Disruption of a Proto-Planetary Disk by the Black Hole at the Milky Way Centre

Ruth A. Murray-Clay & Abraham Loeb

Institute for Theory & Computation
Harvard-Smithsonian Center for Astrophysics
60 Garden Street, Cambridge, MA 02138, USA

Recently, Gillessen et al. discovered an ionized cloud of gas plunging toward the supermassive black hole, SgrA*, at the centre of the Milky Way.[1] The cloud is being tidally disrupted along its path to closest approach at ∼3100 Schwarzschild radii from the black hole. Here, we show that this cloud of gas naturally originates from a proto-planetary disk surrounding a low-mass star, which was scattered a century ago from the observed ring of young stars orbiting Sgr A*. As the young star approaches the black hole, its disk experiences both photo-evaporation and tidal disruption, producing a cloud with the observed properties. Our model implies that planets form in the Galactic centre, and that tidal debris from proto-planetary disks can flag low mass stars which are otherwise too faint to be detected.

The apocenter of the cloud's orbit, at 0.04pc from the black hole, coincides with the inner edge of the ring of young stars orbiting SgrA*, and the plane of the cloud's orbit coincides with that of the ring.[1,2] Because this ring contains O/WR stars, its age is $\lesssim$10 Myr and plausibly younger. At ages $\lesssim$3 Myr, typical low mass stars host protoplanetary gas disks with radii of order 100 AU.[3,4] Given the black hole mass of $M_{\rm BH} = 4.3 \times 10^6 M_\odot$,[5,6] the tidal radius around a star of mass $m_\star$ at a distance $r = 0.04$ pc from SgrA* is $r_t \sim r(m_\star/3M_{\rm BH})^{1/3} \sim 40{\rm AU}(m_\star/M_\odot)^{1/3}$. A solar mass star could therefore host a stable disk with a radius of $\sim r_t/3 \sim 13$ AU on a roughly circular orbit near the inner edge of the young stellar ring.

We suggest that the newly discovered gas cloud[1] surrounds such a star, which was recently scattered away from its original ring orbit and is currently on its first plunge toward the supermassive black hole (Figure 1). The star itself is too low mass to be observable (given the high level of dust extinction at the Galactic centre), but the debris produced through the disruption of its proto-planetary disk allowed it to be detected. We first calculate the properties of the system at the cloud's observed location and argue that they match the observations—an ionized cloud $\sim$100 AU in radius with density $n \sim 3 \times 10^5$ cm^{-3}, an electron temperature of 10^4K, and a dust temperature of $\sim$550K, trailed by a stream of gas. We provide predictions regarding the evolution of the cloud as it approaches pericenter. Finally, we demonstrate that the probability of producing such an object is plausibly high, and we calculate the implied rate of mass deposition by this process within the young stellar ring.

Although the tidal radius for a solar-mass star at $r = 0.04$pc is 40AU, the tidal radius at the cloud's pericenter distance of $r_p \approx 10^{-3}$pc is only 1AU. At the most recently observed epoch,[1] the cloud was approximately $6r_p$ from the black hole, with a tidal radius of 6AU. Hence, the circumstellar disk will experience substantial tidal disruption. At the same time, the Galactic centre hosts an extreme flux of ionizing and FUV photons. Protoplanetary disks in the ionizing environment near O stars in the Trapezium cluster are known to experience photoevaporation.[7] The stars experience mass loss due to heating both by FUV and by Lyman limit photons.[8] The former heat the disk to $\sim 10^3$K, generating outflows at the sound speed of ~ 3 km s^{-1}, corresponding to the escape velocity at $\sim$100 AU from a solar mass star. Well within this distance, the FUV-driven outflow is diminished, though not entirely quenched.[9] At the $\sim$10 AU and smaller distances of interest here and given the extreme ionizing environment, Lyman continuum (ionizing) photons dominate the outflow, generating a $\sim 10^4$K ionized outflow moving at the sound speed of $\sim$10 km s^{-1}. This speed matches the escape velocity at a distance of $\sim$10 AU from a solar mass star. Loss from smaller distances occurs at a reduced rate, but still generates a $\sim$10 km s^{-1} outflow by the time the gas reaches $\sim$10 AU.

Which process—tidal stripping or photoevaporation—dominates mass loss from the disk? Currently, tidal stripping dominates the unbinding of mass from the star, and at large distances from the star tidal stripping determines the ultimate fate of the gas. However, the outflow properties of the observed cloud are nevertheless currently determined by photoevaporation. This can be understood as follows. Gas at $r_d > r_t$ from its host star is accelerated by the tidal potential to a relative speed of Δv as it moves of order its own radius away from its host star: $\Delta v \sim (GM_{\rm BH}/r^2)(r_d/r)(r_d/\Delta v)$, so that $\Delta v \sim v_{\rm orb}(r_d/r)$, with $v_{\rm orb} = (GM_{\rm BH}/r^3)^{1/2}$. At the cloud's current separation from SgrA*, $r \approx 6 \times 10^{-3}$ pc $\approx$ 1300 AU, $v_{\rm orb} \approx$ 1700 km s^{-1} and $\Delta v \sim$ 10 km s^{-1}, comparable to the wind outflow rate. At earlier times in the star's plunge, Δv was smaller, meaning that wind gas flowed out faster than tidally disrupted gas. Although the current mass disruption rate, $\dot{M}_{\rm dis}$, is larger than the wind outflow rate, $\dot{M}_w$, wind gas emitted at earlier times dominates the currently observed cloud. In the short time that the infalling star has spent in an enhanced tidal field with $r_t < r_d$, the disk has only had the opportunity to expand by a few times its 10 AU size. At $r_d =$ 10AU, the time since $r_t = r_d$ along the infalling star's orbit is $\Delta t =$ 2yr. Decoupled material has traveled only $\sim \Delta v \Delta t \sim$ 4 AU further from the host star in that time. Figure 2a illustrates this point. We ask how far a test particle, released at a given disk radius, r_d, from the star when $r_t = r_d$ and moving only under the gravity of the black hole, will be from its current orbit. Exterior to the decoupled material, gas originally launched in a wind dominates.

The tidal decoupling rate is $\dot{M}_{\rm dis} \sim 2\pi\Sigma r_t \dot{r}_t \sim 2\pi\Sigma r_t \dot{r}(m_\star/3M_{\rm BH})^{1/3}$, where $\Sigma(r)$ is the original surface density of the disk and $\dot{r} \approx 2000$ km s^{-1} at the current position in the cloud's orbit. For illustration, we choose a profile similar to the minimum-mass solar nebula: $\Sigma = \Sigma_0(r_d/r_0)^{-1}$ with $\Sigma_0 = 2 \times 10^3$ g cm^2 and $r_0 = 1$AU.[4] This choice yields a current $\dot{M}_{\rm dis} \sim 3\times10^{-3}M_\odot$ yr^{-1}, where we set r_d equal to the current tidal radius. Photoevaporation, on the other hand, gives mass loss rates of $\dot{M}_w \sim 3 \times 10^{-10}(r_d/10\text{ AU})^{3/2}(\Phi_i/d^2)^{1/2}M_\odot$ yr^{-1},[10,11] where Φ_i is the ionizing luminosity in units of 10^{49} s^{-1} of a source at distance d (in pc) from the disk. This expression may be understood as follows. Near $r_d = 10$AU, where the escape velocity is comparable to the wind's sound speed $c_s = 10$km s^{-1}, $\dot{M}_w \approx 4\pi r_d^2 m_p n_b c_s$, where m_p is the mass of a proton and we have neglected an order unity correction arising from the non-sphericity of the flow. At the base of the wind, a balance between photoionization and radiative recombination yields a number density of $n_b \sim (\Phi_i/4\pi d^2)^{1/2}(r_d\alpha_{rec})^{-1/2}$, where α_{rec} is the radiative recombination constant and we have used the fact that the optical depth to ionizing photons is unity. Hence, $\dot{M} \sim (4\pi/\alpha_{rec})^{1/2}m_p c_s r_d^{3/2}(\Phi_i/d)^{1/2}$. Observations yield $10^{50.8}$ s^{-1} Lyman continuum photons in the central parsec[1,12], corresponding to $\Phi_i = 63$. Using $d = 1$, $(\Phi_i/d^2)^{1/2} = 8$. The central concentration of S-stars within 0.01 pc, which we estimate to contribute $\Phi_i = 0.2$ from each of ten approximately $10M_\odot$ stars comparable to the second-most luminous Trapezium star,[10] yields a small total of $\Phi_i = 2$ but in a more concentrated region. At the current position of the cloud, these stars contribute $(\Phi_i/d^2)^{1/2} \sim 230$ for $d = 6 \times 10^{-3}$. At $d = 0.04$, this number is 35. For $r_d = 10$AU and smaller, mass loss from these ionizing fluxes dominates over FUV-driven mass loss. Using an intermediate value of $(\Phi_i/d^2)^{1/2} = 100$, at $r_d = 10$ AU, $\dot{M}_w \sim 3 \times 10^{-8}M_\odot$ yr^{-1}. On the cloud's original orbit, $\dot{M}_w \sim 10^{-8}M_\odot$ yr^{-1}, allowing our nominal disk, which contains $\sim 10^{-2}M_\odot$ between 1 and 10 AU, to survive for $\sim 10^6$ yr. Disk masses several times larger are plausible, and hence a protoplanetary disk could have survived until the current time on the star's birth orbit in the ring.

Currently, gas farther than ∼25 AU from the star (see Figure 2a) was originally ejected in the photoevaporative wind. This ejected material itself (which starts in a ring-like configuration) undergoes tidal stripping. Along the star's original orbit, the extent of the wind moving at ∼10 km s^{-1} is set by the 40 AU tidal radius. Ram pressure with the ambient gas exceeds the ram pressure of the photoevaporative wind when $n_{amb}v_\star^2 > nv_w^2$, where n_{amb} is the ambient number density of gas and $v_\star$ is the star's velocity along its orbit. The mean density of ambient gas within the central 1.5pc, known as the central cavity, is $n_{amb} \sim 10^3 \mathrm{cm}^{-3}$.[13] Models place the density at $\sim 3 \times 10^2$–6×10^3 cm^{-3} at the cloud's current location and $\sim$ (1–5) $\times$ 10^2 cm^{-3} on its original orbit.[14] Along the star's original orbit, $v_\star \approx 700$ km s^{-1}, and these two forces are in rough balance at the star's tidal radius. Currently, $v_\star \approx 2300$ km s^{-1}, so ram pressure with the surrounding medium has increased by 1–2 orders of magnitude at 40 AU separations, and the tidally-disrupted photoevaporative wind is undergoing ram pressure stripping. At the current tidal radius, however, the two pressures remain in rough balance.

The time for a parcel of wind to travel from 10 to 40 AU is ∼15 yr, smaller than the 70 year time to plunge to pericenter on the cloud's current orbit. This wind-generated cloud in turn experiences tidal disruption with $\Delta v \sim 30$ km s^{-1} at 40 AU. By its current location, the original wind cloud will have reached an extent of a few hundred AU. Figure 2a illustrates this extent as well. The number density of the observed ionized cloud on a scale of $r_c = 100$ AU is $n = \dot{M}_w/(m_p 4\pi r_c^2 v_w) = 3 \times 10^4$ cm^{-3}, comparable to the observed density.

The dust in the wind, in analogy to dust in HII regions, does not reach temperature equilibrium with the 10^4K gas. Gillessen et al. argue that the dust continuum emission at about 550 K comes from small, transiently heated grains, having a total mass equal to $\sim 10^{-5}$ the total gas mass of the cloud.[1] Additional colder dust may be present. This relatively small dust mass may result from grain growth and settling in the protoplanetary disk, leaving relatively few small grains available to be lofted into the photoevaporative wind. The neutral, cooler disk does not contribute substantially to the observed emission.

In the tidally disrupted portion of the cloud, the density is much higher, reflecting the substantially larger $\dot{M}$. As the cloud plunges toward the supermassive black hole in the next 1.5 years, *we predict that its observed density will increase by several orders of magnitude (see the right-hand-side panel of Figure 2).* This disrupted gas, however, will not all be ionized. The future evolution of the density and dynamics of a debris cloud around a low-mass star on a Keplerian orbit are easily distinguishable from those of a pressure-confined cloud with no self gravity or central mass supply.

How likely is it that such a star would plunge toward the black hole? Given that the star is undergoing its first inward plunge, we require similar events to occur roughly once per half the orbital time of the cloud t_o, implying a rate $f \sim 2/t_o \sim (70\ \mathrm{yr})^{-1}$. If we conservatively ignore the enhancement in the scattering rate due to binaries, the star must have scattered multiple times off massive perturbing stars of mass $m_{\rm pert}$ at impact parameters greater than $b \sim G m_{\rm pert}/\sigma_\star^2$, such that each encounter did not disrupt the disk. The rate of a significant velocity change due to multiple gentle scatterings is $f \sim pN_*[N_{\rm pert}/(\pi R^2 h)]\pi b^2 \sigma_\star \ln\Lambda \sim pN_\star N_{\rm pert} b^2 \Omega \ln\Lambda / R^2$, where N_* is the number of low-mass stars in the young stellar ring, $N_{\rm pert}$ is the number of perturbing ring stars, $\sigma_\star$ is the velocity dispersion of ring stars, R is the ring radius, $h \sim \sigma_\star/\Omega$ is the ring scale height (with $h/R \sim 10^\circ$),[12] $\ln\Lambda \equiv \ln(0.04\ \mathrm{pc}/10\mathrm{AU}) \sim 7$ is the Coulomb logarithm due to multiple gentle scatterings, and $\Omega = (GM_{\rm BH}/R^3)^{1/2}$ is the angular orbital velocity of the ring. Since $f \propto N_{\rm pert} m_{\rm pert}^2$, high-mass stars provide the most frequent scatterings. The probability of a scattered star being directed toward SgrA* is[15] $p \sim r_p/R$. The average eccentricity of massive ring stars is observed to be[12] ~ 0.3–0.4, implying that a tail population of low-mass (previously unobserved) stars could diffuse into the observed orbit of the gas cloud around SgrA*.

For the top-heavy mass function of stars inferred in the young stellar ring,[16] the number of stars above a mass $m_\star$ scales as $N_\star \propto m_\star^{0.55\pm0.3}$. We find that the number of low-mass stars required for producing the appropriate rate is, $N_\star \sim 6\times10^3(m_\star/M_\odot)^{0.275}(m_{\rm pert}/20M_\odot)^{-1.275}$, for $R = 0.04$pc (the location of the proposed initial stellar orbit at the inner edge of the young stellar ring). Given the inferred mass in the young stellar ring of[12] $\sim 10^4 M_\odot$, the probability of sufficient scattering over a 70 year timescale is significant, $\gtrsim 2\%$. Scattering on binary stars in the ring or on stars which do not reside in the ring[12] further enhances this probability. The diffusion of lighter stars out of the ring may have led to the unusually top-heavy mass function of stars that are found in the ring at present.[16]

The nominal protoplanetary disk described above contains $\sim 10^{-2}M_\odot$ of gas between 1 and 10AU, outside the tidal radius at pericenter. The actual disk may be a few times more massive, ensuring a lifetime against photoevaporation in its birth orbit of at least the ∼3 Myr, typical for protoplanetary disks. If a 0.03 $M_\odot$ disk is disrupted every $(t_o/2)(2\%)^{-1} \sim 4\times10^3$yr (corresponding to a rate $\lesssim N_\star/10$ Myr), the related events deliver $\sim 8\times10^{-6}M_\odot$ yr^{-1} to the inner 10^{-3}pc around SgrA*, substantially in excess of the presently inferred accretion rate onto the black hole.[17]

The existence of proto-planetary disks in galactic nuclei has important implications: it could lead to a fragmentation cascade to comets, asteroids, and dust around quasars,[18] and to bright flares due to the tidal disruption of planets.[19] In the Milky Way centre, the debris of proto-planetary disks offers a new probe of the low mass end of the mass distribution of stars which are too faint to be detected otherwise.

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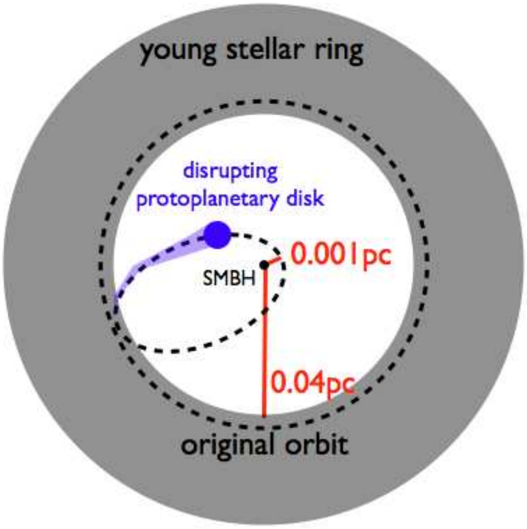

Fig. 1.— Schematic illustration of our scenario. A young, low-mass star hosting a protoplanetary disk is dynamically dislodged from the Galactic centre's young stellar ring. As it plunges toward the supermassive black hole (SMBH) at the Galactic centre, the disk is photoevaporated and tidally disrupted, generating an extended dusty cloud. A trail of dust and gas is deposited along the star's orbit.

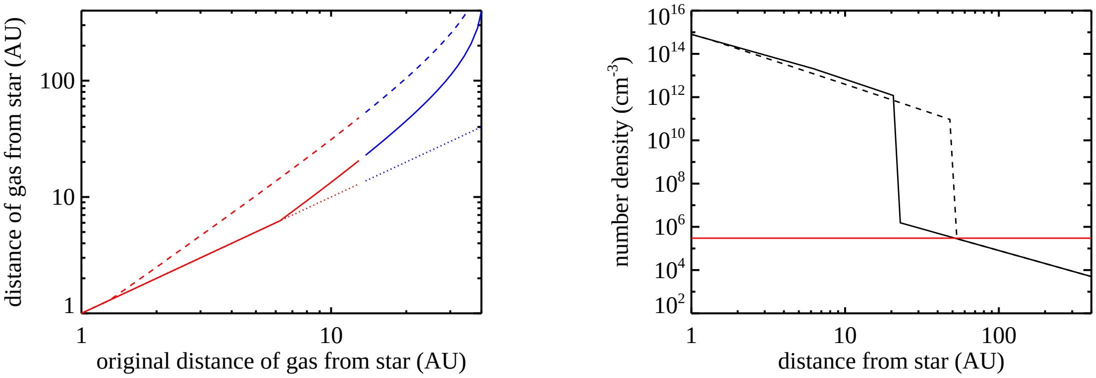

Fig. 2.— As the star plunges toward the Galactic centre, its disk and the surrounding photoevaporative wind are tidally disrupted. **Left:** The distance of gas from the host star, r_d, at the current epoch (solid line) and at the time of pericenter passage (dashed line) as a function of initial separation from the host star, $r_{d,i}$. The dotted line represents no change. For this calculation, we assume that the material is instantaneously decoupled from the star when its separation equals the tidal radius and that it subsequently moves as a test particle in the gravitational field of the supermassive black hole. Red portions of the curve represent gas initially in the disk, while blue portions represent gas initially in the photoevaporative cloud. Note that the actual calculation performed is the same for both the red and the blue portions of the curve. **Right:** Gas number density as a function of distance from the star at the current epoch (solid) and the time of pericenter passage (dashed). Where disk gas dominates, we plot $n = m_p^{-1}\Sigma_0(r_{d,i}/r_0)^{-1}h_d^{-1}(r_{d,i}/r_d)^2$, using a disk scale-height $h_d \sim 0.1r_d$. Where wind gas dominates, we estimate $n = \dot{M}_w/(2\pi m_p r^2 v_w)$, assuming that the wind geometry is not yet spherically symmetric. The currently measured density at scales of $\sim$100AU is indicated for reference (red).