Red giant stellar collisions in the Galactic Centre

James E. Dale, Melvyn B. Davies, Ross P. Church, and Marc Freitag

1 Lund Observatory, Box 43, SE-221 00 Lund, Sweden
2 School of Mathematical Sciences, Monash University, Victoria 3800, Australia
3 Institute of Astronomy, Madingley Road, Cambridge CB3 0HA

ABSTRACT

We show that collisions with stellar-mass black holes can partially explain the absence of bright giant stars in the Galactic Centre, first noted by Genzel et al. We show that the missing objects are low-mass giants and asymptotic giant branch stars in the range $1-3 \, M_\odot$. Using detailed stellar evolution calculations, we find that to prevent these objects from evolving to become visible in the depleted $K$ bands, we require that they suffer collisions on the red giant branch, and we calculate the fractional envelope mass losses required. Using a combination of smoothed particle hydrodynamic calculations, restricted three-body analysis and Monte Carlo simulations, we compute the expected collision rates between giants and black holes, and between giants and main-sequence stars in the Galactic Centre. We show that collisions can plausibly explain the missing giants in the $10.5 < K < 12$ band. However, depleting the brighter ($K < 10.5$) objects out to the required radius would require a large population of black hole impactors which would in turn deplete the $10.5 < K < 12$ giants in a region much larger than is observed. We conclude that collisions with stellar-mass black holes cannot account for the depletion of the very brightest giants, and we use our results to place limits on the population of stellar-mass black holes in the Galactic Centre.

Key words: stars: late-type – Galaxy: centre.

1 INTRODUCTION

In common with many other galaxies, the Milky Way hosts at its centre a supermassive black hole (SMBH), Sagittarius A* (Sgr A*), whose mass is $\approx 4 \times 10^6 \, M_\odot$ (e.g. Schödel et al. 2003). Surrounding Sgr A* is the Galactic Centre cluster, the study of which offers unique insights into many areas of astrophysics, such as the dynamics of star clusters with central massive objects, the formation history of SMBHs and the emission of gravitational waves by extreme mass-ratio inspirals (for a recent review of this topic, see Amaro-Seoane et al. 2007).

The study of the Galactic Centre cluster is hindered by $\sim 30$ mag of intervening visual extinction. Nevertheless, a great deal has been learned about the stellar population in the central few parsecs by observations made in X-rays and in the near-infrared, in which the extinction is only $\sim 3$ mag.

The Galactic Centre cluster is one of the densest stellar systems known. Genzel et al. (1996) concluded that the cluster had a dense core with a radius of $\approx 0.38$ pc and a density of $4 \times 10^6 \, M_\odot \, pc^{-3}$. Later measurements by Genzel et al. (2003) and Schödel et al. (2007) found that the cluster was more cusp like and reported still higher number densities, reaching $\approx 10^7 \, pc^{-3}$ at a radius of 0.1 pc.

These number densities are well in excess of those of globular clusters ($\lesssim 10^3 \, M_\odot \, pc^{-3}$; Harris 1996) or young clusters such as the Arches ($3 \times 10^6 \, M_\odot \, pc^{-3}$; Figuer et al. 1999). The cusp is composed largely of old- and intermediate-age stars (Genzel et al. 2003; Schödel et al. 2007). However, mixed with this population are two unusual groups of young stars. The S stars (e.g. Ghez et al. 2005), orbiting within $\sim 0.01$ pc have attracted considerable attention because they appear to be young B stars living in a volume in which star formation should be strongly suppressed by the tidal field of Sgr A*. Alternative suggestions for the origin of the S stars include the inward migration and dissolution of a dense stellar cluster (e.g. Gerhard 2001; Hansen & Milosavljević 2003; Portegies Zwart, McMillan & Gerhard 2003; Gürkan & Rasio 2005) or the disruption of a massive binary injected from larger radii (Gould & Quillen 2003), in which case they are young but formed elsewhere, and the tidal stripping of giant stars (Davies & King 2005), in which case the S stars are locally formed but not young.

Further out, between radii of $\sim 0.04$ and $\sim 0.3$ pc, there appear to be two discs of young stars oriented at large angles both to each other and to the Galactic plane (Genzel et al. 2003; Paumard et al. 2006). There is strong evidence that these discs contain large numbers of massive stars and have an unusually flat initial mass function (IMF; Paumard et al. 2006).

In this paper, we investigate a peculiar property of the background cluster of older stars; within $\sim 0.2$ pc, the Galactic Centre
cluster is deficient in bright giant stars. This was first documented by Genzel et al. (1996) who observed the Galactic Centre in the near-infrared $K$ band. They used the presence or absence of CO bandhead absorption to distinguish late-type from early-type stars and divided their sample into three $K$ bands: $12 < K < 15$, $10.5 < K < 12$ and $K < 10.5$. While the surface density of late-type stars in the faintest of these bands appears to continue smoothly inwards to very small radii, there are clear holes in the distributions of late-type stars in the other bands, with projected radii of $\sim 0.08$ and $\sim 0.2$ pc, respectively.

Since the Galactic Centre is a densely populated region, Genzel et al. (1996) proposed that the missing giants had been destroyed by collisions with main-sequence (MS) stars. This scenario was investigated by Alexander (1999) and Bailey & Davies (1999) but these authors reached different conclusions. Alexander (1999) found that collisions with MS stars could explain the observed depletion of giants, while Bailey & Davies (1999) concluded that collisions with MS stars, white dwarfs and neutron stars would not do sufficient damage to a giant to prevent it becoming visible in the depleted $K$ bands. Their different conclusions largely arise from the criteria they used to determine whether or not an impact had done sufficient damage to prevent a given giant appearing in the depleted $K$ bands in the Galactic Centre. Bailey & Davies (1999) studied encounters involving two very late giants. They found that the mass losses achieved by collisions with MS and compact-object impactors were small, no greater than 10 per cent of the envelope. They also considered that removal of ‘most if not nearly all of the envelope’ was required to prevent the giant becoming visible in the depleted $K$ bands (as we will show later, this is largely correct for giants towards the tip of the giant branch). They therefore concluded that collisions with MS stars were unable to explain the depletion of giants. Conversely, Alexander (1999) made the assumption that a collision with a single MS impactor would result in the total destruction of a giant’s envelope if the ratio of the impact parameter to the giant radius, $x_c$, were less than 0.25, and that an impact with a binary would destroy the giant envelope if $x_c < 1$. Essentially taking collisions to be more effective than Bailey & Davies (1999), Alexander (1999) found that encounters could explain the depletion of giants within a radius of $\sim 2$ arcsec. By performing hydrodynamic modelling of encounters between MS impactors and younger, less extended giants than those studied by Bailey & Davies (1999), we improve on and extend the work of both of these authors. Davies et al. (1998) investigated the possibility that collisions with binary MS stars or neutron stars might be responsible for removing the giants. They concluded that such encounters would not have a significant effect on the giant population in the Galactic Centre unless an unrealistically large proportion of binaries was assumed.

On theoretical grounds, a large population of stellar-mass black holes (BHs) is expected to exist in the Galactic Centre (e.g. Morris 1993; Miralda-Escudé & Gould 2000; Freitag, Amaro-Seoane & Kalogera 2006) (for reviews of stellar relaxation processes around SMBH, see Alexander 2006, 2007). This population is of great interest, but is by its nature extremely difficult to study. In this paper, we explore the possibility of using the effects of collisions involving these BHs to study this population indirectly.

We extend the work of Bailey & Davies (1999) by considering collisions between giants and stellar-mass BHs, and also by allowing for multiple collisions of a single giant with BHs, MS stars or a combination of the two types of object. We then consider what can be learned from our results about the population of stellar-mass BHs that surely exists in the Galactic Centre.

In Section 2, we discuss the properties of the Galactic Centre stellar population and identify the stars that are missing. In Section 3, we derive the expected collision rates of giant stars with MS stars and BHs. We describe our numerical methods in Section 4, and in Section 5, we explain how we have modelled the effects of mass loss on giant stars. In Section 6, we present the results of our simulations of collisions of giants with BHs and MS stars. We discuss our results in Section 7 and draw our conclusions in Section 8.

## 2 Missing Stars in the Galactic Centre

Observations by Genzel et al. (1996) in three different infrared $K$ bands showed that there is a region very close to Sgr A* devoid of bright giant stars. They detected no late-type stars with $K$ magnitudes brighter than $K = 10.5$ within $\sim 0.2$ pc and no late-type stars with $K$ magnitudes in the range $12 > K > 10.5$ within $\sim 0.08$ pc of the SMBH. In a fainter band, $15 > K > 12$, they observed that the surface density of late-type stars continued smoothly in to much smaller radii. For the remainder of the paper, we will refer to the three bands defined in Genzel et al. (1996) as the bright, middle and faint bands, respectively. Following Bailey & Davies (1999) and referring to fig. 6 in Genzel et al. (1996), we estimate that the number of objects missing from the bright band is between 11 (assuming that the surface density distribution of these objects is flat inside 6 arcsec) and 25 (extrapolating the surface density inwards). Similarly, we estimate that the number of objects missing from the middle band is between six and 11. The sharp drops in surface density at $\sim 6$ arcsec in the bright band and $\sim 3$ arcsec in the middle band argue against the depletion being caused by peculiarities in the IMF and we do not think it can be due to tidal stripping, as will be explained in a later paper. Instead, the nature of the depletion strongly implies a collisional origin.

### 2.1 Identifying the Missing Stars

In Fig. 1, we show a Hertzsprung–Russell (HR) diagram depicting the evolutionary tracks of 1, 2, 3, 4, 8, 15, 20 and 30 $M_\odot$ stars derived using the stars code (Eggleton 1971; Pols et al. 1995). We overlay $K$ contours of 10.5, 12 and 15 mag calculated using colours and bolometric corrections from Johnson (1966) and adopting a distance modulus of 14.6 (Genzel et al. 1996) and an extinction $A_k$ of 3.0 (Rieke, Rieke & Paul 1989) and assuming solar metallicity. Dotted lines show contours appropriate for MS stars and dashed lines are contours appropriate for giants. This plot shows that objects brighter than $K = 10.5$ are low-mass asymptotic giant branch (AGB) stars or high-mass red supergiants, while those whose $K$ magnitudes lie between 12 and 10.5 are likely to be low-mass red giants and AGB stars or high-mass MS stars.

To obtain a more detailed picture of which segment of the Galactic Centre stellar population is missing, we calculate the length of time spent by each star within a given $K$ band. If we assume that the stellar population in the Galactic Centre has been forming stars continuously at a steady rate following a Miller–Scalo IMF for 14 Gyr, we can estimate the relative proportions of objects in a population of this age which are visible at a given $K$ magnitude. We also attempted realizations using different assumptions. We found that a Salpeter IMF was unable to reproduce the numbers of giants that are observed outside the depleted regions in the Galactic Centre (e.g. Genzel et al. 1996) in the $K$ bands using a realistic total mass for the Galactic Centre cluster – the result is a giant population in which the bright band is overpopulated with respect to the middle...
and faint bands. We were unable to significantly improve the fit to the observed numbers of giants by varying the slope of the Salpeter mass function from its canonical value of 2.35 and the overabundance of bright giants becomes significantly worse for slopes flatter than 1.5. However, we note that, in accord with the Miller–Scalo IMF, Salpeter-like IMFs result in the bright K band being largely populated by 2–4 M⊙ objects and the middle band by 1–2 M⊙ objects, unless the slope was <1.5. In addition, we found that assuming a burst of star formation (i.e. that the Galactic Centre stars are all the same age) was unable to reproduce the observed numbers of giants regardless of the time at which the burst occurred, since giants of a very narrow age (and therefore mass) range all have very similar K band magnitudes. In particular, a single burst occurring >10 Gyr ago would result in only giants of ≈1 M⊙ being visible now, leaving the bright band almost unpopulated throughout the Galactic Centre, which is not what is observed. We also attempted to reproduce the Galactic Centre cluster using an exponentially declining star formation rate, starting from a maximum at 14 Gyr. We found that, if the time-scale on which the star formation rate drops off is significantly less than the assumed age of the cluster (14 Gyr), the model produces too few bright giants and too many faint ones. We concluded that, if the star formation rate has been declining, it must have done so slowly, so that the assumption of a constant rate is reasonable.

In summary, the simple and conservative assumptions we have made about the IMF and star formation history of the Galactic Centre generate a model which matches the observed numbers of giants outside the depleted regions well and the alternative models we studied produced significantly worse fits. In Fig. 2, we show the results of a Monte Carlo realization of the Galactic Centre population constructed using these assumptions. The area of the square at each point in the (mass–K–magnitude) grid represents the relative number of stars of that mass which will be visible at that K magnitude. We see that the three bands observed by Genzel et al. (1996) are dominated by low-mass objects in the range 1–4 M⊙. There is a small contribution from higher mass objects, but it is suppressed both by the IMF, which makes these objects intrinsically rare, and by their rapid evolution. Middle band objects (12 < K < 10.5) are likely to be 1–2 M⊙ stars, while bright band objects (K < 10.5) are likely to be 2–3 M⊙ stars. Figs 1 and 2 clearly show that the missing objects are giant stars with masses in the range 1–3 M⊙ (the turnover mass in our models is ≈0.9 M⊙). We now seek to explain why there should be a deficit of these stars near Sgr A∗.

2.2 Possible causes of the depletion of giants

It has been suggested (e.g. Davies & King 2005) that stars on the red giant branch (RGB) or AGB on eccentric orbits about Sgr A∗ could be tidally stripped of their envelopes as they pass through periape. Since objects on eccentric orbits spend most of their time at apaspe, this could potentially produce a depletion of such stars at distances from Sgr A∗ much larger than the separations required to tidally strip RGB or AGB stars. We think that tidal stripping of this nature will make at most a minor contribution to the depletion of giant stars in the Galactic Centre, since stripping must occur during the short RGB phase. This will form the subject of a later paper.

Alternatively, numerous authors (Genzel et al. 1996; Alexander 1999; Bailey & Davies 1999) have suggested that the depletion of red giants is due to collisions of the giants with other members of the Galactic Centre stellar population. Collisions would remove mass.
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Within a few pc of the Galactic Centre, the stellar distribution follows a broken power-law cusp (Genzel et al. 2003; Schödel et al. 2007). Genzel et al. (2003) find that the three-dimensional (3D) number density of visible stars \( n_v \) varies with Galactocentric radius as

\[
N_v(r) \propto \begin{cases} 
  r^{-1.4} & \text{for } r \leq 0.4 \text{ pc}, \\
  r^{-2.0} & \text{for } r > 0.4 \text{ pc}
\end{cases}
\]

(1)

and Schödel et al. (2007) find

\[
N_v(r) \propto \begin{cases} 
  r^{-1.2} & \text{for } r \leq 0.22 \text{ pc}, \\
  r^{-1.75} & \text{for } r > 0.22 \text{ pc}
\end{cases}
\]

(2)

Since the break radii of both of these power-law models comfortably exceed the radius within which depletion of bright giants is observed (\( \gtrsim 0.1 \) pc), we adopt a single power-law model for the visible stars of the form

\[
N_v(r) \propto r^{-1.4}.
\]

(3)

Strictly adopting the power law of Schödel et al. (2007) affects only slightly the rates of collisions between giants and MS stars, and has little influence on our results.

To obtain a realistic normalization at small radii, we use the results of simulations of the Galactic Centre performed by Freitag et al. (2006) using the mcstisy*2 Monte Carlo stellar dynamics code (Freitag & Benz 2001, 2002). The initial conditions were \( \eta \)-models (Dehnen 1993) with \( \eta = 1.5 \) and a central massive object representing Sgr A* (models with \( \eta = 2 \), corresponding to a lower-cusp, were also run, but produced very similar results).

The mass of the central object, the mass of the Galactic Centre cluster and the break radius at which the \( \eta \)-model steepens to \( \rho(R) \propto R^{-4} \) were taken to be \( 3.5 \times 10^6, 7 \times 10^7 \) M\(_\odot\) and 14 pc, respectively, designed to match observations of the Galactic Centre by Schödel et al. (2003) and Ghez et al. (2005). Freitag et al. (2006) found that the MS stars relax into a cusp with \( \gamma = 1.3-1.4 \), in agreement with the observations of Genzel et al. (2003). Using their results (e.g. their fig. 2), we adopt a normalization for the MS stars such that \( M(0.1 \) pc \( ) = 4 \times 10^4 \) M\(_\odot\). For an evolved stellar population with a Miller–Scalo IMF, the mean stellar mass is \( \sim 0.5 \) M\(_\odot\), so this normalization corresponds to \( 8 \times 10^4 \) MS stars within a Galactocentric radius of 0.1 pc.

The population of stellar-mass BHs in the Galactic Centre is expected to have the form of a cusp with a power-law exponent of 1.75 provided that they dominate the relaxation rate (Bahcall & Wolf 1976). This relation should hold at least in the innermost few tenths of a parsec (Amaro-Seoane et al. 2007, and references therein). However, setting the normalization of this population is very difficult, since the BHs are not directly observable.

Morris (1993) estimated that all the BHs formed within \( \sim 4 \) pc of the Galactic Centre would sink into the centre over the age of the Galaxy, resulting in a total mass in stellar BHs there of \( \sim 10^6 \) M\(_\odot\). They were not able to say whether such a migration would result in a dense cluster of BHs, or would simply add mass to Sgr A*.

Miralda-Escudé & Gould (2000) estimated, in good agreement with Morris (1993), that all BHs formed within 5 pc would migrate in over the age of the Bulge. Using a model of the stellar mass density as a function of Galactocentric radius from Genzel et al. (2000) and assuming a piece-wise IMF from which all stars in the mass range 30–100 M\(_\odot\) yield BHs, they estimated that \( 2.4 \times 10^4 \) BHs should have migrated into the central 0.7 pc. They calculated that...
the time-scale on which stellar-mass BHs would be captured by Sgr A* would be considerably longer than a Hubble time, so that all these stellar-mass BHs should still be within this volume. A similar indirect means of estimating the number of BHs within a given Galactocentric radius is given by Alexander & Livio (2004). They assume that stellar-mass BHs have migrated into the Galactic Centre by mass segregation and estimate the maximum number that can survive there by requiring that the time-scale on which the BH population is lost by scattering into the loss cone is longer than a Hubble time. For a population of 10 M⊙ BHs, their analysis yields a maximum number of BHs that can be within 0.1 pc of Sgr A* of ~5000.

Stellar-mass BHs can be directly observed if they are accreting material at sufficient rates to be visible as X-ray sources. Muno et al. (2005) reported four X-ray transients within 1 pc of Sgr A*, an overabundance of a factor of ~20 when compared to the field. Baganoff et al. (2003) detected diffuse X-ray emission with a 2–10 keV luminosity of 10^{36} erg s^{-1} coincident with the position of Sgr A* to within 0.27 arcsec and with an intrinsic size of 0.61 arcsec. They consider the possibility that the source may be a population of compact objects accreting from the ambient gas, but point out that the luminosity of such a system would be orders of magnitude less than that of Sgr A* itself accreting from the same gas. They point out that a single X-ray binary, in which the compact object is supplied with a strong accretion flow, would have a luminosity comparable to that observed. However, the number of X-ray binaries expected within this volume (r < 0.03 pc) is very small, since binaries are difficult to form in a region with such a high velocity dispersion, and would also be quickly disrupted by stellar encounters. Taking into account that the observed extent of the source is consistent with Sgr A*’s Bondi radius, Baganoff et al. (2003) conclude the emission is most likely to be due to accretion on to the SMBH itself.

Deegan & Nayakshin (2007) examined the question of whether the X-ray emission could be due to compact objects accreting from the interstellar medium (ISM), specifically the minispiral (Paumard, Maillard & Morris 2004), in more detail. They modelled the minispiral as a half-disc of 50 M⊙ of gas in a circular orbit between 0.1 and 0.5 pc around Sgr A*. They constructed a Bahcall and Wolf cusp of BHs extending to 0.7 pc, allowed the BHs to accrete the gas and calculated their instantaneous luminosity as they moved along their orbital tracks. By following how many BHs were detectable at any given time, they placed constraints on the maximum number of compact objects. They found that the number of stellar-mass BH within 0.1 pc was likely to be at most a few thousand. None of these authors considers the possibility that X-ray sources may be lone stellar-mass BHs accreting material captured during a stellar collision.

We again use the results of Freitag et al. (2006) to obtain a fiducial model for the number and distribution of BHs in the innermost few tenths of a parsec. Freitag et al. (2006) found that the stellar-mass BHs migrated inwards by mass segregation, forming a cusp with γ = 1.8, in very good agreement with Bahcall & Wolf (1976), and that the central 0.1 pc contained a few × 10^5 BH. We therefore adopt a BH population with a cusp of the form

$$n_{BH}(r) \propto r^{-1.8}$$

(4)

normalised so that \(n_{BH}(0.1 \text{pc}) = 5 \times 10^5\). The radius at which the total enclosed mass of our MS and BH populations becomes equal to the mass of Sgr A* (4 × 10^6 M⊙) is then ~1.4 pc.

In this work, it will be assumed that stars lie inside the sphere of influence and hence that their orbits are Keplerian with one-dimensional (1D) velocity dispersion \(\sigma_{1D}\) is \(\propto r^{-1/2}\). If the stellar density distribution has the form of a cusp with 3D radial distribution

$$\sigma_{1D}(r) = \left(\frac{GM}{\gamma r} \right)^{1/2}.$$

(5)

If a star of mass \(M_{imp}\) and radius \(R_{imp}\) moves through a cluster of impactors of mass \(M_{imp}\) and radius \(R_{imp}\) such that the relative encounter velocity is \(v_{\text{imp}}\), the effective cross-section \(\sigma_{1D}\) of the star is given by

$$\sigma_{1D}(r) = \frac{2G(M_{*} + M_{imp})}{(R_{*} + R_{imp})v_{\infty}^2}.$$

(6)

The second term inside the square brackets on the right-hand side of equation (6) is the increase in the star’s effective cross-section due to gravitational focussing.

At a given Galactocentric radius \(r\), stars will in reality have a distribution of velocities which must be integrated over to yield an accurate determination of the collision rate at that radius. We find that the velocity distribution in an \(\eta\)-model is very similar to a Maxwellian distribution. Following Binney & Tremaine (1987), we define the collision time averaged over the velocity distribution by

$$t_{col}(r)^{-1} = 4\sqrt{\pi}(R_{*} + R_{imp})n_{imp}(r)\sigma_{1D}(r) \times \left[ 1 + \frac{G(M_{*} + M_{imp})}{2\sigma_{1D}(R_{*} + R_{imp})} \right],$$

(7)

where \(n_{imp}(r)\) is the number density of the impactors.

Since the radius of a star changes drastically during its lifetime, \(R_{*} = R_{*}(t)\) and \(t_{col}\) is a function of time as well as Galactocentric radius. As a result, a more useful quantity is the integrated probability \(p(r)\) of the star experiencing a collision over its lifetime, given by

$$p(r) = \int_{0}^{r_{*}} \frac{dr}{t_{col}(r,t)}.$$

(8)

where \(r_{*}\) is the lifetime of the star. In this paper, we are primarily interested in collisions occurring to stars while they are on the giant branch, in which case the collision probability of interest is

$$p_{PRGB}(r) = \int_{0}^{t(\text{TRGB})} \frac{dr}{t_{col}(r,t)}.$$

(9)

where \(t(\text{TRGB})\) is the age of the star at the base of the red-giant branch and \(t(\text{TRGB})\) is its age at the tip. We define the base of the red-giant branch as the point at which the star’s luminosity reaches a minimum at the end of the Hertzsprung gap, and the tip of the red-giant branch as the point where the star’s luminosity reaches its maximum value on the giant branch.

In Fig. 3, we plot the integrated collision probability given by equation (9) as a function of Galactocentric radius for 1, 1.5, 2 and 3 M⊙ stars, assuming that the impactors are 1 M⊙ MS stars (solid lines) or 10 M⊙ BHs, distributed according to equations (3) and (4). For reasons of clarity, we have assumed that the inner power law \(\alpha = 1.4\) holds at all radii –since the break in the cusp power law derived by Genzel et al. (2003) occurs at radii where the integrated probability of suffering a collision with a MS impactor is small (<10 per cent), this does not affect our results.

In deriving equation (9), it is assumed that \(n_{imp}(r)\) and \(v_{\infty}\) are constant over the lifetime of the star, which can only be true if either the star’s orbit is circular, or if the star’s lifetime is much shorter than its orbital period. Since neither of these of these conditions is true in general, we integrated the collision probability self-consistently on orbits with a variety of eccentricities. The effect of orbital eccentricity was to increase the probability of a star with a given semimajor axis suffering a collision by a factor of at most 2 over the collision probability.
probability obtaining from a circular orbit with the same semimajor axis.

A further simplification made in estimating these collision rates is that the impactors are all either 1 $\text{M}_\odot$ MS stars or 10 $\text{M}_\odot$ BHs. Given the lack of knowledge about the mass function of stellar-mass BHs, the latter assumption is reasonable (and will be discussed in more detail later), but the former may not be. We therefore recalculated the collision rates assuming that the MS impactors were distributed according to a Miller–Scalo IMF between 0.08 and 1 $\text{M}_\odot$. We found that this makes little difference to the collision rates.

We see from Fig. 3 that the probability of a 1–2 $\text{M}_\odot$ giant suffering a collision with a MS star exceeds unity within a radius of $\sim 0.1$ pc and the probabilities of the same giants being struck by a BH exceeds unity within a radius of $\sim 0.03$ pc. The 3 $\text{M}_\odot$ star has a very short giant phase in comparison to the lower mass objects, and the radii at which the probabilities of the 3 $\text{M}_\odot$ giant being struck approach unity are approximately an order of magnitude smaller.

We interpret collision probabilities in excess of unity as implying that stars at that radius will suffer more than one collision. Fig. 3 shows that the region of space within 0.1 pc of Sgr A* is a highly collisional environment. In the following sections, we investigate the effect of stellar collisions on the population of bright giant stars in the Galactic Centre.

4 NUMERICAL METHODS

4.1 Stellar evolution code

To evolve the stellar models presented in this paper we used STARS, the Cambridge stellar evolution code. STARS was originally written by Peter Eggleton (1971) and has been extensively modified since (see Pols et al. 1995, and references therein for a complete description). We use the Reimers mass-loss law on the RGB (Kudritzki & Reimers 1978) with $\eta = 0.4$ and the Vassiliadis & Wood (1993) mass-loss law on the AGB; on the MS the mass loss is assumed to be negligible for the low-mass stars considered here. Convective overshooting was included with $\delta_{ov} = 0.12$ (Schröder, Pols & Eggleton 1997).

Following Eldridge & Vink (2006) we modify our mass-loss rates for high-mass stars. For OB stars, we use the mass-loss predictions of Vink, de Koter & Lamers (2001) which scale with metallicity as $(Z/Z_\odot)^{1/2}$. For all other pre-WR (Wolf–Rayet) phases, we employ the rates of de Jager, Nieuwenhuijzen & van der Hucht (1988) scaled similarly with metallicity. When the star becomes a WR star ($X_{\text{surf}} < 0.4$ and log ($T/K) > 4.0$), we use the rates of Nugis & Lamers (2000).

4.2 Smoothed particle hydrodynamics

For the hydrodynamical simulations presented here, we used a smoothed particle hydrodynamics (SPH) code based on that described in Benz (1990). The code uses the SPH formalism to solve fluid equations and a binary tree to calculate gravitational forces. The code has been modified to include point masses, particles which only interact with other particles via gravitational forces and are used to model compact objects (Davies, Benz & Hills 1991). Their gravitational fields are smoothed in the same way as those of ordinary SPH particles, although the smoothing lengths of the point masses are fixed. We use the standard SPH artificial viscosity formalism with $\alpha = 1$, $\beta = 2$. Gas particles are assumed to behave adiabatically.

We constructed SPH stellar models using 1D density and temperature profiles from the STARS code. SPH particles are placed on a uniform hexagonal close-packed grid and their masses iteratively adjusted so that the local density matched that of the 1D model.

The extreme density gradients in the envelopes of giant stars, both very near the core and near the stellar surface, are difficult to model. In order to reproduce the density profiles of the outer envelopes of our giants while retaining sufficient resolution of the material near the core and avoiding very large particle numbers, we deformed the uniform particle grid in our models. Using results from our stellar evolution calculations, we determined the critical mass loss required to prevent the giant evolving to become bright enough to appear in the depleted $K$ bands. This gave us a minimum mass (enclosed by a radius $r_{\text{crit}}$) that we needed to resolve. We constructed a uniform particle grid so that $r_{\text{crit}}$ contained at least 2000 particles. The particle grid was then deformed according to

$$r_i = \begin{cases} r_i \cosh \left[ \alpha \left( \frac{r_i}{r_{\text{crit}}} - 1 \right) \right], & \text{for } r_i > r_{\text{crit}}, \\ r_i, & \text{for } r_i \leq r_{\text{crit}}, \end{cases}$$

where $r_i$ is the initial radius of a given particle, $r_f$ is the final radius and $\alpha$ is a constant ensuring the outer radius of the deformed grid is equal to the radius of the star.

We modelled the giant cores as point masses. To stabilize the interaction between the point mass core and the envelope, the innermost 477 gas particles (i.e. those surrounding the core, corresponding to an enclosed mass about 1 per cent of the envelope) were ‘frozen’—their velocities were constrained during simulations to be equal to that of the core particle. Ensuring adequate resolution of the outer envelope and the core region and guaranteeing that the model be stable required $\sim 175\ 000$ particles.

The models were allowed to relax in isolation for several freefall times with a linear damping term acting to remove any residual
oscillations in the particle grids. Collision simulations were started with the stars sufficiently far apart that tidal effects were negligible. Most calculations were run on single CPUs on PCs. However, in order to examine numerical convergence, we repeated several simulations at high resolution on the UK Astrophysical Fluids Facility (UKAFF) at Leicester University, UK. In these calculations, we used ~1.2 million particles in our giant models. The factor of ~7 greater particle number gives a factor of ~2 better linear resolution.

4.3 Restricted three-body code

In order to extend the range of simulations we could perform without consuming unacceptable quantities of computer time, and as an independent check on our SPH calculations, we also studied red giant collisions using a simple restricted three-body code. As pointed out by Livne & Tuchman (1988), if the impact velocity is much greater than the speed of sound in the giant’s envelope, the envelope cannot react to the passage of the intruder. The interaction can then be approximated by an encounter between two point masses (the impactor and the giant core) with the envelope represented by a third, extended particle with the enclosed mass profile of the undisturbed envelope. The force between the core and the intruder $F_{\text{c-int}}$ is then given by

$$F_{\text{c-int}} = \frac{GM_{\text{core}}M_{\text{int}}}{r_{\text{c-int}}^2},$$

and the force between a point particle $i$ and the envelope particle is given by

$$F_{\text{i-env}} = \frac{GM_{\text{env}}(r_{\text{i-env}})}{r_{\text{i-env}}^2},$$

where $M_{\text{env}}(r_{\text{i-env}})$ is the envelope mass enclosed within a radius $r_{\text{i-env}}$. The equations of motion of the three particles can then be easily integrated.

In collisions in which the impactor imparts a significant velocity to the core relative to the envelope, the fraction of the envelope retained by the core can be estimated by computing the mass within the Bondi-Hoyle radius, given by

$$r_{\text{BH}} = \frac{GM_{\text{core}}}{v_{\text{rel}}^2},$$

where $v_{\text{rel}}$ is the relative velocity between the core and the envelope. This analysis can be improved upon slightly by instead computing the mass contained within the Bondi–Hoyle–Lyttleton radius, given by

$$r_{\text{BHL}} = \frac{GM_{\text{core}}}{v_{\text{rel}}^2 + c_s^2(r_{\text{BHL}})^2},$$

where $r_{\text{BHL}}$ must be found iteratively since it depends on the sound speed at that radius. We find in practice that the two schemes give very similar results.

The envelope mass retained by the core may thus be estimated for any given collision by using the three-body technique to find the relative velocity induced between the core and the envelope, yielding $r_{\text{BH}}$ or $r_{\text{BHL}}$, and determining the enclosed mass at this radius from the giant’s density profile.

4.4 Monte Carlo multiple-collision code

Since the collision rates shown in Fig. 3 imply that giants may suffer multiple collisions with a mixture of BH and MS impactors, we explored this possibility using a Monte Carlo technique. For a population of $10^8$ giants, we simulated collisions at all the relative velocities for which we have SPH simulations (400, 800 and 1200 km s$^{-1}$ for the 1 and 2 $M_\odot$ giants, 800 km s$^{-1}$ only for the 1.5 and 3 $M_\odot$ objects) and at randomly chosen periastrons (distributed so that the probability of a collision at a periastron $R$ is proportional to $R^2$, appropriate for non-focused encounters) with the numbers of BH and MS impactors being set by the collision rate, and thus the Galactocentric radius. For each impact, we first constructed a synthetic mass loss against $R_{\text{min}}$ curve from the results of the SPH and three-body simulations of that encounter. As we will show in detail later, the three-body code agrees very well with the SPH calculations in encounters at small periastrons, in which the core is ejected from the giant, but hydrodynamic effects become important at larger periastrons (particularly at lower relative velocities). We therefore use the smooth three-body curve for very close encounters where our SPH calculations are sparse, out to a periastron where it begins to underestimate the mass loss derived from the SPH calculations, and from this periastron outwards, we use the SPH mass-loss curve. Using this synthetic mass-loss curve, we calculate the mass lost at the randomly chosen periastron by interpolation.

The mass lost in successive collisions can either be assumed to be multiplicative or additive. If a given collision removes a fraction of mass $f_i$, the total mass lost $f_{\text{tot}}$ after $N$ collisions can be estimated by

$$1 - f_{\text{tot}} = (1 - f_1)(1 - f_2) \cdots (1 - f_N),$$

or by

$$f_{\text{tot}} = f_1 + f_2 + \cdots + f_N.$$

We found that it made little difference to the results which of these assumptions was made. From the total mass lost by each giant, we determined the fraction of the $10^8$ objects prevented from evolving into the bright and middle bands for each impactor number.

5 MODELLING THE EFFECT OF COLLISIONAL MASS LOSS ON THE EVOLUTION OF STARS

To study the effects of mass loss on the giants, we constructed in the STARS code models of stars of 1, 1.5, 2 and 3 $M_\odot$ at several different ages on the MS, RGB, horizontal branch and AGB.

In order to simulate the rapid mass loss caused by a collision we removed the desired quantity of mass from the star at a rate of $5 \times 10^{-6} M_\odot$ yr$^{-1}$, which is the largest mass-loss rate at which we could reliably converge models for low-mass stars. This rate is much lower than the mass-loss rates observed in our SPH calculations, which could reach $\sim 10^4 M_\odot$ yr$^{-1}$ (the equivalent of $\sim M_\odot$ h$^{-1}$) but is still much faster than the evolutionary time-scales for low-mass stars. During this time we turned-off composition changes owing to nuclear burning but retained the energy generation; this prevents nuclear evolution occurring whilst the mass is removed but also keeps the star’s structure consistent. This is equivalent to making the collisional mass-loss instantaneous on a nuclear time-scale.

We removed increasing fractions of the models’ envelopes and studied their evolution, using the Johnson (1966) colours and bolometric corrections to calculate the $K$-band magnitude of the objects as functions of time. We were therefore able to determine, for a star of a given mass, how much mass a collision at any given stage in the star’s life would need to expel such that the star would never evolve to become brighter than a given $K$ magnitude. In Fig. 4, we show by means of four HR diagrams the effect on the evolution of a 1 $M_\odot$ star of removing increasing fractions of its envelope at a point halfway up the giant branch. In each panel, the normal evolution of the star is denoted by the thick black line. The star is then taken to instantaneously lose mass, leaving it with the envelope fraction given in each figure panel. We see that leaving the object with 93
Red giant collisions in the Galactic Centre

Figure 4. Plot showing the effect on the evolution of a 1 M⊙ star of removing increasing fractions of its envelope mass, once it has reached a point halfway up the RGB. The star’s normal evolution up to this point is shown by the thick black line, and the evolution after mass loss by the dashed line. The fraction of the object’s envelope remaining is given in the bottom right of each panel.

per cent of its envelope has little effect on its evolution – it follows a normal AGB track and becomes a white dwarf. However, leaving the star with 79 per cent of its envelope results in an object resembling a subdwarf-B star, with a short AGB significantly fainter than that of the undisturbed star (although the luminosity of the tip of the RGB is not significantly changed). Leasing the star with 66 or 56 per cent of its envelope, as shown in the lower panels of Fig. 4, prevents the star igniting helium, thus removing the AGB phase altogether, and also makes the tip of the RGB fainter. In summary, removing a few tens of per cent of the envelope of a low-mass giant is sufficient to make its AGB phase significantly fainter, but to radically alter its evolution such that it never ignites helium at all requires the removal of ~40 per cent of the envelope.

In all post-MS phases, the fractions of the stars’ envelopes that must be expelled in order to significantly affect their evolution are substantial, and especially so for HB or AGB stars. We find that, in order to significantly alter the evolution of a star, mass must be removed whilst it is on the MS or the RGB. In Fig. 5, we illustrate this point by comparing the effect of removing 60 per cent of a 1 M⊙ star’s envelope at three different phases of its life. Each panel in the plot shows the evolution with time of the star’s K-band magnitude. The top left-hand panel shows the evolution of the undisturbed object. The top right-hand panel shows the result of removing 60 per cent of the envelope mass halfway along the RGB, the bottom left-hand panel shows the result of removing this mass halfway along the horizontal branch and the bottom right-hand panel shows the result of removing mass on the early AGB. In all cases, the solid lines represent evolution of the undisturbed object and dashed lines represent evolution after mass loss has occurred. The plots clearly show that this mass loss occurring on the RGB has a strong effect on the star’s evolution, making the tip of the giant branch ~1.5 mag fainter (although having little effect on the duration of the RGB phase) and preventing the object evolving into the HB or AGB phases. Conversely, removing the same fraction of envelope mass on the HB or AGB has almost no effect on the star’s subsequent evolution and, in particular, does not noticeably reduce the brightness of the tip of the AGB. The effects of mass loss on MS stars will be discussed in a companion paper and here we concentrate on mass loss due to collisions on the RGB.

Stellar evolution on the RGB is very fast and stellar properties, particularly core mass and radius (and hence luminosity), change significantly on the RGB. The age of a star is not a useful coordinate against which to measure its evolution and instead, we define a quantity based on the evolution of the core mass, which we use as a proxy for time:

\[ \tau_{core}(t) = \frac{M_{core}(t) - M_{core}(BRGB)}{M_{core}(TRGB) - M_{core}(BRGB)}, \]  

(15)

where \( M_{core}(BRGB) \) is the core mass at the base of the RGB and \( M_{core}(TRGB) \) is the core mass at the tip. To illustrate the relationship between \( \tau_{core} \) and the actual age of the giant, we plot \( \tau_{core} \) as a function of time on the RGB for a 1 M⊙ giant in Fig. 6. We show in Fig. 7 the lifetimes of 1 M⊙ giant stars in the middle band (12 > K > 10.5) after encounters at five different positions along the giant branch (characterized by \( \tau_{core} \) on the y-axis) which leave them with between 1 and 100 per cent of their envelopes remaining.

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Figure 5. Plot showing the effect on the evolution of the $K$-band brightness of a $1 \, M_\odot$ star of removing 60 per cent of its envelope mass halfway along the RGB (top right-hand panel), halfway along the HB (bottom left-hand panel) and on the early AGB (bottom right-hand panel). Top left-hand panel and solid lines in other plots represent undisturbed evolution.

Figure 6. Plot showing the relationship between $\tau_{\text{core}}$ and elapsed time on the RGB for a $1 \, M_\odot$ giant.

The mass loss required to prevent the $1 \, M_\odot$ giant evolving to become visible in the middle band increases as the object ascends the giant branch, the quantities of mass that must be removed to seriously affect the giant’s evolution are substantial – several tens of per cent at least.

6 COLLISIONS INVOLVING GIANT STARS

6.1 Collisions of giants with stellar-mass black holes

The depleted $K$ bands reported by Genzel et al. (1996) are dominated by 1, 1.5, 2 and $3 \, M_\odot$ stars, as shown in Fig. 2. We chose to model collisions involving giants approximately halfway up the giant branch, as measured by the quantity $\tau_{\text{core}}$, taking these objects to be representative of giants of a given mass. This has the advantage that such objects are not yet bright enough to be visible in the depleted $K$ bands and that they lie close to the point at which the cumulative probability of suffering a collision while on the giant branch is approximately 0.5. We give the parameters of our model giants in Table 1.

The quantities of interest in these simulations are the masses of gas bound to the giant core, and captured by the intruding BH. To calculate these masses, we employed an iterative scheme. For each point mass, the gas particles in its immediate vicinity were fetched, their velocities relative to the point mass determined and hence their kinetic, potential and thermal energies in the frame of the point mass were calculated. Those particles with negative total energy were taken to be bound to the point mass. A composite object was then constructed from the point mass and those particles bound to it. The mass, centre of mass and centre-of-mass velocity of the composite object were calculated and the procedure repeated until the mass of the composite object converged.
Red giant collisions in the Galactic Centre

Figure 7. Plot showing the effect on the time-scale for which a 1 $M_\odot$ giant is visible in the middle band ($12 > K > 10.5$) of stripping mass from the giant at various stages of evolution on the giant branch. The evolutionary stage at which mass is stripped is denoted by the increase in core mass as a fraction of the total change in the core mass along the whole giant branch (defined in equation 15), given on the $y$-axis and the fraction of the envelope mass remaining after stripping is given on the $x$-axis. The symbols denote the length of time for which each stripped model is visible in the middle band for the duration of its life.

Table 1. Properties of giants used in our SPH calculations.

| $M$ ($M_\odot$) | $M_{\text{core}}$ ($M_\odot$) | $R$ ($R_\odot$) | Age (yr) | $\tau_{\text{core}}$ | $K$ (mag) |
|----------------|-----------------------------|----------------|----------|----------------|-----------|
| 1.0            | 0.30                        | 25.2           | $1.22 \times 10^{10}$ | 0.51          | 14.5      |
| 1.5            | 0.29                        | 18.8           | $2.95 \times 10^{9}$   | 0.62          | 15.5      |
| 2.0            | 0.34                        | 31.9           | $1.21 \times 10^{9}$   | 0.54          | 13.4      |
| 3.0            | 0.39                        | 27.6           | $3.76 \times 10^{8}$   | 0.40          | 13.6      |

After a sharp decrease around the time of the BH impact, the mass retained by the giant core declined at an ever-decreasing rate for long periods of time. To avoid running simulations for prohibitively long times, we devised a procedure to estimate the final mass of the collision product. Plotting the fraction of the envelope bound to the core, $f_{\text{env}}$, as a function of $1/t$ revealed that, except near the time of the impact, $f_{\text{env}}$ could be well fit by a straight line and extrapolated by least-squares fitting to $1/t = 0$ (i.e. $t = \infty$), yielding the final envelope mass retained by the core. In Fig. 8, we show an example plot, taken from the collision of a 1 $M_\odot$ giant star with a 10 $M_\odot$ BH at an $R_{\text{min}}$ of 10 $R_\odot$ and a $v_{\infty}$ of 800 km s$^{-1}$. This plot shows that at the late stages of the collision (i.e. for small $1/t$), the curve is very well fit by a straight line, giving a robust estimate of the final mass loss from the encounter.

To check for numerical convergence, we repeated several calculations at much higher resolution on the UKAFF at the University of Leicester. In Fig. 9, we compare the evolution of the orbital separation (top panel) of the giant core and impacting BH, and of the energies of the system (bottom panel), in the low-resolution calculation (black squares) and the high-resolution calculation.

Figure 8. Plot of the envelope fraction remaining against $1/t$ for the encounter between a 1 $M_\odot$ giant and a 10 $M_\odot$ BH with a $v_{\infty}$ of 800 km s$^{-1}$ at an $R_{\text{min}}$ of 10 $R_\odot$. The solid line with the crosses is the measured envelope fraction remaining from the SPH calculation and the dashed line is the fit applied to estimate the final remaining envelope fraction.

Figure 9. Plot comparing the evolution of the separation between the red giant core and the BH (top panel) and the energies of the system (bottom panel) for a collision between a 1 $M_\odot$ giant star and a 10 $M_\odot$ BH at a periastron of 10 $R_\odot$ and $v_{\infty}$ of 400 km s$^{-1}$. Solid lines are results from the high-resolution calculation and black squares are from the low-resolution calculation. Note that the initial separation between the giant and the BH in the high-resolution calculation was smaller to save computer time.
Comparison of density slices taken through the $z = 0$ plane 1.6 crossing times after periastron passage. The agreement between the low-resolution (top panel) and high-resolution (bottom panel) calculations is again very good. The same structures are visible in both images, including the disc of captured material around the BH, and the wake of the BH through the red giant, including the hole where it has exited the envelope. We also find that the low- and high-resolution runs agree well on the fraction of the envelope retained by the core, giving 15 and 17 per cent, respectively, in these calculations.

We observed, particularly at smaller periastrons, that the mass loss was often due to the core being ejected and carrying part of the envelope away with it. This is clearly visible in Fig. 10. This phenomenon was pointed out by Livne & Tuchman (1988) and is essentially due to the inability of the envelope to react to the supersonic impact of the intruding BH. We use our restricted three-body code to determine the velocity of the core relative to the envelope and estimate the mass retained by the mass within the Bondi–Hoyle–Lyttleton radius corresponding to that velocity.

For each of our SPH giant–BH encounters at a given $v_{\infty}$, we performed reduced three-body calculations over a range of periastrons and calculated the mass retained by the core using the Bondi–Hoyle/Bondi–Hoyle–Lyttleton formalism. In Fig. 11, we show the results of SPH calculations of collisions between a $1 M_\odot$ giant star and a $10 M_\odot$ BH performed at a range of periastrons and at $v_{\infty} = 400$, $800$ and $1200$ km s$^{-1}$ (black lines with squares) compared with the results of our reduced three-body simulations over a similar range of periastrons and with $v_{\infty} = 800$ km s$^{-1}$.

The SPH simulations and the reduced three-body analysis agree very well at small periastrons ($\lesssim 10 R_\odot$), but depart at larger values, with the SPH results giving systematically smaller fractions of the envelope being retained (i.e. predicting that more mass is expelled).

At the high velocities considered in this paper, there are two regimes of mass loss in interactions between giants and stellar-mass BHs, delineated by the periastron of the collision. At large periastrons ($\gtrsim R_{\text{giant}}/2$), mass loss is largely due to the shock driven by the impactor expelling parts of the giant’s outer envelope, leaving the core region relatively undisturbed. Conversely, at periastrons $\lesssim R_{\text{giant}}/2$, the core receives a strong impulse and is displaced from the envelope, carrying some of the envelope material away and leaving the rest of the giant to disperse on a dynamical time-scale.

The critical periastron, inside which collisions expel enough mass to prevent the $1 M_\odot$ giant evolving to become brighter than $K = 12$ at the Galactic Centre, is predicted to be $\sim 12 R_\odot$ by the SPH calculations and $\sim 10 R_\odot$ by the Bondi–Hoyle analysis, resulting in a significant difference in the critical collision cross-section if collisions are unfocused. Hydrodynamic effects thus cannot be neglected in this problem and SPH simulations are essential in determining the collision parameters required to prevent giants evolving into the brighter $K$ bands in the Galactic Centre.

Since little is known about the mass function of BHs, we explored the consequences of impacts with BHs of different mass, to see if, for a BH population of a fixed total mass a smaller number of higher mass BHs would have a greater affect on a population $1 M_\odot$ giants than a larger number of lower mass BHs. For this to be the case, the critical encounter periastron $R_{\text{critical}}$ for stripping enough of the giant’s envelope to prevent it becoming visible in the depleted bands must increase faster than $R_{\text{critical}} \propto \sqrt{M_{\text{BH}}}$, if collisions

**Figure 10.** Comparison of density slices taken through the $z = 0$ plane of snapshots from the low- (top) and high-resolution (bottom) runs 1.6 crossing times after periastron passage in the encounter between a $1 M_\odot$ giant star and a $10 M_\odot$ BH at a periastron of $10 R_\odot$ and $v_{\infty}$ of $400$ km s$^{-1}$. Yellow colours represent densities of $6 \times 10^{-2}$ g cm$^{-3}$ and red represents densities of $6 \times 10^{-3}$ g cm$^{-3}$. The BH (moving from right to left) and the giant core are represented by white dots. Images are $150 R_\odot$ on a side. The ejection of the core and retention of some of the envelope is clearly visible. In this calculation, the envelope fraction retained by the core was $\sim 15$ per cent in the low-resolution run and $\sim 17$ per cent in the high-resolution run, which is sufficiently small that the giant will not evolve to become visible in the middle band.
Red giant collisions in the Galactic Centre

Figure 11. Plot of the results of collisions between a 1 M⊙ giant star and a 10 M⊙ BH (black squares) at velocities of 400 (solid line), 800 (short-dashed line) and 1200 km s⁻¹ (long-dashed line). The periastron of the collision is given on the x-axis and fraction of the envelope remaining after the collision is given on the y-axis. Black lines with squares are the results from SPH calculations. The dotted line is the predicted envelope remaining from the reduced three-body treatment, including the sound speed inside the envelope when calculating the capture radius, taking v∞ = 800 km s⁻¹. The horizontal lines represent the maximum envelope fraction remaining with which this giant does not evolve to become visible in the middle and bright bands at the Galactic Centre.

Figure 12. Plot of the fraction of 1 M⊙ giants prevented from evolving to become visible in the middle band against the number of collisions with 10 M⊙ BHs, assuming that the mass loss as a function of collision periastron is given by the results of SPH simulations at velocities of 400 (solid line), 800 (short-dashed line) and 1200 km s⁻¹ (long-dashed line).

are not focused. We found that this is not the case and hence that the increase in Rcritical with BH mass was not enough to offset the smaller number of impactors and therefore that a population of BHs with the canonical mass of 10 M⊙ is likely to have the greatest effect on the giant population.

In collisions with 10 M⊙ BH, the critical periastron required to prevent the 1 M⊙ giant evolving to become brighter than K = 12 is ~Rgiant/2. Hence, if collisions are unfocused, ~25 per cent of single encounters will prevent the giant evolving to become brighter than K = 12 at the Galactic Centre. This fraction is, however, a lower limit. The collision rates depicted in Fig. 3 imply that giant stars can expect to experience >1 encounter with stellar-mass BHs in the innermost 0.1 pc of the Galactic Centre, roughly the region where the population of giants is observed to be depleted. In addition, Fig. 11 shows that significant mass loss occurs at periastrons larger than the critical one, so several successive encounters may remove a large enough fraction of the a giant’s envelope to affect it to the degree required.

We used our Monte Carlo code, with BH impactors alone, to generate the fraction of giants prevented from evolving into the middle and bright bands for a given number of impactors at three velocities for the 1 and 2 M⊙ giants and a single velocity for the 1.5 and 3 M⊙ giants. The results of our calculations for the 1 M⊙ giant are shown in Fig. 12.

A given Galactocentric radius uniquely determines a relative velocity and cumulative impact probability. To map the fractions of objects prevented from evolving into the bright and middle bands, we performed two-dimensional (2D) interpolation in v∞ and collision probability for the 1 and 2 M⊙ giants to determine the fraction of these objects prevented from evolving into the middle and bright bands as a function of Galactocentric radius. For the 1.5 and 3 M⊙ giants, we interpolated in collision probability only.

This analysis assumes that all giants of a given mass may be represented by the models at the halfway stage on the giant branch used in the SPH calculations. To check the influence of the evolution of the giants, we repeated the Monte Carlo simulations using 10⁴ 1 M⊙ giants with ages randomly distributed on the giant branch. Once the age of each giant was chosen, a three-body mass-loss/Rmin curve was generated by interpolating between the mass-loss curves generated from the three-body calculations using giants bracketing the chosen age. As Fig. 11 shows, the three-body calculations underestimate the mass loss at large values of Rmin where hydrodynamic effects become important. We allowed for this by calculating from Fig. 11 the factor by which the Rmin resulting in a given fraction of the giant envelope was larger in the SPH results than in the three-body results. Assuming that these factors were the same for giants of any age, we produced a synthetic mass-loss curve for each giant of the randomly chosen age. Collisions with these giants and a range of numbers of BH impactors were then performed in the same way and the fraction of giants prevented from evolving into the middle and bright bands as a function of Galactocentric radius determined. In Fig. 13, we compare the fraction of 1 M⊙ giants prevented from evolving into the middle band as a function of Galactocentric radius, taking all giants to be the representative τcc = 0.51 model (solid line), or accounting for the giant’s evolution in the way described. We see that the giant’s evolution has little influence on the results and that the models we chose to perform hydrodynamic simulations with are well representative of giants of each given mass.

We see that collisions with BHs alone reduce the population of giants in the middle band by ≳50 per cent inside a radius of 0.04 pc, comparable to the size of the region depleted in this band. However,
near the tip of the AGB. We have chosen to study encounters with giants towards the middle of the RGB which are representative of all giants of a given mass, so we extend our study to include encounters between giants and 1 M⊙ MS impactors, which we again treat as point masses. In addition, we extend the work of Bailey & Davies (1999) by considering the cumulative effect of multiple impacts. We do not consider white dwarf or neutron star impactors. This is partly because, from a numerical point of view, there is little difference between a white dwarf, a neutron star and a low-mass MS stars, since they are all point masses of similar mass. In addition, our population synthesis models suggest that that MS stars outnumber white dwarfs by ∼4:1 and that neutron stars are even less numerous. A flatter IMF than the Miller–Scalo one we have used could increase the ratio of white dwarfs to MS stars but we found that such an IMF was not well able to reproduce the observed Galactic Centre giant population. We do not think it is likely that the number of white dwarfs in the Galactic Centre exceeds the number of MS stars. It is also possible that a significant fraction of neutron stars would be ejected from the Galactic Centre by their natal kicks.

The smallest values of Rmin considered by Bailey & Davies (1999) corresponded to ≈Rgiant/4 for their two models. We repeated our three-body/Bondi–Hoyle analysis using 1 M⊙ impactors and found that collisions in which Rmin < Rgiant/6 may eject the giants’ cores and therefore strip the cores of sufficient mass to affect the giants’ evolution in a similar manner to encounters with BHs at larger periastrons. Although the critical encounter cross-section for a MS impactor to have similar effects to a BH impactor is then much smaller, the number density of MS stars at the Galactic Centre is much larger than that of BHs, so that encounters with MS stars may have an effect on the giant population comparable to or greater than those with BHs.

We performed SPH simulations to check the results of our restricted three-body analysis. In agreement with Bailey & Davies (1999), we found that encounters at Rmin > Rgiant/4 eject little mass, at most ∼10 per cent of the envelope. However, as shown in Fig. 14, the SPH results and the three-body results both suggest that single impacts at smaller periastrons may be able to expel significant quantities of mass, or eject the giant core. We caution, however, that we have not performed SPH simulations of encounters between giants and MS stars in which the separation between the giant core and the centre of mass of the MS was less than 4 M⊙ since the treatment of the MS star as a point mass may lead to misleading results at such small separations.

In addition, Fig. 3 suggests that giants can expect to suffer several tens to of order 100 impacts with MS stars at Galactocentric radii <0.1 pc. We therefore repeated the Monte Carlo calculations from the previous section allowing for multiple impacts with a mixture of MS and BH impactors. We used the collision probabilities from Fig. 3 to determine the expected numbers of BH and MS impactors at a given Galactocentric radius. We then performed Monte Carlo calculations and calculated the cumulative effect of all the impactors. In Fig. 15, we show the results of this analysis for the 1 M⊙ giant. The figure depicts, as a function of Galactocentric radius, the fraction of 1 M⊙ giants prevented from evolving to become visible in the middle band, assuming BH impactors acting alone (short-dashed line), assuming MS impactors acting alone (solid line) and assuming a mixture of BH and MS impacts in proportions dictated by the relevant collision probabilities (long-dashed line). Fig. 16 depicts the fraction of 2 M⊙ stars prevented from evolving into the bright band.

We find that the MS stars are approximately as effective – somewhat more so in the case of the 1 M⊙ giant – in changing the visible

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**Figure 13.** Fraction of 1 M⊙ giants prevented from evolving to become visible in the middle band as a function of Galactocentric radius, assuming that all giants are the ‘standard’ model with $t_{	ext{cond}} = 0.51$ (solid line), or assuming giants are randomly distributed in age along the giant branch (dashed line). The vertical dotted line represents the radius within which the middle band is depleted.

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we will not draw any conclusions about the overall effect of collisions on the giant population until we have considered collisions with MS stars, described in the next section.

In all of our SPH calculations, some material was captured by the BH during its passage though the giant’s envelope, the captured gas remaining in orbit in a disk-like structure around the hole. The BH will accrete this material and the resulting energy release will make it visible as an X-ray source. In order to see how many such sources we might expect to observe, we assume that the captured material will be accreted at the Eddington rate, given by $\dot{M} = 2 \times 10^{7} \, M_{\odot} \, \text{yr}^{-1}$ for a 10 M⊙ BH. The BHs typically capture a few $\times 10^{-2}$–$10^{-1} M_{\odot}$ of material, so the time for which they will be visible as accreting X-ray sources is $\sim 5 \times 10^{2}$–$5 \times 10^{3}$ yr. If we assume that the collision rate per giant is given simply by $n_{\text{BH}} \sigma_{\text{giant}} v_{\infty}$ and take fiducial values appropriate for the innermost 0.1 pc of $n_{\text{BH}} = 10^{6} \, \text{pc}^{-3}$, $\sigma_{\text{giant}} = \pi R_{\text{giant}}^{2}$ (neglecting gravitational focussing) with $R_{\text{giant}} = 50 R_{\odot}$ and $v_{\infty} = 1000 \, \text{km} \, \text{s}^{-1}$, we obtain a collision rate per giant of $4 \times 10^{-3}$ yr$^{-1}$. Our Galactic Centre models imply that the central 0.1 pc should contain $\sim 10^{6}$ giants, so that the rate of giant–BH collisions within this volume would be $4 \times 10^{-3}$ yr$^{-1}$. Since this figure is approximately the inverse of the accretion time-scale, we would expect to observe one or zero BHs accreting material which they have acquired during a collision with a giant. This result is consistent with Muno et al. (2005).

### 6.2 Collisions of giants with main-sequence stars

Encounters between giants and MS stars have already been studied in the context of the giant depletion in the Galactic Centre by Bailey & Davies (1999). However, the two giant stars studied by Bailey & Davies (1999) were both in quite extreme evolutionary stages. Their 2 M⊙ giant was near the tip of the RGB and their 8 M⊙ giant...
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Figure 14. Plot of the fractional envelope mass remaining after collisions between a 1 $M_\odot$ giant star and a 1 $M_\odot$ MS star (black squares) at a velocity of 800 km s$^{-1}$. The periastron of the collision is given on the x-axis and fraction of the envelope remaining after the collision is given on the y-axis. The dotted line is the predicted envelope remaining from the reduced three-body treatment, including the sound speed inside the envelope when calculating the capture radius. The horizontal lines represents the maximum envelope fraction remaining with which this giant does not evolve to become visible in the middle and bright bands at the Galactic Centre.

Figure 15. Fraction of 1 $M_\odot$ giants prevented from evolving into the middle band as a function of Galactocentric radius by collisions with MS stars (solid line) and BHs (short-dashed line), assuming collision rates boosted by a factor of 2 due to eccentricity of giant’s orbit around Galactic Centre, and using 2D interpolation to determine number of impactors, relative velocity and thus kill fraction as functions of Galactocentric radius for the BH impactors and assuming a single velocity of 800 km s$^{-1}$ for the MS impactors. The long-dashed line is the fraction of 1 $M_\odot$ giants prevented from evolving into middle band by a mixed population of BHs and MS stars.

Figure 16. Fraction of 2 $M_\odot$ giants prevented from evolving into the bright band as a function of Galactocentric radius by collisions with MS stars (solid line) and BHs (short-dashed line), assuming collision rates boosted by a factor of 2 due to eccentricity of giant’s orbit around Galactic Centre, and using 2D interpolation to determine number of impactors, relative velocity and thus kill fraction as functions of Galactocentric radius for the BH impactors and assuming a single velocity of 800 km s$^{-1}$ for the MS impactors. The long-dashed line is the fraction of 2 $M_\odot$ giants prevented from evolving into the bright band by a mixed population of BHs and MS stars.

7 DISCUSSION

7.1 Main sequence versus black hole impactors

We used the results of Monte Carlo modelling combined with SPH calculations and three-body simulations to quantify the mass lost by a given giant in an encounter at a given $R_{\text{min}}$ with a BH or a MS star. Taking successive collisions to be independent and assuming giant population as the BH impactors. This result demands some explanation.

In Fig. 17, we plot for 1 and 2 $M_\odot$ giants, the ratio as a function of Galactocentric radius, of the probability of the giant being hit by a MS star to the probability of it being hit by a BH. We see that, in the range 0.01 > $r$ > 0.1 pc, this ratio is $\approx 10$ for both giants. In Fig. 18, we plot the fraction of 1 $M_\odot$ stars prevented from evolving to become visible in the middle band as a function of the number of impactors, assuming BH impactors alone (dashed line) and MS impactors alone (solid line). We see that the factor by which the number of MS impactors must exceed the number of BH impactors in order to deplete the same fraction of giants is at most $\sim 5$. It is therefore not surprising, given the assumptions inherent on our model, that MS impactors are as effective in depleting giants as BHs.

The cumulative effect of collisions with BHs and MS stars on the 1 $M_\odot$ giants which dominate the middle band is to evacuate a 3D volume $\sim 0.04$ pc in radius of giants. The effect of collisions on the 2 $M_\odot$ giants dominating the bright band is smaller, evacuating a region $\sim 0.02$ pc in radius.
that BH impactors and MS impactors acted alone or in concert, we found that the effects on the visible giant population of the two types of impactor were comparable, owing to the much greater number density of MS stars than BHs in the Galactic Centre.

This result should be treated with some caution, however. In the three-body and SPH calculations, we have treated the impactors as point masses. While this is clearly valid for the BHs, it may not always be so for the MS stars, particularly in the encounters at very small $R_{\text{min}}$ required to expel the giant core.

The periastron necessary to notionally eject the core may be so small that it is not valid to approximate the MS star as a point mass, either because it is physically too small to fit, or because it approaches the core so closely that it experiences Roche lobe overflow on to the core.

The size of the Roche lobe is given by (Eggleton 1983)

$$r_R^i = \frac{0.49(m_i/m_j)^{2/3}a}{0.6(m_i/m_j)^{2/3} + \ln(1 + (m_i/m_j)^{1/3})}.$$  \hspace{1cm} (16)

Given the core masses given in Table 1, we find that, for all the giants, the MS star cannot approach the core closer than $2.0 - 2.2 R_\odot$ without experiencing Roche lobe overflow. The consequences of this phenomenon are not obvious. The high velocity of the intruding MS star may render the amount of mass actually transferred in the flyby with the giant core very small. In this case, the MS star will exit the giant envelope relatively unscathed and the giant core will probably be ejected. However, it is possible that the tidal distortion of the MS star (or simply an impact at a periastron less than the radius of the MS star) will lead to a collision between the core and the MS star. This encounter may dissipate enough energy that the MS star becomes bound to the core and sinks or spirals into the centre of the giant to smother the core. The ultimate result of such an encounter may be that the MS star becomes part of the giant envelope, resulting in a larger and brighter giant. Understanding which (if either) of these scenarios is correct and what effect they would have on the giant’s evolution require detailed high-resolution hydrodynamic calculations which are unfortunately beyond the scope of this paper, but would make an interesting topic of further work.

Our three-body analysis shows that it becomes significant for giants of $3 M_\odot$ and above, as the $R_{\text{max}}$ required for a $1 M_\odot$ object to expel core is $\sim 2 R_\odot$. The fractions of giants prevented from evolving to become visible in the depleted $K$ bands by MS impactors should therefore be regarded as upper limits and it may be that encounters with BHs are in reality significantly more important.

### 7.2 Encounters with main-sequence binaries

Davies et al. (1998) studied the effects of encounters between MS binaries and giants. Since binaries have much larger cross-sections than single stars, even a relatively small population of binaries could be involved in a significant number of collisions. The maximum binary cross-section that can be considered is set by the requirement that the binary must be hard (so that it is not disrupted by encounters) and is therefore determined by the local velocity dispersion. As the velocity dispersion increases, the hard–soft boundary semimajor axis and therefore the cross-section of the binary decreases. Additionally, Davies et al. (1998) found that, at higher relative velocities, a smaller fraction of interactions resulted in outcomes destructive to the giant. The relative velocities considered by Davies et al. (1998) ranged from 50 to $150 \text{ km s}^{-1}$. We extrapolate their results to the velocities considered in this paper of $\sim 1000 \text{ km s}^{-1}$. Following Hut & Bahcall (1983) and Davies et al. (1998), we define the maximum interaction separation $s_{\text{max}}$ as a function of $v_{\infty}$ as

$$s_{\text{max}} = \left(\frac{4.0}{v_{\infty}/v_{\text{crit}}} + 0.6\right) d,$$  \hspace{1cm} (17)

where $v_{\text{crit}}$ is the critical velocity of the chosen binary, defined as the velocity at infinity an intruder of the same mass as the binary components must have such that the total energy of the three-body systems is zero, and $d$ is the binary separation. If we adopt the same binary parameters as Davies et al. (1998), $d = 23.5 R_\odot$ and...
\( v_{\text{eff}} = \frac{116.7 \text{ km s}^{-1}, \text{ if } v_{\text{sc}} \text{ is } 1000 \text{ km s}^{-1}, \text{ we obtain the cross-section of the binary } \sigma_{\text{max}} \sim 630 R_{\odot}^2. \text{ Even if we make the assumption that all interactions at } R_{\text{max}} < \sigma_{\text{max}} \text{ prevent the giant evolving into the depleted } K \text{ bands, for the } 93 R_{\odot} 2 M_{\odot} \text{ giant considered by Davies et al. (1998), this is } \approx R_{\text{giant}}^2 / 13. \text{ Given that the cross-section for a single encounter with a } 1 M_{\odot} \text{ impactor to prevent this giant evolving into the depleted } K \text{ bands is } \approx R_{\text{giant}}^2 / 36, \text{ this implies that binary interactions are a factor of } \approx 3 \text{ more effective in altering the giant population, implying that the stellar population must consist of at least } 25 \text{ per cent binaries in order that binary encounters are more significant than encounters with single MS stars. In agreement with Davies et al. (1998), we find that the fraction of binaries would have to be unrealistically high in the Galactic Centre to have a significant collisional effect on the population of giants there.}

7.3 Effect of collisions on the observed giant population

For a single impact with a given giant, more mass has to be ejected to prevent the giant evolving into the middle band than to prevent it evolving into the bright band, since the former entails a more severe perturbation to the star’s evolution. The collision cross-section to prevent a giant evolving into the bright band is correspondingly larger than that to prevent the same giant from evolving into the middle band. However, ejecting a given fraction of the envelope from a } 2 M_{\odot} \text{ giant is intrinsically more difficult than ejecting the same envelope fraction from a } 1 M_{\odot} \text{ star, since the } 2 M_{\odot} \text{ giant’s envelope is more strongly bound. In addition, the times which stars spend on the giant branch decrease strongly as the stellar mass increases. These two facts largely explain why we find that the bright band is dominated by } 2–3 M_{\odot} \text{ giants which have more strongly bound envelopes and which are less likely to be struck by MS or BH impactors while on the giant branch.}

We have calculated for each model giant the probability at a given Galactocentric radius that a combination of collisions with BHs and MS stars will prevent the giant evolving to become visible in the middle or bright bands. However, in order to compare our results with observations, we must examine the effect of these collisions on the projected surface density of sources at the Galactic Centre, since this is what is actually observed. If we assume that the giant stars are distributed in the same way as the MS stars, i.e. that \( n_{\text{giant}}(r) \propto r^{-1.4} \) and that the distribution has a maximum radius \( r_{\text{max}} \) sufficiently large that changing it by factors of 2 does not influence the result significantly, we can simply integrate the surface density \( \Sigma \) of stars at any projected radius \( x \) as

\[
\Sigma(x) = \int_{r_{\text{max}}}^{x} \left[ 1 - f(z) \right] n(z) dz, \tag{18}
\]

where \( z = \sqrt{(r^2 - x^2)}, \) \( z_{\text{max}} = \sqrt{(r_{\text{max}}^2 - x^2)} \) and \( f(z) = f(r) \) [where \( r = \sqrt{(z^2 + x^2)} \)] is the fraction of giants prevented from evolving into the relevant band at 3D radius \( r \). The quantity of interest is then the ratio, as a function of projected radius \( x \), of \( \Sigma(\text{collisions})/\Sigma(\text{no collisions}) \), since this reveals the effect of collisions on the observed surface density of sources. The results of performing this analysis on the } 1 M_{\odot} \text{ giant in the middle band are shown in Fig. 19. The two curves show the depletion expected due to collisions with MS stars and (i) our standard population of BH (5000 within 0.1 pc, short-dashed line), (ii) a BH population enhanced by a factor of 4. We find that the standard population of BHs (in combination with the MS stars) depletes 50 per cent or more giants from the middle band within a projected radius of } \approx 0.02 \text{ pc, while the enhanced BH population depletes 50 per cent or more middle band giants within } \approx 0.04 \text{ pc. This is comparable in size to the depleted region observed in the middle band by Genzel et al. (1996). The BH population required to achieve this is somewhat larger than that predicted by Alexander & Livio (2004) and Deegan & Nayakshin (2007).}

7.4 Monte Carlo simulations of the Galactic Centre

To examine the influence of collisions on the Galactic Centre environment in more detail, we used our Monte Carlo population synthesis model of the Galactic Centre cluster (from which Fig. 2 was constructed). We assume that star formation there has been proceeding at a constant rate for 14 Gyr and that stars are born with a Miller–Scalo IMF. As discussed in Section 2, when we varied these assumptions, we obtained a stellar population that was a significantly worse fit to the observed numbers of giants in all three } K \text{ bands throughout the whole Galactic Centre cluster, so we conclude that these assumptions are reasonable. We use the same stars evolution tracks and Johnson (1966) colours and bolometric corrections to calculate the evolutionary phase and } K \text{ magnitude of each star. The stars are distributed in a sphere 2 pc in radius according to the power laws derived by Genzel et al. (2003) using the normalization described in equation (3). We constructed model clusters neglecting the effects of stellar collisions, models including collisions with MS stars and our standard and enhanced populations of BHs. We then compared all our models with new observational data obtained from Tripp & Genzel (private communication).

We constructed plots of the mean cumulative number of stars in our Monte Carlo models in the middle band against projected Galactocentric radius and compared them to the same plot generated from the observational data. In Fig. 20, we show the cumulative number of stars in the middle band against projected Galactocentric radius generated by our
Monte Carlo models (lines with ±1σ standard deviation) and compare these with the observed numbers of objects (squares, also with ±1σ errors). It is clear that both models in which collisions are included (dashed and dotted lines in Fig. 20) give a much better fit to the observations than a model in which collisions are not included (solid line in Fig. 20), and that the model with the enhanced BH population gives a good fit to the observed data. We therefore conclude that collisions with MS stars and BHs may be able to account for the depletion of giants in the middle band, although with a rather large BH population.

Repeating this analysis for the bright band (dominated by 2 M⊙ giants), we find that the region evacuated of giants by collisions is too small (~0.02 pc in radius) to explain the observed depletion, even using our enhanced population of BHs. We determined that the BH population required to deplete the 2 M⊙ giants out to a radius of 0.1 pc is at least 30 times more populous than our standard model, so that there would be 1.5 × 10⁵ BH within 0.1 pc. The effect of this population would be to deplete the middle band giants out to a radius of ~0.3 pc, which is much greater than the observed depletion radius. This BH population is also much larger than that inferred by e.g. Alexander & Livio (2004), Deegan & Nayakshin (2007). In addition, in Fig. 21, we plot the total mass density against Galactocentric radius for the model with our standard BH population and models with BH populations four and 30 times large, and compare it to that inferred in Schödel et al. (2007). We see that, at 0.1 pc, the model with four times our standard number of BHs has a mass density ~two times that inferred by Schödel et al. (2007) and the model with 30 times the standard number of BHs has a mass density ~10 times greater. We therefore conclude that the observed depletion of the brightest giants in the Galactic Centre cannot be due purely to collisions of giants with MS stars or BHs. The depletion of the brightest giants may instead be due to tidal stripping of stars on very eccentric orbits, and it is also possible that modification of the stellar population by collisions of MS stars with each other may decrease the numbers of low- and intermediate-mass giants that contribute to the bright K band. We will look at these scenarios in detail in subsequent papers.

We also checked to see what effect collisions would have on giants in the undepleted faint band (15 > K > 12). This band is dominated by 1–2 M⊙ objects. Preventing giants of these masses evolving into this brightness band is extremely difficult, requiring the loss of >99% of the giant’s envelopes – even with the enhanced BH population of 2 × 10⁵ within 0.1 pc, the radius to which faint band objects would be depleted is < 0.01 pc. We conclude that collisions with BHs and MS stars are unlikely to have an observable effect on the fainter population of giants.

8 CONCLUSIONS

Our main conclusions may be summarized as follows.

(i) The stars missing from observations in the bands K < 10.5 and 10.5 < K < 12 in the Galactic Centre are low-mass giant stars, in the mass range 1–4 M⊙.

(ii) The Galactic Centre is a highly collisional environment. In particular, within a Galactocentric radius of 0.1 pc, giant stars are likely to suffer multiple collisions with both MS stars and BHs.

(iii) We have shown that significantly altering the evolution of giant stars by means of collisions requires the ejection of large quantities of mass (>20 per cent of the envelope) while the giant is on the first giant branch. Removal of ~20 per cent of the envelope of a 1 M⊙ giant is sufficient to make the AGB significantly fainter, but has little effect on the RGB phase. Mass losses of >40 per cent occurring on the RGB are sufficient to decrease the brightness of the RGB tip by ~1 mag and prevent the star evolving on to the HB or...
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AGB. Mass loss on the horizontal branch and AGB has essentially no effect on a star’s subsequent evolution, as we showed in Fig. 5.

(iv) We have shown that penetrating encounters with 10 $M_\odot$ BHs expel the cores of giants. The cores carry away some fraction of the envelope, resulting in very large fractional mass losses. Such mass losses in single collisions can affect the evolution of the giants to such a degree that they never evolve to become brighter than $K = 12$.

(v) We have also found, using a restricted three-body analysis, that encounters at very small $R_{\text{min}}$ with 1 $M_\odot$ MS impactors can also eject the giant core, leading to the severe mass losses required to prevent the giant evolving to become visible in the depleted $K$ bands.

(vi) The cumulative effects of collisions with BH and MS impactors are able (for a population of BHs of $2 \times 10^4$ within 0.1 pc) to deplete a region $\approx 0.04$ pc ($\approx 1$ arcsec) in radius of giants in the middle $K$ band, comparable in size to the region observed to be devoid of these objects by Genzel et al. (1996). Collisions can plausibly explain the depletion in this band.

(vii) The cumulative effects of collisions deplete the 2–3 $M_\odot$ giants which dominate the bright $K$ band to a somewhat smaller radius ($\approx 0.02$ pc). This is considerably less than the size of the region observed to be depleted of these giants by Genzel et al. (1996). The depletion of the very brightest giants cannot be explained by collisions without invoking a BH population so large that it would deplete the middle band out to radius much larger than observed.

(viii) Owing to the extreme mass losses required to prevent giants evolving into this band, collisions are not likely to have an observable effect on the faint band ($15 > K > 12$).

ACKNOWLEDGMENTS

JED gratefully acknowledges support from a Wenner–Gren fellowship. MBD is a Royal Swedish Academy Research Fellow supported by a grant from the Knut and Alice Wallenberg Foundation. RPC gratefully acknowledges support from a Swedish Institute scholarship. The high-resolution simulations reported in Section 6 were performed at the UKAFF at the University of Leicester, UK. All other hydrodynamical simulations were performed on machines funded by the Royal Physiographic Society, Lund.

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This paper has been typeset from a T\textsc{t}X/\textsc{f}I\textsc{t}X file prepared by the author.