

Sgr A* envelope explosion and the young stars in the centre of the Milky Way

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ABSTRACT

Sgr A* is the supermassive black hole residing in the centre of the Milky Way. There is plenty of observational evidence that a massive gas cloud fell into the central parsec of the Milky Way ~ 6 Myr ago, triggering formation of a disc of young stars and activating Sgr A*. In addition to the disc, there is an unexplained population of young stars on randomly oriented orbits. Here we hypothesize that these young stars were formed by fragmentation of a massive quasi-spherical gas shell driven out from Sgr A* potential well by an energetic outflow. To account for the properties of the observed stars, the shell must be more massive than 10^5 solar masses, be launched from inside ~ 0.01 pc, and the feedback outflow has to be highly super-Eddington albeit for a brief period of time, producing kinetic energy of at least 10^{55} erg. The young stars in the central parsec of the Galaxy may be a unique example of stars formed from atomic rather than molecular hydrogen, and forged by extreme pressure of black hole outflows.

Key words: black hole physics – Stars: formation – galaxies: individual: Milky Way.

1 INTRODUCTION

The central ~ 2 pc of the Milky Way is dominated in terms of mass by Sgr A*, the $\approx 4.3 \times 10^6 M_{\odot}$ supermassive black hole (SMBH; Paumard et al. 2006; Gillessen et al. 2017). Surprisingly, Sgr A* is orbited by over a hundred massive stars aged only ~ 6 Myr (Lu et al. 2009). This stellar population is confined strongly to the central ~ 0.5 pc (Yelda et al. 2014). Roughly 25 per cent of the young stars reside in a relatively well-defined disc (Levin & Beloborodov 2003) with stars on low eccentricity orbits (Bartko et al. 2009; Yelda et al. 2014). The disc of stars has an inner edge of ~ 0.04 pc and a top-heavy mass function with an unprecedented fraction of stellar mass in massive O/Wolf-Rayet stars (Nayakshin & Sunyaev 2005; Paumard et al. 2006).

Self-gravitational collapse of a massive ($\sim 10^4$ – $10^5 M_{\odot}$) gaseous disc explains the data for the stellar disc remarkably well. The disc cannot fragment inside ~ 0.03 pc (Nayakshin & Cuadra 2005), yields low eccentricity orbits (Alexander, Armitage & Cuadra 2008), and is expected to churn out very massive stars (Levin & Beloborodov 2003; Nayakshin 2006). 3D simulations (Bonnell & Rice 2008; Hobbs & Nayakshin 2009) demonstrated how the gas disc forms via deposition of a massive gas cloud, and predicted that a fraction of the cloud would have low enough angular momentum to accrete on to Sgr A*. Strong Sgr A* activity ~ 6 Myr

ago is supported by the discovery of two ~ 10 -kpc scale giant lobes emitting gamma-rays (the Fermi Bubbles; Su, Slatyer & Finkbeiner 2010). Lobes of a similar shape and energy content form naturally as a result of feedback outflow launched by Sgr A* running into the ambient medium in the inner Galaxy (Zubovas, King & Nayakshin 2011; Zubovas & Nayakshin 2012). The lobes were recently shown to be approximately coeval with the young stars (Miller & Bregman 2016; Bordoloi et al. 2017), disfavouring the competing star-formation feedback model for the origin of the *Fermi* lobes (Crocker & Aharonian 2011; Crocker 2012), which would make the lobes much older.

In this paper we focus on the majority (~ 75 per cent) non-disc population of young stars in the central parsec. Since they are on more isotropically distributed and more eccentric orbits, their formation cannot be explained by a gas disc fragmentation. Furthermore, inside the ~ 0.04 pc hole in the stellar disc, there is at least a dozen of less massive B-type stars called S-stars (Schödel et al. 2003; Ghez et al. 2005), which are even more eccentric (eccentricity $e \sim 0.4$ – 0.9), and are also isotropically distributed in the angular momentum directions (Gillessen et al. 2017). For similar reasons, they too cannot be explained by a disc fragmentation (although some of the S-stars may migrate in from the larger scale stellar disc, see Griv 2009). The leading scenario for formation of S-stars is tidal disruption of stellar binaries that pass too close to Sgr A* on nearly parabolic orbits (e.g. Hills 1988). However, Habibi et al. (2017) very recently found that the S-stars are coeval with the disc

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stars within the errors, challenging the binary disruption model. The model predicts post-disruption S-star eccentricities $e \sim 0.94\text{--}0.99$ (Hills 1991; Perets et al. 2009). This is too large: relaxing these to the observed thermal eccentricity distribution (Gillessen et al. 2017) requires time at least an order of magnitude longer (see fig. 3 in Alexander 2017) than the age of the S-stars. Additionally, in this model one also expects hundreds of B-type stars further out from Sgr A*, at distances $0.04 \text{ pc} < R < 0.5 \text{ pc}$, with very large eccentricities $\gtrsim 0.95$ (see figs 1–3 in Perets & Gualandris 2010). The observed population is not as numerous or eccentric (Bartko et al. 2009).

Here we hypothesize that the non-disc population of young stars orbiting Sgr A* was formed via fragmentation of a very massive gas shell driven outward and compressed by Sgr A* feedback. Such shock-induced star formation is well known in the field of general star formation (Whitworth et al. 1994; Machida et al. 2005; Chiaki, Yoshida & Kitayama 2013), on scales of both individual star forming associations (Deharveng et al. 2003; Liu et al. 2017) and also whole galaxies (Keto, Ho & Lo 2005). Star formation inside active galactic nucleus (AGN) driven outflows was proposed recently by Nayakshin & Zubovas (2012) and Silk (2013), and was possibly confirmed by Maiolino et al. (2017) in a galactic outflow.

2 A MODEL FOR S-STAR FORMATION

2.1 Fragmenting shell

Consider a spherical shell with thickness Z much smaller than its radius R , with surface density Σ , and isothermal sound speed c_s . Approximating the shell as plane parallel, in the direction parallel to the shell, gravitational collapse of the fastest growing mode occurs on time-scale (Whitworth et al. 1994) $t_f \sim 2c_s/G\Sigma$, and the corresponding linear size of the mode is

$$r_f \sim \frac{2c_s^2}{G\Sigma}. \quad (1)$$

For the problem at hand, the shell is likely to be either expanding or contracting, depending on the balance of gravity, $F_g/(4\pi R^2) = -GM_{\text{BH}}\Sigma/R^2$, and the outward pressure of Sgr A* outflow. For self-gravitational collapse of the shell we therefore shall require that it occurred on a time-scale similar to the local dynamical time, $t_{\text{dyn}} = \Omega_K^{-1} = (R^3/GM_{\text{BH}})^{1/2}$, i.e.

$$Q_{\text{sh}} \equiv \frac{t_f}{t_{\text{dyn}}} = \frac{2c_s\Omega_K}{G\Sigma} \sim 1. \quad (2)$$

Note that $Q_{\text{sh}} = Q_{\text{T}}/(2\pi)$, where Q_{T} is the Toomre (1964) parameter for a gas disc with same values of Σ and c_s , so the collapse of the shell requires somewhat similar conditions albeit in a very different geometry. The mass of the shell fragment associated with the fastest growing mode is

$$M_f \sim \pi r_f^2 \Sigma = 0.92 M_{\odot} R_{0.01}^{3/2} \hat{T}^{3/2} Q_{\text{sh}}, \quad (3)$$

where $\hat{T} = T/(3 \times 10^3 \text{ K})$ is the scaled gas temperature in the layer, and $R_{0.01} = R/(0.01 \text{ pc})$ is the distance from Sgr A* to the layer. This mass is much larger than the minimum mass of stars formed in ‘normal’ Galactic conditions, $\sim 0.01 M_{\odot}$ (Low & Lynden-Bell 1976).

The column density of the shell is

$$\Sigma = \frac{2c_s\Omega_K}{GQ_{\text{sh}}} = 5.6 \times 10^4 R_{0.01}^{-3/2} \hat{T}^{1/2} Q_{\text{sh}}^{-1} \text{ g cm}^{-2}. \quad (4)$$

While collapse starts initially in the plane of the shell, eventually it should turn into a 3D collapse. Therefore, we require the density

of the shell, ρ_{sh} , to at least exceed the tidal density,

$$\rho_{\text{sh}} \gtrsim \rho_t = \frac{M_{\text{BH}}}{2\pi R^3} \simeq 4.6 \times 10^{-11} R_{0.01}^{-3} \text{ g cm}^{-3}. \quad (5)$$

The shell should also cool rapidly so that the compressional heat is removed before the internal pressure in the shell could resist collapse. The shell optical depth is $\tau = \kappa \Sigma$, where $\kappa(\rho_{\text{sh}}, T)$ is the Rosseland mean gas opacity at Solar metal abundance that we take from Zhu, Hartmann & Gammie (2009). We shall assume that the shell temperature can be estimated via

$$T \sim T_{\text{bb}} = \left(\frac{ll_{\text{Edd}}}{4\pi\sigma_{\text{SB}}R^2} \right)^{1/4} \approx 5.2 \times 10^3 l^{1/4} R_{0.01}^{-1/2} \text{ K}, \quad (6)$$

where T_{bb} is the effective blackbody temperature at luminosity ll_{Edd} at distance R away from Sgr A*, σ_{SB} is the Stefan–Boltzmann constant, and l is a dimensionless parameter. The assumption $T \approx T_{\text{bb}}$ is reasonable because at temperatures much higher than this the shell will cool down rapidly at distances commensurate with S-star orbits (see below).

In the optically thin limit, gas clumps more massive than $\sim 0.01 M_{\odot}$ can collapse dynamically due to rapid radiative cooling (Rees 1976). The collapse is considerably more difficult for an optically thick shell. We therefore consider this limit, when the radiative cooling time of the shell is

$$t_{\text{cool}} = \frac{\Sigma c_s^2 \tau}{\sigma_{\text{SB}} T_{\text{bb}}^4}. \quad (7)$$

The left-hand panel of Fig. 1 shows the gas opacity as a function of temperature (see Zhu et al. 2009) for several values of gas density. The right-hand panel of the figure shows various properties of the shell calculated for $Q_{\text{sh}} = 3$. The green curve in particular shows the ratio t_{cool}/t_f . Only in the regions where the time-scale ratio is less than unity could star formation take place. From this we conclude that the shell cannot collapse at radii smaller than $R_{\text{min}} \sim 0.005 \text{ pc}$ (shaded region). The transition between regions where star formation is allowed or forbidden is very sharp because it corresponds to the $T \sim 10^4 \text{ K}$ ‘wall’ of the opacity gap, where hydrogen atoms become ionized. Inside the gap the opacity is very low because hydrogen is almost all neutral or molecular, and the dust grains are also not present to contribute to the opacity.

The right-hand panel in Fig. 1 also shows the S-star mass versus apocentre of the orbits (red circles, see Section 3 for why the apocentres are relevant here) for stars for which these quantities are both known (see Gillessen et al. 2017; Habibi et al. 2017). The red curve shows the fragment mass (equation 3). The agreement with observation in both S-star masses and allowed apocentres is surprisingly good given the approximate nature of our model, and should therefore be considered somewhat fortuitous.

2.2 Shell’s origin: an explosion at Sgr A*?

The required mass of the shell, $M_{\text{sh}} \gtrsim 10^5 M_{\odot}$, is comparable to the mass of the gas cloud invoked to be deposited in the central parsec (Bonnell & Rice 2008; Hobbs & Nayakshin 2009) to explain the sub-parsec scale disc of young massive stars orbiting Sgr A*. To form the shell capable of making S-stars, however, we require this much gas to be deposited at $R \sim 0.01 \text{ pc}$. Nevertheless, this could occur if the *average* angular momentum of the cloud was small and significant angular momentum cancellation took place in self-collisional shocks (e.g. Hobbs et al. 2011).

To estimate the rate of mass deposition into the $R \lesssim 0.01 \text{ pc}$ shell due to the cloud infall into the central parsec, we assume that gas

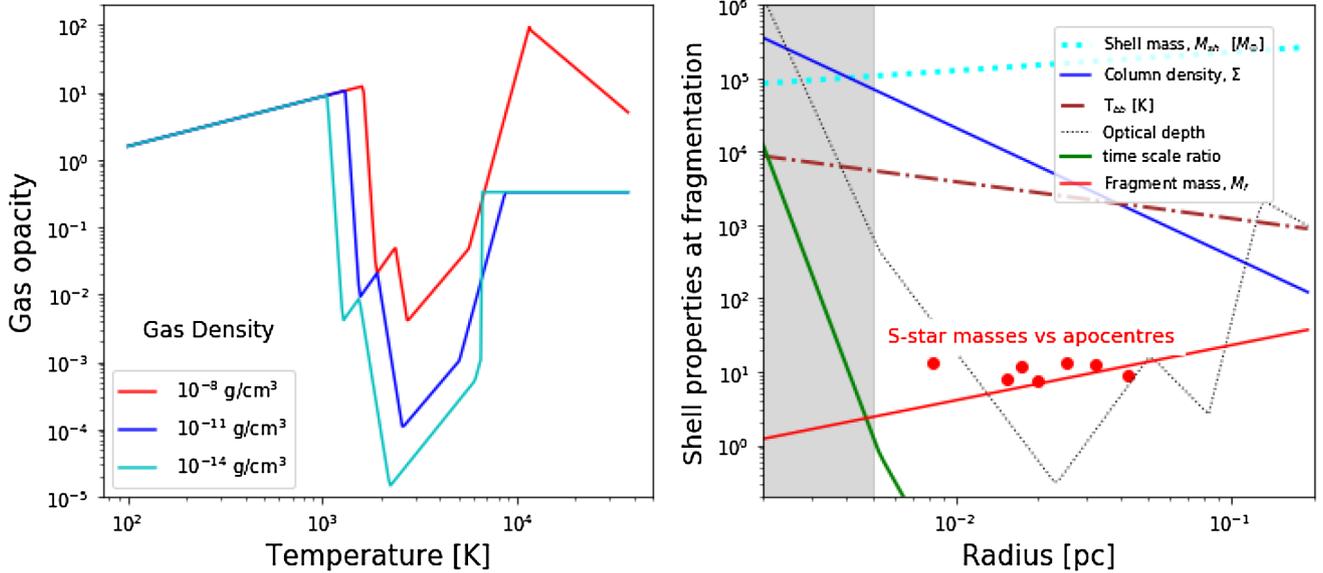


Figure 1. **Left:** Gas opacity κ from Zhu et al. (2009) as a function of gas temperature, for three different values of gas density. Note the opacity gap at temperature $2000 \text{ K} \leq T \leq 10000 \text{ K}$. S-star formation could not occur without this opacity feature. **Right:** Properties of the shell at collapse of the most unstable wavelength and the masses and apocentres of S-stars (filled circles; Gillessen et al. 2017). S-star formation is only possible outside the shaded region, inside of which $t_{\text{cool}}/t_{\text{dyn}} > 1$.

fell towards Sgr A* at free-fall from $R_{\text{cl}} \sim 0.5 \text{ pc}$. This radius marks the outer edge of the stellar disc (Yelda et al. 2014), so we know there was a significant amount of gas deposited inside that region. We get

$$\dot{M}_{\text{dep}} \sim \frac{M_{\text{cl}}}{t_{\text{dyn}}(R_{\text{cl}})} \sim 40M_5 R_{0.5}^{-3/2} M_{\odot} \text{yr}^{-1} = 460 \dot{M}_{\text{Edd}}, \quad (8)$$

where $M_5 = M_{\text{cl}}/10^5 M_{\odot}$, $R_{0.5} = R/(0.5 \text{ pc})$, and $\dot{M}_{\text{Edd}} = 0.086 M_{\odot} \text{yr}^{-1}$ is the Eddington accretion rate on to Sgr A*.

2.2.1 Accumulation from outside

The infall rate in equation (8) is very large, which raises the question: could the shell's significant mass accumulate *in situ*, purely by infall from larger scales, while the shell is held up by feedback from Sgr A* a suitable distance from it, e.g. at $R \sim 0.01 \text{ pc}$?

It is possible to arrange a feedback outflow from Sgr A* to produce just enough radial force to stop the material from falling into Sgr A*. However, $\sim 5000 \text{ yr}$ are required to accumulate enough gas for shell fragmentation, whereas dynamical time at 0.01 pc is $\sim 7 \text{ yr}$. So the shell needs to be stable for a very long time and then become unstable for star formation. The feedback from Sgr A* would also need to increase with time to offset the increasing weight of the shell. This scenario is very finely tuned. Furthermore, the shell suspended some distance away from Sgr A* is unstable to fluid instabilities developing on short time-scales, e.g. a few local dynamical times at the shell radius (Nayakshin & Zubovas 2012). The shell would hatch dense filaments as the result of those instabilities. The filament weight per unit area is higher than the average for the shell, and they therefore fall deeper towards Sgr A*, despite the feedback emanating from the black hole. Since these instabilities develop on time-scale of a few local dynamical times, before Σ necessary for star formation in the shell is accumulated, we reject this scenario.

2.2.2 Shell ejected from smaller scales

Let us consider the opposite possibility, that the shell came from much closer in, $R \ll 0.01 \text{ pc}$. This could happen if gas falling from larger distances was deposited very close to Sgr A* in a massive accretion disc or a quasi-spherical envelope, and a fraction of that was then ejected due to an episode of super-Eddington activity of Sgr A*.

Begelman, Rossi & Armitage (2008) studied ‘quasi-stars’, massive quasi-spherical gas envelopes around stellar mass black holes in the very centres of young high-redshift galaxies. For these systems, the envelope mass greatly exceeds that of the black hole. In the case of Sgr A*, its gaseous envelope is unlikely to have been as massive as Sgr A*, at least not 6 Myr ago, but the physical principles governing the structure of the envelope are similar.

Quasi-stars are strongly dominated by radiation pressure, and have outer radiative zones with temperature rising from a few $\times 10^3 \text{ K}$ on the envelope's outer radius, R_e , to $\sim 10^5 \text{ K}$ at the convective-radiative boundary. The radiative zone can be large and its mass may be comparable to the total mass of the quasi-star (equation 29 in Begelman et al. 2008). Since the luminosity of quasi-stars is limited by the Eddington luminosity, the outer radius of the envelope is given by

$$R_e = \left[\frac{L_{\text{Edd}}}{4\pi\sigma_{\text{SB}}T_e^4} \right]^{1/2} = 0.0075 \text{ pc} \left(\frac{6000 \text{ K}}{T_e} \right)^2 \quad (9)$$

where T_e is the envelope's effective temperature. The contraction (cooling) time of quasi-stars is very long compared with t_{dyn} at 0.5 pc .

3D radiative simulations of massive gas discs show that once magneto-rotational instability in the disc sets in, gas accretion rate on to the SMBH can rise much above the Eddington accretion rate (e.g. Jiang, Stone & Davis 2017, finds accretion rates up to $\sim 1500 \dot{M}_{\text{Edd}}$). The disc in this case becomes very geometrically thick, and an outflow is launched. Jiang et al. (2017) also finds

their discs strongly radiation-pressure dominated, and they find that magnetic field pressure also exceeds that of gas.

Such an unstable rapidly accreting inner disc with a very powerful outflow may form inside the quasi-star and eventually blow it apart from the inside. Since the quasi-star's optical depth is very large, radiation and energy released on small scales is trapped there, but the increased pressure will drive a nearly adiabatic expansion of the outer layers. Due to expansion, the temperature of these layers drops. Since the opacity of gas is such a strong function of temperature for $T \lesssim 10^4$ K, the outer layers of the star rapidly become optically thin once they cool below 10^4 K, allowing radiation to leak out. This leads to a very large pressure drop in the outer layers, so that they can now be compressed to much higher density by the combined force of gravity and the outward acceleration from the expanding inner part of the quasi-star. This may then lead to fragmentation, as described in Section 2.1.

2.3 Energetics and observational consequences

The proposed scenario for star formation results in strongly non-circular stellar orbits. In perfect spherical symmetry, stars born from the shell would be on exactly radial orbits, with eccentricity formally equal to one (we assume here that stars are born with velocities smaller than the escape velocity, although stars may be on escaping trajectories if the shell accelerates enough by the time it fragments, see Zubovas et al. 2013). However, non-axisymmetric shell instabilities (Vishniac 1983; Mac Low & Norman 1993) result in additional, non-radial components to stellar velocities (e.g. see figs 1 and 2 in Nayakshin & Zubovas 2012), which would bring the eccentricity of newly made stars below 1, provided they remain bound to Sgr A*. Additional non-radial velocity components are expected if the quasi-star explosion itself is not spherical, e.g. if the shell surrounding Sgr A* is not perfectly spherical or if Sgr A* feedback is directed preferentially along SMBH's spin axis. Finally, magnetic fields might induce transverse motion in individual gas streams or clumps, reducing orbital eccentricity as the gas accumulates; these non-radial motions are destroyed by self-collision of gas streams, but some net angular momentum or turbulence might remain until the shell is blown away.

The semimajor axes of stars in this scenario depend on gas clump velocity at shell fragmentation. If clump velocity is significantly smaller than the local circular speed then the radius of the shell at fragmentation will set the apocentre of the stellar orbits. As the shell is driven outward, young stars may form on orbits with semimajor axes significantly larger than 0.01 pc, perhaps accounting for all of the young stars in the inner half parsec of the Milky Way that are not in the stellar disc.

Pressure within the quasi-star bubble, P_{bub} , needed to lift up the shell out of Sgr A* potential well is found from $4\pi R^2 P_{\text{bub}} = (GM_{\text{BH}}/R^2)M_{\text{sh}}$. Cast in units of ram pressure from an Eddington-limited momentum feedback outflow,

$$\frac{4\pi R^2 P_{\text{bub}}}{L_{\text{Edd}}/c} = \kappa_{\text{es}} \Sigma = 2.2 \times 10^4 \hat{T}^{1/2} R_{0.01}^{-3/2} Q_{\text{sh}}^{-1}, \quad (10)$$

the pressure is very high. One can show that such a pressure is well above not only momentum-driven but also energy-driven *optically thin* AGN feedback outflows (e.g. Faucher-Giguère, Quataert & Murray 2012) limited by the Eddington luminosity, therefore requiring Sgr A* to be highly super-Eddington.

The duration of the super-Eddington phase does not have to be long, however. The bubble minimum thermal energy is

$$E_{\text{bub}} = 3P_{\text{bub}}V \sim 10^{55} \text{ erg } \hat{T}^{1/2} R_{0.01}^{-1/2} Q_{\text{sh}}^{-1}, \quad (11)$$

where $V = (4\pi/3)R^3$ is the bubble volume. This energy could be produced by accreting a rather modest amount of mass

$$\Delta M = \frac{3P_{\text{bub}}V}{\epsilon c^2} \approx 5000 M_{\odot} \hat{T}^{1/2} R_{0.01}^{-1/2} Q_{\text{sh}}^{-1} \epsilon^{-1} \quad (12)$$

where $V = (4\pi/3)R^3$ is the bubble volume and $\epsilon = 0.01\epsilon_{-2}$ is feedback energy efficiency (see Jiang et al. 2017). For example, if Sgr A* accreted at 1000 times \dot{M}_{Edd} , then just ~ 60 yr suffice to produce the needed energy. In fact, a comparatively short duration of the quasi-star expansion phase is required for the self-consistency of the model. If the expansion takes many dynamical times at the outer edge of the quasi-star, pressure-deflated dense outer layers will become Rayleigh–Taylor unstable and fall through inside the quasi-star, just as was argued in Section 2.2.2. This is likely to drive very large scale convection on the outer edge rather than fragmentation. For this reason it is appropriate to call the hyper-Eddington expansion episode of the quasi-star an explosion.

The velocity that the shell is ejected with is of the order of local escape velocity,

$$v_{\text{bub}} \sim \left[\frac{2GM_{\text{BH}}}{R} \right]^{1/2} = 1300 \text{ km s}^{-1} R_{0.01}^{-1/2}, \quad (13)$$

although it can be larger if bubble expansion is accelerated by a continuous energy release by Sgr A*. The shell will also be slowed down when it runs into ambient interstellar medium.

These values for the outflow velocity and the kinetic energy are commensurable with the observational constraints from the Fermi Bubbles (Su et al. 2010; Zubovas et al. 2011). The velocity kick that the gas in the central molecular zone (CMZ) acquires due to interaction with the ejected shell is also of interest. Assuming that a fraction $\zeta \leq 1$ of the shell's minimum momentum, $M_{\text{sh}}v_{\text{bub}}$, is passed on to the CMZ, which weighs $M_{\text{mz}} \sim 5 \times 10^7 M_{\odot}$, the kick is

$$v_{\text{k}} \sim \zeta \frac{M_{\text{sh}}v_{\text{bub}}}{M_{\text{mz}}} \sim 3 \zeta \text{ km s}^{-1}, \quad (14)$$

which is very much smaller than the circular velocity in the CMZ ($\sim 150 \text{ km s}^{-1}$). This implies that the ~ 200 pc scale CMZ as a whole is not strongly affected by the shell ejection, although the smaller inner regions of the CMZ are much more susceptible to Sgr A* feedback.

3 DISCUSSION

We proposed that the quasi-spherical population of young stars in the central parsec of the Milky Way was formed inside a very dense shell of gas compressed and driven outward by a feedback outflow from Sgr A*. This mode of star formation is related to the AGN feedback induced star formation proposed recently (Nayakshin & Zubovas 2012; Silk 2013) and observed by Maiolino et al. (2017) on much larger spatial scales. Note that the S-stars in this scenario are formed from gas dominated by atomic rather than molecular hydrogen, in contrast to the stars formed in the more benign conditions: even the clockwise disc stars in the central parsec form out of molecular gas (Levin & Beloborodov 2003; Nayakshin 2006). S-star formation proposed here proceeds at much higher gas densities and temperatures as set by the properties of the expanding quasi-star.

The model predictions for S-star masses, semimajor axes and eccentricities are in a reasonable agreement with the observations (see Fig. 1). The required shell mass is large, $M_{\text{sh}} \gtrsim 10^5 M_{\odot}$, but perhaps could be lowered significantly if fragmentation occurred only in the filaments formed by the instabilities inside the shell (see figs 1 and 2 in Nayakshin & Zubovas 2012). We also concluded that the shell must have originated from within the S-star orbits, requiring a very energetic, explosion-like feedback event very close to Sgr A*.

Our hypothesis makes the S-stars and the quasi-spherical population of young stars further out physically distinct from the disc stars (Levin & Beloborodov 2003; Paumard et al. 2006). However, we argue that these two populations are ultimately related through a *single* event that deposited a large quantity of gas into the central parsec (Bonnell & Rice 2008; Hobbs & Nayakshin 2009; Lucas et al. 2013). The distinction would be the average angular momentum of the gas from which the two populations were made – tiny for the quasi-spherical population, and finite, yielding the circularization radius of $\sim 0.05\text{--}0.5$ pc, for the disc stars.¹

Numerical testing of this scenario for S-star formation requires 3D simulations that would model radiation-dominated fluid dynamics, and also resolve fluid instabilities to length scales much smaller than $0.01R$. Stellar orbits predicted by such simulations can be then compared with the observed stellar orbits. Another avenue to test our hypothesis is to model the ejected shell interaction with the well studied ambient gas distribution within the central Milky Way.

We also expect similar black hole envelope explosions to occur in external galaxies. While these events may be very short lived compared to cosmological time-scales, they should be longer in duration than the observable phases of supernovae, more luminous, and located at the very centres of the host galaxies.

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¹Faber & Dehnen (2018) have investigated collisional cascades feeding supermassive black holes. They also suggested that young stars in the Galactic Centre are formed via fragmentation of a disc and on plunging streams. Their model is similar to ours in that it also requires Sgr A* feedback for the shell formation, but their shell is orders of magnitude larger spatially than ours at the point of fragmentation.

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