The Keplerian Three-body Encounter. I. Insights on the Origin of the S-stars and the G-objects in the Galactic Center

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Abstract

Recent spectroscopic analysis has set an upper limit on the age of the S-stars, the ~30 B-type stars in highly eccentric orbits around the supermassive black hole (SMBH) in the Galactic center. The inferred age (< 15 Myr) is in tension with the binary breakup scenario proposed to explain their origin. However, the new estimate is compatible with the age of the disk of O-type stars that lies at a farther distance from the SMBH. Here, we investigate a new formation scenario, assuming that both S-stars and the O-type stars were born in the same disk around SgrA∗. We simulate encounters between binaries of the stellar disk and stellar black holes from a dark cusp around SgrA∗. We find that B-type binaries can be easily broken up by the encounters and their binary components are kicked into highly eccentric orbits around the SMBH. In contrast, O-type binaries are less frequently disrupted and their members remain in low-eccentricity orbits. This mechanism can reproduce 12 S-stars just by assuming that the binaries initially lie within the stellar disk as observed nowadays. To reproduce all the S-stars, the original disk must have been extended down to 0.006 pc. However, in this case many B- and O-type stars remain in low-eccentricity orbits below 0.03 pc, in contrast with the observations. Therefore, some other mechanism is necessary to disrupt the disk below 0.03 pc. This scenario can also explain the high eccentricity of the G-objects, if they have a stellar origin.

Key words: binaries: general – black hole physics – celestial mechanics – Galaxy: center – methods: numerical

1. Introduction

The Galactic center harbors thousands of young stars within a parsec distance from the Milky Way’s supermassive black hole (SMBH), SgrA∗. Hundreds of Wolf–Rayet (WR) and O-type stars, with an estimated age of 6 Myr, lie in the region between 0.03 and 0.4 pc from SgrA∗. A fraction of these young stars (20%–50%) appear to form a nearly Keplerian, eccentric (e ≈ 0.3) disk, named the clockwise (CW) disk (Paumard et al. 2006; Barollo et al. 2009; Lu et al. 2009; Do et al. 2013; Yelda et al. 2014). The ensemble of the closest stars to the SMBH is called the S-star cluster. No WR and O-type stars have been observed among the S-stars, most of which are B-type stars (32 out of 40, Gillessen et al. 2017). Out of the 32 B-type S-stars, 8 appear to be part of the CW disk, while the remaining 24 have randomly oriented orbits.

The origin of the young stars is puzzling; their young age poses serious constraints on any dynamical migration scenario (e.g., Kim & Morris 2003; Portegies Zwart et al. 2003; Kim et al. 2004; Fujii et al. 2008, 2009, 2010). Moreover, the tidal shear from the SMBH would disrupt molecular clouds, preventing in situ star formation (see Mapelli & Gualandris 2016, for a review). However, it has been shown that star formation can still occur in a gaseous disk around the SMBH (Toomre 1964; Nayakshin & Cuadra 2005; Nayakshin et al. 2007; Collin & Zahn 2008). The most accepted scenario for the formation of the CW disk is the infall and disruption of a molecular cloud, which settled into a gaseous disk around SgrA∗ (Bonnell & Rice 2008; Mapelli et al. 2008; Hobbs & Nayakshin 2009; Alig et al. 2011; Lucas et al. 2013; Mapelli & Trani 2016; Trani et al. 2016a). This mechanism leads to the formation of stars in mildly eccentric orbits, successfully reproducing the dynamical properties of the CW disk. However, this scenario fails to explain the highly eccentric, random orbits of the S-stars.

Many solutions have been suggested to explain the origin of the S-stars: binary breakup by the SMBH (Hills 1991; Perets et al. 2009), disk migration (Levin 2007), Kozai–Lidov oscillations (Chen & Amaro-Seoane 2014; Šušr & Haas 2016), and fragmentation of active galactic nucleus outflow (Nayakshin & Zubovas 2018).

In the binary breakup scenario, the S-stars are captured by the SMBH via tidal disruption of binary stars. This mechanism can produce stars with very high eccentricities (e ~ 0.95–0.99, Hills 1988), which can then relax via scalar resonant relaxation toward a thermal eccentricity distribution, similar to the observed one (Perets et al. 2009; Madigan et al. 2011; Antonini & Merritt 2013; Hamers et al. 2014). Binaries can come either from the outer parsec or from a disk of stars between 0.04 and 0.1 pc. In the former case, binaries are scattered into radial orbits by a massive perturber (Perets et al. 2007; Perets & Alexander 2008), while in the latter case eccentricity is excited by Kozai–Lidov resonances, resulting in a very small pericenter passage that allows the tidal disruption of the binary (Madigan et al. 2009, 2014; Šušr & Haas 2016). However, these scenarios cannot explain the lack of WR/O-type stars in highly eccentric orbits.

Recently, Habibi et al. (2017) analyzed the combined spectroscopic data for eight S-stars. They infer an age of 6.6 Myr for the star S2 and less than 15 Myr for the remaining S-stars. This is in tension with the binary breakup scenario, which requires the eccentricity to relax for at least 40 Myr after the breakup of the
binary (Bar-Or & Fouvy 2018). Interestingly, the new age estimate for the S-stars is compatible with the age of the CW disk. While the S-stars and the CW disk appear nowadays to be two distinct populations, their similar age raises the question of whether they were a single stellar population in the past.

Finally, there is another class of highly eccentric objects orbiting around SgrA*: the G-objects (Gillessen et al. 2012, 2013; Witzel et al. 2014; Shahzamanian et al. 2016; Plewa et al. 2017). These are faint, dusty objects visible in the L’ band and Bγ line, but lacking any K-band emission proper of a star. So far, only two objects, G1 and G2, have been observed, but more are expected to be found in the near-future. Several theories have been proposed to explain the nature of the G-objects, but only a few studies have tried to explain the origin of their high eccentricity (Murray-Clay & Loeb 2012; Trani et al. 2016b).

Here we investigate a new formation mechanism for the S-stars and the G-objects, assuming that the S-stars and the CW disk were born in the same star formation episode, via the fragmentation of a gaseous disk. There are at least three known binaries in the CW disk, and many more binary candidates exist (Pfuhl et al. 2014; Naoz et al. 2018). It is also well known that a dark cusp of compact remnants is expected to have grown around the SMBH, via dynamical friction and in situ star formation (Bahcall & Wolf 1976, 1977; Hopman 2009; Merritt 2010; Antonini 2014; Generozov et al. 2018; Hailey et al. 2018). In particular, Alexander & Hopman (2009) predict that stellar black holes with mass \( \gtrsim 10 M_\odot \) will sink toward the SMBH and develop a steep cusp with a density power-law exponent of \( \sim 2–3 \).

Since binaries have a larger cross section, their encounter rate is enhanced with respect to single stars. It is therefore possible that an encounter can result in the ionization of the binary, kicking the ionized binary components into highly eccentric orbits. While the isolated three-body encounter has been studied in detail (e.g., Heggie 1975; Hut & Bahcall 1983; Hut 1983; Goodman & Hut 1993; Hut 1993; Heggie & Hut 1993; Heggie et al. 1996; McMillan & Hut 1996), no studies were dedicated so far to the Keplerian three-body encounter, in which all encountering bodies lie in Keplerian orbits about an SMBH.

In this paper, the first in the series, we investigate the formation of S-stars via ionizing three-body encounters, assuming that both S-stars and the CW disk were born in the same star formation episode.

In Section 2 we describe the numerical setup of our four-body simulations. Section 3 presents our main results regarding the production of S-stars via ionizing encounters. In Section 4, we discuss the implications and caveats of our work. Finally, our conclusions are summarized in Section 5.

2. Methods

We perform four-body simulations in which a binary from the CW disk and a stellar black hole undergo a three-body encounter. We run four sets of realizations, referred to as sets A, B, Aex, and Bex. In sets A and Aex, the binary components are WR/O-stars, while in sets B and Bex they are modeled as B-type stars. For the sets Aex and Bex, we assume that the CW disk was more extended toward the SMBH in the past.

2.1. Initial Conditions

The SMBH mass is set to \( 4.31 \times 10^6 M_\odot \) (Gillessen et al. 2009, 2017).

The binary orbit about the SMBH is modeled following the observed properties of the CW disk (Bartko et al. 2009; Do et al. 2013; Yelda et al. 2014). The semimajor axis is drawn from a power-law distribution with index \( -1.93 \), in the range \( 0.03–0.1 \) pc for sets A and B, and in the range \( 0.006–0.06 \) pc for sets Aex and Bex, consistent with the surface density \( \Sigma(r) \propto -0.93 \) reported by Do et al. (2013). The eccentricity is drawn from a normal distribution with \( \langle e \rangle = 0.3 \pm 0.1 \). We fix the orbit of the binary in the \( x-y \) plane and vary the orbital orientation of the third-body so that the encounter always occurs along the \( x \)-axis.

For the semimajor axis and eccentricity of the inner binary we adopt the distributions from Sana et al. (2012). The eccentricity distribution follows a power-law with index \( -0.45 \) between 0 and 1. The period distribution follows \( f(P) \propto \log_{10}(P)^{-0.55} \) with \( \log_{10} P \in (0.15, 0.55) \) and \( P \) is in days. We truncate the binary semimajor axis to the Hill radius at pericenter

\[
r_H = 0.5 a_{\text{bin}} (1 - e_{\text{bin}})^{1/3} \left( \frac{m_{\text{bin}}}{3M_{\text{SMBH}}} \right)^{1/3}
\]

if the semimajor axis exceeds \( r_H \). Likewise, we redraw the semimajor axis and eccentricity of the inner binary if they would immediately lead to a collision, i.e., \( a_{\text{in}}(1 - e_{\text{in}}) < R_1 + R_2 \). All the other Keplerian elements (\( i, \omega, \Omega, \nu \)) are randomly sampled.

In sets A and Aex the mass of the binary stars is randomly drawn from a power-law distribution with exponent \( \alpha = -1.7 \) between 25 and 150 \( M_\odot \), consistent with the WR and O-type population of the CW disk (Lu et al. 2013). In sets B and Bex, the mass of the binaries is uniformly sampled between 8 and 14 \( M_\odot \), representing the B-type population. The stellar radius is set to \( R = (M/M_\odot)^{0.8} \).

Motivated by the LIGO detections and population synthesis studies (e.g., Spera et al. 2018) we set the mass of the intercepting stellar black hole to 30 \( M_\odot \). Supplementary sets of simulations with different black hole masses \( (m_{\text{bh}} = 10, 500 \) and 1000 \( M_\odot \)) can be found in Appendix B. The orbital eccentricity of the stellar black hole about the SMBH is drawn from a thermal distribution. The orbital orientation is uniformly sampled over the sphere, and the azimuthal angle at the encounter is randomly picked in the range allowed by the eccentricity. The impact parameter is a three-dimensional vector drawn from a sphere of radius \( 2 a_{\text{in}} \), where \( a_{\text{in}} \) is the semimajor axis of the binary, surrounding the center of mass of the binary. We set the radius of the black hole to its tidal radius \( R_{\text{toce}} = \sqrt{2\pi m_{\text{bin}}/3 \rho_s} \approx 6.4 R_c \), where \( \rho_s = 1.41 \text{ g cm}^{-3} \) is the mean solar density. This lets us detect collisions and exclude those simulations that would end in the tidal disruption of one of the stars. Table 1 lists the main initial conditions of our model.

We run \( 10^5 \) realizations for each set. The simulations are run for about one-eighth of the orbital period of the binary about the SMBH at \( T_{\text{bin}} \), with the encounter occurring approximately \( T_{\text{bin}}/16 \) after the start of the simulations.

2.2. Setting up a Keplerian Two-body Encounter

Setting up a three-body encounter in a Keplerian potential is not as straightforward as in the isolated case. Here, we describe how we set up an encounter between two bodies in Keplerian orbits, and how we map eccentricity and the semimajor axis about the central SMBH to velocity and impact parameter at the encounter.

Consider two encountering bodies \( A \) and \( B \). We first fix the encounter position in space \( R_{\text{A}} \), which has to lie along the orbit

\[
\frac{2 \sqrt{\frac{m_{\text{bin}}}{3M_{\text{SMBH}}}}}{\frac{m_{\text{bin}}}{3M_{\text{SMBH}}}}
\]
of body Α. Then we choose a velocity vector $\mathbf{V}_A$ at encounter position $\mathbf{R}_A$ that is consistent with the semimajor axis, eccentricity, and orbital orientation of $\mathcal{A}$. From $\mathbf{V}_A$ and $\mathbf{R}_A$ we can then compute the full set of Keplerian orbital parameters of $\mathcal{A}$ ($a$, $e$, $i$, $\omega$, $\Omega$, $\nu$)$_A$. We repeat the same steps for body $\mathcal{B}$ using $\mathbf{R}_B = \mathbf{R}_A + \mathbf{B}$, where $\mathbf{B}$ is a chosen impact parameter vector. Once a consistent velocity vector $\mathbf{V}_B$ is also chosen for $\mathcal{B}$, we can compute its six Keplerian orbital parameters ($a$, $e$, $i$, $\omega$, $\Omega$, $\nu$)$_B$.

We then shift the true anomaly $\nu$ back in time by solving the Kepler equation twice for each body. In this way, we ensure that an encounter will occur between the two bodies. Afterwards, we can convert the new Keplerian elements ($a$, $e$, $i$, $\omega$, $\Omega$, $\nu$) of each body to Cartesian coordinates for the numerical integrator.

### 2.3. Mikkola’s Algorithmic Regularization Code

We run the simulations using TSUNAMI, an implementation of Mikkola’s algorithmic regularization (MAR; Mikkola & Tanikawa 1999a, 1999b). This code is particularly suitable for studying the dynamical evolution of few-body systems in which strong gravitational encounters are very frequent and the mass ratio between the interacting objects is large. The MAR scheme solves the equation of motions derived from a time-transformed Hamiltonian, for which the timestep does not go to 0 for $r \to 0$ (see Mikkola & Tanikawa 1999a for the details).

Since the timestep evaluations are sparse in physical time, the MAR scheme can potentially allow for particle interpenetration even when checking for collisions at each timestep. Therefore, we implemented a collision checking algorithm that uses the predicted pericenter passage during close encounters.

TSUNAMI uses a second-order leapfrog scheme in combination with the Bulirsch–Stoer extrapolation algorithm (Stoer & Bulirsch 1980) to increase the accuracy of the numerical results. Our code includes velocity-dependent forces following the algorithm described in Mikkola & Merritt (2006, 2008). Among these, we included the post-Newtonian terms 1PN, 2PN, and 2.5PN (Blanchet 2006) and the tidal drag-force from Samsing et al. (2018), although these terms are not switched on in the present work.

TSUNAMI integrates the equations of motion employing relative coordinates by means of the so-called chain structure. This change of coordinates reduces round-off errors significantly (Aarseth 2003).

More details on the TSUNAMI code will be presented in a following work (A. A. Trani et al. 2019, in preparation).

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**Table 1**

| Properties | Set A | Set B | Set $A_{\alpha}$ | Set $B_{\alpha}$ |
|------------|------|------|------------------|------------------|
| $\alpha_{\text{bin}}$ [pc] | $10^6$ | $a^{-1.93}$, $a \in (0.03, 0.1)$ | $10^6$ | $a^{-1.93}$, $a \in (0.006, 0.06)$ |
| $e_{\text{bin}}$ | $\langle e \rangle = 0.3 \pm 0.1$ | Sana et al. (2012) | Sana et al. (2012) | Sana et al. (2012) |
| $a_{\text{in}}$ | Sana et al. (2012) | $m_1, m_2 [M_\odot]$ | $m^{-1.7}$, $m \in (25, 150)$ | unif $\in (8-14) M_\odot$ |
| $e_{\text{in}}$ | $f(e) \propto e$ | $2 a_{\text{in}}$ | $f(e) \propto e$ | $2 a_{\text{in}}$ |
| $b$ | | | | |

**Note.** Row 1: semimajor axis of the binary orbit about the SMBH; row 2: eccentricity of the binary orbit about the SMBH; row 3: semimajor axis of the inner binary; row 4: eccentricity of the inner binary; row 5: mass of the binary components; row 6: semimajor axis of the single body orbit about the SMBH; row 7: eccentricity of the single body orbit about the SMBH; row 8: impact parameter of the single star about the binary center of mass.

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**Figure 1.** Trajectories of the bodies in individual realization, in the reference frame at rest with the SMBH. Black cross: SMBH. Green line: stellar black hole. Blue and red lines: binary star members.

**3. Results**

Figure 1 shows the trajectory of the bodies in a single realization. In this particular realization, the binary is ionized and the binary components are scattered into eccentric orbits.

Ionization occurs in 4.70% and 24.50% of the runs of sets A and B, respectively. If the binary remains bound, we classify this outcome as flyby. Other kinds of outcomes may occur: collisions/tidal disruptions between stars and the stellar black hole; exchanges, in which a binary member is exchanged with the black hole; and ejections, in which any of the bodies is ejected from the system and becomes unbound with respect to the SMBH. Table 2 summarizes the outcomes of the simulations.

The outcome crucially depends on the relative velocity at the encounter between the binary center of mass and the stellar black hole, as shown in Figure 2. For low relative velocity, most encounters lead to exchanges. As the relative velocity increases, the total energy of the three-body system becomes positive and ionizations become possible. However, for higher relative velocity the encounter is very rapid and little energy is exchanged, so that the ionization cross section rapidly falls off (Hut & Bahcall 1983; Hut 1983).
Note that the relative velocity is mainly due to the relative orbital orientation of the binary and the black hole, with some additional velocity dispersion given by the orbital eccentricity. Low relative velocity results when the encountering bodies orbit in the same plane and direction, while high velocity dispersion results from head-on encounters. The peak of ionizations occurs when the binary and the stellar black hole are mutually inclined by $\approx 21^\circ$.

In Figure 3 we show the semimajor axis and eccentricity of the ionized binary components for sets A and B, along with the observed parameters of the B-type S-stars, and the known G-objects.

In set A, the ionized stars remain at mild eccentricity, comparable to that of the original binaries. O and WR stars are too massive to receive a strong kick from the stellar black hole. Therefore, the O/WR stars from set A can match the orbital properties of only a few of the low-eccentricity S-stars, and none of the G-objects.

In contrast, the B-stars from set B get scattered into higher eccentricity orbits.

While the initial eccentricity of the binaries does not exceed 0.6, the ionized binary components distribution has a tail with 0.6–0.99 eccentricity. In particular, the semimajor axis and eccentricity of ionized stars from set B is compatible with the orbits of 12 S-stars in the semimajor axis range 0.016–0.075 pc (S1, S6, S8, S19, S29, S31, S33, S42, S54, S60, S71, R34) and the G2 object. The remaining S-stars have an exceedingly small semimajor axis compared to the ionized binaries of set B.

Figure 4 shows the semimajor axis-eccentricity map for the ionized stars of sets A and Bex, in which the CW disk is extended down to 0.006 pc. The distribution of ionized binary components from set Bex overlaps with that of the S-stars. As in set A, stars from set Aex cannot reproduce S-stars with an eccentricity greater than $\sim 0.7$.

### 4. Discussion

No star from set B can match the semimajor axis of the S-stars with a semimajor axis smaller than 0.016 pc. This is not surprising, since the orbits before and after the scattering event have to be crossing, i.e., the apocenter of the final orbit must be larger than the pericenter of the initial orbit. This sets a constraint on the initial binary orbit that depends on the final apocenter distance. The star S55 has an apocenter of 0.007 pc, the smallest apocenter among the S-stars. In order to reproduce its orbit via scattering, the initial orbit must have a semimajor axis of at least 0.01 pc, assuming an initial eccentricity of 0.3. Therefore, it is not possible to reproduce the innermost S-stars via this mechanism without assuming that the disk was more extended in the past.

One issue with our scenario is the abundance of stars that remain at lower eccentricity: only a few percent of stars end up in highly eccentric orbits. In other words, most stars remain within the initial disk. This is not an issue in the case of sets A and B, since the distribution of surviving binaries follows the CW disk properties as observed nowadays.

This is clear from Figure 5, which compares the eccentricity distributions of stars from set B with that of the S-stars with a semimajor axis between 0.016 and 0.075 pc. In this range, 46% of the stars are survived binary stars while ionized binary

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**Table 2**

| Outcomes | Set A | Set B | Set Aex | Set Bex |
|----------|-------|-------|---------|---------|
| Ionization | 4.70% | 24.50% | 2.71%   | 18.95%  |
| Collision  | 17.14%| 23.14%| 14.84%  | 20.15%  |
| Flyby     | 77.50%| 50.77%| 82.27%  | 60.51%  |
| Exchange  | 0.71% | 1.58% | 0.21%   | 0.40%   |
| Ejection  | 4.11% | 3.03% | 1.86%   | 1.04%   |

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8 Note that S22 is already compatible with the initial conditions; therefore, we do not include it in our list. The reason why Gillessen et al. (2017) do not classify it as part of the CW disk is because S22 has a different orbital orientation with respect to the CW disk. While our model is not able to reproduce tilting/disruption of the CW disk, several authors pointed out the mechanisms to explain the presence of young stars outside the disk (e.g., Subr et al. 2009; Alig et al. 2011; Lucas et al. 2013; Trani et al. 2016a).
components constitute the remaining 54%. This is slightly more than $2 \times 24.50 = 49\%$ from the total results reported in Table 2.

The bulk of the stars remains at mild eccentricity, consistent with the observed distribution of CW disk stars. However, the high-eccentricity tail is not consistent with the CW disk.

In order to isolate the high-tail component, we fit the eccentricity of all ionized and binary stars with $e < 0.5$ to a normal distribution, obtaining a value consistent to the initial one ($\mu = 0.2993$, $\sigma = 0.1053$). We then isolate the subset of data consistent with the obtained normal distribution by Monte Carlo sampling. We find that for set B, the high-eccentricity tail consists of 15% of the total stars, of which 14% are single stars and 1% are binaries. Thus, an average of $\approx 86$ B-stars must have resided in binaries to produce the 12 S-stars observed in the region.

Current spectroscopic studies of binaries in the Galactic center are limited down to $\approx 10M_{\odot}$ (Do et al. 2013). As such, the number of B-type stars in the region is largely unconstrained. Lu et al. (2013) estimates a total cluster mass between $1.4 \times 10^4$ and $3.7 \times 10^4 M_{\odot}$ assuming an initial mass function slope of $\alpha = -1.7$, extrapolated down to $1 M_{\odot}$. Their estimate gives an average of 194 B-type stars, which is more than a factor of 2 larger than our estimate above, assuming 100% binary fraction. Therefore, our scenario is consistent with the current state of observations. A better constraint on the B-type population in the Galactic center will be possible in the near-future with the advent of 30 m class telescopes (i.e., the Extremely Large Telescope, and the Thirty Meter Telescope; see Do et al. 2014; Gullieuszk et al. 2014). However, it is an issue for the observed distribution of S-stars to produce the 12 S-stars observed in the region.

Figure 4. Same as Figure 3, but for sets $B_{ex}$ (top) and $A_{ex}$ (bottom).

Figure 5. Eccentricity distributions of stars in the semimajor axis range of 0.016–0.075 pc. Green solid line: all ionized stars and survived binaries from set B. Gray dashed line: survived binary stars. Red dotted line: ionized binary stars. Yellow line with bootstrapped 1σ confidence band: normal fit to all stars and binaries with eccentricity less than 0.5. Blue short-dashed line: ionized and binaries consistent with the normal fit (consistent with CW disk distribution). Magenta dotted-dashed line: ionized and binary stars not consistent with the normal fit. Cyan dotted-dashed line: observed distribution of the S-stars in the considered semimajor axis range (arbitrary scale). All the other distributions are normalized so that the total distribution of binaries and ionized stars (green solid line) is normalized to one.

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Haas 2014), Kozai–Lidov mechanism within the disk itself (Chen & Amaro-Seoane 2014; Subr & Haas 2016), and resonant relaxation (Rauch & Tremaine 1996; Kocsis & Tremaine 2015; Bar-Or & Fouvy 2018). However, none of these mechanisms are able to disrupt the disk below a certain radius.

The simulations show that Keplerian three-body encounters can strongly affect the semimajor axis and eccentricity distribution of the stars about the SMBH. On the other hand, they can barely affect the orientation of the ionized binary components. Scattered stars mostly inherit the orbital orientation of the parent binary. However, this is not an issue for our scenario. Vector resonant relaxation can in fact randomize the orbits of the S-stars below 0.03 pc in a few million years (Hopman & Alexander 2006, see also Bar-Or & Fouvy 2018).

Note that not all the young stars in the outer 0.030 pc of the Galactic center are observed within the disk. The current estimate of the disk fraction varies between 20% and 50% (Bartko et al. 2009; Yelda et al. 2014). Our numerical setup does not include any torque, due to additional components (e.g., an outer gaseous torus) able to disrupt or tilt the disk. Therefore, we do not model the change of orientation of the young binaries and stars from the original stellar disk.

As shown in Figure 2 and Table 2, a large fraction of binaries survive the three-body encounter. These binaries have their orbital properties altered by the three-body encounter. This can have a strong impact on the production of binary mergers, including the triggering of gravitational-waves–induced coalescence for binaries of compact remnants. More details on this topic will be presented in the next paper of this series.

Recently, Szöllgyén & Kocsis (2018) found that vector resonant relaxation in Galactic nuclei tends to redistribute massive remnants in a disk configuration. If their result applies to the Galactic center, it would strongly affect the outcome type of the three-body encounters, depending on the relative inclination between the stellar and the remnant disk. If the
the stellar density estimate from Schödel et al. (2007) on the observed S-stars. The present location of the CW disk is highlighted by the orange line. In Figure 6 we show the encounter rate as a function of distance from the SMBH for a binary semimajor axis of 0.1 au (dotted line), 1 au (dashed line), and 10 au (solid line), using the stellar density estimate from Schödel et al. (2007). The blue line indicates the present location of the CW disk. The orange line highlights the region of the observed S-stars.

Disks were aligned, the low velocity dispersion would decrease the chance of ionization and increase exchanges and tidal disruptions (Figure 2). In contrast, a counter-aligned disk would result in increased flybys. A disk misalignment of 20°–30° would maximize the number of ionizing encounters. Note that a misaligned disk would likely induce Kozai–Lidov oscillation in the disk, albeit damped by the spherical cusp of old stars.

It is worth noting that the eccentricity of the S-stars increases toward a small semimajor axis. This is in agreement with the predictions of our model; as the encounter rate increases toward the center, it is natural to expect a higher chance of producing stars in highly eccentric orbits.

4.1. Rates and Timescales

In Figure 6 we show the encounter rate between binaries and single stars as a function of the radius from the SMBH, computed using Equation (11) from Leigh et al. (2016). For the density profile, we use the broken power law of Schödel et al. (2007). Note that both stellar and compact remnant distribution below 0.1 pc is highly uncertain, so the derived encounter rates also suffer from the same uncertainties. Nonetheless, the Galactic center is expected to host ~10,000 black holes in its central parsec from both theoretical considerations and observational evidence (Bahcall & Wolf 1976, 1977; Merritt 2010; Hailey et al. 2018).

A binary formed in the Galactic center can undergo 1–10^3 encounters in less than 6–15 Myr, which is the recent estimated age of the S-stars (Habibi et al. 2017). Therefore, the binaries that survive the first encounter can be ionized during subsequent encounters. In Appendix A we present supplementary sets of simulations that follow the surviving binaries from sets A and B, undergoing repeated encounters.

5. Conclusions

We have run four-body simulations of three-body encounters between binary stars and stellar black holes orbiting the SMBH in our Galactic center. We assume that both the S-stars and the CW disk stars were born in binaries in the same nearly Keplerian disk around SgrA*. We consider binaries composed of O/WR-type or B-type stars, undergoing an encounter with 30 M⊙ black holes.

B-type binaries can be easily ionized by the encounter, and their components can get scattered into highly eccentric orbits. On the other hand, O/WR-type binaries are less easily disrupted, and the ionized stars remain in low-eccentricity orbits.

We can reproduce the orbits of 12 S-stars and the G2 object just by assuming that the initial binaries lie in the CW disk as observed nowadays. To reproduce the S-stars below 0.016 pc, we need to extend the initial binary distribution down to 0.006 pc. Even though in this way we can reproduce the whole population of S-stars, the simulations also predict a low-eccentricity population of B- and O-type stars within the inner 0.5 arcsec of the Galactic center, in contrast with current observations.

These findings would suggest that the population of S-stars below 0.016 pc is a different population from the stars of the CW disk, despite their similar age. A single origin for both the S-stars and the CW disk via this scenario can be plausible if a mechanism to disrupt the stars in the disk below 0.03 pc is provided.

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Appendix A

Repeated Encounters

The surviving binaries can also undergo multiple encounters, if the encounter rate is high enough. This does not alter only the orbital parameters of the inner binary, but also the orbital parameter of the binary around the SMBH. In this section we investigate whether these repeated encounters can drive the binaries to migrate in the a–e space, until they are finally ionized by an encounter. In principle, this might result in the production of stars in highly eccentric orbits well below the inner edge of the original disk at 0.03 pc.

We take the orbital properties of the binaries that survive the encounter in sets A and B, and use them as initial conditions for a new encounter. We repeat this procedure in order to simulate three encounters after the first. Figure 7 shows the distribution of the surviving binaries and corresponding ionized stars after the multiple encounters. Because the binaries are, on average, more massive than the stellar black hole, the binaries do not migrate significantly in the a–e space with respect to the initial conditions. As a consequence, the distribution of stars ionized after multiple encounters does not change very much with respect to the distribution shown in Figure 3.
Appendix B

Simulations with Different Black Hole Masses

To check if black holes with smaller masses can also result in the ionization of B-type binaries, we have three additional sets of simulations using the same setup of set Bex but setting the mass of the black hole to $\epsilon M_{10}$, $\epsilon M_{500}$, and $\epsilon M_{1000}$. In Figure 8 we show the $a$–$e$ distribution of the ionized stars and surviving binaries for these supplementary sets. As expected, the ionized stars reach a lower eccentricity when the stellar black hole mass is smaller. Nonetheless, the achieved eccentricity is still high enough to match the orbital properties of several S-stars with $e \approx 0.8$. Conversely, for $m > 500 M_\odot$ (i.e., intermediate mass black holes; IMBHs), more stars get ionized and kicked into highly eccentric orbits.

Interestingly, for $m_{bh} = 500$ and $1000 M_\odot$, binary stars are also scattered into a highly eccentric orbit. Current observations do not rule out that some of the S-stars may in fact be binaries (Chu et al. 2018). Furthermore, the binary merger scenario for the origin of G2 requires the presence of binaries in highly eccentric orbits about the SMBH (Witzel et al. 2014; see also Stephan et al. 2016).

The formation of binary S-stars via encounters with IMBHs will be investigated in more detail in our forthcoming work.

Figure 7. Semimajor axis-eccentricity map of ionized binary components and surviving binaries for multiple encounters in sets B (left) and A (right). Black contours: initial conditions derived from the first (solid), second (dashed), and third (dotted) encounter. Red solid contour with backward diagonal fill: ionized binary components in the second encounter. Green dashed contour with backward diagonal fill: ionized binary components in the third encounter. Purple dotted contour with forward diagonal fill: ionized binary components in the fourth encounter.

Figure 8. Semimajor axis-eccentricity map of ionized binary components in set B, for encounters with a stellar black hole mass of $\epsilon M_{10}$ (red contour with backward diagonal fill), and $\epsilon M_{300}$ (blue contour with forward diagonal fill). Black contour: initial conditions. Yellow circles with green cross: S-stars (from Gillessen et al. 2017). Yellow stars with green contour: G1 and G2 objects.

Appendix B

Simulations with Different Black Hole Masses

To check if black holes with smaller masses can also result in the ionization of B-type binaries, we have three additional sets of simulations using the same setup of set Bex but setting the mass of the black hole to $10 M_\odot$, $500 M_\odot$, and $1000 M_\odot$. In Figure 8 we show the $a$–$e$ distribution of the ionized stars and surviving binaries for these supplementary sets.

As expected, the ionized stars reach a lower eccentricity when the stellar black hole mass is smaller. Nonetheless, the achieved eccentricity is still high enough to match the orbital properties of several S-stars with $e \lesssim 0.8$. Conversely, for $m > 500 M_\odot$ (i.e., intermediate mass black holes; IMBHs), more stars get ionized and kicked into highly eccentric orbits.

Interestingly, for $m_{bh} = 500$ and $1000 M_\odot$, binary stars are also scattered into a highly eccentric orbit. Current observations do not rule out that some of the S-stars may in fact be binaries (Chu et al. 2018). Furthermore, the binary merger scenario for the origin of G2 requires the presence of binaries in highly eccentric orbits about the SMBH (Witzel et al. 2014; see also Stephan et al. 2016).

The formation of binary S-stars via encounters with IMBHs will be investigated in more detail in our forthcoming work.

Figure 8. Semimajor axis-eccentricity map of ionized binary components in set B, for encounters with a stellar black hole mass of $10 M_\odot$ (red contour with backward diagonal fill), and $30 M_\odot$ (blue contour with forward diagonal fill). Black contour: initial conditions. Yellow circles with green cross: S-stars (from Gillessen et al. 2017). Yellow stars with green contour: G1 and G2 objects.

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