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Making massive stars in the Galactic Centre via accretion on to low-mass stars within an accretion disc

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ABSTRACT

The origin of the population of very massive stars observed within ∼0.4 pc of the supermassive black hole in the Galactic Centre is a mystery. Tidal forces from the black hole would likely inhibit *in situ* star formation whilst the youth of the massive stars would seem to exclude formation elsewhere followed by transportation (somehow) into the Galactic Centre. Here, we consider a third way to produce these massive stars from the lower mass stars contained in the nuclear stellar cluster which surrounds the supermassive black hole. A passing gas cloud can be tidally shredded by the supermassive black hole forming an accretion disc around the black hole. Stars embedded within this accretion disc will accrete gas from the disc via Bondi–Hoyle accretion, where the accretion rate on to a star, $\dot{M}_\star \propto M_\star^2$. This super-exponential growth of accretion can lead to a steep increase in stellar masses, reaching the required 40–50 $M_\odot$ in some cases. The mass growth rate depends sensitively on the stellar orbital eccentricities and their inclinations. The evolution of the orbital inclinations and/or their eccentricities as stars are trapped by the disc, and their orbits are circularized, will increase the number of massive stars produced. Thus accretion on to low-mass stars can lead to a top heavy stellar mass function in the Galactic Centre and other galactic nuclei. The massive stars produced will pollute the environment via supernova explosions and potentially produce compact binaries whose mergers may be detectable by the LIGO–VIRGO gravitational waves observatories.

Key words: Galaxy: centre.

1 INTRODUCTION

Observational studies of the very centre of our own Milky Way Galaxy reveal a very unusual stellar population (see e.g. Genzel, Eisenhauer & Gillessen 2010). A disc of very massive stars (10–60 $M_\odot$) are found within 0.4 pc of the supermassive black hole (e.g. Genzel et al. 2000; Levin & Beloborodov 2003). About 200 stars above 20 $M_\odot$ are seen (cf. fig. 3 of Bartko et al. 2010). The high masses of these stars require them to be young (around 6 Myr). They seemingly have a top-heavy IMF, with $dN/dm \propto m^{-0.45}$, i.e. much flatter than a normal IMF. In addition, stellar dynamics at the Galactic Centre limits the number of low-mass stars formed together with the massive stars (Alexander, Begelman & Armitage 2007).

Forming these stars from gas *in situ* is problematic owing to their proximity to the supermassive black hole (and its large tidal forces that would shred a normal giant molecular cloud (GMC) at sub-pc distances). An infalling cluster, if formed relatively locally, could have been tidally shredded producing the population of young, massive stars (Gerhard 2001). However, such a process would likely leave the stars further away from the central supermassive black hole than observed.

In this paper, we consider a third option. A GMC passes close to the supermassive black hole and is shredded forming an accretion disc. The observed Fermi bubble (Su, Slatyer & Finkbeiner 2010) could well have formed due to a recent accretion episode from a disc formed in such a way. It has been suggested that star formation within such a disc, through fragmentation due to self-gravity within the disc, could produce the observed young, massive stars (e.g. Levin & Beloborodov 2003; Nayakshin & Cuadra 2005; Nayakshin 2006; Levin 2007). Here, we consider a variation on this model, where we make use of the pre-existing lower mass stars within the nuclear stellar cluster. These stars may become more massive as they accrete material from the disc (Levin & Beloborodov 2003). As we will see in this paper, given suitable disc properties, and favourable stellar orbits, the accretion rate may be sufficient to grow Solar-like stars into very massive stars comparable to those observed.

This paper is set out as follows. We describe the accretion disc model used in Section 2. In Section 3, we derive the time evolution of a star's mass as it accretes gas from the accretion disc and present time-scales for growth due to the accretion disc presented in Section 2. In Section 4, we discuss results, noting the possible importance of migration within the disc, as well as considering how the accretion of gas might be inhibited once the star reaches very large masses (where the sum of stellar and accretion luminosities may exceed the Eddington luminosity). We present our conclusions in Section 5.

2 ACCRETION DISC MODEL

We follow here the approach given by MacLeod & Lin (2020). Namely, we consider an accretion disc with material accreting at

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a constant rate on to the supermassive black hole, $\dot{M}_{\rm smbh}$. Both the Toomre Q parameter, which relates to whether the disc would be vulnerable to forming self-gravitating lumps, and the viscosity parameter α are assumed to be constant throughout the disc.

The Eddington mass accretion rate $\dot{M}_{\rm Edd} = L_{\rm Edd}/\eta c^2$, where the Eddington luminosity is given by $L_{\rm Edd} = 4\pi G M_{\rm smbh} m_{\rm p} c/\sigma_{\rm T}$, $\sigma_{\rm T}$ being the Thompson cross-section for electron scattering and $m_{\rm p}$ being the proton mass. Here, we take $\eta = 0.1$, and thus obtain

$$\dot{M}_{\rm smbh} = \lambda \dot{M}_{\rm Edd} = 0.088\lambda \left(\frac{M_{\rm smbh}}{4\times 10^6 {\rm M}_\odot}\right) {\rm M}_\odot\ {\rm yr}^{-1}. \qquad (1)$$

The surface density of the disc Σ is given by the expression

$$\Sigma = \frac{\dot{M}_{\rm smbh}}{2\pi r v_{\rm r}}, \qquad (2)$$

where the radial inflow in the disc $v_{\rm r} = \alpha h^2 (G M_{\rm smbh}/r)^{1/2}$ and h is the ratio of disc scale height H to radius (i.e. $h = H/r$), which is given by

$$h^3 \simeq \frac{Q}{2\alpha}\frac{\dot{M}_{\rm smbh}}{M_{\rm smbh}\Omega}, \qquad (3)$$

where the disc angular frequency $\Omega = (G M_{\rm smbh}/r^3)^{1/2}$. The surface density of the disc can be rewritten in terms of the critical surface density required for the disc to be self-gravitating

$$\Sigma = \frac{\Sigma_{\rm c}}{Q} = \frac{h}{Q}\frac{M_{\rm smbh}}{\pi r^2} = \frac{1}{(2\alpha)^{1/3} Q^{2/3}}\frac{M_{\rm smbh}^{2/3}\dot{M}_{\rm smbh}^{1/3}}{\pi r^2 \Omega^{1/3}}. \qquad (4)$$

Thus our accretion disc is therefore characterized by the constants, λ, α, and Q, with $h \propto r^{1/2}$ and $\Sigma \propto r^{-3/2}$.

We take $M_{\rm smbh} = 4\times 10^6$ M$_\odot$ for the mass of the supermassive black hole. We consider here an accretion rate at 10 per cent Eddington (i.e. $\lambda = 0.1$), with the disc on the edge of the self-gravitating instability ($Q = 1.0$), the instability driving the viscosity parameter α to also be of order unity (Papaloizou & Lin 1995). The evolution of such discs has been considered in detail (e.g. Gammie 2001; Nayakshin, Cuadra & Springel 2007). They may fragment into low-mass lumps. Such lumps may coagulate to ultimately form more massive stars (e.g. Levin 2007). Alternatively, energy released via accretion on to the lumps may heat the disc, increasing the disc scale height, and thus h, and therefore increasing the value of Q such that the disc is no longer unstable due to its self-gravity (e.g. Nayakshin 2006). Given that our disc will contain pre-existing stars from the nuclear stellar cluster which happen to find themselves in the disc plane, the accretion energy released as gas flows on to these stars will also heat the disc. Radiation from stars above and below the disc will also increase the disc temperature. One can therefore imagine a disc teetering on the edge of being unstable. We take our disc model here as a simple limiting case. In reality the disc may be slightly thicker, and thus have a slightly lower density and a slightly higher sound speed, which in turn lead to slightly lower accretion rates. However, as we will see shortly, our disc model can produce the massive stars seen on time-scales somewhat less than 10 Myr in some cases, thus massive stars are still likely to be produced within 10 Myr even if the accretion rates are somewhat reduced.

We consider a disc of radius $R_{\rm disc} = 3\times 10^{18}$ cm, and thus obtain a total disc mass of $M_{\rm disc} = 3.16\times 10^5$ M$_\odot$. From equation (1), we see that our disc has an accretion rate of 0.0089 M$_\odot$ yr^{-1}, thus the disc lifetime $\tau_{\rm disc} \simeq 36$ Myr. It is also very thin, with $h \sim 10^{-3} - 10^{-2}$. Though as discussed above, heating via accretion on to stars and from the radiation of stars above and below the disc is likely to increase the thickness of the disc (and thus h).

The disc we use here is broadly consistent with the observed Fermi bubble having been formed during an accretion episode on to the supermassive black hole from such a disc (e.g. Su et al. 2010; Zubovas, King & Nayakshin 2011). Such a disc could be produced by the infall and tidal shredding of a GMC. The infall may be the result of a collision between two gas clouds, resulting in a merged object possessing relatively little angular momentum. We note that the resulting infalling cloud may already in some cases be fragmenting into denser lumps as a result of the collision (e.g. Bonnell & Rice 2008; Hobbs & Nayakshin 2009; Lucas et al. 2013).

3 GROWTH BY ACCRETION

We can place stars on orbits within our accretion disc and follow their evolution as they accrete gas via Bondi–Hoyle accretion. Here, we will make a number of simplifying assumptions: we do not consider the time evolution of the accretion disc, or the eccentricity and inclination of a star's orbit.

For a star of mass $M_\star$ passing through a gas of density ρ with a relative speed v, the Bondi–Hoyle accretion rate is given by (e.g. Edgar 2004)

$$\dot{M}_\star = \frac{4\pi G^2 \rho}{\left(v^2 + c_s^2\right)^{3/2}} M_\star^2, \qquad (5)$$

where the density can be approximated using $\rho \simeq \Sigma/2H$ and c_s is the sound speed of the gas, which is given through the relation $h \sim (c_s/v_\phi)$ where $v_\phi = \sqrt{G M_{\rm smbh}/R}$. One can also make the approximation, $v \simeq e v_\phi$ where e is the eccentricity of the star's orbit. Integration of an entire orbit reveals that v varies between $\sim$0.5 and 1.0 $e v_\phi$ with a time-average probably close to about $\sim$0.75 $e v_\phi$. Solving $\dot{M}_\star = K M_\star^2$, assuming K is a constant, we obtain:

$$M_{\star,{\rm b}} = \frac{M_{\star,{\rm a}}}{1 - K M_{\star,{\rm a}}(t_{\rm b} - t_{\rm a})}, \qquad (6)$$

where $M_{\star,\rm a}$ and $M_{\star,\rm b}$ are the masses of the star at times $t_{\rm b}$ and $t_{\rm a}$ (the initial time) respectively. As can be seen from above, the stellar mass increases to very large values once $K M_{\star,\rm a}(t_{\rm b} - t_{\rm a}) \sim 1$. This leads us to introduce the *interesting time-scale*, $t_{\rm int}$ which is given by:

$$t_{\rm int} = \frac{1}{K M_{\star,{\rm a}}}, \qquad (7)$$

where $M_{\star,\rm a}$ is the initial stellar mass. It worth pointing out a simple extrapolation from the initial accretion rate would substantially underestimate the total increase in mass. For example, for $M_{\star,\rm a} = 1$ M$_\odot$, and an initial accretion rate, $\dot{M}_{\star,a} = 0.1$ M$_\odot$ Myr^{-1}, one would formally reach an infinite mass in 10 Myr, whereas by a simple extrapolation, one would have estimated that the mass gained in 10 Myr would be only $\Delta M_\star \simeq 0.1\times 10 = 1$ M$_\odot$.

We initially only consider stars lying within the accretion disc. We assume the stars are radially distributed with a number density $n = k r^{-\gamma}$ where here we take $\gamma = 1.75$. In Fig. 1, we show $t_{\rm int}$ as a function of radius for orbits with eccentricity $e = 0.2$. One can see from this figure, that growth time-scales can be interestingly short (we need to grow in a few Myr or less as this is the evolutionary time-scale for the massive stars we wish to produce). We also produce a population of 100 stars, each located within the disc, but having eccentricities drawn from a thermal distribution (i.e. $df = 2e de$) between $e = 0$ and $e = 0.2$. One can see from this plot that $t_{\rm int}$ is a sensitive function of eccentricity. As our disc is very thin (and therefore relatively cold), the denominator in equation (5) is dominated by the speed of the star relative to the gas, hence at a given radius, $\dot{M}_\star \propto e^{-3}$.

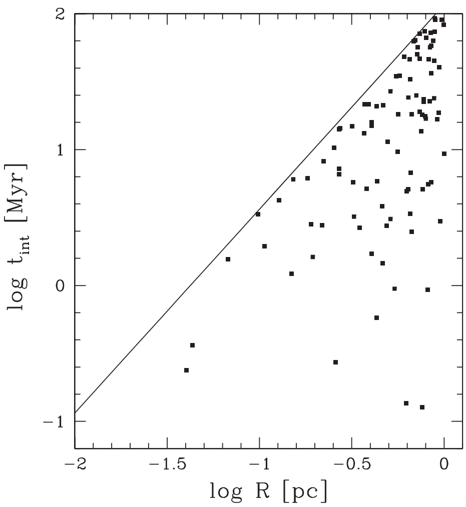

Figure 1. The log of the time-scale for growth in stellar mass, t_{int} plotted as a function of the log of the radius, R. The line is for stars having an eccentricity $e = 0.2$. The dots are for a Monte Carlo population having an eccentricity drawn from a thermal distribution but with $e < 0.2$. All stars, and the line drawn, are placed within the accretion disc.

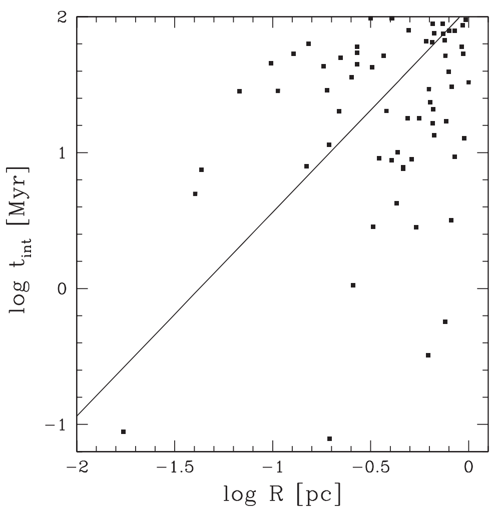

Figure 2. As for Fig. 1 but with the inclinations of the Monte Carlo population of stellar orbits drawn randomly for inclinations, $i < 0.1$ radians.

In Fig. 2, we consider the case where not all stars are within the accretion disc. Explicitly, we randomly sample inclinations up to 0.1 radians. Most of these stars will only spend a fraction of their orbit within the disc. Neglecting for now the effect of stellar capture by the disc, we can estimate the increase in t_{int}, as $t_{int,\,inc} = t_{int} \times i \times R/H$, where i is the inclination of the star's orbit. In reality we expect a number of these stars to settle into the disc thus shortening their growth time-scale. We plot t_{int} as a function of their orbital eccentricity in Fig. 3, clearly showing the dependence on eccentricity.

We evolve the masses of our 100 stars shown in Fig. 2 for 10 Myr. We do not let any mass exceed 40 $M_\odot$. In reality the massive stars will have a spread in masses due to their detailed individual evolutions but here we will simply use this maximum mass as a label for the production of very massive stars. We find that about 25 per cent of our stars become very massive. In Fig. 4, we plot the final stellar mass $M_{\star,\,b}$ as a function of orbital eccentricity. We see here again the critical dependence of the growth on the orbital eccentricity. All stars with $e < 0.1$ become very massive whereas the growth is negligible for $e > 0.15$. In Fig. 5, we plot $M_{\star,\,b}$ as a function of radius. We see here how, interestingly, the formation rate of massive stars is relatively independent of their position within the accretion disc.

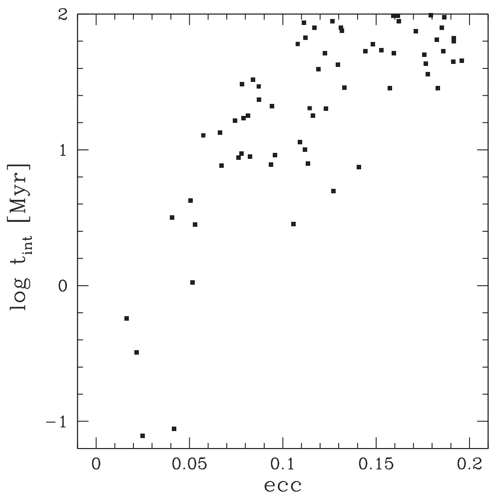

Figure 3. The log of the time-scale for growth in stellar mass t_{int} plotted as a function of eccentricity of the stellar orbits, for the systems shown in Fig. 2.

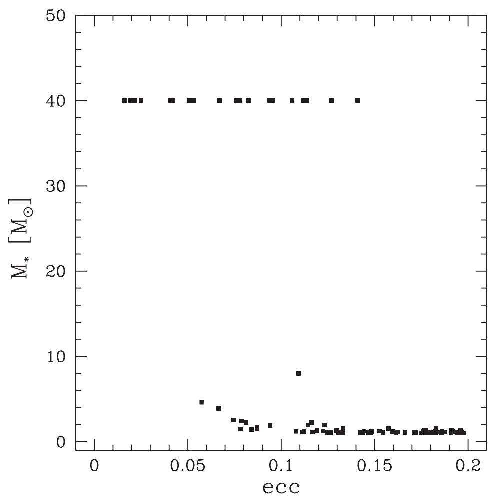

Figure 4. Final stellar masses, $M_\star$ after 10 Myr of evolution (as described in Section 3) plotted as a function of orbit eccentricity.

4 DISCUSSION

As we saw in Section 1, the observed number of very massive stars is around 200. Our calculation presented here with a population of 100 stars, $0 < e < 0.2$, inclination $i < 0.1$, produced around 20 very massive stars. How many massive stars would be produced within a disc from a reasonable nuclear stellar cluster population? If we assume isotropic orbits, then the fraction of stars with inclination $i < 0.1$ is $f = \pi \times (0.1)^2/4\pi = 2.0 \times 10^{-3}$. Assuming there are one million Sun-like stars within 1 pc, yields 2000 stars. *If* the orbital eccentricities of these stars follow the thermal distribution for $0 < e < 1$ then the fraction having $e < 0.2$ is in fact 1/25, thus giving us roughly 80 stars. *However*, this number could be larger for a number of reasons. The current estimates of enclosed mass at 1pc are closer to 4×10^6 $M_\odot$ with the figure rising to over 10^7 $M_\odot$ at less than 2 pc (Schödel et al. 2014) so the number of stars could be closer to 10^7. Also, as discussed above, the evolution of orbital inclinations

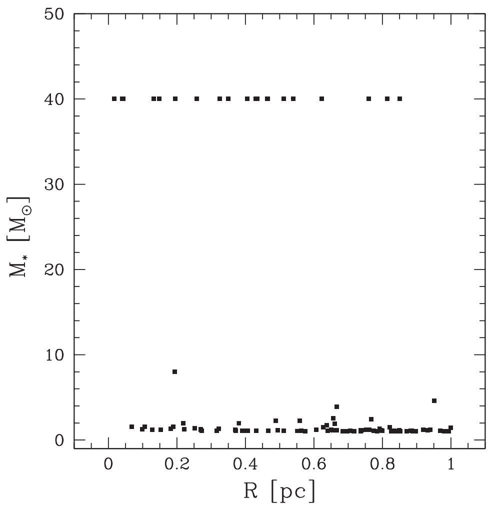

Figure 5. Final stellar masses, $M_\star$ after 10 Myr of evolution (as described in Section 3) plotted as a function of radius.

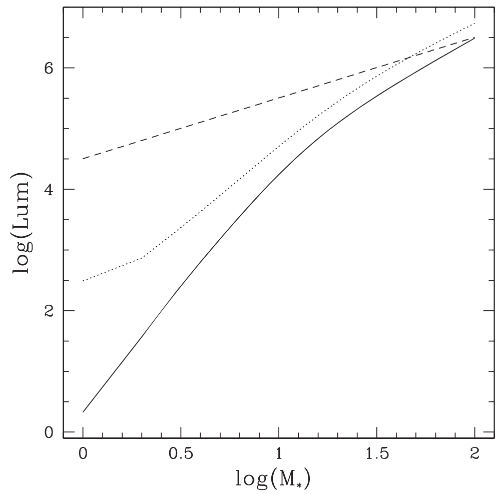

Figure 6. Log of stellar luminosity Log($L_\star$) – solid line, log of Eddington luminosity log($L_{\rm Edd}$) – dashed line, and the log of the sum of stellar luminosity and accretion luminosity, log($L_\star + L_{\rm acc}$) – dotted line, plotted as a function of log($M_\star$) for an evolution producing a very massive star with a very high value of K (where $\dot{M}_\star = K M_\star^2$) corresponding to $t_{\rm int} = 10^5$ yr, comparable to smallest values seen in Figs 1 and 2.

and/or eccentricities could well enhance the rate significantly as stars originally on orbits inclined to the accretion disc will sink into the disc (e.g. Artymowicz, Lin & Wampler 1993). Also the orbits of stars located within the disc will tend to circularize over time (e.g. Artymowicz 1993).

Migration of planets within protoplanetary discs can be extremely important. In the same way, stars may migrate within the accretion disc around the supermassive black hole. The *migration time-scale* can be estimated as (Paardekooper 2014):

$$t_{\rm mig} = \frac{1}{4}\frac{h^2}{q_{\rm d} q_\star} t_{\rm orb}, \tag{8}$$

where $h = H/R$, $q_{\rm d} = M_{\rm disc}/M_{\rm smbh}$, and $q_\star = M_\star/M_{\rm smbh}$. This gives migration time-scales below 1 Myr for our accretion disc. However, migration is a more complex issue, including the effects of corotation torques and interactions, response of disc etc; we may find that the growing stars move outwards rather than inwards. One should also recall that most of the massive stars are found within 0.4 pc, so migration might transport them inwards from around 1 pc.

One can also consider the interaction between the accreting gas and the star receiving the material. Explicitly, one can consider whether the accretion flow ever gets close to being *Eddington limited*. For the accretion histories considered here, using equation (5), one can consider the mass dependence of three luminosities: the luminosity of the star itself, $L_\star$; the luminosity released as a result of accretion of gas, $L_{\rm acc}$; and the Eddington luminosity, $L_{\rm Edd}$. The point is that the accretion will be inhibited and reduced from the value expected in equation (5) when $L_\star + L_{\rm acc} \geq L_{\rm Edd}$.

$$L_{\rm acc} = 3.14 \times 10^7 \frac{(\dot{M}_\star/{\rm M}_\odot {\rm yr}^{-1})(M_\star/{\rm M}_\odot)}{(R_\star/{\rm R}_\odot)} {\rm L}_\odot \tag{9}$$

$$L_{\rm Edd} = \frac{4\pi c G M_\star}{\kappa} = 3.2 \times 10^4 \left(\frac{M_\star}{{\rm M}_\odot}\right)\left(\frac{\kappa_{\rm es}}{\kappa}\right) {\rm L}_\odot. \tag{10}$$

We use the SSE fitting formulae for $L_\star$ and $R_\star$ (Tout et al. 1996; Hurley, Pols & Tout 2000). In Fig. 6, we plot $L_\star$, $L_{\rm Edd}$ and $L_\star + L_{\rm acc}$ as a function of $M_\star$ for an evolution producing very massive stars with a value of K (where $\dot{M}_\star = K M_\star^2$) at the upper end of what we would expect (corresponding to $t_{\rm int} = 10^5$ yr for a star of initial mass 1 M$_\odot$). In such a case, $L_\star + L_{\rm acc} \geq L_{\rm Edd}$ for $M_\star \geq 40$ M$_\odot$. Even for lower values of K, we would expect the stellar mass to be limited when the stellar luminosity approaches the Eddington luminosity once $M_\star \simeq 100$ M$_\odot$. Hence, we expect the growth of the star to be inhibited. For the accretion disc used here, we find this to be the case for about 25 per cent of the very massive stars produced, where the accretion rates (and thus K) are sufficiently large that the accretion luminosity inhibits inflow already at stellar masses around 40 M$_\odot$. Sufficiently massive objects could open gaps in the disc. Indeed gap opening may limit the growth of stellar masses in most cases, where the value of K is sufficiently low that the accretion luminosity is unlikely to inhibit the inflow of gas on to the star.

On a related note, we comment on the likely evolution of any compact objects (stellar-mass black holes, white dwarfs, and neutron stars). Because these objects have much smaller radii than main-sequence stars, a given mass accretion rate will yield a much larger accretion luminosity (as can be seen from equation 9). Equivalently, this means that accretion will be inhibited more often as the Eddington limit will be reached at much lower mass accretion rates ($\dot{M}_\star \sim 10^{-7}$ M$_\odot$ yr^{-1}) for a 10 M$_\odot$ black hole. If accretion rates are limited to this limit then it means that *compact objects will not increase their mass significantly over the 10 Myr evolution considered here* rather the most-massive objects will form first as stars which then evolve to collapse forming black holes.

As we have seen above, about 100 very massive stars are likely to be produced from low-mass stellar seeds within an accretion disc around the supermassive black hole in the Galactic Centre. The majority of these stars will likely evolve to produce stellar-mass black holes in supernovae. How many accretion discs have been produced from tidally shredded GMCs over the entire history of the Galactic Centre? We do not know, but observations of the stellar population within the Galactic centre suggest that a second episode has not occurred within the last 100 Myr (Pfuhl et al. 2011). But a frequency of one disc per 100 Myr would produce something like 10^4 stellar-mass black holes residing within the central parsec today.

This population is roughly ten times larger than one would expect from a regular IMF.

It should be noted that many of the massive stars in the Galactic Centre are observed to be on eccentric orbits (Beloborodov et al. 2006; Paumard et al. 2006; Lu et al. 2009). If the stars that grew within the disc are those having low orbital eccentricities, then one might reasonably have expected these stars to be on rather circular orbits today. However, the system of massive stars produced around the supermassive black hole will behave in a manner similar to an unstable planetary system. Indeed equivalent planetary systems have been studied and shown to become unstable on usefully short time-scales (Chambers, Wetherill & Boss 1996). In such a system, planetary orbits evolve to the point where the orbits cross and planet–planet scattering occurs. Scattering will leave the planets, or in this case the massive stars, on eccentric orbits (e.g. see fig. 1 of Kokaia, Davies & Mustill 2020).

One should note that the process we discuss in this paper is very closely related to what would occur within the longer-lived accretion discs found in active galactic nuclei (AGN). Indeed the production of very massive stars within AGN discs has already been discussed (e.g. Goodman 2003; Goodman & Tan 2004). For both AGN and less-active nuclei such as our Galactic Centre, the population of massive stars produced within the accretion discs will also chemically enrich the central regions with ejecta from their supernova explosions (Artymowicz et al. 1993).

The stellar-mass black holes produced from the massive stars could have a number of important roles. They may sink within the nuclear stellar cluster (kinematically) heating other stars in the process. The enhanced population will increase the rate of so-called extreme mass-ratio inspiral events (EMRIs) where stellar-mass black holes are captured by the supermassive black hole producing inspiralling events potentially visible by the future LISA mission. Black holes within the accretion disc may also encounter each other, as they migrate within the disc, forming black hole binaries (e.g. Secunda et al. 2019). These binaries could spiral together and merge and be visible with LIGO/VIRGO through their gravitational wave emission (e.g. Levin 2007; Bartos et al. 2017; Stone, Metzger & Haiman 2017; McKernan et al. 2018). Indeed this channel could turn out to be the favoured pathway, at least for mergers involving the most massive (stellar mass) black holes. It has also been noted that evolution within the disc could ultimately produce a more massive (intermediate-mass) black hole (McKernan et al. 2012, 2014; Bellovary et al. 2016).

5 CONCLUSIONS

We have shown here that very massive stars could be produced via accretion on to low-mass stars within a gaseous disc surrounding the supermassive black hole in the Galactic Centre. This pathway offers an explanation for the origin of the apparently young population of approximately 200 massive stars found within $\sim$0.4 pc of the supermassive black hole. Given the presence of molecular gas within the central regions, it is not unreasonable to have a GMC encounter the supermassive black hole, and be tidally shredded, forming a disc, once every 100 Myr or so. Thus over time, the very central regions of the Galaxy will become enriched with stellar-mass black holes. The supernovae that produced them will also chemically enrich the region. Black holes may form binaries that merge and are potential gravitational-wave sources. The merger rate between stellar-mass black holes and the supermassive black hole will also be enhanced. As has been pointed out by others, similar processes as we describe for the Galactic Centre will also likely occur within the accretion discs of AGN.

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DATA AVAILABILITY

The data underlying this article will be shared on reasonable request to the corresponding author.

REFERENCES

Alexander R. D., Begelman M. C., Armitage P. J., 2007, ApJ, 654, 907
Artymowicz P., 1993, ApJ, 419, 166
Artymowicz P., Lin D. N. C., Wampler E. J., 1993, ApJ, 409, 592
Bartko H. et al., 2010, ApJ, 708, 834
Bartos I., Kocsis B., Haiman Z., Márka S., 2017, ApJ, 835, 165
Bellovary J. M., Mac Low M.-M., McKernan B., Ford K. E. S., 2016, ApJ, 819, L17
Beloborodov A. M., Levin Y., Eisenhauer F., Genzel R., Paumard T., Gillessen S., Ott T., 2006, ApJ, 648, 405
Bonnell I. A., Rice W. K. M., 2008, Science, 321, 1060
Chambers J. E., Wetherill G. W., Boss A. P., 1996, Icarus, 119, 261
Edgar R., 2004, New A Rev., 48, 843
Gammie C. F., 2001, ApJ, 553, 174
Genzel R., Pichon C., Eckart A., Gerhard O. E., Ott T., 2000, MNRAS, 317, 348
Genzel R., Eisenhauer F., Gillessen S., 2010, Rev. Mod. Phys., 82, 3121
Gerhard O., 2001, ApJ, 546, L39
Goodman J., 2003, MNRAS, 339, 937
Goodman J., Tan J. C., 2004, ApJ, 608, 108
Hobbs A., Nayakshin S., 2009, MNRAS, 394, 191
Hurley J. R., Pols O. R., Tout C. A., 2000, MNRAS, 315, 543
Kokaia G., Davies M. B., Mustill A. J., 2020, MNRAS, 492, 352
Levin Y., 2007, MNRAS, 374, 515
Levin Y., Beloborodov A. M., 2003, ApJ, 590, L33
Lucas W. E., Bonnell I. A., Davies M. B., Rice W. K. M., 2013, MNRAS, 433, 353
Lu J. R., Ghez A. M., Hornstein S. D., Morris M. R., Becklin E. E., Matthews K., 2009, ApJ, 690, 1463
MacLeod M., Lin D. N. C., 2020, ApJ, 889, 94
McKernan B., Ford K. E. S., Lyra W., Perets H. B., 2012, MNRAS, 425, 460
McKernan B., Ford K. E. S., Kocsis B., Lyra W., Winter L. M., 2014, MNRAS, 441, 900
McKernan B. et al., 2018, ApJ, 866, 66
Nayakshin S., 2006, MNRAS, 372, 143
Nayakshin S., Cuadra J., 2005, A&A, 437, 437
Nayakshin S., Cuadra J., Springel V., 2007, MNRAS, 379, 21
Paardekooper S. J., 2014, MNRAS, 444, 2031
Papaloizou J. C. B., Lin D. N. C., 1995, ARA&A, 33, 505
Paumard T. et al., 2006, ApJ, 643, 1011
Pfuhl O. et al., 2011, ApJ, 741, 108
Schödel R., Feldmeier A., Neumayer N., Meyer L., Yelda S., 2014, Class. Quantum Gravity, 31, 244007
Secunda A., Bellovary J., Mac Low M.-M., Ford K. E. S., McKernan B., Leigh N. W. C., Lyra W., Sándor Z., 2019, ApJ, 878, 85
Stone N. C., Metzger B. D., Haiman Z., 2017, MNRAS, 464, 946
Su M., Slatyer T. R., Finkbeiner D. P., 2010, ApJ, 724, 1044
Tout C. A., Pols O. R., Eggleton P. P., Han Z., 1996, MNRAS, 281, 257
Zubovas K., King A. R., Nayakshin S., 2011, MNRAS, 415, L21

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