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.

References

GRAVITY Collaboration 2017, A&A, 602, 23
GRAVITY Collaboration 2018a, A&A, 615, 15G
GRAVITY Collaboration 2018b, A&A, 618, 15
GRAVITY Collaboration 2019a, Phys. Rev. Lett., 122, 101102
GRAVITY Collaboration 2019b, A&A, 625, 10

DOI: 10.18727/0722-6691/5169

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

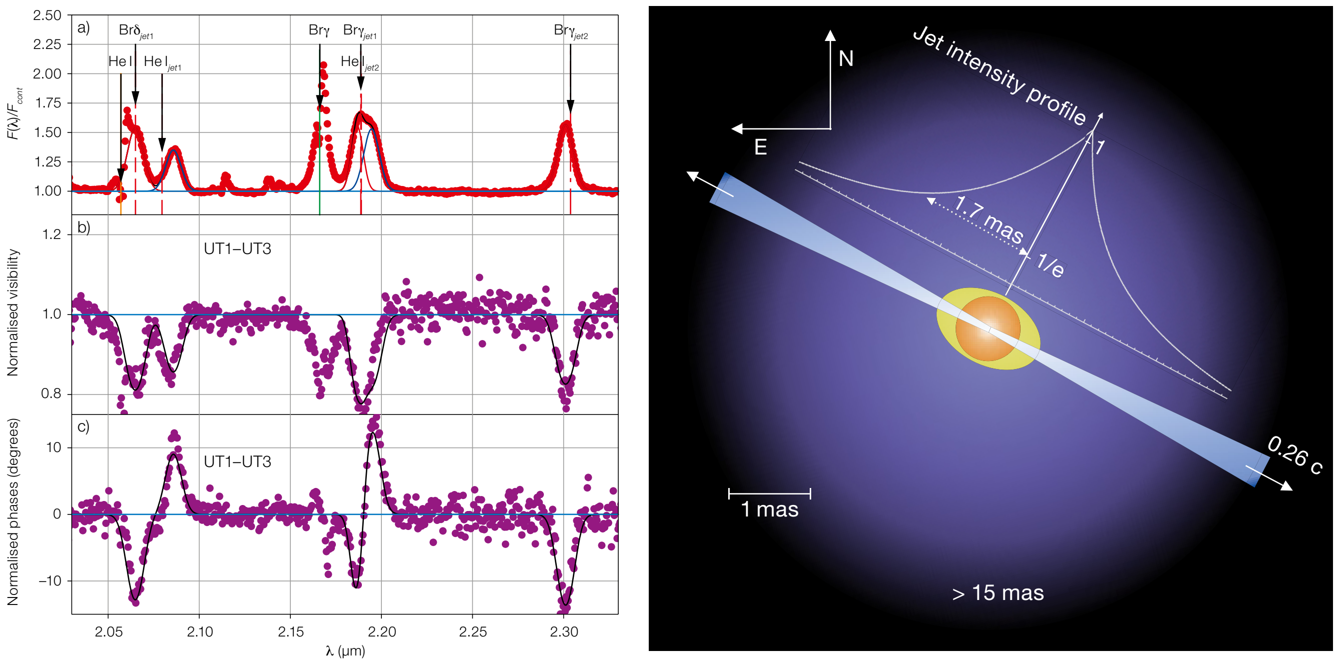

Figure 1. Left: Spectrum (a), differential visibility amplitudes (b), and visibility phases (c) across the "stationary" and baryonic jet emission lines of SS433 in the 2016 GRAVITY observation. The best-fit exponential model for the jet emission (illustrated in the schematic on the right) is shown in black.

collimated baryonic jets, with the latter's precession creating its idiosyncratic moving lines across the X-ray and optical spectra (Margon et al., 1979).

These unique properties — a very bright accretion disc at optical wavelengths and strong, broad and variable emission lines — make SS433 the ideal XRB for NIR interferometry, also providing the only opportunity to spatially study a supercritical accretion disc and its outflows. GRAVITY observations of SS433 carried out in 2016 and 2017 (GRAVITY Collaboration et al., 2017b; Waisberg et al., 2019a,b) have revealed a marginally resolved NIR continuum consisting of (i) the central unresolved binary (with a size < 0.5 astronomical units [au]), and (ii) extended emission of size ~ 40 au in the form of a wind and/or disc (contributing ~ 20% of the *K*-band flux). Much more information, however, is gathered from the spectrally resolved differential visibility amplitudes and phases across the many emission lines (Figure 1).

For instance, the observations have shown that the double-peaked "stationary" Brγ line alternates between a bipolar-outflow dominated mode (aligned with the jets) to an equatorial-outflow dominated mode (perpendicular to the jets) (Figure 2). Although the presence of equatorial outflows in SS433 had been well established from radio observations (for example, Blundell et al., 2001), this is the first time that velocity and size could be combined to show that the outflows are super-Keplerian. The outflows support the conclusion that both the compact object and the donor star in SS433 overfill their Roche lobes significantly, losing mass through their outer Lagrangian points, and that the transfer of specific angular momentum between the binary and the disc-like outflows is very significant for the binary evolution. Future observations of several hours in a single night could harvest the full power of aperture synthesis and provide velocity-resolved, model-independent images of the complex outflow structure beyond simple geometric models.

The GRAVITY observations have also spatially resolved the optical jets of SS433 for the first time, revealing exponential profiles that extend to over 20 au (i.e., several tens of times the binary size) and which peak surprisingly close to the central binary (Figure 1). These observations suggest that optical jets are heated by collimated UV radiation and, in combination with spectroscopic observations, have shown that SS433 is UV-dominated even in the jet funnel. This is important in the context of the acceleration mechanism of the ~ 0.26c jets by line-locking (Milgrom, 1979), which requires intense collimated radiation, as well as in the possible relation between SS433 and ultraluminous X-ray sources (ULXs). Future observations of several hours in a single night could directly detect the relativistic motion (8 mas d^{-1}) of the baryonic jets, providing a further probe of their heating mechanism and an accurate, self-consistent distance to SS433.

Spatially resolved wind accretion in BP Cru

BP Cru (GX 301-2) is composed of an X-ray pulsar accreting from the wind of its hypergiant B1Ia+ companion (Kaper et al., 2006). The latter has unusually powerful winds (~ $10^{-5}\,M_{\odot}\,yr^{-1}$) for a donor star in an XRB, which lead to strong emission lines of HeI and Brγ from its extended wind in its *K*-band spectrum. In addition, its unusually high eccentricity ($e = 0.46$) makes it an ideal target for probing the influence of the gravitational and radiation fields of the pulsar on the surrounding circumstellar environment (for example, Blondin, 1994).

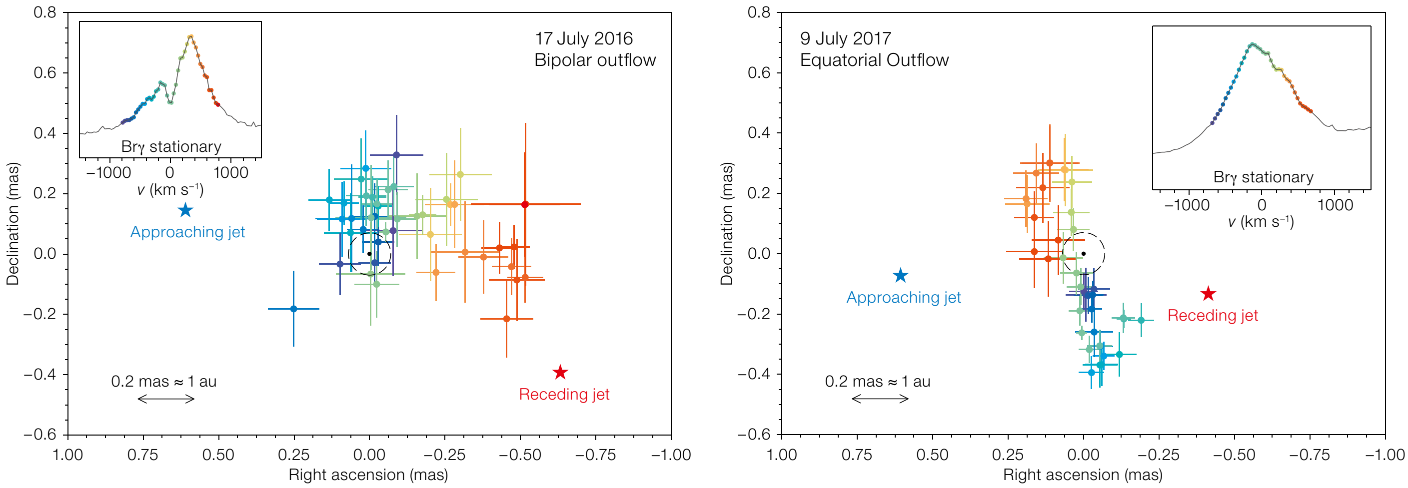

Figure 2. Velocity-resolved emission centroids across the double-peaked Brγ "stationary" line for observations in 2016 (left) and 2017 (right). The emission centroid of the spatially resolved baryonic jets is also shown. The black circles correspond to the estimated binary orbit size.

The spectral differential visibilities measured by GRAVITY (GRAVITY Collaboration et al., 2017a) reveal an extended wind with a size several times the stellar radius, which is also significantly distorted — being more extended on the side that is shielded from the pulsar — and which could be caused by the X-ray ionisation of the stellar wind facing the compact object. In addition, asymmetries revealed by the differential visibility phases across the emission lines may point to an additional component, possibly a stream of enhanced density which has been posited to exist in the system from the analysis of X-ray light curves (Leahy & Kotska, 2008). Further observations at different orbital phases could take advantage of the significant eccentricity in order to disentangle intrinsic variability of the wind from the distortion caused by the pulsar accretion.

Acknowledgements

See page 23.

References

Blondin, J. M. 1994, ApJ, 435, 756
Blundell, K. et al. 2001, ApJ, 562, L79
Fabrika, S. 2004, Space Science Reviews, 12, 1
GRAVITY Collaboration et al. 2017a, ApJ, 844, 177
GRAVITY Collaboration et al. 2017b, A&A, 602, L11
Kaper, L. et al. 2006, A&A, 457, 595
Leahy, D. & Kostka, M. 2008, MNRAS, 384, 747
Margon, B. et al. 1979, ApJ, 233, L63
Milgrom, M. 1979, A&A, 78, L9
Waisberg, I. et al. 2019a, A&A, 623, A47
Waisberg, I. et al. 2019b, A&A, 624, A127

DOI: 10.18727/0722-6691/5170

Images at the Highest Angular Resolution with GRAVITY: The Case of η Carinae

GRAVITY Collaboration (see page 20)

The main goal of an interferometer is to probe the physics of astronomical objects at the highest possible angular resolution. The most intuitive way of doing this is by reconstructing images from the interferometric data. GRAVITY at the Very Large Telescope Interferometer (VLTI) has proven to be a fantastic instrument in this endeavour. In this article, we describe the reconstruction of the wind-wind collision cavity of the massive binary η Car with GRAVITY across two spectral lines: He I and Brγ.

Interferometric imaging

With a resolving power that is a factor of tens of times better than stand-alone telescopes, infrared interferometry offers the possibility to produce milliarsecond (mas) resolution images. Therefore, interferometric imaging is a key means to acquire information addressing a broad range of astronomical problems, ranging from the detection of planets to mapping the cores of active galactic nuclei (AGN).

Interferometers reach a level of detail proportional to the separation between each pair of telescopes in the array, known as baselines. Baselines record information, at a given orientation, of the brightness distribution of the object on the sky. Interferometric observables, called visibilities, are a series of Fourier (spatial) frequencies. These frequencies correspond to different levels of detail in the image. The highest frequencies trace the finest