end up in the marginally star-forming state when enough mass is deposited. The subsequent disc evolution will of course depend on whether mass deposition stops or continues after star formation sets in.

Vertically integrated marginally star-forming disc models have been considered recently by [16] and [23] with applications to Sgr A* in mind. Such a model yields the minimum disk surface density, Σ_d, as a function of radius. The upper panel of Figure 2 shows the resulting minimum disc "mass" as a function of radius, $M_d = \pi\Sigma_d R^2$, and the disc midplane temperature (multiplied by 10^3 for clarity).

Note that if we decided to make stars out of a given amount of gas, then the most economical place to form them would be around 0.1 pc, since this would require the minimum amount of gas, i.e. a fraction of $10^4\,M_\odot$ (see Figure 2). Farther out and further in more gas is needed. In fact, detailed models that bridge the gap between the self-gravitating and "standard" disc regimes predict that star formation does not take place within about $R \sim 0.01 - 0.03$ parsec (depending on opacity and other model details) for Sgr A* mass [2]. Essentially, gas flows into Sgr A* far too fast and is too hot to form stars inside that radius.

Summarising, this basic model makes two predictions that are consistent with the observations: (i) the mass budget should be around $10^4\,M_\odot$, and (ii) there should be an inner edge to stellar disc of about an arcsecond.

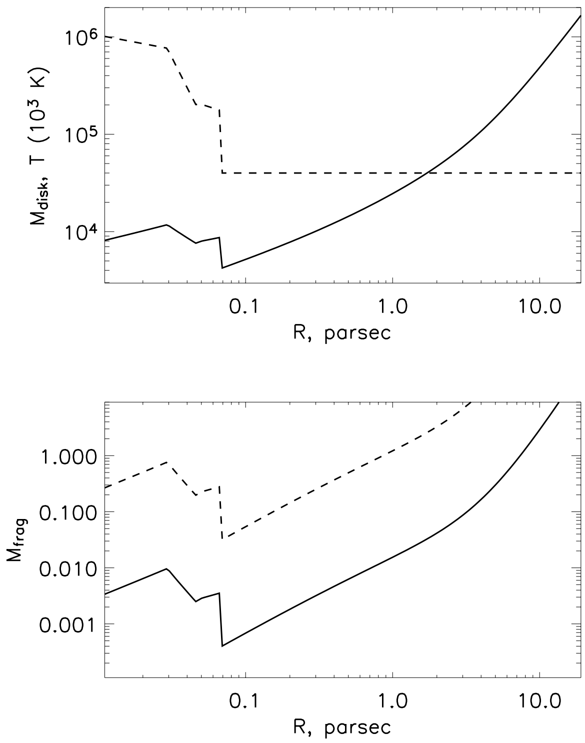

Figure 2. Upper panel: Disk mass (solid curve), $M_d = \pi\Sigma R^2$, in units of Solar masses, and midplane temperature (dashed, in units of $10^3 K$) as a function of distance from the SMBH are shown in the upper panel. The SMBH mass is that of Sgr A*. Lower panel: two estimates of the mass of the first fragments forming in the disk. The realistic value of the fragments mass is likely to be in between these two curves. For more details refer to [23].

6. The IMF of star-forming discs: theory

The estimates for the fragmentation mass, $M_{\rm frag}$, i.e. the mass of the first bound fragments, range between different authors due to an uncertain geometrical coefficient; but they are within the two estimates shown in the lower panel of Figure 2. From the Figure, $M_{\rm frag}$ is always sub-solar in the observationally interesting range of radii, i.e. $R \sim 0.1 - 1$ pc. Hence, if disk were to collapse into clumps of mass of this order, one would expect low-mass stars to dominate the mass spectrum of collapsed objects.

However, in reality, collapse of gas clumps may not be dynamical (as assumed by the simple model), but gradual, regulated by cooling and clump rotation. As gas clump collapse occurs in optically thick conditions, one can show that the minimum mass of a fragment will be $\sim 0.1\,\mathrm{M}_\odot$ (Nayakshin 2006, in preparation). Further, the clumps will have sizes comparable to the dimensions of the "first cores" [14], which are non-negligible. The clumps are thus likely to merge and grow by agglomeration [16]. Therefore one expects that $M_{\rm frag}$ is a strong underestimate of the actual stellar mass. Further, the proto-stars may grow to larger masses by accretion. [23] suggested that luminosity of the young stars accreting gas from within a star-forming disc is sufficient to heat the disc up, increasing the Toomre Q-parameter of the disc above unity and hence making the disc stable to further fragmentation. The proto-stars then continue to accrete mass by accretion, becoming very massive.

It may be that processes discussed by [16] and [23] that lead to a top-heavy IMF both operate, and hence such an IMF may be a general outcome for fragmentation in optically thick self-gravitating AGN discs. Finally, here we neglected possible magnetic fields. If strong enough, these could increase the Jeans mass of the clumps to tens of Solar masses [20].

7. Numerical models of star-forming discs

We shall now present some of the results of numerical simulations of star forming discs that will be published in full elsewhere. We use the SPH/N-body code GADGET-2 [30] to simulate the dynamics of stars and gas in the (Newtonian) gravitational field of Sgr A*. Star formation is treated on an individual star basis, i.e., a "proto-star" is introduced when gas density exceeds a critical density. Some adjustments had to be introduced to model the conditions unchartered by "normal" star formation simulations. Dynamical time scales in our discs are actually shorter than collapse time scale of "first" proto-stellar cores [14]. Therefore, in our approach, the newly born proto-stars have finite sizes, consistent with the size of the first cores (~ 5 AU), and can thus merge with other star particles. Once the proto-stars exceed the mass of $\sim 0.1\,\mathrm{M}_\odot$, the cores should collapse dynamically to much smaller linear scales. Hence stars more massive than $0.1\,\mathrm{M}_\odot$ accrete gas but are not allowed to merge with one another. Radiative cooling of the disc is replaced with a simple locally constant cooling time prescription, $t_{\rm cool} = \beta/\Omega$, where β is a constant of order unity. Value of $\beta = 3$ amounts to assuming that radiative cooling time is *fixed* at the value from the analytical model of marginally star-forming disc.

Circular gas discs without feedback. Following this approach, we ran several models, some designed to test our numerical methods against known results [29]. No star formation feedback was included, assuming that all the radiation generated by star formation leaves the disc freely. The initial condition is a gas disc of mass $2 \times 10^4\,\mathrm{M}_\odot$ in Keplerian circular rotation around Sgr A*, extending from 1" to 4" (1"≈ 0.04 pc). Figure 3 shows a snapshot of a run with $\beta = 3$ well into the non-linear stage, at time $t \sim 10^4$ years, when more than half of the gas were already turned into stars. The innermost disc is almost all turned into stars by that moment.

Surprisingly, gravitational heating generated by stars (scattering off each other and interacting with gas) is sufficient to heat the disc up above its pre-star-formation value, slowing down and even shutting off fragmentation at later times. Clearly, the effect is more pronounced the longer the cooling time, as the disc heats up to higher temperatures during star formation. It should then come as no surprise that the IMF formed in our simulations is a strong function of cooling time (i.e. β), as is evident from Figure 4. The IMF becomes top heavy for $\beta \gtrsim 1$. A cautionary note here is that an accurate modelling of radiative cooling of the disc is necessary for future detailed numerical simulations, as in reality $t_{\rm cool}$ will be a function of time and position. This may be a serious computational challenge for the future, as these discs are often optically thick and nearly razor-thin.

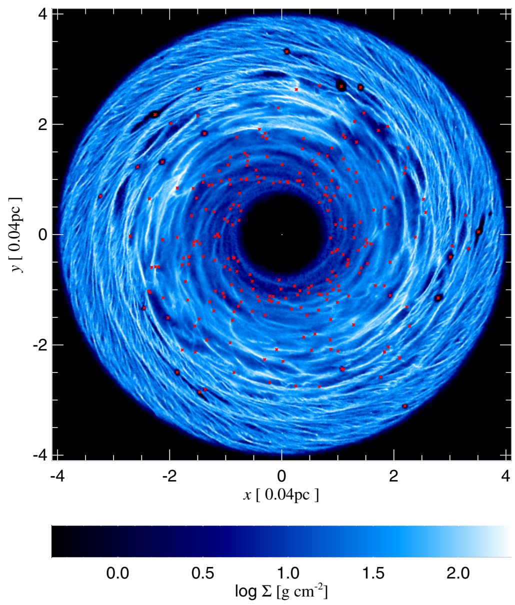

Figure 3. Snapshot of a star-forming disc of initial mass $2 \times 10^4\,\mathrm{M}_\odot$ at time $t = 10,000$ years from the beginning of the simulation. Cooling parameter $\beta = 3$. Stars are shown as asterisks. Star formation is fastest in the innermost region, where most of the gas is already depleted. At the end of the simulation essentially all the gas is turned into stars. [Note that, unlike "normal" star formation, feedback from massive stars will not be very effective in blowing the gas away via radiation pressure or winds as the stars are within the deep potential well due to Sgr A*.] The stars thus steal the majority of Sgr A*'s dinner.

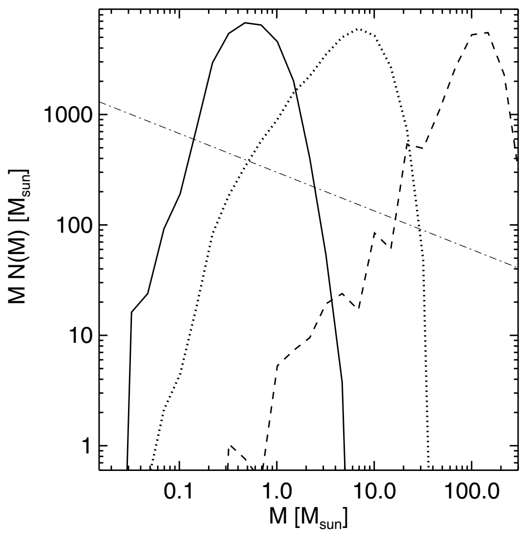

Figure 4. The IMF of three tests with three different values of $\beta = 0.3, 2,$ and 3, shown with the solid, dotted and dashed curves, respectively. The Salpeter-mass function power law is shown with the dot-dashed curve for comparison. The main result is: the longer the cooling time, the more massive stars become, as clumps merging and accretion onto stars overtake disc fragmentation.

Simulations with feedback. We have also ran several tests where *thermal* feedback from gas accretion onto stars was added. These did confirm the suggestion made by [23] that feedback will stifle further disc fragmentation. Unfortunately for the simulations, this reduces not only fragmentation but also accretion onto stars, as gas is hotter. As a result, only $\sim 2\%$ of gas was turned into stars in the simulations with feedback, while in the simulations without thermal feedback, most of gas was reprocessed into stars by the same physical time. We could not run the feedback simulations long enough to obtain the resulting IMF, unfortunately, although the average mass of the proto-stars was increasing during the runs, as predicted.

Eccentric gas discs. To the best of our knowledge, all theoretical literature on star-forming discs was devoted to circular gas discs. Perhaps for this reason, suggestions that star formation cannot occur in eccentric discs were made. This would be a serious flaw of disc models for the

GC young stars, as many stars are on significantly eccentric orbits [17, 27].

However, there is no fundamental law of Nature against star formation in eccentric gas discs. Such orbits could even favour fragmentation because the range of radii, and hence physical conditions sampled by the orbit, is larger than for a circular orbit of same semi-major axis. To test this issue numerically, we ran a test completely analogous to those performed for circular discs but with gas placed on a non-circular orbit (see Figure 5). In particlar, we placed the gas in a small segment of a disc bounded by $4'' \leq R \leq 7''$ and azimuthal angle $0 \leq \phi \leq \pi/4$, and assumed the gas velocity to be 0.7 times the local Keplerian value. The cooling parameter $\beta = 3$. We also included the potential of the older stellar cusp as in [5]. For eccentric orbits, the resulting orbital precession leads to mixing of the orbits and shocks.

We found that eccentric discs can fragment and form stars just like circular discs can. One surprise was that the IMF formed in this simulation was even more top-heavy than in the circular orbit test with the same value of β. It is possible that stronger shock heating helps in a further reduction of disc fragmentation in favour of accretion onto existing stars. Note that stellar orbits differ from that of the gas at latter times because they are not affected by the shocks developing in the gas.

8. Discussion and Conclusions

Key conclusions on the current state of research in the field (in my perhaps biased view) are,

(i) **Origin of young stars:** star formation in situ, inside massive gaseous discs. If, instead, stars originated from outside the inner parsec, a trail of young stars would be seen – in the NIR for bright massive ones [27], and in the X-rays for low mass stars [24].

(ii) **IMF** of young stars in the central parsec is top-heavy, as is evident from both the X-ray [24] and NIR observations [27]. Analytical and numerical models of star forming discs suggests that such a top-heavy IMF can form due to inefficiency with which bound gas clumps collapse. Either these clumps are long-lived and merge quickly with other clumps [16], or (and) that the disc fragmentation as a whole is suppressed by star formation feedback [23]. Alternatively, if magnetic fields are important, the initial Jeans mass can be high [20].

(iii) **Inner edge of stellar discs** is predicted to be around 1" [21] for the star-forming disc model, which agrees well with the observed stellar distribution [27].

(iv) Theoretical prediction for the **stellar mass budget** is at least a fraction of $10^4\,M_\odot$ (see Fig. 2), in agreement with the observations.

(v) **Eccentric stellar orbits.** Numerical simulations, while still in an early stage, show that eccentric gas discs can also form stars with a top-heavy IMF. Orbital precession of a stellar disc filled with eccentric orbits is quicker than that of a circular disc [25], and hence such an eccentric geometrically thin disc would evolve into quite a diffuse feature by now, not unlike the observed counter clock-wise one.

(vi) **Origin of gaseous discs:** infall of one or two large molecular clouds. The observed stellar features form large angles with respect to each other, and the Galaxy plane [27]. The stars in the discs are co-eval within about a million years, which is much shorter than the estimated viscous time of discs [21].This implies that the discs could not have been assembled from larger scale discs via viscous angular momentum transport. The same conclusion follows from the fact that one of the discs should have had eccentric orbits. These orbits would be circularised if viscous angular momentum transfer were important, or if the disc formation time were long, as the orbits would have precessed and destroyed non-circular motions by then.

Amongst most interesting outstanding problems are:

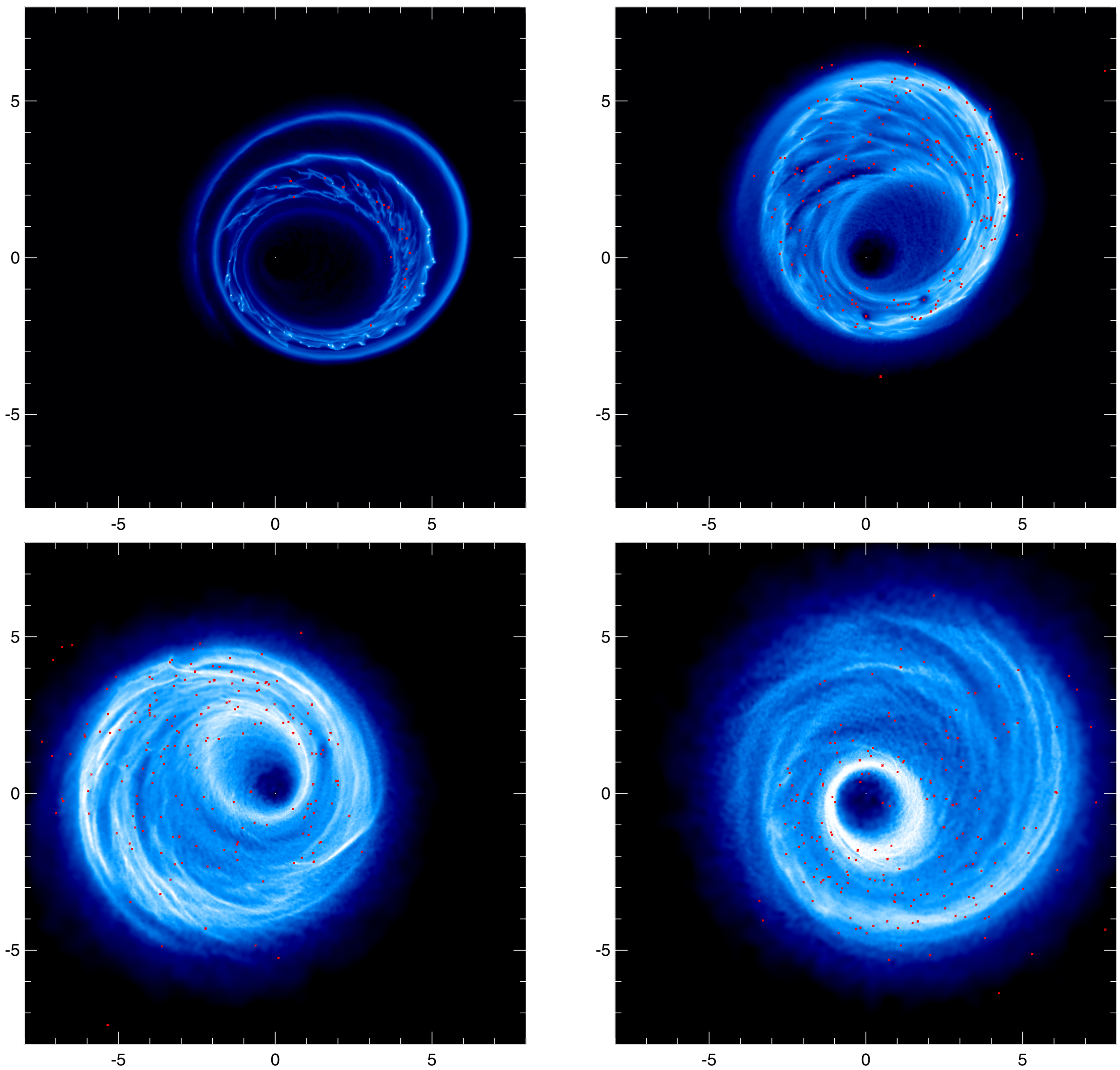

Figure 5. Snapshots of the eccentric disc segment evolution, corresponding to $t = 9, 27, 60$, and 120 thousand years, from left to right and top to bottom. Initially the disc segment is tidally sheared in an eccentric spiral. Precessing, the spiral forms an eccentric disc. Outer and inner edges of the disc precess at different rates. The outer edge of the disc makes slightly more than one revolution during the entire simulation.

(i) **Origin of gas** in the central parsec needs to be quantitatively modelled. Hopefully such a modelling could indicate properties of the gas cloud(s) that formed the discs, e.g., the orbit of the cloud, whether it was clumpy, bound or unbound, etc.

(ii) **IRS13E**: this enigmatic star cluster presents an unsolved problem. In principle, such a cluster could be formed in situ, in an accretion disc, as argued by [19, 21]. In numerical simulations to date, however, gaseous disc fragments on too many independent proto-stars which prevents the growth of a single dominant feature by dynamical interactions between each other. In other words, gaseous mass tends to be spread too evenly in the simulations.

(iii) **S-stars** The early type stars of the inner arcsecond, most of which are on eccentric orbits, remain unexplained in the context of an star-forming disc model (see point *iii* above).

(iv) **Cluster and disc model combined?** In connection with the points (i-iii) just made, we believe it may be premature to rule out the role of a star cluster/IMBH in the formation of the young stars. In particular, a molecular cloud infalling directly into the inner parsec could already have high density regions since "normal" GMC are not homogeneous at all. Some of these regions could start forming stars "on the fly", whereas the lower density gas would have to first get shocked and compressed into the circular clock-wise disc before starting to form stars.

(v) **Implications for AGN and quasars in general.** Young stars near Sgr A* confirm that even moderate amounts of gas, i.e. $\sim 10^4\,\mathrm{M}_\odot$, can become gravitationally unstable and form stars in the inner parsecs of galaxies. This is a fascinating process long predicted by theorists [26]. The problem is that the current models predict too high an efficiency with which gas is turned into stars (e.g., none of our self-gravitating disc models survived long enough to see inside Sgr A*.) Generic theoretical arguments [9] suggest that the same must be true for massive quasar discs, even if star formation feedback is accounted for. Thus, understanding how Sgr A* young stars were formed out of a gaseous disc is a small victory in the face of a bigger problem: how do more massive discs feed AGN and quasars instead of forming stars like Sgr A* did?

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