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THE FRAGMENTING PAST OF THE DISK AT THE GALACTIC CENTER: THE CULPRIT FOR THE MISSING RED GIANTS

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ABSTRACT

Since 1996 we have known that the Galactic Center (GC) displays a core-like distribution of red giant branch (RGB) stars starting at $\sim 10''$, which poses a theoretical problem because the GC should have formed a segregated cusp of old stars. This issue has been addressed invoking stellar collisions, massive black hole binaries, and infalling star clusters, which can explain it to some extent. Another observational fact, key to the work presented here, is the presence of a stellar disk at the GC. We postulate that the reason for the missing stars in the RGB is closely intertwined with the disk formation process, which initially was gaseous and went through a fragmentation phase to form the stars. Using simple analytical estimates, we prove that during fragmentation the disk developed regions with densities much higher than a homogeneous gaseous disk, i.e., "clumps," which were optically thick, and hence contracted slowly. Stars in the GC interacted with them and in the case of RGB stars, the clumps were dense enough to totally remove their outer envelopes after a relatively low number of impacts. Giant stars in the horizontal branch (HB), however, have much denser envelopes. Hence, the fragmentation phase of the disk must have had a lower impact on their distribution, because it was more difficult to remove their envelopes. We predict that future deeper observations of the GC should reveal less depletion of HB stars and that the released dense cores of RGB stars will still be populating the GC.

Key words: Galaxy: center – Galaxy: kinematics and dynamics – methods: analytical – stars: horizontal-branch

1. INTRODUCTION

The observations of the inner 0.5 pc ($12''$) of the Galactic Center (GC) has led in recent years to interesting and challenging discoveries that cannot be fully addressed in the context of standard two-body relaxation theory (for a general summary about the GC, see, e.g., Genzel et al. 2010). On the one hand, Buchholz et al. (2009) and Do et al. (2009) discovered a spherical core of red giants (RGs) with a flat surface-density profile. If these RGs trace an underlying old stellar population (of $\sim 10^9$ yr), the total mass of the old stars might be $\sim 10^5\, M_\odot$ (Merritt 2010). Moreover, Levin & Beloborodov (2003), Tanner et al. (2006), Paumard et al. (2006), Lu et al. (2009), and Bartko et al. (2010) unveiled the presence of a mildly thick ($H/R \simeq 0.1$, with H the height and R the radius) and young (2–7 Myr) stellar disk, of about 100 Wolf–Rayet (WR) and O-type stars in near-circular orbits ($e < 0.4$). The disk has a total mass of $\sim 10^4\, M_\odot$ and a surface-density profile of $\Sigma_d(R) \propto R^{-2}$. The inner and outer edges of the disk are approximately at $R_{\rm in} \simeq 0.04$ pc and $R_{\rm out} \simeq 0.5$ pc. There is also an indication of a second disk, with more eccentric stellar orbits ($e > 0.6$) and smaller disk mass ($< 5 \times 10^3\, M_\odot$), inclined by about 115° relative to the first one, and with a contrary rotation. However, the existence of this second disk is still in debate (Paumard et al. 2006; Lu et al. 2009; Bartko et al. 2009).

The problem of the missing RGs has been addressed by a number of different authors whose approaches can be divided into three general scenarios: (1) along with the discovery of the missing stars in the red giant branch (RGB), Genzel et al. (1996) suggested the interpretation that this could be attributed to stellar collisions due to the extreme stellar densities reached in the GC. This idea has been explored extensively in the works of Davies et al. (1998), Alexander (1999), Bailey & Davies (1999), and Dale et al. (2009), but it cannot fully explain the observations; (2) it has also been hypothesized that a massive black hole (MBH) binary could scour out a core in the GC via three-body slingshots (Baumgardt et al. 2006; Portegies Zwart et al. 2006; Matsubayashi et al. 2007; Löckmann & Baumgardt 2008; Gualandris & Merritt 2012), but in order to reproduce a core as large as what is observed, the mass of the secondary MBH at the GC should be at least $\sim 10^5\, M_\odot$. This would imply that the Milky Way (MW) recently had a major merger, ruled out by current observations (e.g., Hansen & Milosavljević 2003; Yu & Tremaine 2003; Chen & Liu 2013); (3) infalling clusters toward the GC could also steepen the density profile outside $10''$, making the inner $10''$ like a core (Kim & Morris 2003; Ernst et al. 2009; Antonini et al. 2012), but strong mass segregation can rebuild the cusp in the MW in about 1/4 of the relaxation time (Alexander & Hopman 2009; Preto & Amaro-Seoane 2010; Amaro-Seoane & Preto 2011). Hence, this argument would require a steady inflow of a cluster roughly every 10^7 yr to avoid cusp regrowth.

In this Letter we propose a simple, new scenario in which the depletion of RGs is merely a consequence of the natural fragmentation phase that the gaseous disk experienced. We prove that the regions of overdensity in the star-forming disk could have removed the envelope of stars in the RGB after a rather low number of crossings through the disk. The exact number depends on effects of nonlinearity that cannot be addressed in our simple analytical model. In Section 2 we introduce the formation of overdensity regions in the star-forming disk and the conditions for them to annul the envelope of RGB stars. In Section 3 we derive the mean number of crossing times that a star will hit one of the clumps in the disk depending on its orbital parameters and in Section 4 the net effect on the clumps. We summarize our findings in Section 5 as well as the main implications.

2. FORMATION OF CLUMPS IN THE GASEOUS DISK AND ENVELOPE REMOVAL CRITERION

The in situ star formation model suggests that the disk of WR/O giant stars formed 2–7 Myr ago in an accretion disk around the central MBH (Levin & Beloborodov 2003; Genzel et al. 2003). To become self-gravitating and trigger star formation, the disk should initially have had at least $10^4\,M_\odot$ of gas, and could have been as massive as $10^5\,M_\odot$ (Nayakshin & Cuadra 2005). When a RG crosses the gaseous disk with a relative velocity v_*, only that part of the envelope with a surface density lower than

$$\Sigma_* \simeq \frac{v_*}{\sqrt{Gm_*/r_*}}\Sigma_d \tag{1}$$

will be stripped off the RG by the disk because of the momentum imparted to that section of the RG (Armitage et al. 1996). In the above equation, Σ_d denotes the surface density of the disk where the impact happens, and m_* and r_* are the mass and radius of the RG, so that $\sqrt{Gm_*/r_*}$ represents the escape velocity from the RG calculated at its surface. The reason why we use the value of the escape velocity here and not at deeper radii in the RG is that the density of a *homogeneous* disk,

$$\Sigma_d \sim \frac{10^4\,M_\odot}{(0.1\,\mathrm{pc})^2} \sim 10^6\,M_\odot\,\mathrm{pc}^{-2} \sim 200\,\mathrm{g\,cm}^{-2}, \tag{2}$$

is so low that when the RG crosses the disk, it will be barely scratched, i.e., only material at the surface will be removed from it. For example, an impact at a distance 0.1 pc from the central MBH of mass $M_\bullet \simeq 4\times10^6\,M_\odot$ has a relative velocity of $v_* \sim 400\,\mathrm{km\,s}^{-1}$. By comparing Σ_* from Equation (1) and the RG model from Armitage et al. (1996) for $m_* \sim 1\,M_\odot$ and $r_* \sim 100\,R_\odot$, less than $\sim 10^{-7}\,M_\odot$ of the RG envelope will be lost due to the impact. Such a gaseous disk will not induce any noticeable change in the structure of the RG. Only more massive disks, $\gtrsim 10^5\,M_\odot$, which are long-lived in the gaseous phase, $\gtrsim 10^7$ yr, can lead to a more efficient depletion of the envelope,[1] but these numbers strongly contradict current observations (Nayakshin & Cuadra 2005; Paumard et al. 2006).

Because the disk itself is too tenuous to strip the entire envelope of any RG flying through it, we postulate that the regions of overdensity that progressively form in the disk, referred to as "clumps," are dense enough to efficiently remove it completely and release the inner compact core of the RGs. This depletion of RGs leads to their flat spatial distribution and implicates the existence of a similar number of dense cores within the same volume.

During fragmentation, a clump must satisfy the Jeans criterion to become self-gravitating, that is, if its radius is R_c, the initial diameter must be comparable to the Jeans length, i.e., $2R_c \sim \lambda_J \simeq c_s/(G\rho)^{1/2}$, where ρ is the local gas density, and c_s the effective sound speed. Using $M_c \simeq \rho R_c^3$ and $c_s \simeq H\sqrt{GM_\bullet/R^3}$ in hydrostatic equilibrium, we can now link the properties of the clump, its mass M_c and radius R_c, with the scale height H of the disk and the distance R to SgrA*,

$$\frac{R_c}{R} \simeq \frac{4M_c}{M_\bullet}\left(\frac{R}{H}\right)^2 \simeq 10^{-2}\left(\frac{M_c}{10^2\,M_\odot}\right)\left(\frac{H/R}{0.1}\right)^{-2}. \tag{3}$$

From the last equation we can derive the volume density ρ_c and surface density Σ_c for the clumps,

$$\rho_c \simeq \rho \simeq \frac{M_c}{R_c^3} \simeq \frac{M_\bullet}{64R^3}\left(\frac{M_\bullet}{M_c}\right)^2\left(\frac{H}{R}\right)^6$$
$$\simeq 10^{-11}\,\mathrm{g\,cm}^{-3}\left(\frac{M_c}{10^2\,M_\odot}\right)^{-2}\left(\frac{H}{0.1R}\right)^6\left(\frac{R}{0.1\,\mathrm{pc}}\right)^{-3}, \tag{4}$$

$$\Sigma_c \simeq \rho_c R_c \simeq \frac{M_\bullet}{16R^2}\left(\frac{M_\bullet}{M_c}\right)\left(\frac{H}{R}\right)^4$$
$$\simeq 2\cdot 10^4\,\mathrm{g\,cm}^{-2}\left(\frac{M_c}{10^2\,M_\odot}\right)^{-1}\left(\frac{H}{0.1R}\right)^4\left(\frac{R}{0.1\,\mathrm{pc}}\right)^{-2}. \tag{5}$$

The stars in the disk are mainly WR/O, which have been observationally constrained to have masses ranging between 64 and 128 $M_\odot$ (Zinnecker & Yorke 2007), so in the following we adopt $M_c = 10^2\,M_\odot$ as the fiducial value. We take $H/R = 0.1$ as the thickness in view of the current observations of the disk at the GC. Then from Equations (2) and (5), we can see that a clump is typically $\sim 10^2$ more efficient in destroying RGs than its analog in an homogeneous gaseous disk.

We note that the argument that led to Equation (3) at the same time ensures that the clumps will withstand the tidal forces arising from the MBH, because the Roche radius, $R(M_c/M_\bullet)^{1/3} \simeq (R/34)[M_c/(10^2\,M_\odot)]^{1/3}$, is about three times larger than R_c for an $100\,M_\odot$ clump.

When a clump collides with a RG of mass $m_* \simeq 1\,M_\odot$ and radius $r_* \simeq 150\,R_\odot$, at a relative velocity comparable to the orbital velocity of the clump $v_c \simeq 400[R/(0.1\,\mathrm{pc})]^{-1/2}\,\mathrm{km\,s}^{-1}$, the amount of mass stripped off from the star is

$$M_{\mathrm{loss}} \sim 10^{-5}\,M_\odot \frac{v_c}{\sqrt{Gm_*/r_*}}\left(\frac{\Sigma_c}{10^4\ \mathrm{g\ cm}^{-2}}\right)$$
$$\sim 10^{-4.6}\,M_\odot\left(\frac{M_c}{10^2\,M_\odot}\right)^{-1}\left(\frac{R}{0.1\,\mathrm{pc}}\right)^{-5/2}. \tag{6}$$

The first line was derived by Armitage et al. (1996) numerically, and in the second line we have used Σ_c from Equation (5) for scaling.

Successive impacts will remove *even more efficiently* the outer layer of the RG. This is because the density gradient of the RG decreases (see Equation (9) of Armitage et al. 1996 or Kippenhahn & Weigert 1990): the enclosed mass is reduced, and the polytropic constant increases. The envelope therefore expands to even larger radii (see upper panel of Figure 7 in Armitage et al. 1996). The timescale for the expansion is the convective time, much shorter than the orbital period of the star—the RG has achieved hydrostatic equilibrium long before the next impact. To account for this effect, we assume that the nth impact strips a mass of $f_{\mathrm{loss}}^{n-1}M_{\mathrm{loss}}$ from the RG, where $f_{\mathrm{loss}} > 1$. After n impacts, the RG has lost a total mass of $M_{\mathrm{loss}}(f_{\mathrm{loss}}^n - 1)/(f_{\mathrm{loss}} - 1)$. In order to *totally* lose the envelope, we have to equate

$$M_{\mathrm{loss}}\frac{f_{\mathrm{loss}}^n - 1}{f_{\mathrm{loss}} - 1} = M_{\mathrm{env}} \sim 0.5\,M_\odot, \tag{7}$$

[1] As in the work of M. B. Davies & R. P. Church (in preparation).

where $M_{\rm env}$ is the mass in the envelope, and so

$$n_{\rm loss} \simeq \frac{1}{\ln f_{\rm loss}}\left[10 + \ln(f_{\rm loss} - 1) + \ln\left(\frac{M_c}{10^2\,M_\odot}\right) + 2.5\ln\left(\frac{R}{0.1\,{\rm pc}}\right)\right]. \quad (8)$$

For a RG of size $r_* \simeq 150\,R_\odot$, the typical value of $f_{\rm loss}$ is 2 (Armitage et al. 1996). Hence, it takes about 14 impacts with clumps of $M_c \sim 10^2\,M_\odot$ located at $R \sim 0.1$ pc to completely remove the RG envelope. The corresponding $n_{\rm loss}$ will increase to 80 (530) if we assume $f_{\rm loss} = 1.1$ (1.01). We note that for smaller but more common RGs, such as those at the base of the RGB, $f_{\rm loss} < 2$ is more likely.

3. NUMBER OF INTERACTIONS WITH CLUMPS

We now estimate the number of impacts that a RG experiences during successive passages through the fragmenting accretion disk. At a given moment, suppose the disk has a total of N clumps. The eccentricities of these clumps, as we saw in Section 1, are not zero, but range between 0.1 and 0.4, ensuring a covering of the disk surface by a fraction of $N(R_c/R)^2$ for an infalling RG whose velocity vector is perpendicular to the disk plane. Such a RG with a semimajor axis $a \lesssim 10''$ and period $P(a) \simeq 10^{3.2}(a/0.1\,{\rm pc})^{3/2}$ yr, will collide with clumps at a rate $\Gamma \sim 2N(R_c/R)^2/P(a)$. Any RG on such an orbit will interact with clumps for a time scale comparable with the fragmentation phase of the disk, $t_{\rm frag}$. The exact value of this time depends strongly on the initial conditions, but also on the cooling function and other variables (Nayakshin et al. 2007; Wardle & Yusef-Zadeh 2008; Bonnell & Rice 2008; Mapelli et al. 2012; Amaro-Seoane et al. 2013). Notwithstanding, we note that our model does not rely on $t_{\rm frag}$: whatever its value is, a total number of at least $N_c \sim 10^2$ clumps with $M_c \sim 10^2\,M_\odot$ will have formed if we want to match the observed number of WR/O stars in the GC stellar disk. Consequently, at any given moment, the disk will harbor $N \sim N_c(t_c/t_{\rm frag})$ clumps, where we have introduced t_c, the lifetime of a clump, whose value is derived later in this section. The total number of perpendicular collisions during $t_{\rm frag}$, $n_\perp$, can be estimated to be

$$n_\perp \sim \Gamma t_{\rm frag} \sim N_c\left[\frac{2t_c}{P(a)}\right]\left(\frac{R_c}{R}\right)^2. \quad (9)$$

As mentioned earlier, there is no dependence on $t_{\rm frag}$ itself. On the other hand, if the orbital plane of RG is coplanar with the disk, the path of the RG covered inside the disk will be longer than in the perpendicular configuration by a factor of $\pi R/H$, then the number of collisions in the coplanar case is

$$n_\parallel \simeq 31\,n_\perp. \quad (10)$$

For a RG with random orbital inclination, the number of collisions with clumps in the disk will range between $n_\perp$ and $n_\parallel$. So to derive their values, we still need to estimate t_c.

In the standard picture of massive star formation, different parts of a star-forming clump evolve on different timescales (Zinnecker & Yorke 2007): the central part collapses first due to its higher density and hence shorter free-fall timescale. This leads to the formation of a protostar in the core of the clump. The outer layer contracts on a longer timescale because of its lower density, but also due to the new source of heat at the core of the clump, the forming protostar.

Unlike the standard star formation picture, in our case the clump is optically thick. So the heat released by the protostar is kept in the clump, and must be dissipated before the outer layer can contract further, in a self-regulating process of the growth of the protostar and the contraction of the outer layer. This allows us to define t_c. It has been shown that the temperature of the clumps can achieve a value of the order of $T \sim 10^3 K$ (Bonnell & Rice 2008; Mapelli et al. 2012). The opacity in the context of molecular clouds has been estimated to be $\kappa \simeq 0.1(T/1\,{\rm K})^{1/2}\,{\rm cm}^2\,{\rm g}^{-1}$ (Bell & Lin 1994). We can then calculate the optical thickness from Equation (5), $\kappa\Sigma_c \sim 10^5(T/10^3\,{\rm K})^{1/2}$. The assumption of black-body in this context holds, so that the radiative cooling rate at the surface of the outer layer is $4\pi\sigma R_c^2 T^4$, where σ is the Stefan–Boltzmann constant.

For a given size of clump, i.e., before it can contract to a smaller size, the outer layer will emit a total energy of $(4\pi\sigma T^4 R_c^2)t_c$. If we equate this energy with the total amount of heat contained in the clump (i.e., in the gas and the protostar), $GM_c^2/R_c + GM_*^2/R_*$, we have that

$$t_c \sim \frac{GM_*^2/R_*}{4\pi\sigma T^4 R_c^2} \sim 10^5\,{\rm yr}\left(\frac{R}{0.1\,{\rm pc}}\right)^{-2}\left(\frac{M_*}{10^2\,M_\odot}\right)^{-2}\left(\frac{T}{10^3\,{\rm K}}\right)^{-4}. \quad (11)$$

To relate the radius R_* of the protostar to its mass M_*, we adopt the empirical relation for H-burning stars that $R_* \sim 1.29\,R_\odot(M_*/M_\odot)^{0.60}$ for $M_* > 1\,M_\odot$ and $R_* \sim R_\odot(M_*/M_\odot)^{0.97}$ for $M_* < 1\,M_\odot$ (see, e.g., Nayakshin et al. 2007). This is the reason why in Equation (11) we have neglected the contribution from the gas, GM_c^2/R_c, since for protostars as light as $0.2\,M_\odot$, the heat released is already comparable to the gravitational energy of the gas in the clump.

Knowing that $N_c \sim 10^2$ clumps with $M_c = 10^2\,M_\odot$ have formed in the disk at $a \sim 0.1$ pc, we find $n_\perp \sim 2$ and $n_\parallel \sim 60$, therefore RGs with $f_{\rm loss} = 2$ generally satisfy the condition $n_\perp < n_{\rm loss} < n_\parallel$. This means a complete loss of the envelope if the RG is in a low-inclination orbit with respect to the disk, and a partial depletion of the envelope if the RG is in a high-inclination orbit.

There is no good reason to believe that the clumps form in a single mass distribution. A more realistic one would also naturally produce lighter clumps. This is important, because they are more efficient at removing RG envelopes: they have higher surface densities ($\Sigma_c \propto M_c^{-1}$), and each one contributes as many collisions with RGs as a more massive clump can do; while the collisional cross section, $R_c^2 \propto M_c^2$ is smaller, the lifetime, $t_c \propto R_c^{-2} \propto M_c^{-2}$, is elongated. Therefore, a disk harboring smaller clumps, of masses $M_c \sim 1$–$10\,M_\odot$, could in principle contribute significantly more to the depletion of RGs, but this depends on their abundance, which unfortunately is not yet available from observations.

Hence, during the self-gravitating past of the disk at the GC, a stellar core of RGs with flat surface-density distribution will be created. This core, once formed, will last for a relaxation time. We note that these results are in agreement with the best fit to the observed surface density of the RGs in our GC with an anisotropic angular-momentum distribution and a core size of 0.1 pc (Merritt 2010).

4. IMPACT ON THE CLUMPS

At this point one could wonder whether the accumulated impacting of RGs on to the clumps could eventually disrupt or heat them before a successful RG depletion. To address this question, we estimate the amount of gas removed from a clump after one crossing, i.e., the amount of gas "scooped" away in a cylinder of height comparable to the size of the clump, R_c. As for the radius of the cylinder, we note that the ratio between the radius of a RG (such as the ones considered so far) and its Bondi radius $r_{\rm B}$ is

$$\frac{r_*}{r_{\rm B}} \simeq 80 \left(\frac{R}{0.1\,{\rm pc}}\right), \tag{12}$$

with $r_{\rm B} := (Gm_*/v_c^2)$. Therefore the radius is determined by r_* and not $r_{\rm B}$. The RG does scoop away matter from the clump because its surface density is 3–4 orders of magnitude larger than that of the clump. The mass loss, $\Delta m \sim r_*^2 \Sigma_c$, for a typical value of $\Sigma_c \sim 10^{7-8}\, M_\odot\,{\rm pc}^{-2}$ and $r_* = 100\, R_\odot$, is negligible.

One might also be concerned that the energy deposition could heat up the clump and make it less dense, but this is not the case: the maximum energy that can be deposited into a clump during each transit, $\Delta m v_c^2$, is trifling compared to the binding energy of the clump, GM_c^2/R_c, since

$$\frac{\Delta m v_c^2}{GM_c^2/R_c} \sim \left(\frac{r_*^2}{R_c R}\right)\left(\frac{M_\bullet}{M_c}\right) \sim 10^{-3} \tag{13}$$

for our fiducial massive clumps. The envelope of a RG is lost after $n_{\rm loss}$, i.e., some 15 passages. Such number of hits do not suffice to heat up a clump in disk to stop star formation in it.

5. DISCUSSION

The problem of the missing bright RGs has been the focus of an ongoing debate since its discovery, more than 15 yr ago, by Genzel et al. (1996). A number of different scenarios have been invoked to explain this deficit of old stars, but none has until now provided a simple and efficient mechanism to solve the problem. In this Letter, considering a single episode of disk formation at the GC, we explain the missing stars in the RGB in the natural context of the star-forming disk that after fragmentation led to the currently observed stellar disk in our GC. We prove with simple analytical estimates that the distribution of clumps in the disk is sufficient to ensure the removal of the envelopes of the brightest RGs. Successive episodes of disk formation, separated by $\sim 10^8$ yr, based on the AGN duty cycle, would have formed of the order of ten generations of clumps at the GC.

Toward lower luminosities, the horizontal branch (HB) stars, however, have an envelope about 100 times denser (in surface density) than those of RGB stars, as it can easily be derived from the calculated structures of solar-metallicity of HB giants of Girardi et al. (2000). Therefore, due to momentum conservation (Equation (1)), an HB star requires on the order of 100 more impacts with clumps to remove its envelope, although the nonlinearity factor $f_{\rm loss}$ is less clear in this case due to the lack of numerical investigations. We hence predict that only a low percentage of them, those with a low inclination with respect to the disk, will have received significant envelope damage. Number counting of stars in the bin between 16.75 and 17.75 mag in the K-band may indicate a steepening of the surface-density distribution for stars fainter than the HB (Schödel et al. 2007, their Figure 17), pointing to the picture of partial depletion.

We also predict that the released cores of the RGB stars populate the region of the GC where they lost their envelopes. However, detecting these cores in infrared (IR) surveys may be difficult: (1) the core would exhaust the remaining hydrogen envelope in a couple of Myr, and would hence appear as very faint now while (2) shifting its peak emission to shorter wavelengths, becoming invisible in the IR filters (Davies & King 2005).

To prove the densities of HB stars, we need deeper spectroscopic observations and more complete photometric surveys down to the 18th K-magnitude. On the other hand, numerical simulations are required to study the effects of nonlinearity, our $n_{\rm loss}$ and $f_{\rm loss}$, in the interaction between the clumps and the envelops of stars in the RGB but, more importantly, of those in the HB.

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