Ae/Be mass range and need additional observations.

Gap formation scenarios

Gaps in protoplanetary discs can be found in concentric arrangements from the inner regions out to large distances — as nicely evidenced by ALMA images (Zhang et al., 2018). Clearing by dynamical effects due to newly-born planets and photoevaporation by extreme- and far-ultraviolet (EUV/FUV) and X-ray radiation from the central star are key processes of disc dispersal through gap and inner cavity formation. In the photoevaporation scenario, gap formation takes a few 10^6 years and inner disc depletion takes about 10^5 years (Gorti et al., 2009). Since almost all the *K*-band emission we measured with GRAVITY is located at positions smaller than the critical radius where the gap is expected to form as a result of to extreme-/far-ultraviolet/X-ray heating, the discs in our sample might be shaped by forming young planets rather than by depletion resulting from photoevaporation (Figure 2).

With PIONIER, GRAVITY and MATISSE, the VLTI is perfectly equipped to reveal the gas and dust distributions in protoplanetary discs at unprecedented angular and spectral resolution.

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Notes

[1] GRAVITY operates in the near-infrared *K*-band, i.e., with wavelengths between 2 and 2.5 μm.

[2] PIONIER at the VLTI operates in the near-infrared *H*-band, i.e., with wavelengths between 1.5 and 1.8 μm.

[3] MATISSE at the VLTI operates in the mid-infrared *L*-, *M*-, and *N*-bands, i.e., with wavelengths between 3 and 13 μm (Lopez et al., 2018).

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Spatially Resolving the Inner Gaseous Disc of the Herbig Star 51 Oph through its CO Ro-vibration Emission

GRAVITY Collaboration (see page 20)

Near-infrared interferometry gives us the opportunity to spatially resolve the circumstellar environment of young stars at sub-astronomical-unit (au) scales, which a standalone telescope could not reach. In particular, the sensitivity of GRAVITY on the VLTI allows us to spatially resolve the CO overtone emission at 2.3 microns. In this article, we present a new method of using the model of the CO spectrum to reconstruct the differential phase signal and extract the geometry and size of the emitting region.

Protoplanetary discs at high angular resolution

Circumstellar discs are crucial to understanding how stars and planets form. They contain both gas and dust and, although there are many studies of the outer part of the disc, there are very few on the inner disc, in particular the inner gaseous disc. This hinders our understanding of the physical processes taking place in this inner part of the disc. In addition to the study of the size and shape of the continuum emission originating in protoplanetary discs around young stellar objects (YSOs), GRAVITY's spectral resolution of up to $R = 4000$ facilitates studies of the gaseous component of circumstellar material. The two most prominent components are hydrogen, in the form of the Brackett γ and higher levels of the Pfund recombination lines, and molecular gas as traced by CO ro-vibrational transitions. A direct tracer of the gas in the disc is the CO molecule. The CO emission is present at different scales throughout the disc: from the outer, cooler regions detected at millimetre wavelengths to the inner, warmer regions detected at near-infrared wavelengths. In particular, the CO ro-vibrational emission at 2.3 microns is a good tracer of the hot inner gaseous disc. Therefore, spatially resolved observations of the CO ro-vibrational transitions are crucial to constraining the dynamics and chemical composition of the inner dust-free disc.

The source

51 Oph is a fast-rotating star ($v \sin i = 267 \text{ km s}^{-1}$; Dunkin, Barlow & Ryan, 1997) and is located at a distance of 123 parsecs (Lindergren et al., 2016; GAIA Collaboration et al., 2018). Its spectrum is full of atomic and molecular lines and it is one of the very few Herbig Ae/Be stars that shows bright 2.3-micron CO overtone emission, making it an ideal candidate for near-infrared interferometric studies (Thi et al., 2005; Berthoud et al., 2007; Tatulli et al., 2008).

The CO spectrum of the star has been extensively studied spectroscopically

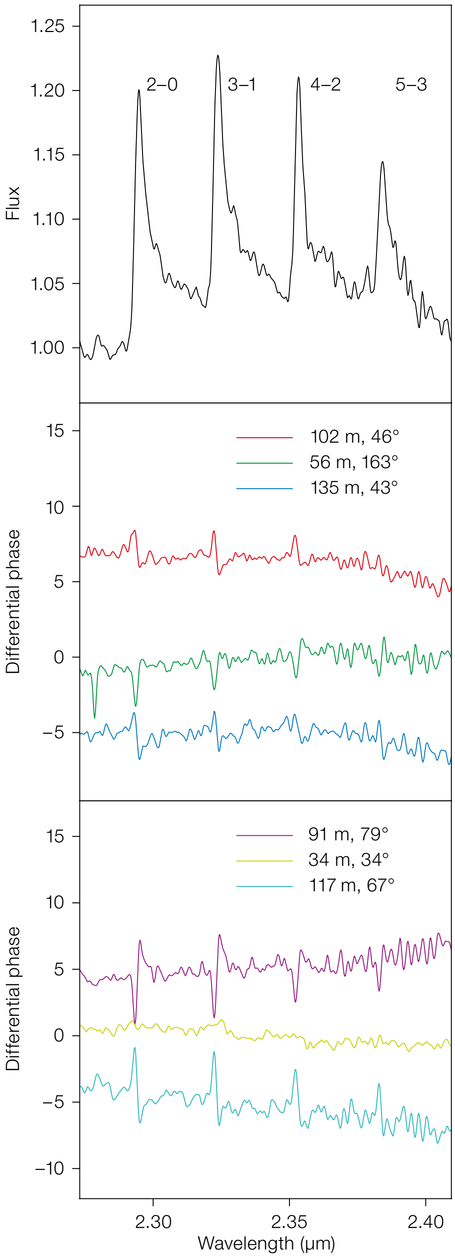


Figure 1. Spectrum (top), and differential phases of the GRAVITY interferometric data at one epoch. Each colour represents a baseline.

and indicates gas close to the star showing Keplerian rotation (Thi et al., 2005; Berthoud et al., 2007). Near-infrared interferometric observations using the Astronomical Multi-BEam combineR (AMBER) — one of the first-generation interferometric instruments on the VLTI — confirmed that the CO is emitted from the very inner disc regions, within the dust sublimation radius (Tatulli et al., 2008). Unfortunately, these observations were at low spectral resolution ($R = 1500$) and no differential phase signal was retrieved.

The circumstellar environment of 51 Oph

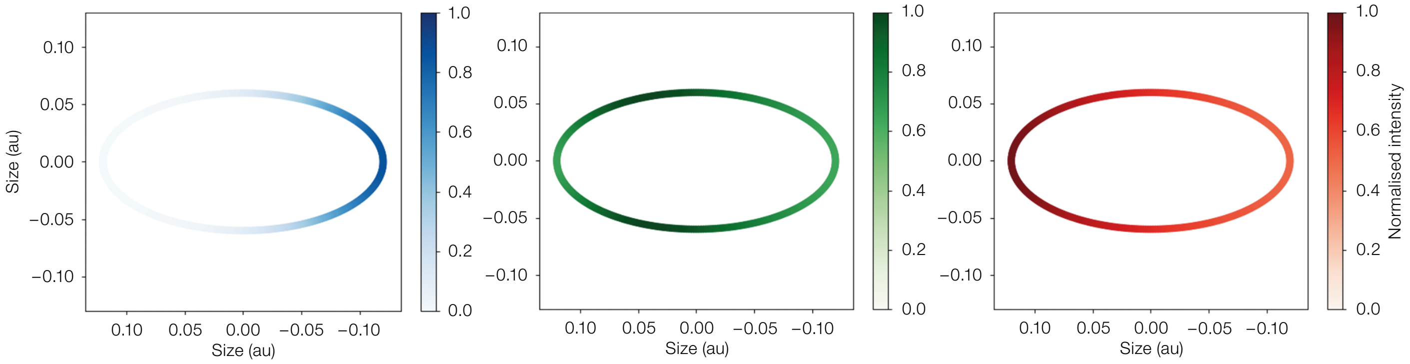
51 Oph was observed with GRAVITY during Guaranteed Time Observations (GTO) at two epochs using the 1.8-metre Auxiliary Telescopes (ATs). From an optical interferometer like the VLTI we can usually extract the following information: spectra, visibilities, differential phases and closure phases. The visibility gives an estimate of the size of the emitting region, with a visibility equal to 0 meaning a resolved source, while 1 is a point source. The differential phase is the photocentre shift of the line with respect to the continuum and the closure phase is an indicator of asymmetries in the circumstellar environment.

One epoch of our VLTI/GRAVITY observations of 51 Oph is shown in Figure 1. The spectrum shows four bright band heads (u = 2–0, 3–1, 4–2 and 5–3). The environment of 51 Oph is compact, both in the line and the continuum emitting regions. The line emitting regions originate closer to the star than the continuum. There is a strong differential phase signal (bottom panels of Figure 1) indicating a photocentre shift of the line with respect to the continuum. There is no indication of an asymmetric circumstellar environment.

By fitting our interferometric observations (i.e., spectrum, visibilities and differential phases) with a local thermodynamic equilibrium (LTE) model of the CO, we find that the CO is emitted from a relatively warm (2400 K) and dense ($N_{CO} \sim 2 \times 10^{21}$ cm^{-2}) region, consistent with gas rotating in a ring at Keplerian velocity ($v \sin i \sim 147$ km s^{-1}) and located at roughly 0.1 au from the star (more details in Koutoulaki et al., in preparation; see also the spatial scales probed in Figure 3). From the model, an intensity map could be created since we know the intensity at each azimuthal angle. An example is shown in Figure 2 for three velocity channels at the blueshifted (left panel), peak (middle panel), and redshifted (right panel) parts of the first band head. This intensity map can be used as an input to the latest version of the interferometric software "Astronomical Software to PRepare Observations" — ASPRO2 — to simulate GRAVITY observations. By varying the inclination and position angle the software creates synthetic observations that can be compared with the real ones.

Assuming Keplerian rotation, the combination of the $v \sin i$ measurement, determination of the inclination, i, of the CO

Figure 2. Intensity maps of the blueshifted (left), peak (middle), and redshifted (right) parts of the first band head.



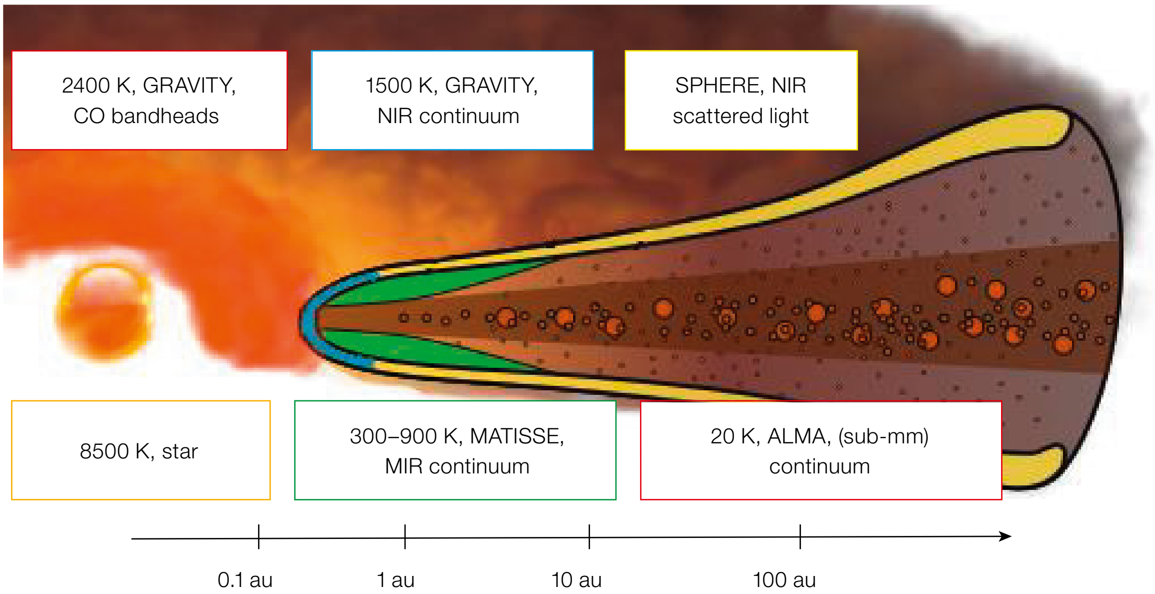


Figure 3. Cartoon of a protoplanetary disc based on Testi et al. (2014). The different boxes correspond to different spatial scales and temperatures of the disc as observed by different instruments.

ring, the angular extent of the CO, and the known distance to 51 Oph from GAIA Data Release 2, results in a direct measurement of the mass of the central star of 3.9 ± 0.6 $M_\odot$.

GRAVITY has opened a new window enabling the use of molecular lines to probe the circumstellar environment of young stars. This new technique of combining the spectrum fit with interferometric observables can provide new insights into the geometry and size of the gaseous disc very close to the star. In the case of 51 Oph we have been able, for the first time, to observationally constrain the physical properties of the gas at 0.1 au from the star; we find physical properties consistent with those expected from LTE models of the gas content of the disc (Muzerolle et al., 2004).

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ESO/P. Carrillo

The 8.2-metre Unit Telescopes of the Paranal Observatory in silhouette against the Sun.