Detection of a sub-arcsecond dust shell around the Wolf-Rayet star WR 112 *

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Received/Accepted

ABSTRACT
A lunar occultation event of the Wolf-Rayet star WR 112 (type WC9) has been observed simultaneously from two independent telescopes at $\lambda = 2.2 \mu m$, allowing us to investigate this source with an angular resolution of $\approx 0.003$ arc-seconds. We have detected a circumstellar dust envelope whose brightness distribution can be approximately fitted by a gaussian with a FWHM of $\approx 0.06$ arc-seconds ($\approx 10^{15}$ cm). We present and discuss the reconstructed brightness profile, which shows an asymmetry in the radial dust distribution. The derived dust grain temperature at the inner dust zone of $\approx 1150$ K is consistent with available model calculations. There is no signature of the central star from our observations, providing a direct confirmation that the circumstellar shell emission dominates over the photospheric emission at 2.2 $\mu m$ as predicted by fits to the spectral energy distribution. Further lunar occultation observations at different position angles are essential to reconstruct the 2-D image of the dust shell around WR 112. The current series of lunar occultations of WR 112 will continue to the end of 1999 and will be visible for all equatorial and southern latitude observatories.

Key words: occultations – stars: fundamental parameters – stars: Wolf-Rayet – stars: circumstellar matter – infrared: stars

1 INTRODUCTION
Wolf-Rayet (WR) stars represent a small population of evolved high-mass stars. They are characterized by strong, broad emission line features in their optical spectra, indicative of powerful stellar winds and in turn of mass loss (Abbott & Conti 1987). This latter is inferred also from P Cygni profiles in the UV and visual, from free-free emissions and thermal dust emissions in the infrared, from continuum excess radiation in radio, and from H$_{\alpha}$ and forbidden-line imaging in the optical. The total wind energy emitted by a WR star during its lifetime is comparable to the energy of a supernova (van der Hucht, Williams & Thé 1987).

WR stars exhibit IR excess, which has been attributed to free-free emission in the case of WN and early-WC type WR stars, and thermal emission from circumstellar dust in the case of late-WC type WR stars. In fact, several late-WC stars have been discovered from infrared survey as these objects are highly obscured in the optical by the circumstellar dust. Initially, the dust grains around WC stars were thought to be graphite (Cohen 1975), but it is widely established now that the grains are made rather of amorphous carbon (Williams et al. 1995; van der Hucht et al. 1996). Episodic dust formation has been witnessed in a few WC7 stars from infrared photometric studies and linked with the orbital motion of a suspected binary system (Williams et al. 1994).

The circumstellar environment around WR stars has been investigated so far mainly by infrared photometry and spectroscopy. Spatially resolved observations of the circumstellar emission around this interesting class of sources in the optical and infrared wavelengths are yet to be carried out on a regular basis, because of the rarity of these objects and of their distance. High angular resolution studies of WR stars could improve our understanding of high-mass stellar evolution and physical processes such as mass loss and dust condensation.

Methods such as speckle or long baseline interferometry in the optical and near infrared lack sufficient angular resolution or sensitivity in order to resolve these sources. To our knowledge, only in one case (namely Ve 2-45) has the circumstellar dust around one WR star been partially resolved by one-dimensional IR speckle observations (Allen, Barton...

* Based on observations collected at TIRGO (Gornergrat, Switzerland) and at Calar Alto (Spain). TIRGO is operated by CNR – CAISMI Arcetri, Italy. Calar Alto is operated by the German-Spanish Astronomical Center.
& Wallace 1981; Dyck, Simon & Wolstencroft 1984). The results of these observations were consistent with the dust shell model calculations.

Lunar occultations in the near-infrared have been very successful in recent times in resolving circumstellar dust around evolved late-type giants, supergiants and carbon stars (Richichi et al. 1998a; Ragland, Chandrasekhar & Ashok 1997). In this paper, we report on lunar occultation observations of the Wolf-Rayet star WR 112 (GL 2104), recorded almost simultaneously and independently from two telescopes in the near infrared. The circumstellar dust shell is well resolved from these observations, which for the first time have reached a resolution at the level of 0.003 arcsecond on such an object.

WR 112 has been classified as WC9 (Massey & Conti 1983). An alternative classification of WC8 can also be found in the literature (Allen et al. 1977; Cohen & Kuih 1976). WR 112 has been discovered from the AFGL survey; while it was overlooked in the visual because of its faint magnitude of $v=18.8$ (note that $v$ is a narrow filter not completely equivalent to the broad band V filter, for which no photometry is available in the literature). By comparison with our near-IR photometry, it is clear that WR 112 is subject to a strong reddening ($A_v \approx 13$). The distance is estimated to be 1.2 kpc, with an uncertainty of about $\pm 20\%$ (van der Hucht et al. 1988).

## 2 OBSERVATIONS AND DATA REDUCTION

The lunar occultation observations reported here were carried out with the 1.5m TIRGO and 1.23m Calar Alto telescopes. At the time of observation, the primary mirror of this latter was partially covered because of optical imperfections and the effective size was only about 70 cm. The recorded event was a disappearance event at the dark limb of the Moon. Table 1 lists the circumstances of the events.

The instruments used were FIRT and FIRPO at TIRGO and Calar Alto respectively. The instrumental details can be found in Richichi et al. (1998b) and references therein. In both cases a standard K broad band filter was used to record the events.

In addition to lunar occultation observations, near infrared photometry of this Wolf-Rayet star has been carried out at the 1.23m Calar Alto telescope one day after the lunar occultations, and yielded the results $H=6.37 \pm 0.1$ mag and $K=4.21 \pm 0.1$ mag.

The occultation data have been rebinned to improve the SNR. This has been achieved at the expense of a loss in angular resolution, which in any case is largely sufficient to resolve the dust shell. The resultant angular resolutions are 3 and 6 milliarcseconds (mas) respectively for the Calar Alto and TIRGO observations. The rebinned light curves have been analyzed using a model independent algorithm (CAL) introduced by Richichi (1989) for lunar occultation work. CAL is a composite algorithm which makes use of non-linear least squares method and Lucy’s deconvolution algorithm, wherein an arbitrary profile is assumed as a initial guess and is iteratively modified to fit the observed occultation data. It is noteworthy that the solution to the problem of recovering the brightness profile is not unique. The CAL algorithm converges towards the most likely solution, which is not necessarily the correct one. Simulations have shown that a uniform disk will be recovered as a gaussian profile, and in Richichi (1989) a ratio of 1.58 between the diameter of a uniform disk and the FWHM of the equivalent gaussian was derived. These considerations will be used in the discussion of our results.

### Table 1. Circumstances of the occultation events

<table>
<thead>
<tr>
<th>Date</th>
<th>Calar Alto</th>
<th>TIRGO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Predicted Time (UT)</td>
<td>22:36:54</td>
<td>22:49:06</td>
</tr>
<tr>
<td>Predicted Position angle</td>
<td>66°</td>
<td>54°</td>
</tr>
<tr>
<td>Predicted Contact angle</td>
<td>−19°</td>
<td>−31°</td>
</tr>
<tr>
<td>Lunar phase</td>
<td>84%</td>
<td>84%</td>
</tr>
<tr>
<td>Projected limb speed (km/s)</td>
<td>0.680</td>
<td>0.693</td>
</tr>
</tbody>
</table>

## 3 RESULTS AND INTERPRETATION

The observed light curves and the corresponding fits are shown in the two upper panels of Fig. 1 while the recovered brightness profiles for each data set are shown in the lower panels of the same figure. Also shown are the formal error bars on the recovered brightness profiles. The scan direction for the two profiles differed by only $12^\circ$ due to the geometry of the events at the two sites (see Table 1) and was roughly in a South-West – North-East direction. This limits the possibility to exploit significantly the potential for 2-D information, but it has on the other hand the advantage that the analysis of the two observations can be independently checked, thus adding reliability to the result. We attribute the extended brightness profile of WR 112 to the presence of warm circumstellar dust close to the stellar photosphere, as discussed below. The data from Calar Alto were noisier because of the smaller telescope aperture, and this is reflected in a lower SNR in the reconstructed profile. Even so, the general features are consistent with the profile obtained from the TIRGO data.

We note the following points: a) there is no evidence of the central star, which is expected to be completely unresolved and should leave a distinctive signature (well defined diffraction fringes) in the occultation trace; b) the profile of this dust shell can be approximately fitted by a gaussian with a FWHM of 0'.059, or $\approx 71$ AU; c) the profile has broader wings than the simple gaussian approximation.

These wings are not symmetric, with the one in the South-West direction significantly broader. This is made more evident by the comparison with the gaussian profile, which is also shown in Fig. 1. It can be noted that the recovered broad feature to the SW is well above the noise level of the TIRGO data, and is present also in the lower SNR data of Calar Alto. The feature to the NE is less evident, but is also recovered consistently in both data sets.

A two component blackbody fit to the photometric data suggests that the central star is about 6 magnitudes fainter than the circumstellar shell in the K band. This is well below our detection limit, and explains why there is no evidence of the central star from our observations.

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The peculiar continuum and the weakness of the CIII line at 4650Å in the optical spectra suggest a possible companion of early spectral type (Cohen & Kuhi 1976; Cohen & Vogel 1978; Massey & Conti 1983): detection of the companion is hampered by the same factors as the WC star, namely being about 6 magnitudes fainter than the dust shell at 2 microns.

One important aspect in the interpretation of the data is the fact that, in spite of the strong reddening, the dust around WR 112 is optically thin. This is deduced from the fact that the IR excess (which has been derived from the model fit to the observed spectral energy distribution) amounts to only 7.9% of the total flux (Williams, van der Hucht, Thé 1987). Most of the reddening must be interstellar in origin, and this is consistent with the fact that WR 112 lies in a region of high interstellar extinction ($l_{II}=12^\circ$, $b_{II}=-1^\circ$). Moreover, it has been shown that $A_v$ can be well correlated with the strength of interstellar absorption features at 3.4μm (Standford, Pendleton & Allamandola 1995) and 9.7μm (Roche & Aitken 1984). In the case of WR 112 this leads to the conclusion that circumstellar extinction contributes very little to the observed reddening. Also, there is strong indirect evidence from the photometric monitoring of WR 112 in the infrared and from its spectral type, that the dust condensation is probably a continuous process in this star. WR 112 has been searched for HCN molecular line emission with negative results (Clair et al. 1979). Recently, the detection of the radio continuum at 3cm has been reported by Leitherer et al. (1997). There is

**Figure 1.** Upper panels: occultation light curves of WR 112 (dots) observed at Calar Alto (left) and TIRGO (right) at 2.2μm. Also shown are the best fits (solid lines). Lower panels: brightness profiles recovered from the two data sets (solid lines). Also shown is a gaussian profile with FWHM of 59 mas (dashed line), and the formal error bars associated with the reconstruction in the two cases.
Table 2. Stellar and dust shell parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stellar effective temperature</td>
<td>19000 K</td>
</tr>
<tr>
<td>Stellar radius</td>
<td>14.6 R⊙</td>
</tr>
<tr>
<td>Distance</td>
<td>1.2 kpc</td>
</tr>
<tr>
<td>Dust grain composition</td>
<td>amorphous carbon</td>
</tr>
<tr>
<td>Dust grain temperature</td>
<td>$T_{\text{grain}} \propto r^{-0.4}$</td>
</tr>
<tr>
<td>Dust grain density</td>
<td>$\rho_{\text{grain}} \propto r^{-2}$</td>
</tr>
</tbody>
</table>

- Inner dust shell angular radius: 0.031
- Inner dust shell linear radius: $5.6 \times 10^{14}$ cm $\approx 550 R_\star$
- Inner dust shell temperature: 1150 K

no appreciable polarization in this source from the infrared measurements carried out by Kobayashi et al. (1978).

The FWHM of the recovered profile, when fitted with a gaussian, is $59 \pm 3$ mas. The corresponding uniform disk angular diameter is $93 \pm 5$ mas, from the arguments given in Sect. 3. Allen et al. (1981) gave a scaling factor of 1.5 between the radius of a uniform disk and of the inner dust shell radius, under the assumption of constant dust condensation and optically thin shell which we have just discussed. Thus we derive an inner dust shell angular radius of 31 mas. At an assumed distance of 1.2 kpc to the source and including the associated uncertainty, this value translates to $(5.6 \pm 1.2) \times 10^{14}$ cm, or $\approx 37$ AU. By comparison, Allen et al. (1981) derived a value of $1.2 \times 10^{15}$ cm for the inner radius of the dust shell around another WC9 star, namely Ve 2-45, at 2.2 μm from speckle observations.

We also note that under the above mentioned assumptions, the models predict a bright rim at the inner zone of the shell where dust condenses (Rowan-Robinson 1980; Rowan-Robinson & Harris 1982). This is expected to be more sharply defined at 2μm than in the visual or at longer wavelengths. Such a bright rim is not evident from our data, but we must caution against a negative conclusion in this sense. In fact, we remind that the profiles shown in Fig. 3 are integrated in one direction (the direction perpendicular to the lunar limb), and it can be shown that in the case of circular symmetry the bright rim feature is effectively canceled (see for instance Ridgway et al. 1986, 1987).

Adopting the chemical composition of the grains to be amorphous carbon, the equilibrium grain temperature is expected to fall off with the distance from the star as $T \propto r^{-0.4}$ (Williams et al. 1994). Assuming the stellar effective temperature to be 19000 K and the stellar radius to be 14.6 R⊙ (van der Hucht, Cassinelli & Williams 1986), we derive the grain temperature at the inner dust shell to be 1150 ± 270 K. The inner dust shell radius is thus at 550 ± 160 R⊙. The derived dust grain temperature is consistent with the expected dust temperature at the condensation zone. In Table 2 we summarize the adopted stellar parameters and the dust grain characteristics, and the derived dust shell parameters.

We compare our derived dust shell parameters with those estimated by Williams et al. (1987) from their detailed dust shell model fits to the observed photometric data. They estimate the dust grain temperature at the inner dust zone and the inner dust shell radius to be 960 K and 690 R⊙ respectively. Our derived dust shell parameters are in good agreement with their estimation. More recently, Zubko (1998) estimate the dust grain temperature at the inner dust zone of 1085 K and the inner dust shell radius of 1500 R⊙ for this WR star. While their estimated dust temperature is consistent with our observations, their value for the dust shell inner radius is about a factor of 2.5 larger than our determination. However, this author has assumed different values for the stellar photospheric parameters ($T_{\text{eff}} = 22000$ K and $R_\star = 10 R_\odot$). We also note that the emphasis is more on far-infrared fluxes than near-infrared measurements (J and H band); on the other hand, near-infrared fluxes are probably more sensitive to the inner dust shell radius.

It is quite probable that the stellar radii of WC9 stars may be much smaller than the value adopted here, i.e. $R_\star = 3 R_\odot$, and a correspondingly larger effective temperature of $T_{\text{eff}} = 35000$ K, but without much change in the stellar luminosity (Crowther, 1997). In this case, the dust shell size reported here would not change in absolute units, but the inner dust shell radius would thus be located at 2680 ± 800 R⊙ at the grain temperature of 1130 K.

The suspected hot companion of WR 112, if present, would also heat up the circumstellar dust shell: the combined luminosity should be then adopted in estimating the dust grain temperature at the inner dust shell zone (Williams, van der Hucht, Thé 1987). In this case, the derived grain temperature at the inner shell radius would be larger by about 18% compared to the case when no companion is assumed.

4 CONCLUSIONS

We have investigated the circumstellar dust environment around a the WC9 Wolf-Rayet star WR 112 from near-infrared lunar occultation observations. The circumstellar dust shell has been directly detected for the first time from these observations carried out at 2.2μm from two independent telescopes.

The recovered brightness profile has a FWHM of 0′′.059, or about 71 AU. Under reasonable assumptions of small optical thickness of the dust and constant dust formation, we also derive some physical parameters for the dust shell: inner radius of dust formation 0′′.031 or ≈37 AU, and temperature of condensation ≈1150 K.

Our observations have also shown departure from circular symmetry, with wings in the brightness profile which are more prominent in the South-West direction than in the North-East one. The SW wing can be traced out to about 0′′.2. There is no signature of the central star from our observations, and we show that this is consistent with the expected properties of the object and the associated interstellar extinction.

The quantitative conclusions that we derive are in good agreement with theoretical predictions and show the potential of high angular resolution observations to investigate the inner structure of this class of objects. Further similar observations would be very useful to constrain further the physical characteristics of this object, and to study the details of its structure. The current series of lunar occultations of WR 112 will continue to the end of 1999 and will be visible for all equatorial and southern latitude observatories.
ACKNOWLEDGMENTS

The authors would like to thank the referee Prof. Peredur Williams for his valuable comments which have greatly improved the quality of this paper. We also thank Prof. Mario Perinotto for his useful suggestions. This research has made use of the Simbad database, operated at CDS, Strasbourg (France).

REFERENCES