A RAPID EVOLVING REGION IN THE GALACTIC CENTER:
WHY S-STARS THERMALIZE AND MORE MASSIVE STARS ARE MISSING

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ABSTRACT

The existence of “S-stars” within a distance of 1″ from SgrA∗ contradicts our understanding of star formation, due to the forbiddingly violent environment. A suggested possibility is that they form far and have been brought in by some fast dynamical process, since they are young. Nonetheless, all conjectured mechanisms either fail to reproduce their eccentricities—without violating their young age—or cannot explain the problem of “inverse mass segregation”: The fact that lighter stars (the S-stars) are closer to SgrA∗ and more massive ones, Wolf-Rayet (WR) and O-stars, are farther out. In this Letter we propose that the responsible for both, the distribution of the eccentricities and the paucity of massive stars, is the Kozai-Lidov-like resonance induced by a sub-parsec disk recently discovered in the Galactic center. Considering that the disk probably extended to smaller radius in the past, we show that in as short as (a few) 10⁶ years, the stars populating the innermost 1″ region would redistribute in angular-momentum space and recover the observed “super-thermal” distribution. Meanwhile, WR and O-stars in the same region intermittently attain ample eccentricities that will lead to their tidal disruptions by the central massive black hole. Our results provide new evidences that SgrA∗ was powered several millions years ago by an accretion disk as well as by tidal stellar disruptions.

Subject headings: Galaxy: center — Galaxy: kinematics and dynamics — methods: analytical — stars: massive — stars: Wolf-Rayet

1. INTRODUCTION

Observations of the Galactic Center (GC) going back as far as 20 years (see Genzel et al. 2010, for a review) reveal three facts: (1) An isotropic cusp of young O/B stars and Wolf-Rayet (WR) stars, starting at a distance of 30″ from SgrA∗ and extending inward to about 1″ (1″ ≃ 0.04 pc); (2) a mildly thick stellar disk, of about 100 WR and O-type stars, spanning from an inner radius of 1″ to an outer radius of about 10″; and (3) populating the innermost region, within 1″ from SgrA∗, are a population of B stars, commonly referred to as the “S-stars”, but no WR/O stars. A single star-formation (SF) episode may have explained the formation of disk and cusp stars (Lu et al. 2013), the S-stars, however, cannot have been born in this scenario, because the violent environmental conditions within 1″ do not allow in-situ SF. One way of populating that region is by dynamical friction, but the associated timescale is too long. For this reason, the problem has the reputation of the “paradox of youth” (Morris 1993; Ghez et al. 2003).

This issue has led to the idea that S-stars could have formed at larger radii and brought in later by an efficient dynamical mechanism. One possibility is tidal separation of binaries (Hills 1991; Gould & Quillen 2003; Ginsburg & Loeb 2006). A binary, formed at larger radius, can be set in such an orbit that at periapsis it will be tidally separated by the central massive black hole (MBH), leaving one star, which could be a B star, bound to the MBH at a typical radius of ≲ 1″. However, the captured stars would have very high eccentricities, typically about 0.93 − 0.99 (see the original work of Hills 1991 and Amaro-Seoane 2012 for a review). It would require some 20 − 50 Myr for them to achieve the observed near-thermal distribution (e.g. Perets et al. 2009; Antonini & Merritt 2013; Zhang et al. 2013), with the aid of a very dense cusp of segregated old stars which is in contradiction with current observations (Buchholz et al. 2009; Do et al. 2009). Even in the presence of a dense cusp, there are two additional issues: (1) the same process would work for WR/O stars, and we do not see them within ≲ 1″ (Alexander 2011) and (2) the oldest O/WR stars are ≲ 10 Myr, so there has to be at least two SF episodes, since S-stars inside 1″ need ≥ 20 Myr to thermalize.

Since the stellar disk initially must be gaseous, it has been proposed as another possibility that B stars migrated in it towards the center (Levin 2007; Griv 2010). However, (1) this cannot explain the eccentricities of the S-stars because the migrating stars will remain on near-circular orbits (Perets et al. 2009; Madigan et al. 2011; Antonini & Merritt 2013), and (2) WR/O stars would have migrated towards the center due to the same mechanisms, but we do not observe them there. Once SF is over (no more gas), the stars in the disk, including the WR/O stars, would secularly torque each other and drift away from nearly-circular orbits to rather eccentric ones (Madigan et al. 2009), and hence at periapsis they would populate the central 1″, but, still, we do not see WR/O-stars there either.

In this Letter we show that, provided the disk was heavier and more extended in the past (Navashin et al. 2007; Wardle & Yusef-Zadeh 2008; Bonnell & Rice 2008; Hobbs & Navashin 2008; Alig et al. 2011; Mapelli et al. 2012), it created a rapid evolving region (RER) inside 1″, where the angular momenta of stars rapidly redistribute because of a Kozai-Lidov-like resonance. This RER can explain both the eccentricities of S-stars and the absence

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of WR/O-stars because the latter are tidally disrupted.

2. DISK-DRIVEN EVOLUTION

2.1. Timescales

To understand the effect of the disk, we first analyze the torque exerted by a wire of mass $\delta m$ and radius $R$ on a background star of semi-major axis $a$ (Ivanov et al. 2005; Subr & Karas 2005; Lockmann et al. 2008). Chen et al. (2011) showed that the timescale for the wire to change the angular momentum of the star by a full cycle, i.e. to vary the eccentricity $e$ of the star from its minimum value to the maximum and back, is

$$T_K = \begin{cases} \frac{2}{3\pi} \frac{M_*}{\delta m} \left(\frac{a}{R}\right)^3 P(a), & \text{Kozai - Lidov}, \ a \leq R/2, \\ \frac{16\sqrt{2} M_*}{3\pi} \left(\frac{a}{R}\right)^{1/2} P(a), & \text{Non - determ.}, \ a > R/2, \end{cases}$$

where $M_* = 4 \times 10^6$ $M_\odot$ is the mass of the MBH, and $P(a) = 2\pi (a^3/GM_*)^{3/2} \simeq 1.4 \times 10^3 (a/[0.1 \ \text{pc}])^{3/2} \ \text{yr}$ is the orbital period of the star. The reason for $R/2$ is a requirement for having all orbits within the radius of the wire, including the most eccentric ones, $R_{apo} = a(1 + e) \approx 2a$, with $R_{apo}$ the apocenter distance. Equation (1) is a generalization of the secular Kozai-Lidov (KL) timescale (see Naoz et al. 2013, and references therein): (1) In the regime $a \lesssim R/2$ we recover this well-known secular phenomenon but (2) when $a \gtrsim R/2$, i.e. when stellar orbits cross a sphere with a radius of the wire, it provides good approximation to the non-deterministic (ND), but not necessarily chaotic, evolution of the stellar orbit.

Admitting that an extended disk is a superposition of wires, one can derive the corresponding timescale $T_K$ for the sum of torques to change the orbital elements of a star in a full cycle (Chang 2009):

$$1/T_K = \int_{R_{in}}^{R_{out}} d(1/T_K),$$

where $R_{in}$ and $R_{out}$ denote the inner and outer radii of the disk. $d(1/T_K) \propto \delta m = 2\pi \Sigma(R)dR$, and $\Sigma(R)$ is the surface density of the disk. During $T_K$, when secular evolution predominates, a star typically oscillates a full cycle between the maximum and minimum eccentricities, which are predetermined by three orbital parameters, namely eccentricity, position angle of periapsis ($\omega$), and inclination angle relative to the disk ($\theta$). At any intermediate stage of that cycle, the “instantaneous” evolution timescale, defined as $t_K(l) \equiv l/|l|$, can be derived from

$$t_K(l) \simeq l T_K'(a)$$

(e.g. Chang 2009, Chen et al. 2011), where $l = \sqrt{1 - e^2}$ is the dimensionless angular momentum and the dot denotes the time derivative. The linear dependence on $l$ reflects the coherence of the disk torque during $t_K(l)$.

The MBH and cusp stars affect the KL-like evolution by perturbing the orbital parameters $(e, \omega, \theta)$. We must distinguish two regimes: (1) At high $e$, $\omega$ is significantly perturbed, because of the induced relativistic (GR) precession rate,

$$\omega_{GR} = 3(GM_*)^{3/2}/\left(\frac{r^2 c^5 a^{5/2}}{2}\right),$$

with $c$ the speed of light. It may even exceed the KL precession rate,

$$\omega_K \simeq 2\pi/(T_K' l)$$

(e.g. Chang 2009). When this happens, the disk coherence is broken and the KL cycle quenched, hence it defines a boundary to the region in phase space where the evolution is driven by the disk. In some loose sense, this boundary is analogous to the Schwarzschild barrier in galactic nuclei (Merritt et al. 2011; Brem et al. 2014). (2) At low $e$, the perturbation on $\omega$ originates from the total stellar mass $M_*(a)$ enclosed by the orbit. The Newtonian precession rate

$$\omega_M \simeq 2\pi l M_*(a)/|M_*(a) P(a)|$$

may exceed $\omega_{GR}$ in this regime, which imposes a second boundary (Chen et al. 2011).

Outside these boundaries, evolution of angular momentum will be determined by either two-body relaxation, with a characteristic timescale of

$$t_{2b}(l) \equiv |l|/|l| \simeq l^2 (M_*/m_*)^2 P(a)/(N \ln \Lambda)$$

(e.g. Kocsis & Tremaine 2011), or (scalar) resonant relaxation (RR, Rauch & Tremaine 1999), on a timescale of

$$t_{RR,s}(l) \equiv l/|l| \simeq l^2 \left(\frac{M_*/m_*}{2}\right)^2 P^2(a)/N \Lambda.$$
we can estimate the instantaneous evolution timescale as:

\[ t_{\text{RR}} = \frac{R}{v_{\text{esc}}} \]

\[ \frac{1 - e}{e} = \frac{e(1 - e)}{l^2} a_{\text{K}}(l) \simeq \frac{e(1 - e)}{l} r_{\text{K}}(a). \]  

We can then identify the lines with constant evolution timescales, i.e. the contours. We call them “isochrones”, and depict them as blue dotted curves. Outside the RER the isochrones are shown in grey and determined by either two-body scattering, \( e (1 - e) \ t_{2b}(l)/l^2 \), or RR process, \( e (1 - e) \ t_{\text{RR}, \alpha}(l)/l^2 \), whichever timescale is shorter.

Two striking conclusions from a first look at this figure are (1) stars in the RER evolve on very short timescales, of the order of \( 10^{3-5.5} \) yrs, to complete a full KL cycle. As discussed previously, after a time of \( t_{\text{RR}, \gamma} \), any star at \( a < 1'' \) would have fully explored the angular-momentum range within the RER. (2) As the disk recedes, the boundaries come closer and the RER shrinks. Any star that finds itself out of the RER will be “frozen” from the point of view of another star which still is in it: The timescales outside RER are long.

Since short evolution timescale leads to low probability of stellar distribution, today (right panel of Figure 1), the absence of S-stars within the RER boundaries may be a plausible observational corroboration that the RER does exit at the GC. At present, the only measured object within the RER boundaries is G2 (red dots, Gillessen et al. 2013). From its nearby isochrones, we see that G2 must have been formed less than \( 10^{3.5} \) yrs ago.

3. SCULPTING THE GALACTIC CENTER

3.1. Rapid Evolving Region

In Figure 1 we display the boundaries of the RER. The left panel corresponds to \( R_{\text{in}} = 10^{-6} \) pc and the right one to \( R_{\text{in}} = 0.04 \) pc. In this \( (1 - e) - a \) plane, at any location, one can estimate the instantaneous evolution timescale as:

\[ t_{\text{RR}, \gamma} \simeq 1.5 \times 10^6 (0.5 + e^2)^{-2}(a/1'')^{-0.65} \text{ yr for stars in the central arcsec of the Galaxy.} \]

The two more successful scenarios of depositing B stars close to the GC, i.e. binary separation and disk migration, place these stars well within the RER (left panel of Figure 1). These stars are able to sufficiently mix in angular-momentum space, on a timescale of \( t_{\text{RR}, \gamma} \simeq 0.7 \) Myr in the binary-separation scenario and of \( t_{\text{RR}, \gamma} \simeq 6 \) Myr in the disk-migration one. The latter mechanism (disk migration) requires much longer time to reach the superthermal distribution in eccentricities because of the \( e \) dependence of Equation (1). We note that these timescales are at least 10 times shorter than those from the earlier models, which neglected the RER.

The fully-mixed eccentricities do not necessarily have a thermal distribution (Brem et al., in preparation). Following the argument that longer evolution timescale correlates with higher probability distribution, we will have \( dN/de \propto dt/de \), and substituting Equation (10) for \( dt/de \), we can derive \( dN/de \propto dt/de \propto e/l \). This distribution function is steeper than a thermal one, \( dN/de \propto e \). The steepness stems from the linear dependence of the evolution timescale \( (l/|l|) \) on the orbital angular momentum \( l \), whereas in the case of two-body relaxation and RR, the evolution time scales with \( 1 - e^2 \).

Figure 2 compares various cumulative probability distribution functions (CPDFs) for \( e \), derived from two theoretical models — a thermal one and our RER model— as well as from observations. It is clear that compared to the thermal distribution, the RER one is in better agreement with the observations.

3.3. Depleting WR/O stars

For a star of mass \( m_\star \) and radius \( r_\star \), if its eccentricity becomes so high that the orbital pericenter distance from SgrA* becomes smaller than the tidal radius

\[ r_t \simeq r_\star \left( \frac{M_\bullet}{m_\star} \right)^{1/3} \simeq 4 \times 10^{-6} \text{ pc} \left( \frac{r_\star}{R_\odot} \right) \left( \frac{m_\star}{M_\odot} \right)^{-1/3} \]

(11)

it will be tidally disrupted (Rees 1988). In Figure 1 we show typical \( r_t \) associated with B, O, and WR stars. Once stars cross it from the right to the left, they are lost. This drain is enhanced in the RER by the shorter
sequence, since they have evolved off the main sequence massive, and shorter-lived. We hence adopt larger radii as main-sequence stars, but O- and WR stars are more massive, and shorter timescales, as the stars progressively move to the left.

To calculate $r_t$, we assume $m_\star = (7, 25, 60) M_\odot$ respectively for the three types of stars (Zinnecker & Yorke 2007). Main-sequence stars less massive than $7 M_\odot$ are below the current detection limit of observations. Correspondingly, we have adopted $r_s = 4 R_\odot$ for main-sequence B stars, and $r_s = 40 R_\odot$ and $80 R_\odot$ respectively for O- and WR stars. B stars can be envisaged as main-sequence stars, but O- and WR stars are more massive, and shorter-lived. We hence adopt larger radii for them, 3–4 times larger than typical radii on the main-sequence, since they have evolved off the main sequence (Paumard et al. 2006; Bartko et al. 2010).

We can see in the left panel of Figure 1 that any WR star in a stripe defined between $0.15'' < a < 0.8''$ and any O star in $0.2'' < a < 0.8''$ will be tidally disrupted, because it will have explored all the $(1-e)$ space in $\sim 10^6$ yrs. Similarly, for B stars, the corresponding stripe is delimited by the narrower zone $0.5'' < a < 0.8''$. In fact, this predicted gap (for B stars) does occur in the current distribution of S-stars (right panel of Figure 1). If we had assumed a disk mass of $M_d > 3 \times 10^4 M_\odot$, this gap would have broadened up to incorporate the region where $a < 0.5''$, and it would contradict current observations. Therefore, an upper limit to the disk mass can be derived, approximately $3 \times 10^4 M_\odot$.

By looking at the left panel again, we realize that only WR/O stars with $a > 0.8''$ and low $e$ can survive, because they are always outside of the RER and cannot drift quickly enough to higher $e$. Indeed, WR/O stars have been discovered only at $a \geq 1''$ but not inside. In principle, our model cannot deplete WR/O stars at $a < 0.1''$, because at such small $a$ the RER does not reach the tidal radii. Observations did not find any WR/O star there, maybe because the extrapolation of the disk density profile $\Sigma(R) \propto R^{-1.4}$ results in $< 1$ WR/O star at $R < 0.1''$.

4. DISCUSSIONS

In this Letter we have presented a picture that explains the distribution of the eccentricities of S-stars and the absence of more massive stars within 1'' of SgrA*. Our sole hypothesis is that around $(1-10)$ Myr ago, the disk had extended down to $R \leq 0.04$ pc. We find that the torque exerted by the disk creates a region at the GC in which the dynamical evolution is significantly accelerated as compared to other regions, by a factor ranging from 10 to 100 times, and we call it the "rapid evolving region".

Our scenario agrees with current observations about the nonexistence of an old segregated cusp in the GC (Buchholz et al. 2009; Do et al. 2009), contrary to other works, which crucially rely on the cusp to thermalize the S-stars (Perets et al. 2009; Madigan et al. 2011).
Antonini & Merritt 2013; Zhang et al. 2013). Because the time that is needed to randomize angular momentum is now shortened to \((0.7 - 6)\) Myr, our model is able to accommodate various possibilities for the formation of S-stars, while other models rely heavily on when S-stars were brought to the GC (Perets et al. 2009; Antonini & Merritt 2013).

Moreover, our RER scenario unifies two observational facts that have been thought until now to be disconnected: We successfully populate the observed range of \(e\) for B stars and we can duplicate the observed discontinuity of WR/O stars above and below \(1''\). Both of them will be established in as short as \((0.7 - 6)\) Myr, so we can even unify the origin of all the young stellar populations in the GC to \textit{only one single SF episode}. This unification does pose a problem for earlier models: If all B stars formed simultaneously with WR/O stars, since this must be less than 6 Myr ago (because WR/O stars cannot be older), two-body relaxation and RR will fail to explain the distribution of \(e\).

At this stage, it is crucial to theoretically understand the dynamical response of the old stellar population to the RER, and test it against the observations of dimmer (than B-type), older stars. If they match, it would be a robust evidence that the RER has indeed played a role in sculpting the GC.

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