Abstract. We consider whether stellar collisions can explain the observed
depletion of red giants in the Galactic center. We model the stellar population
with two different IMFs: 1) the Miller-Scalo and 2) a much flatter IMF. In
the former case, low-mass main-sequence stars dominate the population, and
collisions are unable to remove red giants out to 0.4 pc although brighter red
giants much closer in may be depleted via collisions with stellar-mass black
holes. For a much flatter IMF, the stellar population is dominated by compact
remnants (i.e. black holes, white dwarfs and neutron stars). The most common
collisions are then those between main-sequence stars and compact remnants.
Such encounters are likely to destroy the main-sequence stars and thus prevent
their evolution into red giants. In this way, the red-giant population could be
depleted out to 0.4 pc matching observations. If this is the case, it implies the
Galactic center contains a much larger population of stellar-mass black holes
than would be expected from a regular IMF. This may in turn have implications
for the formation and growth of the central supermassive black hole.

1. Introduction

The Milky Way contains a supermassive black hole at its very center, Sagittarius
A*, whose mass is \( \approx 4 \times 10^6 \, M_\odot \) (e.g. Schödel et al. 2003). A dense stellar cluster
surrounds this black hole, with a central density at least comparable to that seen
in the cores of the densest globular clusters. At least one, and possibly two, discs
containing young stars at distances between \( \sim 0.04 \) and \( \sim 0.3 \, \text{pc} \) from the black
hole are also seen (Paumard et al. 2006). The latter stellar population is thought
to have an unusually flat IMF (Paumard et al. 2006). It has long been known
that the central 0.2 pc or so of the Galactic center is deficient in bright red giants
(Genzel et al. 1996). Since the center of the Galaxy has a high number density
of stars, it is natural to suggest that stellar collisions may explain the observed
depletion.

A recent crop of papers have studied the stellar population in the central
regions (Bartko et al. 2010; Buchholz et al. 2009; Do et al. 2009). They report
that the early-type stars (bright main-sequence stars) follow a cusp-like profile
whilst the surface density of late-type (red-giant) stars that are brighter than a K magnitude of 15.5 is rather flat out to 0.4 pc or 10 arcsec. This surprising result implies that the red-giant population is depleted out to about 0.4 pc from the central supermassive black hole. We will consider here whether stellar collisions could be responsible for this observed depletion. We will consider two different cases: 1) where the stellar population in the Galactic center is drawn from a Miller-Scalo IMF, and 2) where the IMF is much flatter. In each case, we calculate collision probabilities between the various stellar species, and produce, via Monte Carlo techniques, a stellar population. From this we measure the surface density of the early and late-type stars (to compare directly with what is observed) making some reasonable assumptions concerning the effects of collisions on the population.

The masses of stars contributing to the observed early and late-type populations are rather different, as shown in Fig. 1, where we have produced a synthetic population with a flat IMF. We see that the early-type stars are virtually all between 12 and 27 $M_\odot$ whereas stars contributing to the observed late-type population have much lower masses, between 1 and 5 $M_\odot$.

![Figure 1](image.png)

Figure 1. A plot of the distribution of stellar masses contributing to the observed early-type (between 12 and 27 $M_\odot$) and late-type stars (between 1 and 5 $M_\odot$) at the Galactic center, assuming the stellar population is drawn from a flat IMF ($\Gamma = 1.0$).

2. The Effects of Crowdedness

The Galactic center is a crowded environment, with number densities of stars probably of order $10^6$ stars pc$^{-3}$ or more. In such dense environments, collisions
Stellar Collisions in the Galactic Center

between stars will be frequent, and thus affect the stellar population. The cross section for two stars, having a relative velocity at infinity of \( V_\infty \), to pass within a distance \( R_{\text{min}} \) is given by

\[
\sigma = \pi R_{\text{min}}^2 \left( 1 + \frac{V^2}{V_\infty^2} \right)
\]

(1)

where \( V \) is the relative velocity of the two stars at closest approach in a parabolic encounter \( \text{(i.e.} V^2 = 2G(M_1 + M_2)/R_{\text{min}} \text{, where} M_1 \text{ and} M_2 \text{ are the masses of the two stars)} \). The second term is due to the attractive gravitational force between the two stars, and is referred to as the gravitational focusing term. In the very center of the Galaxy, where the supermassive black hole dominates, and stars may be assumed to move on Keplerian orbits around the black hole at speeds exceeding 1000 km/s, \( V \ll V_\infty \) and we recover the result, \( \sigma \propto R_{\text{min}}^2 \). In this regime collisions involving larger red giants will be relatively more frequent despite their short lifetimes compared to main-sequence stars. This is not the case in globular clusters where \( V \gg V_\infty \) and thus \( \sigma \propto R_{\text{min}} \). One may estimate the timescale for a given star to undergo an encounter with another star, \( \tau_{\text{coll}} = 1/n\sigma v \). The collision timescale will therefore be a function of both the number density of stars and the makeup of the stellar population, \( \text{i.e.} \) the distribution of stellar masses and types.

The effects of collisions will depend on the types of stars involved and on the relative speed of the two stars when they collide. Collisions involving two main-sequence stars occurring at relatively low speed (less than the surface escape speed of the stars) are likely to result in the merger of the two objects with relatively low amounts of mass loss. Collisions occurring at much higher speeds are likely to lead to significant mass loss and even to the destruction of the stars involved.

Collisions between main-sequence stars and compact objects \( \text{(i.e.} \) black holes, white dwarfs or neutron stars \( ) \) are likely to be destructive (Dale et al., in preparation). In the case of a black hole impactor, the main-sequence star is often torn apart by tidal forces, with some material being accreted by the black hole and rest being ejected. This is illustrated in Fig. 2 where we show snapshots of a collision between a 1 M_⊙ main-sequence star and a 10 M_⊙ black hole. The close passage of the black hole results in the tidal disruption of the main-sequence star. A small fraction of the material is accreted by the black hole and the rest is dispersed. For neutron star and white dwarf impactors, a larger fraction of the material from the main-sequence star may form an envelope around the compact object. However such an object is likely to be relatively short lived, perhaps appearing as a bright red supergiant, before the envelope is ejected. Thus all collisions between main-sequence stars and compact objects will act to reduce the population of luminous stars.

Even though they are very frequent, collisions between red giants and main-sequence stars in fact have very little effect, as the main-sequence star passes through the envelope and effects very little mass loss \[\text{[Bailey \& Davies 1999]}\). The same is also true for white dwarf or neutron star impactors. More interesting are encounters involving black holes. In Fig. 3 we show snapshots of an encounter between a 1 M_⊙ red giant and and 10 M_⊙ black hole \( (V_\infty = 800 \text{ km/s,} \ r_{\text{min}} = 10 \text{ R}_\odot) \). As the black hole passes close to the red-giant core, it gives it a jerk and
Figure 2. A series of snap-shots of a collision between a main-sequence star and a stellar-mass black hole using our SPH code. The position of the black hole is given by the black filled circle and we show only 1% of the SPH particles.

the core is ejected at high speed, retaining only a small fraction of the envelope (in this case about 13%). Such excessive mass loss will prevent this red giant from becoming brighter: we have thus removed it from the pool of brighter red giants.

Thus we see that in order to deplete the stellar population of red giants (as indicated by the observations), we must consider collisions of three types: 1) encounters between red giants and black holes, 2) encounters between two main-sequence stars, and 3) encounters between main-sequence stars and compact objects (i.e. black holes, white dwarfs and neutron stars). The relative frequencies of encounters will depend on the IMF of the underlying stellar population. With a Miller-Scalo type IMF, where most stars are of low mass, the majority of stars formed will still be on the main sequence today, with relatively few stars having evolved off the main-sequence to ultimately form compact rem-
nants. Thus collisions involving two main-sequence stars will be more frequent than collisions between main-sequence stars and compact objects. Collisions between red giants and black holes may be relatively frequent, at least in the very center, owing to the larger size (and thus collisional cross section) of red giants.

3. Collisions for a Miller-Scalo IMF

We consider first that the stellar population in the Galactic center has been drawn from a Miller-Scalo IMF (Miller & Scalo 1979) where we also assume the stars have a uniform spread in ages from 0 to 14 Gyr. Using a density distribution for the stars given by $n_*(r) \propto r^{-1.4}$ and a density distribution for 10 $M_\odot$ black
Figure 4. The collision rates between the various stellar species. Here the collision probability is the expected collision rate integrated over the entire lifetime of the main-sequence or red-giant phase. In other words, the star has a good chance of being involved in a collision if the collision probability is one. The gray band is for encounters between red giants and black holes, the vertically-shaded region is for encounters between main-sequence stars and compact objects, and the horizontally-shaded region is for encounters between two main-sequence stars. In all cases, we consider stars between $1.0 \, M_\odot$ and $5.0 \, M_\odot$. The stellar population has a Miller-Scalo IMF.

holes of $n_{BH} \propto r^{-1.8}$ (Freitag et al. 2006), we compute the collision probabilities between the various stellar types as a function of Galactocentric radius. The results are shown in Fig. 4. We see that collisions between red giants and black holes are the most frequent in the very central regions whilst collisions between two main-sequence stars dominate further out. For stars following a Miller-Scalo IMF, collisions between main-sequence stars and black holes (or other compact remnants) are relatively less frequent and are unlikely to have a significant effect on the stellar population apart from perhaps in the very central regions. Even though collisions between main-sequence stars are relatively frequent, in the case of a Miller-Scalo IMF with a low-mass cutoff of $0.2 \, M_\odot$ the number of main-sequence stars in the mass range $1$–$4 \, M_\odot$ will not be reduced. The reason is that although some stars in this mass range will be removed as they merge with other stars to produce more massive stars, they will be replaced by stars produced by the merger of lower-mass stars. This process will be investigated in detail in Dale et al. (in preparation). It could be that a stellar population with a Miller-Scalo IMF but with a larger low-mass cutoff may lead to a depletion of
the lower-mass main-sequence stars which later evolve to produce the observed population of red giants.

Collisions between red giants and stellar-mass black holes are able to deplete the red-giant population within the inner 0.08 pc or so but not further out. Collisions can plausibly explain the depletion of red giants of middle brightness ($10.5 < K < 12$) but not those in the brightest band ($K > 10.5$) which are seen to be depleted to about 0.2 pc (Genzel et al. 2003; Dale et al. 2009). Collisions are not able to explain the observed flattening of the red-giant population seen out to 0.4 pc (Bartko et al. 2010; Buchholz et al. 2009).

4. Collisions for a Flat IMF

In this section we consider the case where the stellar population in the Galactic center is drawn from a much flatter IMF than a Miller-Scalo IMF. Observations of the young disc of stars in the Galactic center suggest that they may have been drawn from such an IMF with a power-law slope as low as $\Gamma = 0.45$ (Bartko et al. 2010). A stellar population drawn from such a flat IMF would be quite different from one drawn from a Miller-Scalo IMF. A much larger fraction of stars would be massive, and explode as core-collapse supernovae producing either black holes or neutron stars. In addition, assuming stars have an approximately uniform spread in ages, a very large fraction of all stars will have evolved to become compact remnants. (i.e. black holes, white dwarfs, or neutron stars). In other words, the majority of stellar objects will in fact be compact objects. The most common flavor of collision will then be collisions involving compact objects.

In order to produce a stellar population, we assume a model where a stellar disc, similar to the one seen today, is produced about every $3 \times 10^7$ years up to 14 Gyr ago, with the most recent disc being produced only 6 million years ago to be consistent with observations. The disc mass is set to match the observations of the early-type stars which come entirely from the most-recent disc, whilst the total number of discs produced is set to match the observed late-type population 10 arcsec from the supermassive black hole. One should note that the formation mechanism for such discs of stars is unclear, one suggestion being that gas clouds interact tidally with the supermassive black hole (Bonnell & Rice 2008). We consider here for purposes of illustration the case of $\Gamma = 1.0$. For this IMF (which is flat in log mass), the mass is each disc is $10^4 M_\odot$, with the stars having a range of masses between 1.0 and 32.5 $M_\odot$. It is entirely possible that the star formation rate was higher in the past. As a simple first model, we assume that in addition to the discs produced at a steady rate, there was an excess of discs produced sufficiently early in the history of the Galaxy that essentially all the stars from these earlier discs have evolved into compact remnants. The exact excess of compact objects will depend on the history of the disc formation rate, but here we assume that two thirds of all star formation occurred at this earlier epoch. This will increase the number of compact objects present in the Galactic center population. As collisions involving compact remnants destroy main-sequence stars, increasing the compact object population will enhance the red-giant depletion.

The collision probability for collisions between stars of various types for the stellar population produced as described above are shown in Fig. 5. We see here
Figure 5. The collision rates between the various stellar species. Here the collision probability is the expected collision rate integrated over the entire lifetime of the main-sequence or red-giant phase. In other words, the star has a good chance of being involved in a collision if the collision probability is one. The gray band is for encounters between red giants and black holes, the vertically-shaded region is for encounters between main-sequence stars and compact objects, and the horizontally-shaded region is for encounters between two main-sequence stars. In all cases, we consider stars between $1.0 \, M_\odot$ and $5.0 \, M_\odot$. The stellar population has a flat IMF ($\Gamma = 1.0$).

that collisions between main-sequence stars and compact objects are most likely (at least further out from the center). Main-sequence stars are likely to undergo such a collision, and thus be destroyed, out to a distance of about 0.2 pc.

As discussed earlier, collisions between compact objects and main-sequence stars are likely to be destructive. Therefore with a flat IMF, and a suitably dense stellar population, the low-mass main-sequence stars which would ordinarily have evolved to become the observed late-type population are depleted within a distance of about 0.2 pc of the supermassive black hole. Therefore a stellar population produced from a flat IMF may be able to explain the flat surface density profile which has been observed for the late-type stars (red giants) as stars in the mass range $1-5 \, M_\odot$ within 0.2 pc have simply been destroyed before they could evolve into red giants.

5. Discussion

Equipped with the collision probabilities as a function of radius, we are now able to synthesize a stellar population for both Miller-Scalo and flat IMFs allowing
for the collisional depletion of the red-giant population. In Fig. 6 we show the calculated surface density profiles for early-type stars and late-type stars having K magnitudes brighter than 15.5 for both IMFs. In both cases, the stellar population has been normalised to the surface brightness of late-type stars 10 arcsec from the Galactic center, seen to be about 3 sources per square arcsec (this normalization was also applied to the collision probability calculations and figures shown earlier). In both plots we do not include the effect of stellar collisions on the population of early-type stars as the collisional depletion of these massive stars will be very small. However it should be noted that the existence of the so-called S stars in the very center of the galaxy (distances less than 1 arcsecond from the central black hole) may place limits on the number density of compact objects. The plots shown in Fig. 6 should be compared to Fig. 11 of Buchholz et al. (2009). One can see from the plots that the early-type population only matches the observations in the case of the flat IMF. A Miller-Scalo population is clearly not able to consistently match both the observed early and late populations. It is also clear from these plots that in the case of the Miller-Scalo IMF, the effect of stellar collisions on the red-giant population is negligible. However for the flat IMF, appreciable red-giant depletion occurs out to 10 arcseconds. Thus a flat IMF would seem to have the potential to explain the observed (flat) surface density profile of the red giants.

One problem with the model used here is that the total stellar mass out to 0.4 pc is about $5 \times 10^6 M_\odot$. This is much higher than suggested by observations (Schödel et al. 2003). However, in our calculations using a flat IMF here we have made the unrealistic assumption that stars remain at the radius at which they were formed. In other words, we have not allowed for the effects of mass segregation. In reality, the large population of heavier stellar-mass black holes
will sink in the potential, forming a central sub-cluster. This sub-cluster may then collapse to form a supermassive black hole in the manner envisaged by Quinlan & Shapiro (1987) if a supermassive black hole is not there already, or the stellar-mass black holes may simply be fed into an existing supermassive black hole. In either case, a large fraction of the stellar-mass black holes may end up inside the supermassive black hole. It is interesting in this context to note that the total mass contained in stellar-mass black holes for our flat IMF (about $3.5 \times 10^6 M_\odot$) is close to the observed value for the supermassive black-hole mass. A larger population of black holes produced by a flat IMF would also lead to a much higher rate of EMRI–type events, where stellar-mass black holes spiral in to the central, supermassive black hole, emitting gravitational radiation in the process. EMRIs could be an important source for LISA. Our calculations here have been a simplification. We have made the unrealistic assumption that stars remain at the radius they were formed. In addition we have not allowed for the growth of the supermassive black hole. Early on, before the supermassive black hole has grown, the disc-mode of star formation may be different or not occur at all owing to a lack of a supermassive black hole. A natural next step in these calculations will be inclusion of the dynamical evolution of the stellar cluster and for the growth of the central black hole (Nzoke et al., in preparation).

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