Diffraction-limited bispectrum speckle interferometry of the Herbig Be star R Mon

Gerd Weigelt[(1)], Thomas Preibisch[(1)], Karl-Heinz Hofmann[(1)], Yuri Y. Balega[(2)],

(1) Max-Planck-Institut für Radioastronomie, Bonn, Germany (2) Special Astrophysical Observatory, Russia

Introduction

The variable star R Mon belongs to the group of Herbig Ae/Be stars, i.e. it is an intermediate-mass pre-main sequence star. R Mon is located at a distance of about 800 pc and illuminates the famous fan-shaped reflection nebula NGC 2261, also known as Hubble's variable nebula. CO radio observations showed that R Mon is located in a massive extended flattened molecular torus and drives a bipolar outflow in north-south direction. Jones & Herbig (1982) detected a small group of Herbig-Haro objects, HH 39, about $7.5'$ north of R Mon at a position angle of $350°$, i.e. on the symmetry axis of the NGC 2261 nebula. Brugel et al. (1984) discovered highly collimated bipolar outflows about $10''$ north and south of R Mon, providing evidence for ongoing high-velocity outflow activity from R Mon.

Herbig (1968) was the first to notice that R Mon is not a point source in optical images but has the shape of a triangular nebula. He concluded that the visible light does not come directly from the star but from a small nebula. The shape and orientation of this nebula continues out into the much larger fan of NGC 2261. These results suggest that the star is surrounded by a thick circumstellar disk or a torus, in which a conical cavity was carved out by the outflowing material. The nebular emission is thought to be mainly reflected light from the bright inner wall of this cavity.

A comprehensive study of R Mon, including high-resolution near-infrared adaptive optics imaging and polarimetry, mid-infrared imaging, analysis of HST images, and theoretical modeling, was presented by Close et al. (1997; C97 hereafter). In this study, a binary companion with a separation of $0.69''$ from R Mon was discovered. C97 modeled the system as a young stellar object surrounded by an optically and geometrically thick accretion disk that is embedded in an extended dusty envelope. According to this model, the jet from R Mon has cleared a conical cavity in the envelope, through which light escapes and illuminates the NGC 2261 reflection nebula The images presented by C97 also revealed a complex of twisted filaments with a double-helical structure along the eastern edge of the parabolic shell, which may trace a twisted magnetic field above R Mon.

Observations

Our K- and H-band speckle interferograms were obtained with the 6 m telescope at the Special Astrophysical Observatory (SAO) in Russia. The images were reconstructed using the bispectrum speckle interferometry method (Weigelt 1977; Lohmann et al. 1983) and have a diffraction-limited resolution λ/D of 76 mas (K band) and 56 mas (H band). We also have obtained conventional near-infrared images at the Calar Alto 3.5 m telescope.

Results

In Figure 1 we present our diffraction-limited speckle images, optical images derived from HST WFPC archive data, and our seeing-limited near-infrared images of R Mon. Figure 2 shows the full field of our H-band speckle image with annotations of all the features discussed in the text below. The first thing to note when comparing our near-infrared speckle images with the optical HST image (Fig. 1c) is the different morphology of the diffuse structures.

R Mon A and R Mon B

R Mon B is an unresolved point source in our speckle images. In contrast to the optical images, in which R Mon A is a small triangular-shaped nebula, our K-band speckle image shows R Mon A to be a nearly point-like source; we find a FWHM Gaussian diameter of 83 mas in east-west direction and 78 mas in north-south direction (i.e., the R Mon image is only a few mas larger than the 76 mas Airy disk). In our H-band image, R Mon A has a FWHM Gaussian diameter of 153 mas in east-west direction and 81 mas in north-south direction, i.e. is clearly more extended.

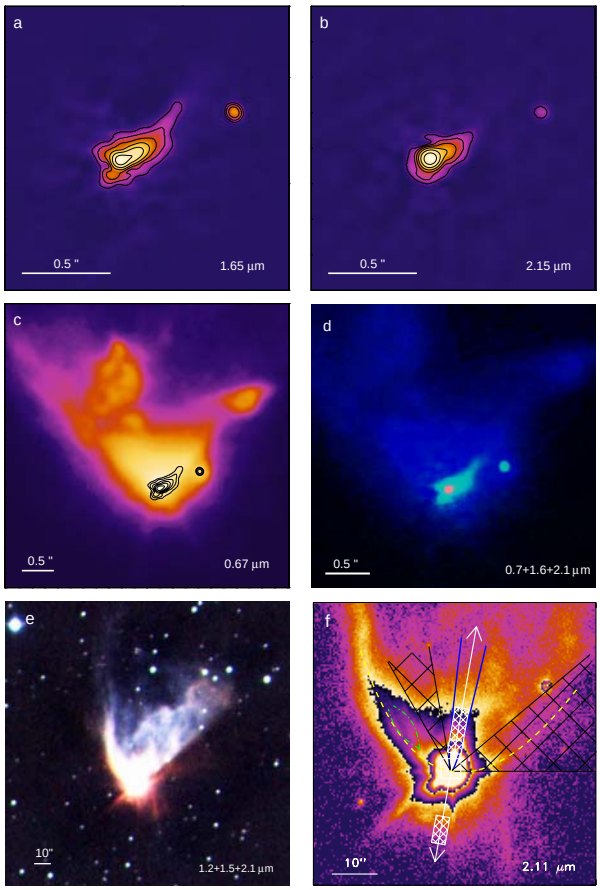

Figure 1: a,b: Central parts of our H- and K-band speckle images of R Mon. c: HST H-band image with contours of the H-band speckle image. d: True-color composit of the H-band (blue) HST image and the H- (green) and K-band (red) speckle images. e: $J\,H,\,K'$ color composit image derived from the Calar-Alto data. f: Calar-Alto K'-band image (wrapped intensity scale) of the inner nebula with annotations.

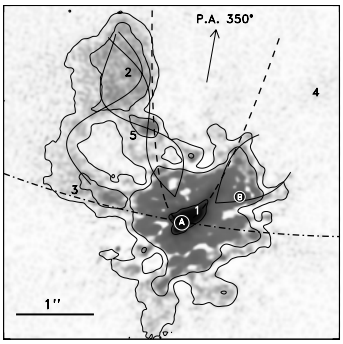

Figure 2: Greyscale + contour representation of our H-band speckle image with annotation of the features discussed in the text. The intensity scale is based on a power-law relation and was adjusted to show both the central bright as well as the outer faint structures with good contrast. The locations of R Mon A and R Mon B are marked by white circles. The features 1 – 5 are marked. The dashed line shows the inner parabola defined in the text. The dashed-dotted line shows the parabola defined by the large-scale structure of the nebulosity (yellow line in Fig. 1f). The solid sin-curves mark the helical features.

Diffuse features near R Mon

In contrast to the relatively symmetric appearance of the optical nebulosity around R Mon in the HST image, our near-infrared speckle images (Fig. 1ab and Fig. 2) show a very pronounced asymmetry. The most prominent structure in our speckle images (Fig. 1a,b) is the bright arc-shaped feature extending directly from R Mon to the north-west, marked as feature **1** in Fig. 2. Up to a distance of $\sim 0.4''$ from R Mon, the arc is rather bright and has a well defined and sharp outline. Further out, it seems to dissolve into more extended nebulosity. The general shape of the brighter parts of this arc can approximately be described by a one-sided parabola. The arc probably represents the surface of dense material near the disk or the outer region of a torus-like structure.

The eastern part of our speckle image in Fig. 2 is dominated by an extended patch of diffuse emission (feature **2**) $\sim 1''$ north-east of R Mon and several faint filamentary structures.

If we fit a parabola (dashed line in Fig. 2) with symmetry axis along PA $350°$ (i.e. the direction of the outflow) to the north-western arc (feature **1**), the eastern part of this parabola coincides approximately with the western boundary of feature **2**. This parabola is much narrower than the large-scale parabolic shape of the extended nebula seen in conventional images (dashed-dotted line in Fig. 2 and yellow line in Fig. 1f). We interpret these two parabolic structures in the following way. The wider parabola probably represents the upper edge of a flattened circumstellar structure, presumably a thick disk or a torus, around R Mon. The space above this disk is partially filled with diffuse material, which is predominantly located close to the surface of the disk and below the narrow parabola. The space inside this narrow parabola seems to contain much less dense material or is essentially empty.

Structure of the filaments

The presence of several large twisted filamentary structures in the NGC 2261 nebula has been known for many years. The adaptive optics images of C97 revealed a twisted double helix about $1''$ north-east of R Mon, which is associated with feature **2**.

Our data suggest that the innermost detectable knot of this double helix is located at a position $\sim 0.4''$ north-east of R Mon. The shapes of the filaments can be well reproduced by sin curves running to the north-east along P.A. $20°$. The spatial period of the curves is $2.0'' \equiv 1600$ AU, their width is $\sim 0.3'' \equiv 230$ AU.

Relation to the wind and outflow activity of R Mon

R Mon is the source of a stellar wind, a bipolar jet, and a bipolar molecular outflow. The wind of R Mon if flowing outwards at about 300 km/sec along the polar axis Jones & Herbig (1982). The jet from R Mon is traced by HH 39, which is moving away from R Mon at a tangential velocity of about 290 km/sec, suggesting a dynamical age of ~ 5900 yrs. The spatial distribution of the individual bright knots of HH 39 corresponds to a jet opening-angle of only $\sim 2°$. Brugel et al. (1984) reported the spectroscopic detection of a bipolar jet close to R Mon, also along P.A. $350°$. The northern component extends $4'' - 14''$ from R Mon and has a width of $\lesssim 3''$; the southern component is $10'' - 16''$ from R Mon. The molecular outflow from R Mon is slow ($\sim \pm 6$ km/sec), very extended, and poorly collimated (cf. Canto et al. 1981).

In Fig. 1f we have marked the two jet components detected by Brugel et al. (1984) as white hatched boxes. It is interesting to note that the northern jet component fits very well into the extrapolated shape of the inner parabola defined in Fig. 2. This suggests that the mostly empty region in the interior of this inner parabola represents the path of the jet, which has cleared its way.

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