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A STAR DISRUPTED BY A STELLAR BLACK HOLE AS THE ORIGIN OF THE CLOUD FALLING TOWARD THE GALACTIC CENTER

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ABSTRACT

We propose that the cloud moving on a highly eccentric orbit near the central black hole in our Galaxy, reported by Gillessen et al., is formed by a photoevaporation wind originating in a disk around a star that is tidally perturbed and shocked at every peribothron passage. The disk is proposed to have formed when a stellar black hole flew by the star, tidally disrupted its envelope, and placed the star on its present orbit with some of the tidal debris forming a disk. A disrupting encounter at the location of the observed cloud is most likely to be caused by a stellar black hole because of the expected dynamical mass segregation; the rate of these disk-forming encounters may be as high as $\sim 10^{-6}$ per year. The star should also be spun up by the encounter, so the disk may subsequently expand by absorbing angular momentum from the star. Once the disk expands up to the tidal truncation radius, the tidal perturbation of the outer disk edge at every peribothron may place gas streams on larger orbits, which can give rise to a photoevaporation wind that forms the cloud at every orbit. This model predicts that, after the cloud is disrupted at the next peribothron passage in 2013, a smaller unresolved cloud will gradually grow around the star on the same present orbit. An increased infrared luminosity from the disk may also be detectable when the peribothron is reached. We also note that this model revives the encounter theory for planet formation.

Key words: Galaxy: center – ISM: clouds – planets and satellites: formation – stars: kinematics and dynamics – stars: winds, outflows

1. INTRODUCTION

Drawing on the vast technological advances in adaptive optics, infrared detectors, and X-ray telescopes, observations over the last two decades have revolutionized our knowledge of the Galactic center region. It is now beyond reasonable doubt that a black hole of mass $4 \times 10^6\, M_\odot$ is present at the center of the Milky Way surrounded by a stellar cusp with a total mass in stars of $\sim 10^6\, M_\odot$ within the central parsec (for a review, see Genzel et al. 2010). Several massive young stars are present in the central 0.1 pc with well-determined orbits, many of which are part of a disk structure and were born in a starburst $\sim$6 Myr ago. Hot gas is also present throughout this region, believed to originate from the stellar winds of these massive stars.

A mysterious cloud of gas was also reported recently by Gillessen et al. (2012), moving along a Keplerian orbit. The cloud emits $5\, L_\odot$ of continuum infrared light interpreted as dust emission at a temperature of 550 K, and hydrogen and helium recombination lines consistent with a photoionized cloud with a gas temperature of 10^4 K. The cloud is being rapidly disrupted as shown by a clear velocity gradient along its resolved long axis of $\sim$100 AU, which is consistent with the tide along its highly eccentric orbit: the cloud has fallen from an apobothron at $\sim$8000 AU and will pass through peribothron at $\sim$250 AU in summer 2013.

The origin of this cloud is a most intriguing question. Three possibilities have been proposed so far. In the first one, the cloud is isolated and diffuse and was formed by the collision of stellar winds from massive stars (Burkert et al. 2012; Schartmann et al. 2012). Stars near the inner edge of the disk at a distance $r = 8000$ AU from the black hole, where the circular velocity is $v_c \simeq 700\,\mathrm{km\,s^{-1}}$, may emit winds at velocities near v_c that can collide and leave material at low velocity. This material might cool after being shocked at high density and form a shell, and then fall on the observed highly eccentric orbit. This model faces some difficulties: clouds produced from wind collisions should have a very high velocity dispersion (resulting from the wind and the star velocities added in quadrature), so it appears unlikely that only one prominent cloud is observed that needs to have formed with a very low velocity at the inner edge of the disk of young stars. There are no clear candidates among the known young stars with winds that might have produced the required cloud near the observed apocenter. The cloud needs to cool down and be confined by the pressure of the external hot medium because its self-gravity is negligible, and it is not clear how the cloud may have avoided fragmentation through the Kelvin-Helmholtz and Rayleigh–Taylor instabilities as it moved through the hot medium from its apocenter. In addition, the presence of dust in a cloud at 10^4 K that has cooled from gas shocked to millions of degrees after being ejected in a wind from a hot star is also difficult to account for.

A second possibility might be that an evolved star is losing mass that is producing the cloud at every orbit, which might be observed as a planetary nebula were it not tidally removed at every peribothron passage. The star would need to be very hot and not highly luminous, and the dust abundance should be very low, to avoid reradiating too much of the stellar light in the infrared and be consistent with the upper limit on the K-band flux (K-band absolute magnitude above 1) and the observed flux at longer wavelengths (Gillessen et al. 2012). This model also has severe problems: in order to be hot enough and faint enough, the star should be smaller than a solar radius, and any wind would then be too fast to produce the observed cloud over the orbital period of 130 years. Furthermore, with no more than $\sim 10^4$ low-mass stars expected within 0.04 pc from the Galactic center, the chances of catching this one at a very brief and rare stage of its stellar evolution, while no other luminous old giant in a stage of longer duration has been found as close to the center, must be very small.

A third possibility is that the cloud is formed by photoevaporation of a circumstellar disk around a star embedded in the cloud (Murray-Clay & Loeb 2012). The circumstellar disk may have accreted from gas as usual when the star was formed in the recent starburst. As long as the star is not very massive, its *K*-band flux is far below the observational upper limit (Gillessen et al. 2012). At an initial orbital radius of 8000 AU for the star, the disk would be tidally limited to a size of ∼10 AU. Murray-Clay & Loeb (2012) proposed that this disk gave rise to the observed cloud of 100 AU after the star was deflected into the present orbit, leading to faster photoevaporation and tidal stretching as the peribothron is approached. The problem with this model is the difficulty in deflecting the star from a low-eccentricity orbit in the disk of young stars to the observed highly eccentric orbit without disrupting the gaseous disk.

This is easily seen by considering the example of an encounter with an $m = 10\,M_\odot$ star, typical among the objects dominating the dynamical relaxation rate, moving with a relative velocity $\sigma \sim 200\,\mathrm{km\,s^{-1}}$ characteristic of the disk velocity dispersion, and at an impact parameter $b = 10$ AU. The velocity deflection caused in this encounter is $\Delta v = 2Gm/(b\sigma) = 10\,\mathrm{km\,s^{-1}}$, which is similar to the disk circular velocity at 10 AU. Therefore, the disk would lose a large fraction of its mass for this impact parameter and would be destroyed in closer encounters. However, deflecting the star from a disk orbit to the observed highly eccentric orbit requires a velocity change $\Delta v \sim 500\,\mathrm{km\,s^{-1}}$, which is clearly impossible to achieve over a single orbit. In fact, the probability for just one such encounter at $b \sim 10$ AU over one orbit for any given star in the disk is much less than unity.

Nevertheless, the possibility to produce the cloud from a photoevaporating circumstellar disk around a low-mass star is an interesting one, since it can naturally produce many of the observed features of the cloud. It is therefore natural to ask if there are other ways of producing a gas disk around a star in the environment of the Galactic center.

This paper proposes that a disk was formed when an old, low-mass star suffered a close encounter with a stellar black hole, which tidally disrupted its outer envelope and deflected the star into its present orbit. Even though some of the tidal debris may have escaped the star, a large fraction of the mass stayed bound and fell back to the star, creating a small disk. The star was also spun up by the encounter and gradually transferred its angular momentum to the disk. The resulting expanded disk can then create a cloud like the one observed at every orbit. Most of the disk mass stays within the tidal radius of 1 AU at the peribothron, while a small fraction migrates out to a larger radius at every orbit, where it is photoionized and drives a wind that generates the cloud.

We shall first discuss the rate at which encounters of stars and stellar black holes that can lead to substantial disruption and disk formation should occur near the Galactic center in Section 2. The possibility to create the observed cloud from the disk is considered in Section 3, and we summarize the tests of the model and our conclusions in Section 4.

2. DISRUPTING ENCOUNTERS OF STARS WITH STELLAR BLACK HOLES

2.1. The Density of Stars and Black Holes

The most likely place in the Galaxy where a disrupting encounter between a normal star and a stellar black hole may take place is near the Galactic center, where the density of both stars and black holes is highest. The density of stellar black holes should be particularly enhanced owing to migration by dynamical friction of the most massive objects in the old stellar population of the bulge toward the center. About 20,000 stellar black holes are estimated to have migrated to the stellar cusp surrounding Sgr A∗ over the age of the Galaxy (Morris 1993; Miralda-Escudé & Gould 2000). A stellar cusp undergoing dynamical relaxation with a constant outflow of orbital energy should have a density profile $\rho(r) \propto r^{-7/4}$ (Bahcall & Wolf 1976, 1977); the total profile may vary when a range of stellar masses is present, but it does not strongly deviate from this form (e.g., Alexander & Hopman 2009). The population of old stars dominates the contribution to the stellar mass at large radius, and there is a critical radius r_b within which the stellar black holes dominate. Inside r_b, the density of stellar black holes, ρ_b, probably approaches the 7/4 slope, and their profile becomes much steeper outside r_b. The density of low-mass stars, ρ_s, probably approaches a 3/2 slope inside r_b, corresponding to a constant phase-space density in the Keplerian potential, although the profile may be a bit flatter if many stars are destroyed by collisions.

Assuming that the total stellar mass roughly follows the 7/4 slope and normalizing the profile to a total mass $10^6\,M_\odot$ within 1 pc (Genzel et al. 2010), and if a total of 20,000 stellar black holes with an average mass of $M_b = 10\,M_\odot$ have migrated to this region, then a mass equal to that of all the stellar black holes is contained within $r_b \simeq 0.3$ pc. Their number density at $r < r_b$ is

$$n_b(r) = n_{b0}\,(r/r_b)^{-7/4} \qquad (r < r_b). \tag{1}$$

We use the normalization $n_{b0} = (5/16\pi)\,5 \times 10^3 r_b^{-3}$, which assumes that 25% of the stellar black holes are inside r_b, while the other 75% are outside following a steeper profile. The remaining 75% of the mass inside r_b is treated here for simplicity as a single population of main-sequence stars with mass $M_s = 1\,M_\odot$, with a profile

$$n_s(r) = 36\,n_{b0}\,(r/r_b)^{-3/2} \qquad (r < r_b). \tag{2}$$

This simple model yields mass densities similar to those found in the Fokker–Planck calculation of Hopman & Alexander (2006).

2.2. Impact Parameters for Disk Formation

In order to create a disk, an encounter needs to be close enough to cause a strong tidal distortion and raise matter into orbit around the star. While many numerical simulations of stellar collisions have been carried out, starting with the work of Benz & Hills (1987, 1992), the question of whether a disk can be formed from the tidal streams that fall back toward the star after an encounter between two objects that remain unbound has not received so much attention. The numerical simulations, however, show a fraction of the tidally stripped mass forming a disk structure immediately after the encounter (see, e.g., Lai et al. 1993 for collisions of massive stars, and Khokhlov et al. 1993 for a tidal interaction with a black hole).

The problem of disk formation after a tidal interaction is related to the encounter theory for the formation of a planetary system, where planets form after a plume of material is lifted from a star due to an encounter with another star. It was pointed out by Spitzer (1939) that the plume cannot condense directly into planets because of its high internal pressure and long cooling time. However, the high internal pressure together with the tidal forces from the perturbing object can provide a lateral force that redistributes angular momentum in the plume, so that some of the material that is left on bound orbits may form a disk instead of falling back onto the stellar surface. The disk should initially be very hot, but after the encounter it can in principle cool over many orbits and eventually form planets. The problem is also similar to the theory of formation of the Moon in a collision of two planets, which has been studied in detail, and where it has been shown that a disk can be formed containing a mass of more than 10^{-2} of the mass of the two colliding planets (see the review by Canup 2004).

To estimate the required impact parameter for strong disruption in our specific problem, we consider a star of mass M_s and radius r_s encountering a stellar black hole of mass M_b with an initial relative velocity v_r, at an impact parameter b leading to a closest approach at peribothron r_p. The velocity of the star at peribothron, approximating the trajectory of its center of mass to be the same as for a point particle, is $v_p = (v_r^2 + 2GM_b/r_p)^{1/2}$, and conservation of angular momentum implies $r_p = bv_r/v_p$. We first consider the case $v_r < v_0$, where we define

$$v_0 \equiv v_e \left(\frac{M_b}{\sqrt{2}M_s}\right)^{\frac{1}{3}} = \left[\frac{G(2M_b)^{2/3}M_s^{1/3}}{r_s}\right]^{\frac{1}{2}}, \tag{3}$$

and $v_e = (2GM_s/r_s)^{1/2}$ is the escape velocity of the star. For this case, we use the strong disruption condition that the tidal acceleration caused by the black hole between the center and surface of the star along the radial line at peribothron, at distances r_p and $r_p - r_s$, is equal to the gravitational acceleration on the surface due to the star. This implies $2M_b r_s/r_p^3 = M_s/r_s^2$, or a maximum peribothron distance for tidal disruption of

$$r_p = r_s \left(\frac{2M_b}{M_s}\right)^{\frac{1}{3}} \qquad (v_r < v_0). \tag{4}$$

This condition agrees with the maximum impact parameter found in numerical simulations required for stripping matter (e.g., Khokhlov et al. 1993; note that the approximation used in these simulations that $r_p \gg r_s$ is only marginally correct for our case). The condition $v_r < v_0$ ensures that the velocity at peribothron is $v_p \simeq (2GM_b/r_p)^{1/2} = v_0$, and the duration of the strong tide is $t \simeq r_p/v_p = \sqrt{2}r_s/v_e$, equal to the free-fall time of the star. For the case $v_r > v_0$, gravitational focusing remains small at r_p, and so $v_p \simeq v_r$ and the duration of the strong tide is shorter than the star free-fall time by the factor v_r/v_0. Our condition for strong distortion is in this case $2M_b r_s/r_p^3(r_p/v_r) = M_s/r_s^2(\sqrt{2}r_s/v_e)$, or

$$r_p = r_s \left(\frac{2M_b}{M_s}\right)^{\frac{1}{3}} \left(\frac{v_0}{v_r}\right)^{\frac{1}{2}} \qquad (v_r > v_0). \tag{5}$$

The corresponding maximum impact parameters are

$$b = r_p \frac{v_p}{v_r} \simeq r_s \left(\frac{2M_b}{M_s}\right)^{\frac{1}{3}} \frac{v_0}{v_r} \qquad (v_r < v_0), \tag{6}$$

$$b \simeq r_p \simeq r_s \left(\frac{2M_b}{M_s}\right)^{\frac{1}{3}} \left(\frac{v_0}{v_r}\right)^{\frac{1}{2}} \qquad (v_r > v_0). \tag{7}$$

We do not take into account a minimum impact parameter, even though the star is totally disrupted when the impact parameter is sufficiently small. The impact parameter required for a complete destruction should be substantially smaller than the maximum values needed for raising matter from the surface. The large degree of concentration of stars implies that the dense core is hard to disrupt and may have a disk forming around it even when a large fraction of the star is tidally pulled out.

For much larger velocities, $v_r > v_e(M_b/M_s)$, strong disruption requires the black hole to cross through the star and becomes inefficient as the tidal acceleration acts over a shorter time. Some material may be dragged out of the star through the narrow cylinder that the black hole perforates in these very fast encounters, but it would be difficult for any disk to be formed.

2.3. The Rate of Disrupting Encounters

The rate of encounters at impact parameters smaller than the maximum values for disruption in Equations (6) and (7) can now be calculated as

$$R = 4\pi^2 \int dr\, r^2\, n_b(r)\, n_s(r)\, \langle b^2\, v_r \rangle, \tag{8}$$

where v_r is the relative velocity between a star and a black hole and $\langle b^2 v_r \rangle$ is computed by averaging over the velocity distributions at a given radius.

Dynamical equilibrium implies that the rms one-dimensional velocity dispersion of a set of particles moving in a Keplerian potential with a density profile $n \propto r^{-\gamma}$ is $\sigma^2 = GM/r/(\gamma + 1)$. Hence, the rms relative velocity of stars and stellar black holes at a distance r from the central black hole of the Milky Way of mass M (referred to as Sgr A$*$) is

$$\langle v_r^2 \rangle = \frac{3GM}{r}\left(\frac{2}{5} + \frac{4}{11}\right) = \frac{126}{55}\frac{GM}{r}. \tag{9}$$

There is a critical radius r_0 at which this rms relative velocity is equal to v_0,

$$r_0 = r_s \frac{63}{55}\frac{M}{M_s}\left(\frac{\sqrt{2}M_s}{M_b}\right)^{\frac{2}{3}} \simeq 6000\,\mathrm{AU}. \tag{10}$$

We also define the radius at which the rms relative velocity reaches $v_e M_b/M_s$, within which disruptions become inefficient,

$$r_f = r_s \frac{63}{55}\frac{M}{M_s}\left(\frac{M_s}{M_b}\right)^2 \simeq 200\,\mathrm{AU}. \tag{11}$$

Approximating also $\langle 1/v_r \rangle \simeq (\langle v_r^2 \rangle)^{-1/2}$, the total rate of encounters from Equation (8) is

$$R = 4\pi^2 r_b^3\, 36 n_{b0}^2 r_s^2 v_e \frac{\sqrt{2}M_b}{M_s} \times \left[\int_{r_f/r_b}^{r_0/r_b} dx\, x^{-\frac{5}{4}} + \left(\frac{r_0}{r_b}\right)^{-\frac{1}{2}} \int_{r_0/r_b}^{1} dx\, x^{-\frac{3}{4}}\right]. \tag{12}$$

The first integral arises from the outer region $r > r_0$, where slow encounters affected by gravitational focusing dominate, and the second integral is for $r < r_0$, where fast encounters limited by the duration of the strongest tidal acceleration dominate. The result is

$$R = 576\pi^2 r_b^3 n_{b0}^2 r_s^2 v_e \frac{\sqrt{2}M_b}{M_s} \times \left[\left(\frac{r_b}{r_f}\right)^{\frac{1}{4}} + \left(\frac{r_b}{r_0}\right)^{\frac{1}{2}} - 2\left(\frac{r_b}{r_0}\right)^{\frac{1}{4}}\right] \simeq 10^{-6}\,\mathrm{yr}^{-1}. \tag{13}$$

The rate of interesting encounters in radial shells of constant logarithmic width is fairly flat, but it is actually maximum at the smallest radius, near r_f. If the observed cloud is indeed being produced by a star that was tidally perturbed, it is interesting to note that even though the encounter might have occurred at any point along the present cloud orbit, the most likely place would be near the peribothron, which is close to r_f. In this case, the black hole would have rushed very close to the surface of the star at $\sim$6000 km s^{-1}.

The predicted rate of encounters implies that the perturbed star needs to produce the observed cloud for many orbits in order to have a reasonable probability to be observing the cloud at a random time.

2.4. *Effects of Other Types of Collisions*

A small disk around a star may also be formed as a result of a tidal interaction or collision between two main-sequence stars. As for the case of black holes, it is useful to divide these encounters into cases when the relative velocity between the two stars is smaller or larger than the escape velocity of the star.

Encounters with a relative velocity smaller than the escape velocity take place mostly at large radius and have effects that are dominated by the tidal interaction. The impact parameters for which an important amount of mass can be tidally raised from a star to form a disk are therefore given approximately by Equation (6). The encounter rates for a specific star are proportional to the number density of perturbers times their mass, i.e., to the mass density of perturbers, which is comparable for stars and stellar black holes at radii up to $\sim r_b$. The total rates are therefore comparable, but encounters among two stars are more likely to be produced at a radius much larger than the orbit of the observed cloud.

Encounters between two stars at radii smaller than $\sim$0.1 pc mostly occur at velocities higher than the escape velocity. In this case, physical collisions are more important than tidal effects, and the required impact parameters are about $2r_s$ independently of the velocity. Stellar collisions may therefore become more frequent than tidal encounters with stellar black holes at small radius, despite the shallower density profile of stars. Most of the debris produced by the direct physical collision in these high-velocity encounters would be left on unbound orbits, but some of the mass may be pushed out of the stars at low velocity, remain bound, and also form a disk. Exactly how much mass might be left on bound orbits can only be estimated with detailed numerical simulations that are beyond the scope of this paper, but in principle stellar collisions might substantially increase the total rate of disk-forming encounters.

3. EVOLUTION OF THE STELLAR DISK AND WIND

After a strongly distorting encounter, a large fraction of the mass of the perturbed star may either be thrown out on unbound orbits or eventually fall back to the star. The fraction of the stellar mass that avoids these two outcomes and is left on bound orbits with enough angular momentum to form a disk depends on many physical parameters and can only be obtained from detailed hydrodynamic simulations. Here, we are going to assume as a characteristic value that the disk may have a mass of $\sim$1% of the stellar mass, a typical value in the case of collisions among terrestrial planets that can account for the formation of the Moon (Canup 2004).

Immediately after the tidal encounter, the disk should be small because most of the debris should not acquire a large specific angular momentum. The star should be strongly spun up during the encounter (see Alexander & Kumar 2001), and afterward it should settle to an equilibrium with an equatorial radius larger than its main-sequence value because of fast rotation and the dissipation of energy into internal heat, which will take a Kelvin–Helmholtz time ($\sim 10^7$ years) to be radiated away.

3.1. *Required Wind Speed*

In order to make the observed gas cloud, the star and disk need to generate a wind with an adequate mass-loss rate to deliver the mass of the cloud over an orbital period, and at a velocity that is low enough not to exceed the observed present size of 100 AU. We simplify the treatment of the motion of a gas element in the wind moving away from the star by approximating the falling trajectory of the star from its apobothron to its peribothron as if it were on a purely radial orbit with zero orbital energy (the actual observed cloud is on an orbit with eccentricity $e = 0.94$). The distance r from the star to Sgr A$*$ at time t is then

$$r(t) = \left[\frac{3}{2}\sqrt{2GM}(t_0 - t)\right]^{\frac{2}{3}}, \tag{14}$$

where t_0 is the time when the star would reach $r = 0$ if it were in a purely radial orbit. A gas element separating along the radial direction at a distance from the star $x(t) \ll r$ is affected by a tidal acceleration $g_t = 2GMx/r^3$. Neglecting the gravity of the star (which is only important at an initial time when the wind is launched from a small value of x) and any ram-pressure force due to the hot medium around Sgr A$*$ (see Gillessen et al. 2012 and Burkert et al. 2012 for a discussion of the effects of ram pressure), the motion for the gas element is described by the equation

$$\frac{d^2x}{dt^2} = \frac{2GMx}{r^3} = \frac{4x}{9(t_0 - t)^2}. \tag{15}$$

Assuming that the gas element is at a distance equal to the observed cloud size, $x_1 \simeq 100$ AU, at the time $t_1 \simeq t_0 - 2$ yr of the observations reported by Gillessen et al. (2012), and that it was emitted by the wind from a distance $x \ll x_1$ near the time of the apobothron, $t_a \simeq t_0 - 70$ yr, the solution to the above equation is (using $t_0 - t_a \gg t_0 - t_1$)

$$x(t) = x_1 \left(\frac{t_0 - t_1}{t_0 - t}\right)^{\frac{1}{3}} \left[1 - \left(\frac{t_0 - t}{t_0 - t_a}\right)^{\frac{5}{3}}\right]. \tag{16}$$

The initial velocity of the wind therefore should be about

$$\dot{x}(t_a) = \frac{5x_1(t_0 - t_1)^{1/3}}{3(t_0 - t_a)^{4/3}} \simeq 4\,\mathrm{km\,s^{-1}}. \tag{17}$$

Any wind that is generated from the small disk that is initially formed after the tidal encounter of a star with a black hole would have a velocity of hundreds of km s^{-1} (not much smaller than the escape velocity of the star), which is much too fast to explain the observed cloud. To generate the required slow wind, a mechanism is needed to expand the disk and to provide energy for launching a wind from large radius.

3.2. *Disk Expansion*

The disk expansion may result from the fast rotation of the perturbed star. Note that the star may already have been a fast rotator before the encounter that created the disk, because previous encounters with stellar black holes in the Galactic center region at larger impact parameters (which occur more frequently) may have gradually spun up the star (Alexander & Kumar 2001); the last, closest encounter may simply have cracked up the rotation rate even further. After the encounter, a process of angular momentum transfer from the star to the disk should result in an expansion of the disk. If the star rotates very fast, it may become prolate and cause a rotating gravitational tide on the inner disk that can transfer the angular momentum. An oblate star that is still rotating faster than the inner disk can continue to transfer angular momentum if it is magnetically connected to the disk. The disk will be spread by internal transport of angular momentum, pushing matter on the outer edge to an increasing orbital size as more angular momentum is acquired from the star on the inner edge.

Let the angular momentum of the star after it has settled to hydrostatic equilibrium following the encounter with the black hole be $L_s = \phi_L \sqrt{G M_s^3 r_s}$. As an example, for a spherical object with a singular isothermal density profile truncated at r_s and a surface rotation velocity equal to the circular orbital velocity, $\phi_L = 2/9$. The angular momentum is even larger for a prolate star rotating near the maximum rate, which has expanded owing to the increase of internal energy (decrease in absolute value) in the tidal event. The angular momentum of the disk of mass M_d is $L_d = M_d \sqrt{G M_s r_d}$, where r_d is the characteristic disk radius obtained from its mass-weighted average of $\sqrt{r}$. If the star transfers most of its angular momentum to the disk, the final radius of the disk is

$$r_d = r_s \left(\frac{\phi_L M_s}{M_d} \right)^2 . \tag{18}$$

For $M_d = 0.1 \phi_L M_s$, the disk can expand out to $100 r_s$, or 0.5 AU for a solar-type star.

If, as proposed in this paper, this star and expanded disk system are inside the observed cloud in the Galactic center, the disk cannot expand beyond $r_d \sim 0.5\,\mathrm{AU}$ because the tidal limit at the peribothron of the cloud orbit, $r_{\rm cp}$, is $r_t = r_{\rm cp}\,[M_s/(2M)]^{1/3} \simeq 0.7\,\mathrm{AU}$, so the disk is truncated at this size at every orbital period of 140 years.

3.3. Mass-loss Rate

The escape velocity from the surface of a disk at $r_d \sim 0.5\,\mathrm{AU}$ is $\sim 60\,\mathrm{km\,s^{-1}}$, still too large to generate a slow wind at a velocity of a few $\mathrm{km\,s^{-1}}$. An additional mechanism is required to first spread a small fraction of the gas in the disk over a larger region around the star at every orbit, which can then be blown out at a low velocity. Moreover, photoionization from the massive stars near the Galactic center can provide the energy required to generate the wind once some material expands to the radius where the escape velocity is reduced to near the isothermal sound speed at the temperature of photoionized gas, $c_i \simeq 11\,(T/10^4\,\mathrm{K})^{1/2}\,\mathrm{km\,s^{-1}}$ (Murray-Clay & Loeb 2012). As the wind escapes the gravity of the star, its velocity can be moderately reduced below c_i to the value required to reproduce the size of the observed cloud.

The total mass-loss rate from a cloud of radius r_c that is being photoevaporated by an external flux of ionizing photons F_i can be roughly estimated as $\dot{M} \sim 4\pi r_c^2 c_i n_e \mu_e$, where n_e is the electron density in the external ionized layer that shields the interior of the cloud and μ_e is the mean mass per electron. The condition that the ionizing flux is balanced by a recombination rate column $\alpha_B n_e^2 \ell$, where α_B is the case B recombination coefficient and $\ell \sim r_c$ is the length of the ionized layer, is then used to estimate $n_e \sim [F_i/(\alpha_B r_c)]^{1/2}$. A detailed calculation was presented by Bertoldi & McKee (1990), who obtained

$$\dot{M} = 1.4 \times 10^{-11} \phi_w \frac{S_{49}^{1/2}}{d_{\rm pc}} r_{\rm AU}^{3/2}\, M_\odot\,\mathrm{yr}^{-1}, \tag{19}$$

where $r_{\rm AU} = r_c/(1\,\mathrm{AU})$ is the radius of the photoevaporating cloud expressed in AU, ϕ_w is a dimensionless factor that is written as a combination of other modeling dimensionless factors in Equation (4.2) of Bertoldi & McKee (1990), and the external flux is expressed as $F_i = 10^{49}/(4\pi) S_{49}/d_{\rm pc}^2\,\mathrm{pc}^{-2}$, with S_{49} equal to the total emission rate of ionizing photons in units of $10^{49}\,\mathrm{s}^{-1}$ from a source at a distance $d_{\rm pc}$ expressed in parsecs. Here, we assume that the stars in the young disk emit $S_{49} = 10$ (which is 15% of all the ionizing luminosity in the central 0.5 pc; see Genzel et al. 2010) from a typical distance of 0.06 pc, which yields $S_{49}^{1/2}/d_{\rm pc} = 50$, or $F_i = 2 \times 10^{14}\,\mathrm{cm}^{-2}$. The parameter ϕ_w depends on a photoevaporation parameter defined as $\psi = \alpha_B F_i r_c / c_i^2$. Using $c_i = 11\,\mathrm{km\,s^{-1}}$ (at $T = 10^4$ K) and $r_c = 5\,\mathrm{AU}$, we find $\psi \simeq 3000$. The value of the dimensionless factor is then $\phi_w \simeq 4$, as shown in Figure 11 of Bertoldi & McKee (1990), and the inferred mass-loss rate is $\dot{M} \simeq 3 \times 10^{-8}\,M_\odot\,\mathrm{yr}^{-1}$ for a cloud size of $r_{\rm AU} = 5$.

Therefore, as long as a mass of at least $3 \times 10^{-6}\,M_\odot$ can be expelled from the disk after the star has passed by the peribothron and can reach out to a distance from the star $r_c \sim 5\,\mathrm{AU}$, then this mass can be slowly lost from the system over an orbital period of $\sim$100 years, roughly at the desired wind speed to produce the observed cloud. This amount of mass in a region of radius $r_c = 5\,\mathrm{AU}$ has a number density $n \sim 10^9\,\mathrm{cm}^{-3}$, which is self-shielded behind an ionized layer with $n_e \simeq 10^{6.5}\,\mathrm{cm}^{-3}$.

How can this mass move from the disk out to $\sim$5 AU and stay there for $\sim$100 years? A possible way for this to happen is discussed next.

3.4. Generation of the Photoevaporating Cloud from the Disk

As described previously, a mass of $\sim 10^{-2} M_s$ can reasonably be placed in a disk and be transported outward to a radius $\sim$0.5 AU. A fraction of only $10^{-3.5}$ of this disk mass needs to be ejected out to a large distance to generate a photoevaporation rate of $3 \times 10^{-8}\,M_\odot\,\mathrm{yr}^{-1}$ over 100 years. If a mechanism to eject this small fraction of the disk mass near the escape velocity exists, this can in principle occur at every orbit after the peribothron passage and create a similar cloud to the one we observe for more than 10^3 orbits, or a total time of more than 10^5 years. The rate of encounters between stars and black holes in Equation (13) would then imply a reasonably large probability of observing one cloud at any random time near the Galactic center. This requires the disk to expand and eject mass at every orbit in an optimal way to produce the observed cloud, but even if the process is much less optimal (with more mass being ejected and perhaps dispersed instead of accumulating in the observed cloud), the probability to observe the cloud at a random time may still be a reasonable one.

We note that the inferred mass of the observed cloud is $M_c \simeq 10^{-5} f_V^{1/2}\,M_\odot$, where f_V is the filling factor of gas with density $n_e \simeq 10^{5.5} f_V^{-1/2}$ in a spherical cloud with radius $\sim$100 AU (Gillessen et al. 2012). A filling factor $f_V \sim 0.1$ is probably most reasonable, because the cloud is expected to have a filamentary shape owing to the tidal acceleration that stretches the cloud in the direction of the orbit and compresses it across both perpendicular directions. Only the long axis of the cloud is observationally resolved.

The mechanism to eject a small fraction of the disk mass may occur when the star–disk system reaches peribothron and the disk undergoes rapid precession and is strongly warped in its outer part by the tidal forces. If the disk expands slowly as the star loses angular momentum, a very small fraction of the disk may diffuse outside the tidal radius during one orbit, but a larger fraction may be present into the intermediate region near 0.5 AU where the disk is not yet torn apart but is substantially warped and perturbed, leading to collisions of gas streams and shocks that can eject gas near the escape velocity. Inevitably, some of the ejected mass will escape the system, but some may simply move out on a large orbit and remain bound to the star. Material that is ejected near the escape velocity from the disk just after the peribothron passage can remain near a separation from the star where the tidal acceleration from Sgr A∗ is comparable to the gravitational attraction of the star. Complex orbits are therefore possible that leave gas streams far from the disk with enough angular momentum to prevent them from falling back to the disk. Furthermore, lateral pressure forces should also redistribute angular momentum in the gas moving away from the disk, which is heated by the ambient ultraviolet light to temperatures above 1000 K even when hydrogen ionization is still prevented by self-shielding. In a disk outflow that is non-spherical and highly inhomogeneous, pressure gradients at this temperature can change the velocity of gas streams by $\sim$3 km s^{-1}, providing substantial angular momentum.

The scenario that this leads to is of a large region of turbulent gas motions around the smaller disk, with random gas streams moving on different orbits. Eventually these gas streams would collide and cool, and if the net angular momentum of the gas is still small, most of the gas should fall back to the disk. However, it may take several orbits for this process to be completed, and gas streams at $\sim$5–10 AU from the star need only survive for a few orbits to produce a steady wind that generates the cloud, until the next peribothron is reached. In practice, a larger amount of mass may come off the disk at every peribothron, but the largest fraction of this may be launched on small orbits where it should indeed cool and fall back to the central disk, while a smaller amount of gas that moves out on larger orbits may suffice to sustain the photoevaporation wind.

4. DISCUSSION

A model is proposed in this paper to explain the origin of the gas cloud described by Gillessen et al. (2012). At some place along the present orbit of the gas cloud, a close encounter of a star and a stellar black hole occurred perhaps 10^4 or 10^5 years ago that strongly disrupted the star, tearing out a substantial fraction of its mass into debris and spinning up the star to near the breakup point. The fraction of the debris that remained bound to the star either fell back on the star or formed a small disk around it. The star, left on the orbit of the present cloud, settled back to equilibrium as a fast rotator, perhaps with a prolate shape initially. Subsequently, the disk gradually expanded as it absorbed the angular momentum of the star, until its outer edge reached the truncation radius at peribothron. Since this time, the disk has been launching a fraction of its mass at every peribothron passage in gas streams that arise from the strong tidal perturbation on the outer disk edge. Most of the streams remain on small orbits and fall back to the disk shortly afterward, and other gas becomes totally unbound from the star, but some of the gas streams on intermediate orbits move out to 5–10 AU of the star and form a turbulent cloud. These turbulent streams complete only a few orbits around the star before the next peribothron passage, and so they do not have enough time to collide, cool, and fall back to the disk. The photoevaporation of these streams by the ambient ionizing radiation generates a wind, which is elongated into a filament by the tidal force as the star falls back to the peribothron on its next orbit and produces a cloud like the observed one.

The material that reaches the outer edge of the disk at $\sim$0.5 AU over the entire duration of the cloud-generating phenomenon may exceed $10^{-2}\,M_\odot$ for a rapidly rotating star. Several inefficiency factors are likely to be present to convert this mass into the photoionized clouds that are produced at every orbit: some mass may rapidly escape the system after being ejected from the disk, and not all the photoionized wind may follow the star in a single coherent cloud for the whole orbit if hydrodynamic instabilities induced by ram pressure from the hot medium fragment the cloud. Even if these inefficiency factors are important or the mass that can reach the disk outer edge is smaller, the probability to see the cloud can still be reasonable. For example, if the cloud were generated for only 100 orbits, requiring a total mass of just $\sim 10^{-3}\,M_\odot$ to be placed on the photoevaporating gas streams over all the orbits, then the rate obtained in Equation (13) would imply a probability of 1% to see this cloud at any random time. This is still a reasonable probability, taking into account that the probability is calculated a posteriori, after having observed a curious phenomenon in the Galactic center that might be one among many unlikely phenomena that could be observed but are not actually happening at our present time.

We have noted also in Section 2.4 that collisions between main-sequence stars might produce similar star–disk systems as tidal encounters with black holes. The main uncertainty there is that any collision occurring as close to the Galactic center as the observed cloud would take place at a very high relative velocity, and it is therefore questionable that much of the debris that are generated may remain on bound orbits around one of the two stars. But if a disk of substantial mass can also be formed in this case, the rate of disk-forming events may be further increased.

The observed cloud actually has a complex head–tail structure. The head is the region of highest surface brightness in the recombination lines, with a long axis of 100 AU in 2011, which emits the observed *L*-band infrared emission that appears unresolved. This head is the cloud we have been considering in this paper, but there is also a lower surface brightness tail that is falling behind. This has been interpreted as a large shell of material from colliding winds that was produced near the orbital apobothron (Schartmann et al. 2012), but it may just as well be material that was barely unbound from the star and was detached from the main cloud near apobothron and is now falling behind because of ram-pressure effects.

The model proposed here can be tested after the cloud passes the peribothron. The present cloud should be totally disrupted whether or not a star is contained inside it. Detailed hydrodynamic simulations predicting the evolution of the disrupted cloud have been presented by Schartmann et al. (2012), which will be very interesting to test the interaction of the tidal debris from the cloud with the hot medium. However, the test that will distinguish the model presented here of a star–disk system inside the cloud is whether a point source emitting in the infrared continuum and recombination lines remains on the unaltered Keplerian orbit after the peribothron passage.

In fact, long after the peribothron passage, a cloud similar to the present one should be regenerated around the star. The new cloud is likely to be initially small and therefore faint in recombination line emission (which is proportional to the cloud area if it arises from the external photoionizing radiation). It might therefore be difficult to distinguish from the surrounding complex debris of the tidally disrupted cloud, but eventually it should appear as a region of higher surface brightness in the recombination lines on the exactly predicted position. Precisely what may happen is difficult to predict and depends on the structure of the disk and the mass of gas streams that are launched from it. Hydrodynamic simulations of the process are required for any quantitative predictions. However, a reasonable expectation is that the tidally induced internal shocks in the disk during the peribothron passage may produce enough heating to cause a substantial brightening of the infrared source. For example, if a mass of $10^{-3}\,M_\odot$ is present near the outer edge of the disk and is shocked at velocities of $\sim 30\,\mathrm{km\,s^{-1}}$, the energy released can be up to 10^{43} ergs and the disk may radiate at $\sim 100\,L_\odot$ during several months after the peribothron passage with a surface temperature near 2000 K, implying a very large brightening in the K band. After the peribothron passage, the observed light curve of the source in both recombination lines and infrared continuum should provide a detailed diagnostic of the process of tidal perturbation and mass ejection from the disk.

Finally, an interesting consequence of the model presented here is the possibility that planets are formed in the disks generated in these encounters. This possibility is basically a revival of the previous encounter theory for the formation of the solar system, in which planets were formed from the tidal plume generated during an encounter between two stars. In environments of a very high stellar density such as the Galactic center, tidal encounters occur at a high rate to form planetary systems around a large fraction of stars over the age of the Galaxy. The problems of the encounter theory (Russell 1935; Spitzer 1939) can be overcome: planets need to form only after the ejected material has formed a disk around the star and cooled down, and the fast rotation of the star can expand the disk and provide angular momentum. It is interesting that planets may have formed in the hypothesized disk within the observed cloud in the Galactic center, and that a type of planetary systems of this special origin might be present in the stellar cusp surrounding Sgr A∗.

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REFERENCES

Alexander, T., & Hopman, C. 2009, ApJ, 697, 1861
Alexander, T., & Kumar, P. 2001, ApJ, 549, 948
Bahcall, J. N., & Wolf, R. A. 1976, ApJ, 209, 214
Bahcall, J. N., & Wolf, R. A. 1977, ApJ, 216, 883
Benz, W., & Hills, J. G. 1987, ApJ, 323, 614
Benz, W., & Hills, J. G. 1992, ApJ, 389, 546
Bertoldi, F., & McKee, C. F. 1990, ApJ, 354, 529
Burkert, A., Schartmann, M., Alig, C., et al. 2012, ApJ, 750, 58
Canup, R. 2004, ARA&A, 42, 441
Genzel, R., Eisenhauer, F., & Gillessen, S. 2010, Rev. Mod. Phys., 82, 3121
Gillessen, S., Genzel, R., Fritz, T. K., et al. 2012, Nature, 481, 51
Hopman, C., & Alexander, T. 2006, ApJ, 645, L133
Khokhlov, A., Novikov, I. D., & Pethick, C. J. 1993, ApJ, 418, 181
Lai, D., Rasio, F., & Shapiro, L. S. 1993, ApJ, 412, 593
Miralda-Escudé, J., & Gould, A. 2000, ApJ, 545, 847
Morris, M. 1993, ApJ, 408, 496
Murray-Clay, R. A., & Loeb, A. 2012, submitted (arXiv:1112.4822)
Russell, H. N. 1935, The Solar System and Its Origin (New York: McMillan)
Schartmann, M., Burkert, A., Alig, C., et al. 2012, ApJ, in press (arXiv:1203.6356)
Spitzer, L. 1939, ApJ, 90, 675