A gas cloud on its way towards the supermassive black hole at the Galactic Centre

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Measurements of stellar orbits4–12 provide compelling evidence4,5 that the compact radio source Sagittarius A* at the Galactic Centre is a black hole four million times the mass of the Sun. With the exception of modest X-ray and infrared flares6,7, Sgr A* is surprisingly faint, suggesting that the accretion rate and radiation efficiency near the event horizon are currently very low6,8. Here we report the presence of a dense gas cloud approximately three times the mass of Earth that is falling into the accretion zone of Sgr A*.

Our observations tightly constrain the cloud’s orbit to be highly eccentric, with an innermost radius of approach of only ~3,100 times the event horizon that will be reached in 2013. Over the past three years the cloud has begun to disrupt, probably mainly through tidal shearing arising from the black hole’s gravitational force. The cloud’s dynamic evolution and radiation in the next few years will probe the properties of the accretion flow and the feeding processes of the supermassive black hole. The kilo-electronvolt X-ray emission of Sgr A* may brighten significantly when the cloud reaches pericentre. There may also be a giant radiation flare several years from now if the cloud breaks up and its fragments feed gas into the central accretion zone.

As part of our NACO9 and SINFONI10,11 Very Large Telescope (VLT) observation programmes studying the stellar orbits around the Galactic Centre supermassive black hole, Sgr A*, we have discovered an object moving at about 1,700 km s\(^{-1}\) along a trajectory almost straight towards Sgr A* (Fig. 1). The object has a remarkably low temperature (about 550 K; Supplementary Fig. 2) and a luminosity about five times the Br\(_{\alpha}\) emission is elongated along its direction of motion with a velocity gradient along the orbital direction. Test particle calculations (Fig. 1) show that the object is a dusty, ionized gas cloud.

The extinction of the ionized gas is typical for the central parsec (0.35–0.7). If so, the requirement of complete photo-ionization sets a lower limit to \(f_v\) of \(10^{-1.1} \pm 0.3\) for the extreme case that the cloud is a thin sheet.

The combined astrometric and radial velocity data tightly constrain the cloud’s motion. It is on a highly eccentric (\(e = 0.94\)) Keplerian orbit bound to the black hole (Fig. 1, Table 1 and Supplementary Information section 2). The pericentre radius is a mere 36 light hours (3,100 Schwarzschild radii, \(R_\odot\)), which the cloud will reach in summer 2013. Only the two stars S2 (\(r_{\text{per}} = 17\) light hours) and S14 (\(r_{\text{per}} = 11\) light hours) have come closer to the black hole since our monitoring started in 1992. Although the cloud’s gas density may be only modestly greater than that of other ionized gas clouds in the central parsec—\(n_e = (0.1–2) \times 10^5\) cm\(^{-3}\)—refs 12 and 14—it has a specific angular momentum about 50 times smaller12.

For the nominal properties of the X-ray detected accretion flow onto the black hole15,16 the cloud should stay close to Keplerian motion all the way to the pericentre (Supplementary Information sections 3 and 4). Its density is currently about 300 times greater than that of the surrounding hot gas in the accretion flow17: extrapolating to the pericentre, its density contrast will then still be about 60 times greater. Similarly, the cloud’s ram pressure by far exceeds that of the hot gas throughout the orbit. In contrast, the thermal pressure ratio will quickly decrease from unity at apocentre and the hot gas is expected to drive a shock slowly compressing the cloud. Whereas the external pressure compresses the cloud from all directions, the black hole’s tidal forces shear the cloud along the direction of its motion, because the Roche density for self-gravitational stabilization exceeds the cloud density by nine orders of magnitude1. In addition, the ram pressure compresses the cloud parallel to its motion. The interaction between the fast-moving cloud and the surrounding hot gas should also lead to shredding and disruption, owing to the Kelvin–Helmholtz and Rayleigh–Taylor instabilities18–20. Rayleigh–Taylor instabilities at the leading edge should in fact break up the cloud within the next few years if it started as a spheroidal, thick blob (Supplementary Information section 3). A thin, dense sheet would by now already have fragmented and disintegrated, suggesting that \(f_v\) is of the order of unity.

We are witnessing the cloud’s disruption happening in our spectroscopic data (Fig. 2). The intrinsic velocity width more than tripled over the last eight years, and we see between 2008 and 2011 a growing velocity gradient along the orbital direction. Test particle calculations implementing only the black hole’s force show that an initially spherical gas cloud placed on the orbit (Table 1) is stretched along the orbit and compressed perpendicular to it, with increasing velocity widths and velocity gradients reasonably matching our observations (Fig. 3 and Supplementary Fig. 4). There is also a tail of gas with lower surface brightness on approximately the same orbit as the cloud, which cannot be due to tidal disruption alone. It may be stripped gas, or lower-density, lower-filling-factor gas on the same orbit. The latter explanation is more plausible given that the integrated Br\(_{\gamma}\) and L’-band...
Figure 1 | Infalling dust/gas cloud in the Galactic Centre. a, b, NACO\(^*\) adaptive optics VLT images showing that the cloud (dashed circle) is detected in the L′-band (3.76 \(\mu\)m, deconvolved and smoothed with a 2-pixel Gaussian kernel) but not in the K\(_s\)-band (2.16 \(\mu\)m, undeconvolved), indicating that it is not a star but a dusty cloud with a temperature of around 550 K (Supplementary Fig. 2). The cloud is also detected in the M-band (4.7 \(\mu\)m) but not in the K\(_s\)-band (2.16 \(\mu\)m) (in 2008) and 1,650 km s\(^{-1}\) (in 2011). c, The combination of the astrometric data in L′ and Br\()\_γ\) and the radial velocity (\(V_{\text{LSR}}\)) data in Br\()\_γ\) tightly constrains the orbit of the cloud (error bars are 1\(\sigma\) measurement errors). The cloud is on a highly eccentric, bound orbit (\(e = 0.94\)), with a pericentre radius and epoch of 36 light hours (3,100R\(_0\)) and 2013.5 (Table 1). The blue ellipse shows the orbit of the star S2 for comparison\(^{-3}\). For further details see the Supplementary Information.

Figure 2 | The velocity shear in the gas cloud. The left column shows data from 2008.3, the right from 2011.3. Panels a and b show integrated Br\()\_γ\) maps of the cloud, in comparison to the point spread function from stellar images shown above. The inferred intrinsic East–West half-width at half-maximum source radii are \(R_e = 21 \pm 5\) mas in 2008 and 19 \(\pm\) 8 mas in 2011 (approximately along the direction of orbital motion), after removal of the instrumental broadening estimated from the stellar images above. A similar spatial extent is found from the spatial separation between the red- and blue-shifted emission of the cloud (\(R_{\text{ax}} = 23 \pm 5\) mas). The minor-axis radius of the cloud is only marginally resolved or unresolved (radius less than 12 mas). We adopt \(R_e = 15\) mas as the ‘effective’ circular radius, by combining the results in the two directions. Panels c and d are position-velocity maps, obtained with SINFONI on the VLT, of the cloud’s Br\()\_γ\) emission. The slit is oriented approximately along the long axis of the cloud and the projected orbital direction and has a width of 62 mas for the bright ‘head’ of the emission. For the lower-surface-brightness ‘tail’ of emission (in the enclosed white dotted regions) we smoothed the data with 50 mas and 138 km s\(^{-1}\) and used a slit width of 0.11′′. The gas in the tail is spread over around 200 mas downstream of the cloud. The trailing emission appears to be connected by a smooth velocity gradient (of about 2 km s\(^{-1}\) mas\(^{-1}\)), and the velocity field in the tail approximately follows the best-fit orbit of the head (cyan curves; see also Table 1). An increasing velocity gradient has formed in the head between 2008 (2.1 km s\(^{-1}\) mas\(^{-1}\)) and 2011 (4.6 km s\(^{-1}\) mas\(^{-1}\)). As a result of this velocity gradient, the intrinsic integrated full-width at half-maximum (FWHM) velocity width of the cloud increased from 89 (\(\pm\) 30) km s\(^{-1}\) in 2003 and 117 (\(\pm\) 25) km s\(^{-1}\) in 2004, to 210 (\(\pm\) 24) km s\(^{-1}\) in 2008, and 350 (\(\pm\) 40) km s\(^{-1}\) in 2011.
...did not drop by more than 30% between 2004 and 2011, and the integrated Brγ flux of the tail is comparable to that of the cloud.

The disruption and energy deposition processes in the next years until and after the pericentre passage are powerful probes of the physical conditions in the accretion zone (Supplementary section 3). We expect that the interaction between hot gas and cloud will drive a strong shock into the cloud. Given the densities of cloud and hot gas, the cloud as a whole should remain at low temperature until just before it reaches the pericentre. Near the pericentre the post-shock temperature of the cloud may increase rapidly to \( t_{\text{post-shock}} \approx 6 \times 10^6 \text{K} \), resulting in X-ray emission. We estimate the observable 2–8-keV luminosity to be less than 10^{34} \text{erg s}^{-1} there, somewhat larger than the current ‘quiescent’ X-ray luminosity of the Sgr A* (10^{33} \text{erg s}^{-1}). Rayleigh–Taylor instabilities may by then have broken up the cloud into several fragments, in which case the emission may be variable throughout this period. Our predictions depend sensitively on the density and disruption state of the cloud, as well as on the radial dependencies of the hot gas properties, none of which we can fully quantify. The steeper the radial profiles are and the higher the value of \( f_v \), the more X-ray emission will occur. Shallower profiles and a low value of \( f_v \) could shift the emission into the un-observable soft X-ray and ultraviolet bands. Together the evolution of the 2–8-keV and Brγ luminosities, as well as the Brγ velocity distribution, will strongly constrain the thermal states and interaction of the cloud and the ambient hot gas in the present regime of \( 10^6 R_S \rightarrow 10^8 R_S \). When compared with test particle calculations and more detailed numerical simulations (Fig. 3 and Supplementary Fig. 4).

The radiated energy estimated above is less than 1% of the total kinetic energy of the cloud, about 10^{54} \text{erg}. As the tidally disrupted filamentary cloud passes near pericentre some fraction of the gas may well collide with itself, dissipate and circularize. This is probable because of the large velocity dispersion of the cloud, its size comparable to the impact parameter and because the Rayleigh–Taylor and Kelvin–Helmholtz timescales are similar to the orbital timescale. Because the mass of the cloud is larger than the mass of hot gas within the central 3,100R_S, or so (approximately 10^{27.3} g; ref. 15), it is plausible that then the accretion near the event horizon will be temporarily dominated by accretion of the cloud. This could in principle release up to around 10^{39} \text{erg} over the next decade, although the radiative efficiency of the inflow at these accretion rates is of the order of 1–10% (refs 23 and 24).

Observations of the emission across the electromagnetic spectrum during this post-circularization phase will provide stringent constraints on the physics of black-hole accretion with unusually good knowledge of the mass available.

What was the origin of the low-angular-momentum cloud? Its orbital angular momentum vector is within 15° of the so-called ‘clockwise’ disk of young, massive O and Wolf–Rayet stars at radii of about 1" to 10", from Sgr A* (refs 3 and 25). Several of these stars have powerful winds. One star, IRS16SW, about 1.4" southeast of Sgr A*, is a massive Wolf–Rayet contact binary. Colliding winds in the stellar disk, and especially along the orbital direction, purely on the basis of the tidal disruption of the cloud by the gravitational force of the supermassive black hole. This toy model is a good description of the velocity (and spatial) data between 2004 and 2011, thus allowing plausible forward projections until pericentre passage. Beyond that, the test particle approach will probably fail owing to the hydrodynamic effects, which will then most probably dominate further evolution. The cloud cannot be described by a simple velocity gradient between 2012 and 2015, and hence we omit the corresponding value in panels m, n and o.
in binaries, may create low-angular-momentum gas that then falls deep into the potential of the supermassive black hole.\textsuperscript{27,28}

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