A gas cloud on its way toward the super-massive black hole in the Galactic Centre

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Measurements of stellar orbits[1,2,3] provide compelling evidence that the compact radio source SgrA*[4,5] at the Galactic Centre is a 4 million solar mass black hole. With the exception of modest X-ray and infrared flares[6,7], SgrA* is surprisingly faint, suggesting that the accretion rate and radiation efficiency near the event horizon are currently very low[3,8]. Here we report the detection of a dense, approximately 3 Earth mass gas cloud that is falling into SgrA*'s accretion zone. Our adaptive optics infrared observations with the ESO VLT tightly constrain the cloud's orbit to be highly eccentric with an innermost radius of approach of only ~3100 times the event horizon in 2013. Over the past three years the cloud has begun to disrupt, probably mainly by tidal shearing due to the black hole's

gravitational force. The cloud's dynamic evolution and radiation in the next years will probe the properties of the accretion flow and the feeding processes of the super-massive black hole. The keV X-ray emission of SgrA* may brighten significantly when the cloud reaches pericentre. There may also be a giant radiation flare several years from now if the cloud suffers breakup with its fragments feeding gas into the central accretion zone.

As part of our NACO[9] and SINFONI[10,11] VLT programmes studying the stellar orbits around the Galactic Centre super-massive black hole, SgrA*, we have discovered an object moving at ~1700km/s along a trajectory almost straight toward SgrA* (Figure 1). The object has a remarkably low temperature (~550K, Figure S2) and luminosity (~5L$_\odot$), unlike any star we have so far seen near SgrA*. It is also seen in the spectroscopic data as a redshifted emission component in the Brγ and Brδ hydrogen, and the 2.058μm HeI lines, with the same proper motion as the L'-band object. Its 3-dimensional velocity increased from 1200km/s in 2004 to 2350km/s in 2011. The Brγ emission is elongated along its direction of motion with a spatially resolved velocity gradient (Figure 2). Together these findings show that the object is a dusty, ionized gas cloud.

The extinction of the ionized gas is typical for the central parsec (S1) and its intrinsic Brγ luminosity is 1.66(±0.25)×10^{-3}L$_\odot$. For case B recombination the implied electron density is $n_c = 2.6\times10^5 f_V^{-1/2} R_{c,15mas}^{-3/2} T_{e,1e4}^{0.54}$ cm^{-3}, for an effective cloud radius of R$_c$~15mas, volume filling factor f_V (≤1) and an assumed electron temperature T_e in units of 10^{4}K, a value typical for the temperatures measured in the central parsec[12]. The cloud mass is $M_c = 1.7\times10^{28} f_V^{1/2} R_{c,15mas}^{3/2} T_{e,1e4}^{0.54}$ g, or about 3$f_V^{1/2}$ Earth masses. It is plausibly photo-ionized by the ultra-violet radiation field from nearby massive hot stars, deduced from a comparison of the recombination rate with the number of impinging Lyman continuum photons[3,13]. This conclusion is supported by the HeI/Brγ line flux ratio of ~0.7, which is similar to the values found in the photo-ionized gas in the central parsec (0.35–0.7). If so, the requirement of complete photo-ionization sets a lower limit to f_V of $10^{-1\pm0.5}$ 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 (Figure 1, Table 1, S2). The pericentre radius is a mere 36 light hours ($3100R_S$), which the cloud will reach in summer 2013. Only the two stars S2 (r_{peri}=17lh) and S14 (r_{peri}=11lh) have come closer to the black hole[2,3] since our monitoring started in 1992. While the cloud's gas density may be only modestly greater than other ionized gas clouds in the central parsec ($n_e \sim 0.1-2\times10^5 cm^{-3}$)[12,14], it has a ≈50 times smaller specific angular momentum[12].

For the nominal properties of the X-ray detected accretion flow onto the black hole[15,16] the cloud should stay close to Keplerian motion all the way to pericentre (Sections S3 & S4). Its density currently is $\sim 300 f_V^{-1/2}$ times greater than that of the surrounding hot gas in the accretion flow[15]; extrapolating to pericentre its density contrast will then still be $\sim 60 f_V^{-1/2}$. 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. While the external pressure compresses the cloud from all directions, the black hole's tidal forces shear the cloud along the direction of its motion, since the Roche density for self-gravitational stabilization exceeds the cloud density by nine orders of magnitude[3]. 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, due to the Kelvin-Helmholtz and Rayleigh-Taylor instabilities[17-20]. 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 (S3). A thin, dense sheet would by now already have fragmented and disintegrated, suggesting that f_V is of order unity.

We are witnessing the cloud's disruption happening in our spectroscopic data (Figure 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 put 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 (Figure 3, S4). There is also a tail of lower surface brightness gas approximately on 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 since the integrated Brγ and L'-band luminosities 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 pericentre are powerful probes of the physical conditions in the accretion zone (section S3). We expect that the interaction between hot gas and cloud drives 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 pericentre. Near pericentre the post-shock temperature may increase rapidly to T_{pc}~6−10×10^{6}K resulting in X-ray emission. We estimate the observable 2−8keV luminosity to be ≤10^{34}erg/s there, somewhat larger than the current 'quiescent' X-ray luminosity of SgrA* (10^{33}erg/s)[6,15,21]. Rayleigh-Taylor instabilities may by then have broken up the cloud into several sub-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 2-8keV 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 presently un-probed regime of 10^3−10^{4}R$_S$, when compared with test particle calculations and more detailed numerical simulations (Figures 3 and S4).

The radiated energy estimated above is <1% of the total kinetic energy of the cloud, ~10$^{45.4}$erg. As the tidally disrupted filamentary cloud passes near pericentre some fraction of the gas may well collide with itself, dissipate and circularize[22]. This is likely because of the large velocity dispersion of the cloud, its size comparable to the impact parameter and because the Rayleigh-Taylor and Kelvin-Helmholtz time scales are similar to the orbital time scale. Since the mass of the cloud is larger than the mass of hot gas within the central ~3100R$_S$ (~10$^{27.3}$g)[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 ~10^{48}erg over the next decade, although the radiative efficiency of the inflow at these accretion rates is of order 1-10%[23,24]. 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 'clock-wise' disk of young, massive O and Wolf-Rayet stars at r~1−10" from SgrA* [3,25]. Several of these stars have powerful winds. One star, IRS16SW, ~1.4" south-east of SgrA* is a massive, Wolf-Rayet contact binary[26]. Colliding winds in the stellar disk, and especially in binaries, may create low angular momentum gas that then falls deep into the potential of the supermassive black hole[27,28].

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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Author contributions: S.G. collected and analyzed the data and discovered the orbit of the gas cloud. R.G. and S.G. wrote the paper. R.G., A.B. and E.Q. derived the cloud's properties, its evolution and the estimate of the X-ray luminosity. T.F. detected the high proper motion and extracted the astrometric positions and the photometry. R.G., E.Q., A.B. and C.G. contributed to the analytical estimates. C.A. and J.C. set up numerical simulations to check the analysis. F.E., O.P. and K.D.-E. helped in the data analysis and interpretation. T.O. provided valuable software tools.

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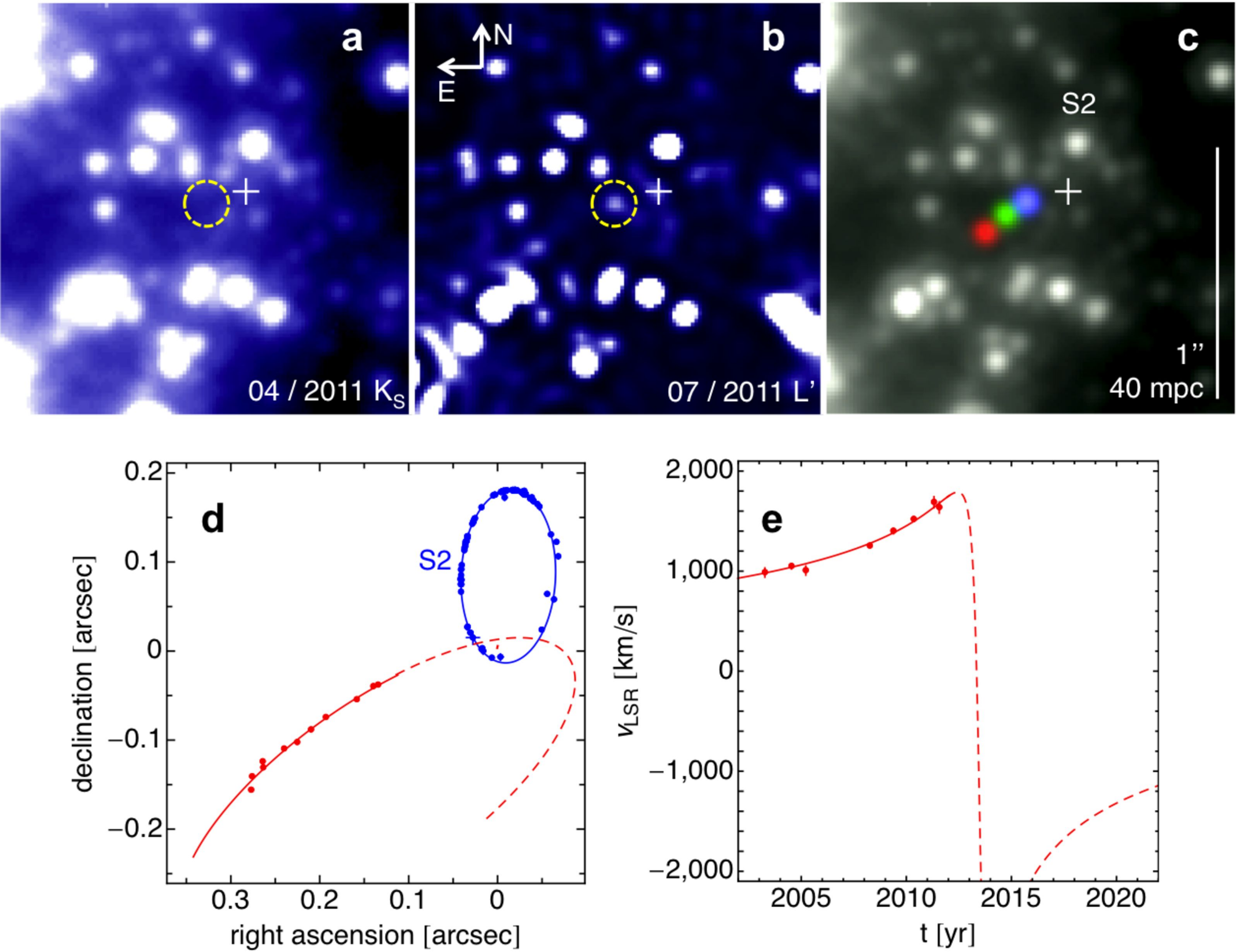
Table 1. Orbit Parameters of the Infalling Cloud

parameters of Keplerian orbit around 4.31×10^6 $M_\odot$ black hole at R_0 = 8.33 kpc	**best fitting value**
semi-major axis a	521 ± 28 milli-arcsec
eccentricity e	0.9384 ± 0.0066
inclination of ascending node i	106.55 ± 0.88 degrees
position angle of ascending node Ω	101.5 ± 1.1 degrees
longitude of pericentre ω	109.59 ± 0.78 degrees
time of pericentre t_{peri}	2013.51 ± 0.035
pericentre distance from black hole r_{peri}	$4.0 \pm 0.3 \times 10^{15}$cm = 3140 R_S
orbital period t_o	137 ± 11 years

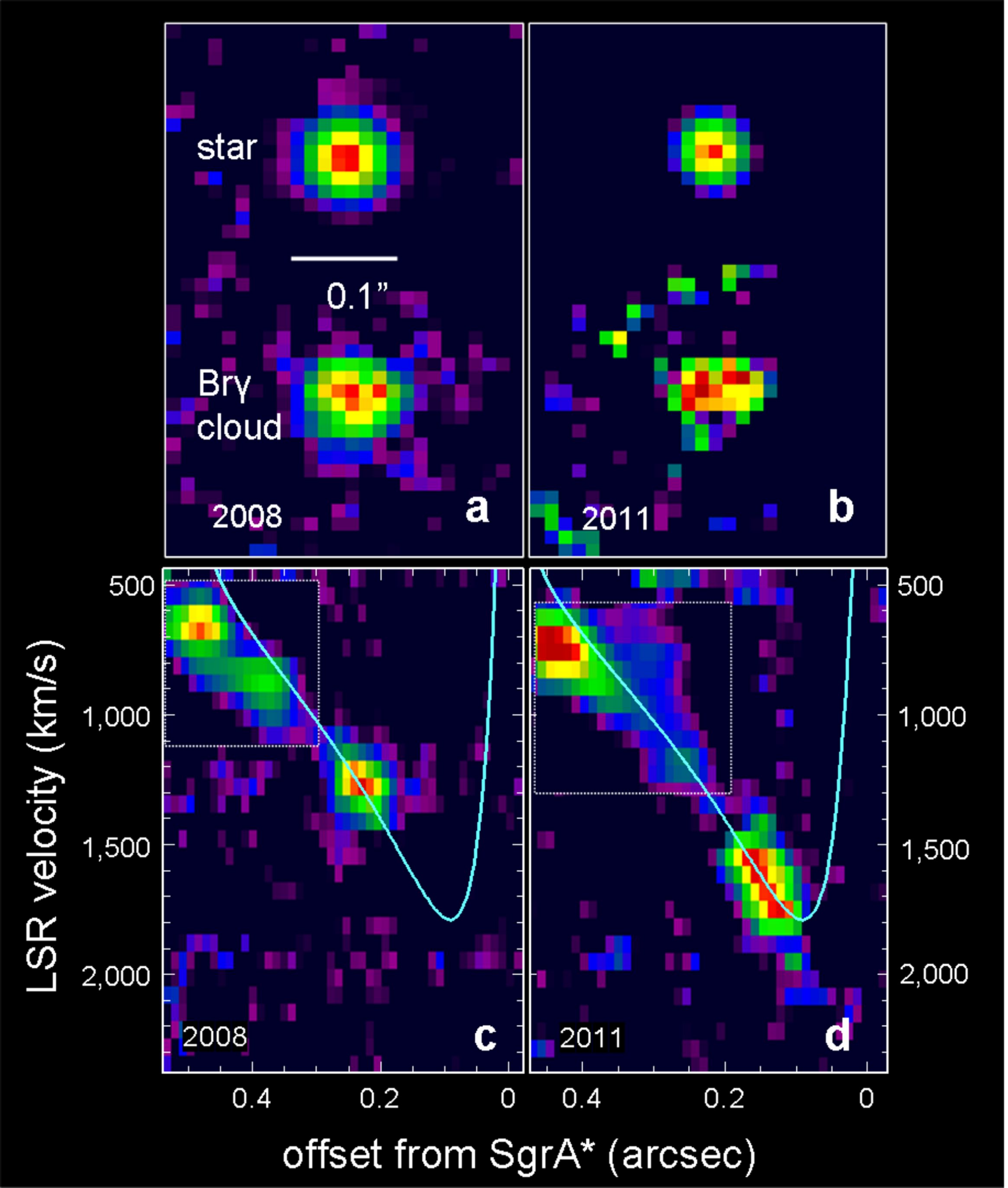
Figure 1: Infalling dust/gas cloud in the Galactic Centre. Panels a and b give NACO[9] adaptive optics VLT images showing that the cloud is detected in L'-band (3.76 μm) but not in K_s-band (2.16 μm), indicating that it is not a star but a dusty cloud with a temperature of ~550 K (Figure S2). The cloud is also detected in M-band (4.7μm) but not seen in H-band (1.65μm). North is up, East is left. The proper motion derived from the L-band data is ~42 milli-arcseconds (mas)/yr, or 1670 km/s (in 2011), from the south-east towards the position of SgrA* (panel c, red for epoch 2004.5, green for 2008.3 and blue for 2011.3, overlayed on a 2011 K_s-band image). It is also detected in deep spectroscopy with the adaptive optics assisted integral field unit SINFONI[10,11] in the HI n=7-4 Brγ recombination line at 2.1661 μm and in HeI 2.058 μm, with a radial velocity of 1250 km/s (in 2008) and 1650 km/s (in 2011). From the combination of the astrometric data in L' and Brγ and the radial velocity data in Brγ the orbit of the cloud is tightly constrained (panels d & e, error bars are 1σ measurement errors). The cloud is on a highly eccentric, bound orbit (e = 0.94), with a pericentre radius and time of 36 light hours (3100 R_S) and 2013.5 (Table 1). For further details see Supplementary Information.

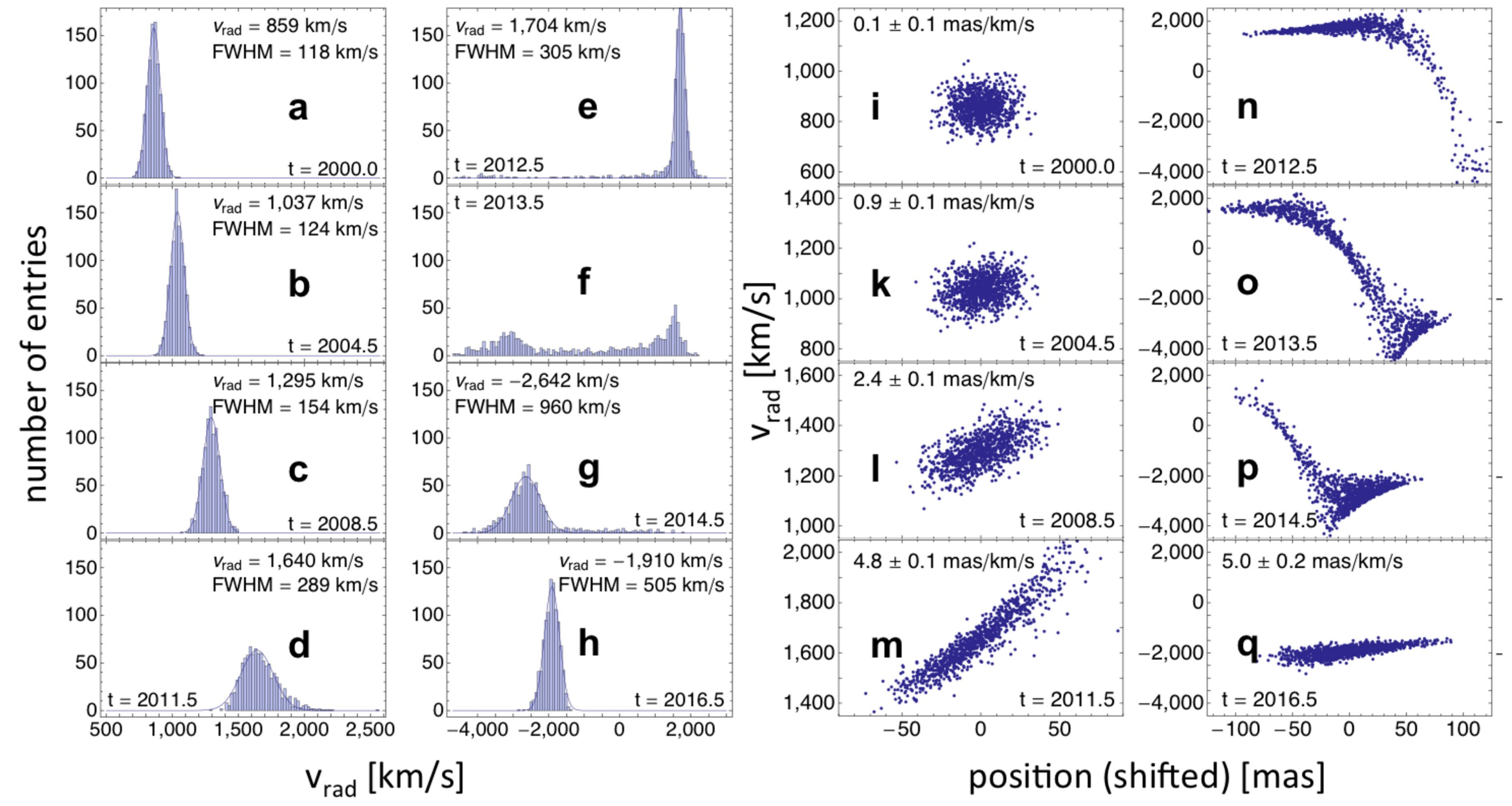
Figure 2: The velocity shear in the gas cloud. The left column shows data from 2008.3, the right from 2011.3. Panels a and b show integrated Brγ maps of the cloud, in comparison to the point spread function from stellar images shown above. The inferred intrinsic East-West HWHM source radii are R_c = 21 ± 5 mas in 2008 and 19 ± 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- und blue-shifted emission of the cloud (R_c = 23 ± 5 mas). The minor axis radius of the cloud is only marginally resolved or unresolved (radius ≤ 12 mas). We adopt R_c=15 mas as the 'effective' circular radius, from 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 Brγ 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 and used a slit width of 0.11". The gas in the tail is spread over ~200mas downstream of the cloud. The trailing emission appears to be connected by a smooth velocity gradient (of ~2km/s/mas), and the velocity field in the tail approximately follows the best-fit orbit of the head (cyan curves, Table 1). An increasing velocity gradient has formed in the head between 2008 (2.1 km/s/mas) and 2011 (4.6 km/s/mas). As a result of this velocity gradient, the intrinsic integrated FWHM velocity width of the cloud increased from 89 (± 30) km/s in 2003 and 117 (± 25) km/s in 2004, to 210 (± 24) km/s in 2008, and 350 (± 40) km/s in 2011.

Figure 3. Test particle simulation of the orbital tidal disruption. An initially Gaussian cloud of initial FWHM diameter 25 mas and FWHM velocity width 120 km/s is placed on the orbit in Table 1. As described in section 4 of the Supplementary Information (see also Figure S4) panels a through h show the evolution of the cloud integrated velocity width (vertical axis shows the number of entries), and panels i through q show the evolution of the velocity change as a function of position (measured in milli-arcseconds) along the orbital direction, purely on the basis of the tidal disruption of the cloud by the gravitational force of the super-massive 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 pericenter passage. Beyond that, the test particle approach probably will fail due to the hydrodynamic effects, which then most likely will dominate the further evolution.



a
04 / 2011 K_S
b
N
E
07 / 2011 L'
c
S2
1"
40 mpc
d
S2
0.2
0.1
0
−0.1
−0.2
declination [arcsec]
0.3
0.2
0.1
0
right ascension [arcsec]
e
2,000
1,000
0
−1,000
−2,000
v_{LSR} [km/s]
2005
2010
2015
2020
t [yr]


star
0.1"
Brγ
cloud
2008
a
2011
b
500
1,000
1,500
2,000
LSR velocity (km/s)
2008
c
2011
d
0.4
0.2
0
offset from SgrA* (arcsec)



v_{rad} = 859 km/s
FWHM = 118 km/s
a
t = 2000.0
v_{rad} = 1,037 km/s
FWHM = 124 km/s
b
t = 2004.5
v_{rad} = 1,295 km/s
FWHM = 154 km/s
c
t = 2008.5
v_{rad} = 1,640 km/s
FWHM = 289 km/s
d
t = 2011.5
v_{rad} = 1,704 km/s
FWHM = 305 km/s
e
t = 2012.5
t = 2013.5
f
v_{rad} = −2,642 km/s
FWHM = 960 km/s
g
t = 2014.5
v_{rad} = −1,910 km/s
FWHM = 505 km/s
h
t = 2016.5
number of entries
v_{rad} [km/s]
0.1 ± 0.1 mas/km/s
i
t = 2000.0
0.9 ± 0.1 mas/km/s
k
t = 2004.5
2.4 ± 0.1 mas/km/s
l
t = 2008.5
4.8 ± 0.1 mas/km/s
m
t = 2011.5
n
t = 2012.5
o
t = 2013.5
p
t = 2014.5
5.0 ± 0.2 mas/km/s
q
t = 2016.5
v_{rad} [km/s]
position (shifted) [mas]