Disruption of a Protoplanetary Disk as it Plunges Toward the Galactic Center

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Gillessen et al. report the observation of an ionized cloud of gas plunging toward the supermassive black hole at the center of our galaxy. Further tidal disruption of this cloud as it reaches its closest approach to the black hole in 2013 will provide constraints on the environment at its pericenter distance of ∼3100 Schwarzschild radii. Here, we argue that this cloud of gas originates from a circumstellar disk orbiting a low-mass (and hence unseen) star which was dynamically dislodged from the young circumnuclear disk of O and Wolff-Rayet stars orbiting Sag A*. As the young star plunges toward the black hole, its disk experiences both photoevaporation and tidal destruction. These processes combine to produce a cloud having properties consistent with the observations.

The apocenter of the cloud's orbit, at 0.04pc from the black hole, coincides witht he inner edge of the circumnuclear ring (cite). Because this ring contains O stars, its age is $\lesssim$10 Myr. At such young ages, typical low mass stars host protoplanetary gas disks with radii of order 100 AU. The tidal radius around a star at a distance r from the black hole is $r_t \sim r(M_*/3M_{BH})^{1/3} \sim 40\text{AU}(M_*/M_\odot)^{1/3}$ at $r = 0.04$ pc, where we have used $M_{BH} = 4.3 \times 10^6 M_\odot$ (cite). A solar mass star could host a stable disk with radius $r_d \sim r_t/3 \sim 10$ AU, residing on a roughly circular orbit near the inner edge of the circumnuclear disk.

We argue that the observed dust cloud is such a star, recently dislodged from such an orbit and currently on its first plunge toward the supermassive black hole (Figure 1). The star itself is too low mass to be observable—we are seeing its evolving disk. We first calculate the properties of such a system at the cloud's observed location and argue that they match the observations—an ionized cloud ∼100 AU in radius with density $n \sim 3 \times 10^5$ cm^{-3}, an assumed electron temperature of 10^4K, and a dust temperature of ∼550K, trailed by residual 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 sufficient to make this interpretation plausible, and we calculate the implied rate of mass deposition by this process within the circumnuclear ring.

Though 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, the cloud was approximately $6r_p$ from the black hole, with a tidal radius of 6AU. Hence, the plunging disk will experience substantial tidal disruption. At the same time, the galactic center hosts an extreme flux of ionizing and FUV photons. Protoplanetary disks in the ioninzing environment near O stars in the Trapezium cluster are known to experience photoevaporation (cites). Storzer & Hollenbach demonstrate that they experience mass loss due to heating both by FUV and by Lyman limit photons. The former heat the disk to ∼10^3K, generating outflows a the sound speed of ∼3 km/s, corrensponding to the escape velocity at ∼100 AU from a solar mass star. Well within this distance, the FUV-driven outflow is diminished, though not entirely quenched (Adams et al.). At the ∼10 AU and smaller distances of interest here and given the extreme ionizing environmnet, Lyman continuum (ionizing) photons dominated the outflow, generating a $\sim 10^4$K ionized outflow moving at the sound speed of $\sim$10 km/s. This speed matches the escape velocity at $\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 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: $\Delta v \sim (GM_{BH}/r^2)(r_d/r)(r_d/\Delta v)$, so that $\Delta v \sim v_{orb}(r_d/r)$, with $v_{orb} = (GM_{BH}/r^3)^{1/2}$. At the cloud's current $r \approx 6 \times 10^{-3} pc \approx 1300$AU, $v_{orb} \sim 1700$km/s and $\Delta v \sim 10$km/s, 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. Though the current mass disruption rate, $\dot{M}_{dis}$ is larger than the wind outflow rate, $\dot{M}_w$, both estimated below, nevertheless 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 $r_d = 10$AU, the time since $r_t = r_d$ along the infalling star's orbit is $\Delta t = 2$yr. Decoupled material has traveled only $\sim \Delta v \Delta t \sim 4$ AU further from the host star in that time. Figure 2 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 $\dot{M}_{dis} \sim 2\pi\Sigma r_t \dot{r}_t \sim 2\pi\Sigma r_t \dot{r}(M_*/3M_{BH})^{1/3}$, where $\Sigma(r)$ is the original surface density of the disk and $\dot{r} \approx 2000$km/s 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. This choice yields a current $\dot{M}_{dis} \sim 3 \times 10^{-3} M_\odot$/yr, where we set r_d equal to the current tidal radius. Photoevaporation, on the other hand, gives mass loss rates of $\dot{M}_w \sim 8 \times 10^{-12} r_d^{3/2} (\Phi_i/d^2)^{1/2} M_\odot$ yr^{-1} (Storzer & Hollenback, Scally & Clarke), 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, which has radius r_d in AU. Papers cited by Genzel et al. 2010 measure $10^{50.8}$ s^{-1} Lyman continuum photons in the central parsec, 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 (Scally & Clarke), contributes a small total of $\Phi_i = 2$, but in a more concentrated region. At the current position of the dust 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 100 for the ionizing flux, at $r_d = 10$ AU, $\dot{M}_w \sim 2 \times 10^{-8} M_\odot$/yr. This rate may be understood roughly as the total rate at which the disk absorbs ionizing energy divided by the square of the escape velocity. (I need to calculate whether the gas is still mostly neutral at $\tau = 1$ to photoionization. If not, the wind loss rate will change some.)

Currently, gas further than ∼25 AU from the star (see Figure 2) was originally ejected in the photoevaporative wind. This ejected material itself undergoes tidal stripping. On the star's original orbit, the extent of the wind, moving at ∼10 km/s is set by the 40 AU tidal radius (compare to interactions with surrounding medium to be sure). 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 $\Delta v \sim 30km/s$ at 40 AU. By its current location, the original wind cloud will have reached an extent of a few hundred AU. Figure 2 illustrates this extent as well. The number density of the observed ionized cloud on a scale of $r_c = 100$ AU is $n = \dot{M}/(m_H 4\pi r_c^2 v_w) = 2 \times 10^4$ (factor of 10 went somewhere—need to find it), comparable to the observed density.

The dust in the wind does not come into temperature equilibrium with the 10^4K gas. In analogy to dust in HII regions, we balance heating by

In the tidally disrupted portion of the cloud, the density is much higher, reflecting the substantailly larger $\dot{M}$. As the cloud plunges toward the supermassive black hole, we predict that its density at 100 AU scales will increase by several orders of magnitude. Figure 2b provides a comparable plot to 2a for the pericenter distance. This disrupted gas, however, will not all be ionized.

How likely is it that such a star would plunge toward the black hole? We are arguing that the star is undergoing its first inward plunge. Given that we are seeing this event, we would like similar events to occur with frequency $f \sim 2/P_c \sim ?\mathrm{yr}^{-1}$. If we pessimistically ignore the role of binaries, then the star was likely perturbed by another star through a strong scattering event, with impact parameter $b \lesssim GM_{pert}/v_{disp}^2$. The rate of such an event is approximately $f \sim pN_* N_{pert}/(\pi r_d^2 H_d) b^2 v_{disp} \sim pN_* N_{pert} b^2 \Omega_d / \pi r_d^2$, where N_* is the number of low-mass stars comparable to the infalling object in the disk, N_{pert} is the number of perturbing stars, M_{pert} is the mass of a typical perturber, v_{disp} is the velocity dispersion of disk stars, r_d is the disk radius, $H_d \sim v_{disp}/\Omega$ is the disk scale height, and $\Omega = (GM_{BH}/r_d^3)^{1/2}$ is the angular velocity. Since $f \propto N_{pert} M_{pert}^2$, high-mass stars provide the most frequent strong scatterings. We estimate the probability of a strongly scattered star being directed toward Sag A* as $p \sim r_p^2/4r_i^2$.

For an IMF with $N \propto M^{-1.35}$ (a Salpeter IMF), we obtain $N_* \sim 8\times10^6 (M_*/M_\odot)^{-0.675} (M_{pert}/20M_\odot)^{-0.325}$, where we have used $r_d = 0.04$pc, the location of the proposed initial stellar orbit at the inner edge of the circumnuclear disk, and a disk thickness of ∼10° (cite Ghez or other). A top-heavy IMF reduces this number, as the number of high-mass perturbers per total mass is increased. However, the dependence is weak. The total mass in the circumnuclear disk is estimated to be $\sim 10^? M_\odot$,

Soft binaries—those with separations $\gtrsim GM_*/v_{disp}^2$—present a larger cross-section for strong scattering. If such encounters dominate, a lower-mass stellar disk could produce the desired rate of infalling stars.

The nominal protoplanetary disk described above contains $\sim 10^{-2} M_\odot$ of gas between $r_{t,p} \sim$ 1AU and $r_{t,i} \sim 10$ AU. If such a disk is disrupted every $P_c/2 \sim 70$yr, such events deliver $\sim 10^{-4} M_\odot$/yr to the inner 10^{-3}pc around Sag A*, substantially in excess of the black hole's inferred accretion rate.