expected for the dust sublimation region, and the apparent orientation is similar to that of the maser disc, arguing for a common origin. The structure and photometry are consistent with dust at ~ 1500 K behind A_K ~ 5.5 magnitudes of foreground extinction. This matches what is expected from the upper limit to the broad Brα line, and could originate in the dense and turbulent gas distribution observed on scales of 1–10 pc. In such a scenario, much of the mid-infrared continuum would originate in a separate structure, likely associated with the AGN-driven outflow.

Acknowledgements

See page 23.

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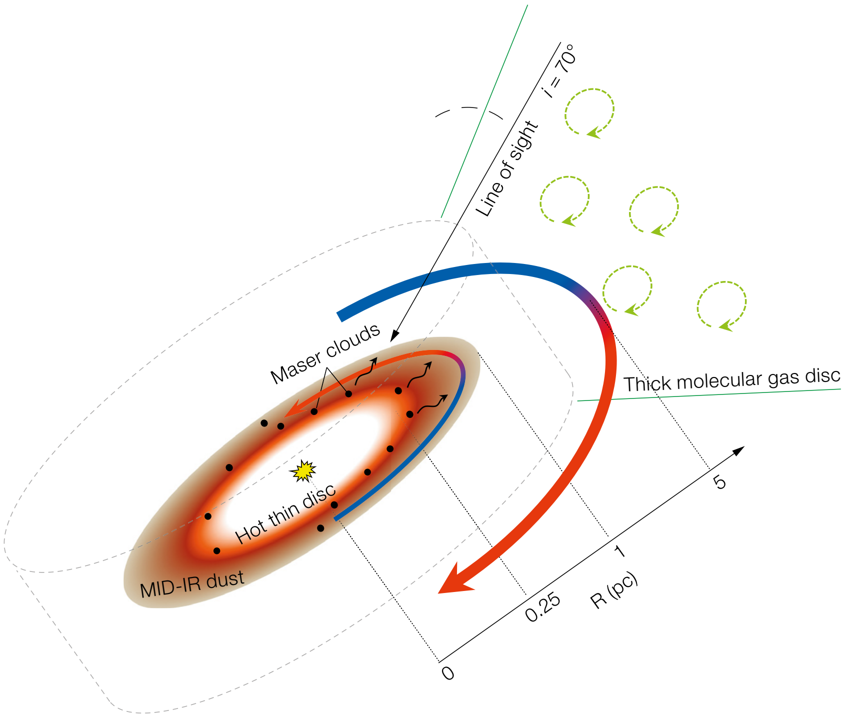

Figure 2. Sketch of the observed central structures. The *K*-band emission traces the inner rim of a thin disc of hot gas and dust, at or close to the dust sublimation radius of 0.24 pc. The inner water masers are cospatial with the hot *K*-band dust. The masers stretch out to 1 pc (Gallimore et al., 2001). Mid-infrared observations show warm dust on roughly the same scales as the outer masers, likely originating from the disc periphery. ALMA observations of HCN and HCO+ show a turbulent structure, which rotates in the opposite direction to the maser disc (Imanishi et al., 2018). The turbulence found in the molecular gas structure argues for a thick disc, which contains enough gas mass to reach column densities that screen the central region from the observer by A_K ~ 5.5 magnitudes.

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GRAVITY and the Galactic Centre

GRAVITY Collaboration (see page 20)

On a clear night, our home galaxy, the Milky Way, is visible as a starry ribbon across the sky. Its core is located in the constellation of Sagittarius, approximately where the bright glow is interrupted by the darkest dust filaments. There, hidden, lies a massive black hole. To peer through the obscuring clouds and see the stars and gas near the black hole we use GRAVITY. The main GRAVITY results are the detection of gravitational redshift, the most precise mass-distance measurement, the test of the equivalence principle, and the detection of orbital motion near the black hole.

The heart of the Milky Way

At the heart of the Milky Way, 26 000 light-years from Earth, is Sagittarius A* (Sgr A*, pronounced “Sag-A-star”), the closest massive black hole to us and, with a lensed angular diameter of 53 microarcseconds (µas), the largest one on the sky. It is embedded in hot gas and surrounded by a cluster of high velocity stars. They buzz around the black hole on trajectories which are, like the behaviour of the hot gas, governed by the gravitational field of the black hole.

With GRAVITY we are unravelling what is happening in the centre of our Galaxy with unprecedented angular resolution. The instrument operates at infrared wavelengths around 2 microns. GRAVITY combines the light beams of the four individual 8.2-metre Unit Telescopes at

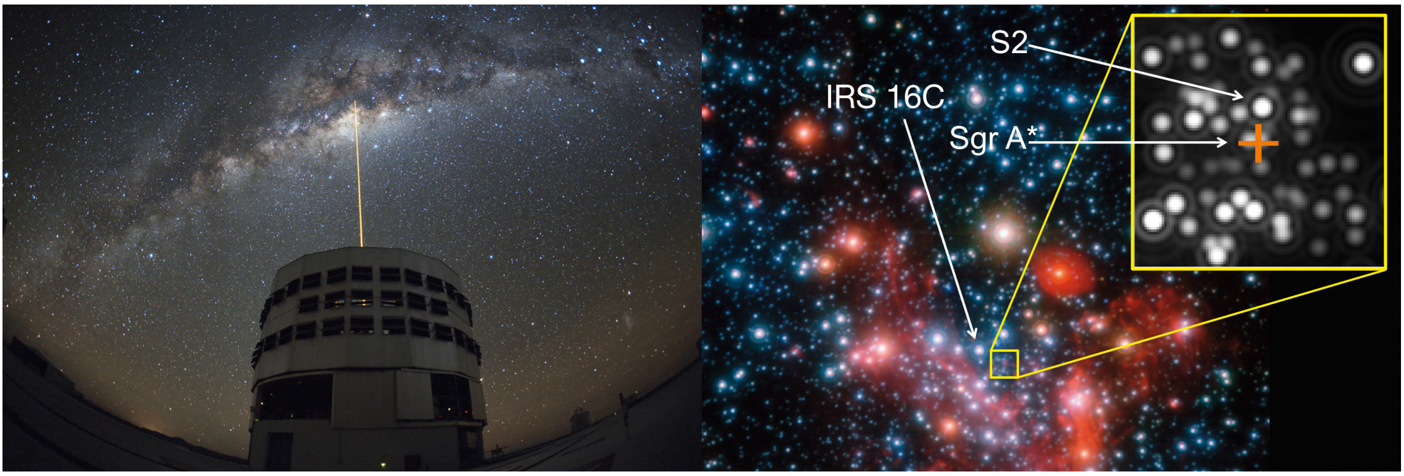

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Figure 1. Left: The sky above the VLT at Paranal. The laser of Unit Telescope 4 (Yepun) points at the Galactic centre. Right: Infrared image of the Galactic centre. For the interferometric GRAVITY observations the star IRS 16C was used as a reference star and the actual target was the star S2. The position of the centre, which harbours the (invisible) 4 million solar mass black hole known as Sgr A* is marked by the orange cross.

ESO's Very Large Telescope (VLT) in Chile to form the VLT Interferometer (VLTI). Together they achieve a spatial resolution equivalent to that of a telescope of approximately 130 metres in diameter (GRAVITY Collaboration, 2017). GRAVITY has also been equipped with a system to track interference fringes and it uses adaptive optics to correct for atmospheric turbulence in order to resolve small and faint structures in the sky.

Measurement of gravitational redshift in the Galactic centre

We have traced a partial astrometric and a full 16-year radial velocity orbit of the star S2 with GRAVITY on the VLTI and the Spectrograph for INtegral Field Observations in the Near Infrared (SINFONI) on the VLT. During its recent closest approach to the black hole, the pericentre passage in May 2018, we collected both astrometric and spectroscopic data. These data allowed the detection of the combined gravitational redshift and transverse Doppler effect on S2 for the first time. Gravitational redshift is one of the three classical tests of Einstein's general theory of relativity. Einstein was the first to accurately predict a gravitational time dilation, i.e., that a clock near a gravitational mass ticks slower than a distant reference clock. As a result of this effect an observer sees a photon emitted near a massive object at a longer, redder wavelength. This prediction has so far only been tested in weak gravity regimes like the gravitational fields of Earth, the Sun, and white dwarfs. With GRAVITY and SINFONI we were able to test the strong gravitational field of a massive black hole. During its recent closest approach to Sgr A* the spectral absorption lines in the light of S2 were significantly shifted towards redder wavelengths, in excellent agreement with Einstein's general theory of relativity (GRAVITY Collaboration 2018a).

Mass and Distance of the Galactic Black Hole

Our measurements of the position and radial velocity of S2 allow us to calculate both the mass of the black hole and the distance to the Galactic centre with unprecedented precision and accuracy. By combining the precise astrometry from GRAVITY with the spectral measurements of SINFONI, we can determine the distance to the Galactic centre to be 26 673 light-years and the black hole mass to be 4.1 million solar masses (GRAVITY Collaboration, 2019b).

Local position invariance

One of the cornerstones of general relativity is Einstein's equivalence principle. It consists of three parts: the weak equivalence principle, the local Lorentz invariance and the local position invariance (LPI). We use the orbit of S2 to test the LPI, which states that the results of a non-gravitational experiment are independent of the position in space-time.

The star S2 experiences very strong changes in gravitational potential in the course of its eccentric orbit around Sgr A*. This makes it a unique probe and allows us to test the LPI. The spectrum of S2 has absorption lines of helium and hydrogen, which are formed by atomic processes and are thus non-gravitational. We can observe how they change in wavelength as the star moves on its trajectory towards us, around the black hole, and away from us again. During the pericentre passage both the hydrogen and helium lines are redshifted. We did not detect a different shift of the two absorption lines. This puts a limit on the violation of the LPI to below 5%. While current tests on Earth have a much higher accuracy, our experiment in the Galactic centre laboratory tests gravitational field changes a million times larger (GRAVITY Collaboration, 2019a).

Flares

The Galactic centre black hole is, given its huge mass, surprisingly faint. That is, the hot gas that swirls around it has a comparatively low luminosity. Most of the radiation is emitted at radio and infrared wavelengths and is quasi-steady — it flickers only a little. In the near-infrared

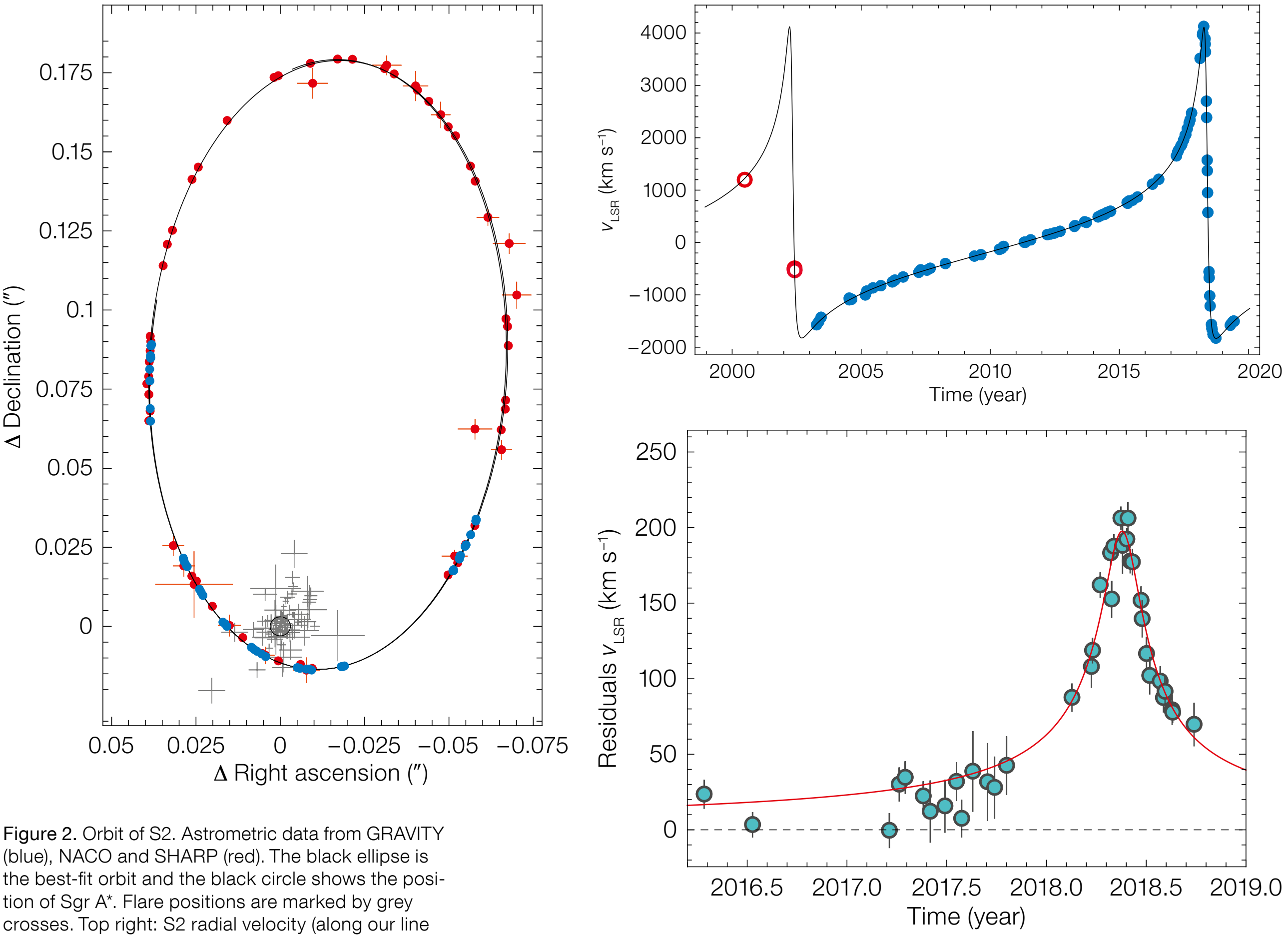
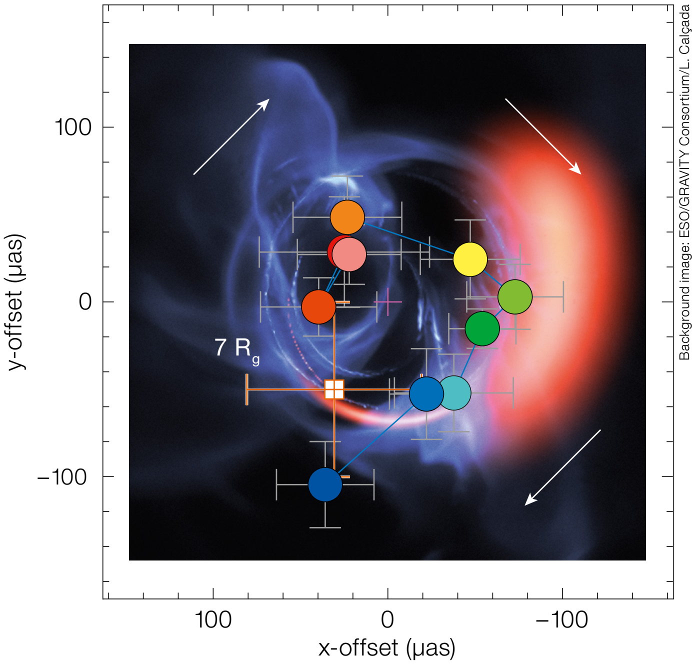


Figure 2. Orbit of S2. Astrometric data from GRAVITY (blue), NACO and SHARP (red). The black ellipse is the best-fit orbit and the black circle shows the position of Sgr A*. Flare positions are marked by grey crosses. Top right: S2 radial velocity (along our line of sight) measured over more than one orbit. Bottom right: The combined gravitational redshift and relativistic transverse Doppler effect manifest in an excess in the radial velocity of 200 km s^{-1}.

where GRAVITY and SINFONI operate, the long-term light curves are well described by a log-normal noise, indicating that there are statistical fluctuations in the way the hot gas is accreted by the black hole. On average, about once per day for 1–2 hours this slightly variable emission becomes a bright flare, and at times it contains so much energy that it even emits X-rays. The true nature of these flares seen at infrared and X-ray wavelengths is not yet known and may be explained as a hot spot in the gas or an ejected blob of gas (as in a jet).

Observations during the summer of 2018 with GRAVITY revealed that the emission near the black hole during an infrared flare moves in a loop around an unseen centre (GRAVITY Collaboration, 2018b). These loops are typically a few times larger than the event horizon of the black



Background image: ESO/GRAVITY Consortium/L. Calçada

Figure 3. Projected orbit of the flare recorded on 22 July 2018 over its 30-minute duration (colour ranging from brown to dark blue indicates the time). The background shows a flare “hot spot” simulation.

hole and are consistent with a small region of heated electrons (a “hot spot”), moving in an orbit around the black hole. The GRAVITY observations also revealed changes in the polarisation angle over the course of the flare. In particular, as the centroid of the emission region completes one orbit around the black hole, the polarisation angle also makes a single loop. These polarisation measurements indicate the presence of a strong magnetic field in the immediate vicinity of the black hole and might indicate a magnetic origin of the flare.

What’s next?

Continuing observations of S2 are expected to reveal a second relativistic effect on the star’s orbit, namely the Schwarzschild precession. General relativity predicts that the orbit of S2 is not a closed Keplerian ellipse but an open rosette-like trajectory, where the periapse, i.e., the closest point to the black hole, shifts by a small angle per revolution which rotates the ellipse over time. Moreover, studying multiple flares as an ensemble will shed light on accretion properties, for example, the sense of rotation of the hot gas.

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Spatially Resolved Accretion-Ejection in Compact Binaries with GRAVITY

GRAVITY Collaboration (see page 20)

The GRAVITY instrument at the Very Large Telescope Interferometer has led to the first spatially resolved observations of X-ray binaries at scales comparable to the binary orbit, providing unprecedented spatial information on their accretion-ejection mechanisms. In particular, observations of the hypercritical accretor SS433 have revealed a variety of spatial structures at the heart of this exotic microquasar, including bipolar outflows, super-Keplerian equatorial outflows and extended baryonic jets photoionised by collimated ultraviolet radiation.

X-ray binaries (XRBs) are composed of a compact object (neutron star or black hole) accreting matter from its donor star. The accretion process leads to a variety of inflow-outflow structures such as discs, streams, winds and jets. While large-scale jets are often resolved with very long baseline interferometry (VLBI) at radio wavelengths, capable of achieving approximately milliarcsecond (mas) spatial resolution, the inner parts of the accretion-ejection structures, at scales comparable to the binary orbit, had remained unresolved for a long time because the required sub-milliarcsecond spatial resolution is significantly beyond the diffraction limit of even extremely large telescopes. Resolving these structures is, in fact, challenging even for optical interferometry, since these sizes are below the canonical spatial resolution of an optical interferometer such as the Very Large Telescope Interferometer (VLTI), which is around 3 mas for a baseline of 100 metres. Therefore, in order to get to such scales, exquisite precision in the interferometric observables is required, which is best achieved with spectrally resolved measurements using strong emission lines. This technique is called spectral differential interferometry and it can be used to acquire robust velocity-resolved microarcsecond (μas) spatial information.

GRAVITY has led to a breakthrough in the ability to fringe-track on faint objects, allowing interferometric quantities to be measured in the near-infrared (NIR) at high spectral resolution ($R \sim 4000$) with unprecedented precision. When applied to X-ray binaries, this has led to the first spatially resolved observations of accretion-ejection structures at NIR wavelengths. Here, we review pioneering GRAVITY observations of two such objects: the hypercritical accretor and exotic microquasar SS433, and the wind-accreting high-mass XRB BP Cru.

Resolving super-Eddington outflows in SS433

SS433 is unique in the Galaxy as the only known steady hypercritical accretor; the donor star provides the compact object (the nature of which remains enigmatic, but is likely to be a black hole) with matter at a rate hundreds of times above Eddington (see, for example, Fabrika, 2004 for a review of SS433). The resulting geometrically and optically thick supercritical accretion disc thermally downgrades the X-ray radiation produced close to the compact object (and typically seen in ordinary X-ray binaries) to ultraviolet (UV) and optical wavelengths, turning the compact object into an accretion-powered quasi-star that outshines its donor star at all wavelengths. In addition, the enormous radiation pressure leads to powerful outflows producing strong emission lines, seen not only from the ~ 2000 km s^{-1} accretion disc winds (the so-called “stationary” lines) but also from the ~ 80 000 km s^{-1} (0.26c) highly