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An Image of the Dust Sublimation Region in the Nucleus of NGC 1068

GRAVITY Collaboration (see page 20)

The superb resolution of the Very Large Telescope Interferometer (VLTI) and the unrivalled sensitivity of GRAVITY have allowed us to reconstruct the first detailed image of the dust sublimation region in an active galaxy. In the nearby archetypal Seyfert 2 galaxy NGC 1068, the 2 μm continuum emission traces a highly inclined thin ring-like structure with a radius of 0.24 pc. The observed morphology challenges the picture of a geometrically and optically thick torus.

Introduction

NGC 1068 is one of the best studied nearby active galactic nuclei (AGN), in which accretion onto a central supermassive black hole contributes a significant fraction of the galaxy's total luminosity. The observation of broad polarised emission lines by Antonucci & Miller (1985) in the nucleus of this Seyfert galaxy was central to the development of the unified model that explains the differences between Seyfert 1 and Seyfert 2 objects as being due to the presence of a nuclear equatorial structure that both obscures and scatters the central emission depending on the line of sight.

Since the first seminal paper addressing its physical properties (Krolik & Begelman, 1988), and following numerous observations at many different wavelengths, the "torus" concept has evolved and been modified considerably. At the same time, increases in computational power have facilitated detailed modelling of clumpy torus structures. Such models are consistent with the near- to mid-infrared spectral energy distribution as well as dust reverberation measurements. Observations of almost two dozen galaxies using the MID-infrared Interferometric instrument (MIDI) on the VLTI have resolved the 1–3 pc scales where warm dust is responsible for the mid-infrared continuum (Burtscher et al., 2013 and references therein). However, measuring the size of the small (< 1 pc) region containing hot dust that emits at near-infrared wavelengths has been possible in very few galaxies. Also, until GRAVITY observed NGC 1068, there were no data showing spatial structure in this dust sublimation region.

Observations and Image Reconstruction

Data on NGC 1068 were obtained in November and December 2018 using GRAVITY and the four 8-metre UTs. Under superb conditions, with seeing ~ 0.5 arcseconds and a coherence time of up to 13 ms, it was possible to fringe-track on the nucleus of NGC 1068 despite its large size and moderate brightness. The data obtained were of excellent quality, with typically < 1% visibility and closure-phase accuracy. The wealth of information provided by the six VLTI baselines has enabled us to reconstruct a *K*-band image based on the obtained closure phases and visibilities with 3-milliarcsecond (mas) resolution.

We used the publicly available Multi-aperture image Reconstruction Algorithm (MiRA; Thiébaut, 2008) to generate the image shown in Figure 1, which contains a total flux of 155 mJy. The structures present are robust, having been reproduced consistently over a wide variety of parameter settings, and with a signal level much higher than that expected for spurious sources. Full details are in GRAVITY Collaboration (2019).

A new view of NGC 1068

The image in Figure 1 is dominated by knots of continuum arranged in a ring around a central hole, with the south-western side about a factor of two brighter than the north-eastern side. Fitting an

(X-ray) NASA/CXC/MIT/C. Canizares, D. Evans et al., (optical) NASA/STScI, (radio) NSF/NRAO/VLA

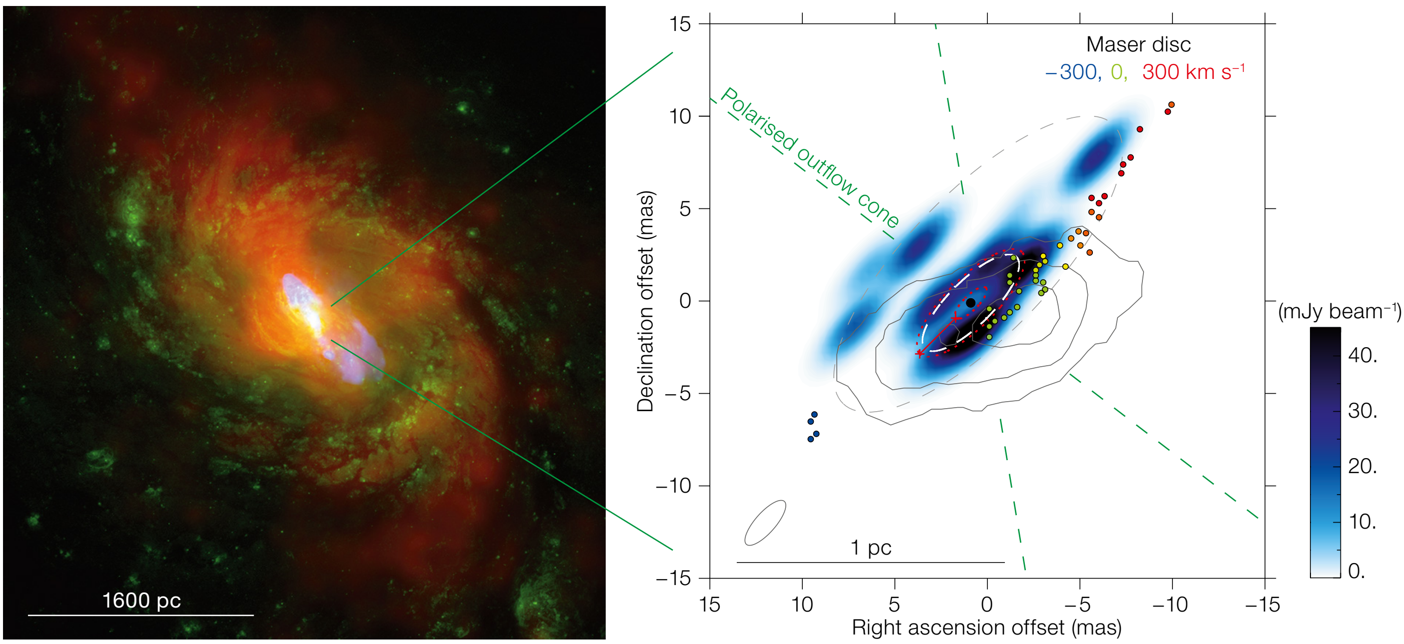

Figure 1. Left: Three-colour image of NGC 1068. The optical emission is shown in green, the X-ray in red and the radio jet in blue. Right: Reconstructed image of the 2 μm continuum (blue colour scale) in the central 2.1 pc of NGC 1068, showing the reconstructed beam size in the lower left. The white dashed ellipse, fitted to the brightest knots, traces a ring that matches the expected range of dust sublimation radii (orange dotted ellipses). The filled black circle in the centre of the ring, denoting the location of the AGN, has been matched to the kinematic centre derived from the maser kinematics, and hence fixes the relative position of the maser distribution. The radio continuum has been positioned using the masers as a coordinate reference. The green dashed lines outline the bipolar ionised outflow also seen in polarisation data. The grey dashed ellipse indicates the size of the 10-metre continuum in the MIDI data.

ellipse to these knots yields a position angle of 50 degrees west of north, an inclination of 70 degrees and a radius of about 0.24 pc. The size matches remarkably well the expected dust sublimation radius for large graphite grains in the radiation field of an AGN with an intrinsic bolometric luminosity of ~ 4 × 10^{45} erg s^{-1} as expected for NGC 1068. And if one aligns the central hole in the near-infrared continuum to the location of the central black hole inferred from the maser kinematics (Gallimore & Impellizzeri, 2019), then the positions of the lower-velocity maser spots match up remarkably well with the south-western side of the ring. This suggests that the masers and the hot dust trace a common disc, and hence that the brighter south-western side of the ring is the near side. This geometry is consistent with that implied by the jet and the ionisation cone, which are oriented toward us on the northern side.

The near-infrared continuum is very difficult to reconcile with geometrically thick clumpy torus models, which can only reproduce a ring-like structure in systems that are relatively face-on, and struggle to make the near side of the ring brighter. Similarly, the presence of a thin maser disc is inconsistent with a vertically extended structure, since this would impede the escape of far-infrared photons that would otherwise thermalise the population of masing molecules. In an additional test, we have compared the spectral energy distributions predicted by models with the photometry from MIDI and GRAVITY. For reasonable parameter ranges, the models tend to over-predict the mid-infrared continuum and have a near-infrared slope that is too shallow.

As an alternative, we considered whether the mid- and near-infrared continua have a common origin at all. Cool (~ 700 K) dust behind a screen of extinction provides an unexpectedly good fit to the spectral energy distribution, including the silicate dip. But the modest A_K ~ 0.9 magnitude extinction is far less than the lower limit of A_K ~ 6 magnitudes required by the non-detection of broad Brα at 4 μm (Lutz et al., 2000) and the high-column density implied by the HCN1–0 emission at 3 mm (García-Burillo et al., 2016; Imanishi et al., 2018).

Instead, our preferred interpretation is in terms of a hot dust disc close to the sublimation temperature. Dust at 1500 K behind a screen with A_K ~ 5.5 magnitude extinction is able to reproduce the slope of the near-infrared continuum. And a modest scale height of $h/r < 0.14$, as indicated by the data, is sufficient to couple the AGN luminosity to the dust disc because of the misalignment between it and the accretion disc. This scenario requires that most of the mid-infrared continuum originates in a different structure on larger scales. Disc-plus-wind models such as those described by Hönig (2019) would imply that the other structure is in fact the outflow driven by the AGN.

Conclusion

K-band observations with GRAVITY at a spatial resolution of 3 mas have resolved a ring-like structure on sub-parsec scales in the centre of NGC 1068. These observations do not support ideas of a geometrically and optically thick clumpy torus and instead trace a dusty disc around the AGN. The size matches that 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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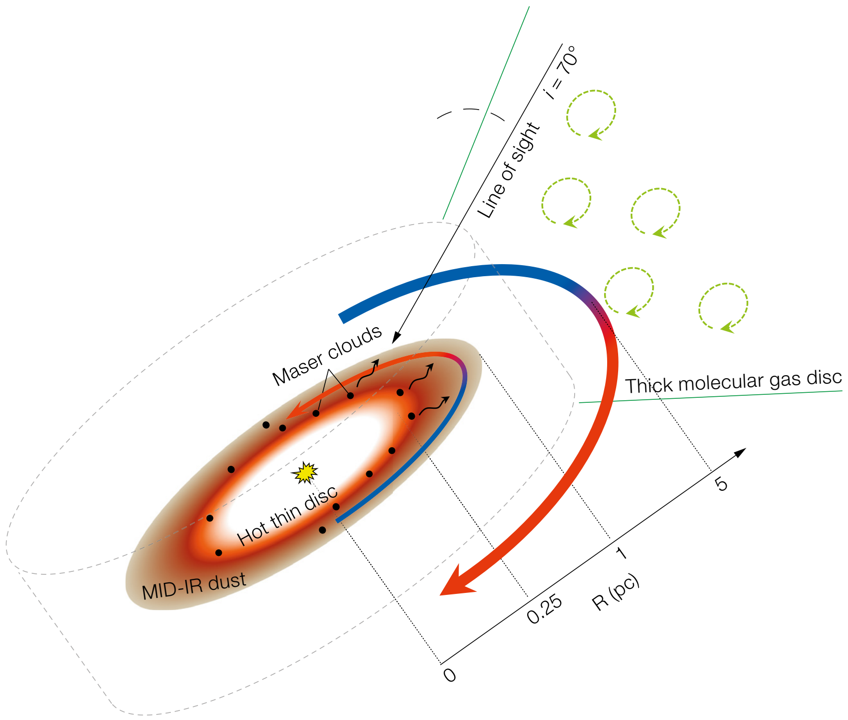

Figure 2. Sketch of the observed central structures. The K-band emission traces the inner rim of a thin disc of hot gas and dust, at or close to the dust sublimation radius of 0.24 pc. The inner water masers are cospatial with the hot K-band dust. The masers stretch out to 1 pc (Gallimore et al., 2001). 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