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*Research Note*

# High-resolution imaging of the bipolar nebula Red Rectangle

## Evidence for unstable mass transfer in a close binary system*

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**Abstract.** We present the first diffraction-limited speckle-masking bispectrum observations of the central part of the Red Rectangle at optical wavelengths ($\lambda \sim 656$ nm and $\lambda \sim 800$ nm). The results confirm infrared observations which show that the object is a bipolar nebula. The dark lane separating the two lobes is probably produced by an obscuring dust disk slightly inclined with respect to the line of sight. The fainter northern lobe appears not to be reddened by the disk. This implies an upper limit of the outer disk radius of about 200 AU. We propose that the observed nebula is the result of recent mass ejection induced by unstable mass transfer from an AGB star to a close companion.

**Key words:** techniques: image processing – techniques: interferometric: speckle interferometry – planetary nebulae: individual (Red Rectangle) – stars: mass-loss – stars: AGB, post-AGB

### 1. Introduction

The Red Rectangle (AFGL 915) is an extended ($\sim 40''$) reflection nebula with a pronounced bipolar structure. According to Cohen et al. (1975) the distance to the object is about 330 pc, and they assign its central object a spectral type of B9-A0 III. Knapp et al. (1995) deduce a central star spectral type of earlier than B3 and they propose a larger distance of about 940 pc. Waelkens et al. (1992) suggest an upper limit for the distance of 0.8 to 1.4 kpc. The presence of carbon-rich dust in the Red Rectangle and its large inferred bolometric flux suggest a post-AGB nature for the central stellar object HD 44179 (cf. van Winckel et al. 1995). Extreme abundance peculiarities were reported by Waelkens et al. (1992), Waters et al. (1992) and Van Winckel et al. (1992). High resolution infrared observations (Leinert & Haas 1989, Christou et al. 1990, Roddier et al. 1995 and Cruzalèbes et al. 1996) show that the central region of the Red Rectangle is a bipolar nebula. Recent photometric and radial velocity measurements of HD 44179 by Van Winckel et al. (1995) and Waelkens et al. (1996) show that the central object is a spectroscopic binary with a separation of $a \sin\, i = 0.32$ AU ($\sim 1$ mas) for a distance of 330 pc.

### 2. Observations and data reduction

The Red Rectangle speckle data was obtained with the 2.2 m ESO/MPG telescope on March 9, 1995. The data was recorded through a Schott edge filter RG780 and through an interference filter with center wavelength/bandwidth of 656 nm/60 nm. The observational parameters were as follows: the number of speckle frames was 3000 per filter, the exposure time per frame was 50 ms for the 656 nm data and 70 ms for the RG780 data, seeing was $\sim 0\farcs6$, the pixel size $\sim 11.3$ mas, and the field of view was $5\farcs78$.

The speckle raw data was recorded with the speckle camera described by Baier & Weigelt (1983). The new detector used for the observations was an image intensifier with a gain of 500 000 coupled optically to a fast CCD camera ($512^2$ pixels/frame, frame rate 4 frames/s, correlated double sampling). A system of Digital Signal Processors was used for fast data storage on 4 Exabyte streamers simultaneously. The quantum efficiency of the image intensifier was 12% at 500 nm, 9% at 600 nm, 8% at 700 nm and $\leq 1\%$ at 900 nm.

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* based on observations collected at the European Southern Observatory, La Silla, Chile

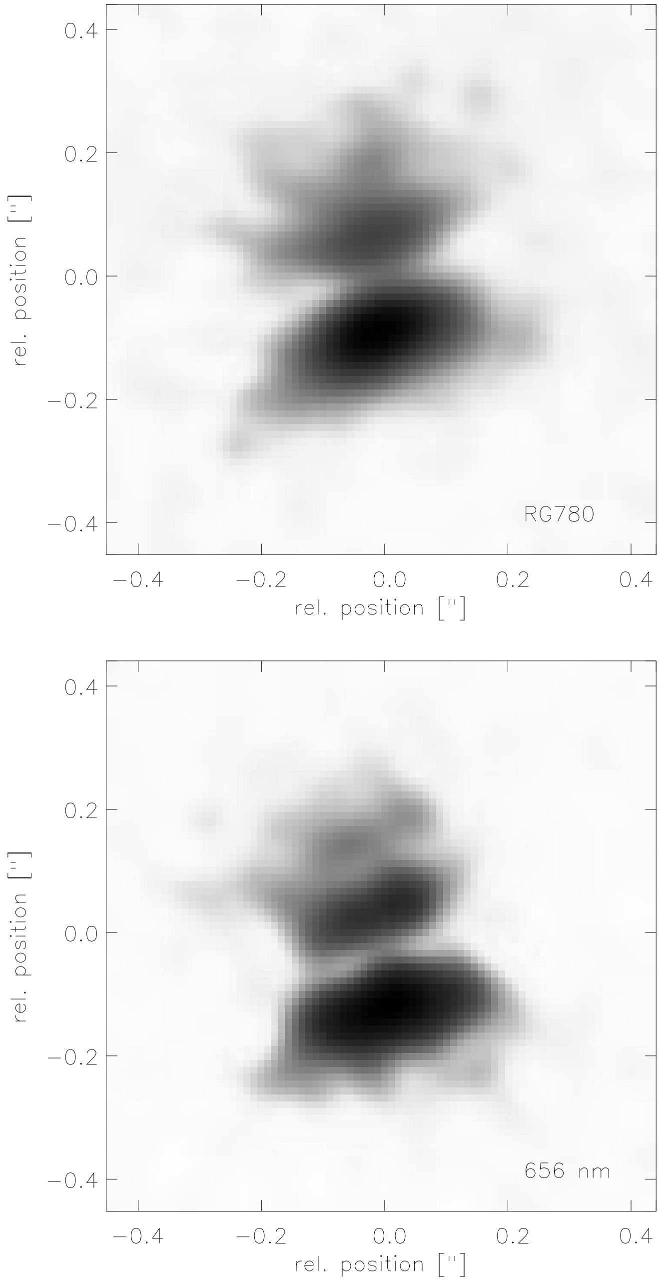


**Fig. 1.** Speckle masking images of the Red Rectangle reconstructed from the RG780 (top) and the 656 nm (bottom) speckle interferograms. North is at the top and east to the left

Diffraction-limited images were reconstructed from the speckle interferograms by the speckle masking bispectrum method (Weigelt 1977; Lohmann et al. 1983; Hofmann & Weigelt 1986). The image processing steps applied were described by Hofmann et al. (1995). The atmospheric speckle transfer function was derived from speckle data of the unresolved star SAO 152044. The bispectrum of each frame consisted of ∼ 30 million elements (maximum length of bispectrum vectors: u ≡ 50% of the telescope diffraction cut-off frequency $u_{DL}$, v ≡ 101% of $u_{DL}$). No postprocessing by image restoration methods was applied to the speckle masking reconstructions.

## 3. Results

Fig. 1 shows the speckle masking results. The size of the displayed region is 80 × 80 pixels or about $0.''9 \times 0.''9$. The inner region of the Red Rectangle has a bipolar structure. It consists of two lobes which are clearly separated by a dark lane. This lane is probably produced by a dust disk obscuring the central object. The angle between the northern direction and the polar axis of the nebula is about 15°. The southern lobe has a bright central region, which, however, is more extended than a point source image. We conclude that we do not see the stellar light directly, but scattered light from the material surrounding the central object. Filamentary structures can be identified along several directions. These features can be seen in both images but are most pronounced in the 656 nm/60 nm filter.

Fig. 2 shows contour plots of Fig. 1 and intensity profiles along three cuts through the images as indicated by the dashed lines. The curves in the upper and middle frame refer to cuts perpendicular to the polar axis of the bipolar nebula through the intensity maximum of the southern and the northern lobe, respectively. The slopes on the western side of the lobes are steeper than on the eastern side. The lower frame shows the intensity profile parallel to the polar axis through the brightest peak in the southern lobe.

Our results allow us to determine the intensity ratio of the two lobes at visible wavelengths. For the 656 nm image we find a peak-to-peak ratio of 0.52 and for the RG780 image of 0.43. The ratios of the integrals are about 0.72 and 0.60, respectively. The results of Roddier et al. (1995), Christou et al. (1990) and Cruzalèbes et al. (1996) suggest comparable values for the intensity ratios in H and K. One can therefore assume that there is no reddening of the northern lobe by the inclined dust disk. The projected size of the disk (in north-south direction) is then smaller than the separation of the lobes of about $0.''15$. Assuming a maximum value for the projected radius of $0.''1$ we find an upper limit $r_{\rm max}$ for the outer disk radius $r_{\rm out}$ of

$$r_{\rm out} \lesssim r_{\rm max} \approx 5\,10^{14}{\rm cm} \times (D/330\,{\rm pc})/\sin(i)\ ,$$

where $D$ is the distance of the Red Rectangle and $i$ the inclination of the dust disk. Appropriate values for $i$ can be estimated from the intensity ratio of the lobes. This leads roughly to a range from 10° to 15° (cf. Roddier et al. 1995, Lopez et al. 1995) and further to an upper limit of $r_{\rm max} \approx 140 \ldots 200$ AU. A lower limit for the outer disk radius $r_{\rm out}$ can be derived from the extension of the dark lane in our images (Fig. 1) roughly in east-west direction (perpendicular to the polar axis) which is about $0.''4$ corresponding to a radius of $r_{\rm out} > 65$ AU. Jura et al. (1997) estimated $r_{\rm out} \approx 200 \ldots 1300$ AU on the basis of their VLA radio observations. An outer disk radius of $r_{\rm out} \approx 200$ AU therefore seems to be appropriate to account for all observations.

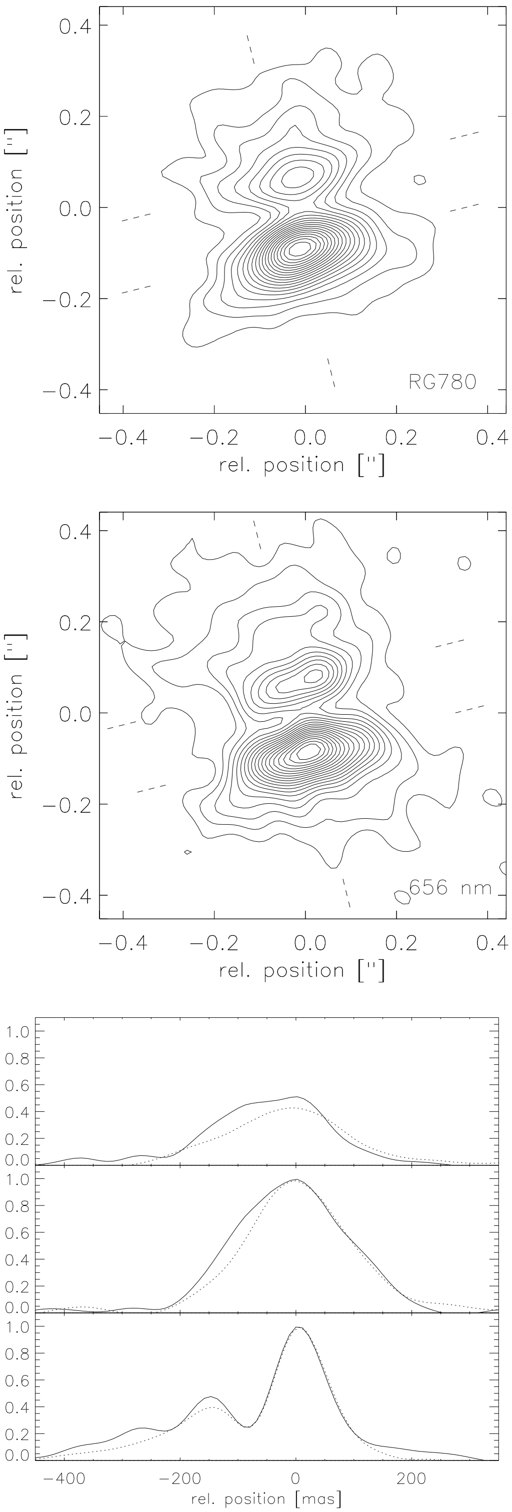


**Fig. 2a–c.** Contour plots of the speckle masking images reconstructed from the RG780 (**a**) and 656 nm (**b**) data. The contour levels are plotted from 5% to 95% of the peak intensity in steps of 5%. North is at the top and east to the left. The dashed lines indicate the directions of the cuts shown in **c**. The solid lines in plot c refer to the 656 nm image, dotted lines to the RG780 image. Top and middle in image **c** cut through the northern and southern lobe, respectively, parallel to the dark lane. East is to the left. Bottom: cut parallel to the polar axis and through the brightest peak in the images. North is to the left

## 4. The origin of the nebula

The interpretation of observations of the central source of the Red Rectangle are somewhat controversial. Three different types of binaries have been proposed: a visual binary with a separation of $\sim 0.''2$, a visual primary (HD 44179) with an infrared component at $\sim 0.''15$ and a spectroscopic binary with $\sim$0.5 AU ($\sim$1 mas) separation (see discussion in Cohen et al. 1975 and Leinert & Haas 1989).

We believe that claimed optical detections of the visual binarity, which have been doubted previously (cf. Van Winckel et al. 1995), may be ascribed to the pronounced double structure of the inner nebula seen in Fig. 1. This is consistent with the results of Leinert & Haas (1989), Christou et al. (1990), Roddier et al. (1995) and Cruzalèbes et al. (1996) who found the bipolar structure of the inner part of the nebula at NIR wavelengths. In any case, a visual binary with a separation as large as $\sim 0.''1$ to $\sim 0.''2$ ($\sim$30 - 60 AU) is unlikely to be the cause for the observed highly bipolar matter distribution. On the other hand, the spectroscopic companion to HD 44179 found by Van Winckel et al. (1995) must inevitably have consequences for the circumstellar matter. Stellar evolution calculations of mass exchanging binary systems (e.g. De Greve 1993, Braun & Langer in prep.) show that for short mass transfer time scales, which are very likely in the considered system (see below), the mass donor may be largely under-luminous and the mass gainer (i.e. the secondary) very over-luminous. It may therefore be inappropriate to deduce the primary status for the brighter component from its luminosity. In either case, however, Van Winckel et al.'s conclusion that mass transfer has occurred in this system remains valid since AGB stars are more extended than the current binary orbit.

Components of binary systems with initial masses less than $\sim 8\,M_\odot$ may evolve into an AGB star. For sufficiently close systems, mass transfer from the AGB star to the less massive companion may then commence. Since this leads to a shrinking of the orbit, and due to the deep convective envelope of the AGB star this mass transfer is supposed to be dynamically unstable (Paczynski & Sienkiewicz 1972) and is assumed to lead to a common envelope evolution (cf. Livio 1996). Recent dynamical studies of this situation (Terman et al. 1994, Yorke et al. 1995) show that a large fraction of the AGB envelope can be expelled from the binary system. Yorke et al. obtain outflow velocities of the order of some $10\,\mathrm{km\,s^{-1}}$, which is in agreement with the short time scale of only $\sim 15$ yr associated with the inner nebular dynamics (Knapp et al. 1995). Furthermore, Yorke et al. find that most of the gas remains in a disk-like configuration, confined within 20...30° of the orbital plane. This model might explain the obscuring disk which separates the two main lobes in Figs. 1 and 2. Lopez et al. (1995) present radiative transfer calculations for a dusty disk-like post-AGB star environment. They can reproduce the shape of the emission of the Red Rectangle quite well, at least on scales of some arcseconds.

However, the outcome of the common envelope evolution – in case the merging of the C/O-core of the AGB star with the companion is avoided – is likely to be a system with a compact spherical orbit with a period of $\sim 1$ day (Livio 1996). On the other hand, Podsiadlowski et al. (1992) discuss the possibility of avoiding catastrophic mass transfer from red giants, e.g. in case of a relatively large core to envelope mass ratio of more than 0.46 (Hjellming & Webbink 1987); this may be found in AGB stars of the lowest possible initial masses. A determination of the mass of the Red Rectangle might allow to confirm or reject this possibility. Moreover, pulsed mass transfer may have a stabilizing effect (Eggleton & Tout 1989); this may be related to Mira-instabilities of AGB stars (cf. Vassiliadis & Wood 1993) or to the large eccentricity of the system HD 44179. Detailed numerical calculations of this quasi-dynamical mass transfer phase do not exist, but Podsiadlowski et al. (1992) do not exclude the possibility that mass loss from the binary system also occurs in this situation. Perhaps the Red Rectangle is the most favorable case for the formation of a stationary circum-system disk with a reaccretion of metal deficient gas, which is proposed by Waters et al. (1992) and Van Winckel et al. (1995) in order to explain the extremely low observed [Fe/H] ratio in HD 44179.

## 5. Conclusion

We have resolved the central part of the Red Rectangle into two main lobes, which appear separated by about $0\rlap{.}''15$ due to an obscuring dust disk. This confirms earlier NIR observations of this object but adds now the first detection of the central bipolar structure at optical wavelengths with diffraction-limited resolution. We can identify small scale structures which are similar when observed at different wavelengths and which are resolved for the first time. They appear to be connected with the X-shaped structure found on larger scales. We see predominantly scattered light of the central star of the Red Rectangle rather than direct light. The extension of the dark lane in east-west direction allows to derive a lower limit for the outer radius of the dust disk of $r_{\rm out} > 65$ AU. From the fact that there is no reddening of the fainter northern lobe, an upper limit for the outer radius of $r_{\rm out} \lesssim 200$ AU can roughly be estimated. This is in a reasonable agreement with the results of Jura et al. (1997).

We cannot confirm the central star to be a visible binary. Rowan-Robinson & Harris (1983) suggest an extinction of about 22 mag in the visible, which would allow the star to be seen only in the infrared (see also the detailed discussion by Roddier et al. 1995 concerning this question). In any case, the detected morphology and its interpretation as two lobes separated by an obscuring disk appear to be consistent with a close ($\sim 1$ mas) companion to HD 44179 (Van Winckel et al. 1995) which induced unstable mass transfer and accompanying mass loss into the circumstellar environment.

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