2002MNRAS.334..143M

Mon. Not. R. Astron. Soc. **334,** 143–148 (2002)

Dust structure around the Wolf–Rayet star WR104 from lunar occultation observations at 2.2 μm

Soumen Mondal★ and T. Chandrasekhar★
Physical Research Laboratory, Ahmedabad-380 009, India

Accepted 2002 March 12. Received 2002 March 6; in original form 2001 November 19

ABSTRACT

A rare opportunity of observing a lunar occultation of a Wolf–Rayet star (WR104) in the near-infrared *K* band (2.2 μm) was utilized to probe the thick dust envelope surrounding the star at a high one-dimensional angular resolution (∼ 2 mas). Analysis of the occultation light curve shows a dust structure departing significantly from the uniform disc profile. Our results are in good agreement with recent aperture-masking interferometry carried out at the Keck I telescope, which shows a pinwheel structure around WR104. We report additional fine structures in the dust envelope.

Key words: occultations – Moon – circumstellar matter – stars: individual: WR104 – stars: Wolf–Rayet – infrared: stars.

1 INTRODUCTION

Wolf–Rayet (WR) stars are massive and highly luminous blue stars at the end of their nuclear burning phase, and are thought to be immediate precursors to supernovae which would terminate their lives. It has been known since the early days of infrared astronomy that a small fraction of WR stars belonging to the latest WC evolutionary stage show strong infrared emission signifying the presence of a heated dust shell mainly made up of hot carbon grains (Allen, Harvey & Swings 1972; Gehrz & Hackwell 1974; Cohen, Barlow & Kuhi 1975; Williams, van der Hucht & Thé 1987). The dust shell is the result of heavy mass loss from the star [$\dot{M} = (2–10) \times 10^{-5}\,M_{\odot}\,yr^{-1}$] and a strong stellar wind ($v_{\infty} =$ 1000–2500 $km\,s^{-1}$) (van der Hucht 1992). These WC stars are further classified as variable or persistent dust-producers, depending upon the variability of infrared emission (Williams & van der Hucht 1992). The existence and survival of the dust shells in the intense radiation field encountered in the vicinity of the Wolf–Rayet stars has however been difficult to explain by the conventional spherically symmetric outflow scheme (Williams et al. 1987). The episodic formation of dust in a long-period WR binary system like WR140 appears to coincide with periastron passage, with colliding stellar winds at close binary separation of a few au inducing dust formation (Williams et al. 1990). However, the brightest infrared WR stars like WR104 and WR98a are generally non-variable and are classified as persistent dust-makers (van der Hucht et al. 1996). The nature of the dust formation in these system is still not fully understood. It has been suggested that short-period binaries lie buried in these systems, with wind–wind collisions again catalysing dust formation (Usov 1991). On the other hand, it has been argued that dust can form in the spherically symmetric wind of a single WR via novel dust formation processes (Zubko 1998). Apart from persistent and episodic dust-makers, eclipse-like variations of infrared emission attributed to episodic obscuration of clumps of dust in the line of sight had been reported from three WC9 spectra by Veen et al. (1998). These variations are similar to R Coronae Borealis (RCB)-type variations, but have a small amplitude of ∼ 1 mag. High angular resolution observations of the dust envelopes are clearly needed to understand the phenomena of dust production, survival and dissipation around persistent dust-makers among the WR stars.

2 CIRCUMSTELLAR DUST SHELL AROUND WR104

WR104 (Ve 2-45) is the brightest WR star in the mid-infrared (∼ 20 μm). It is surrounded by a huge circumstellar dust shell. WR104 is classified as spectral subtype WC9 star by Smith (1968). Its visual magnitude is 13.54 (Smith 1968; Torres & Massey 1987). Allen et al. (1972) estimated that the observed flux corresponded to that of a 900-K blackbody with an angular diameter of 400 mas using 1.6- and 2.2-μm photometry. Based on 2.3–23 μm photometry, Hackwell, Gehrz & Smith (1974) found that the spectrum of WR104 can be fitted by a two-temperature blackbody, one temperature corresponding to a hot stellar continuum at ∼ 35 000 K and the other to a cool circumstellar component at ∼ 1080 K. Cohen et al. (1975) estimated a shell size of 121 mas and a corresponding dust shell temperature of ∼ 920 K. They suggested that WR104 is viewed edge-on, with appreciable circumstellar extinction ($A_v \sim 3.6$ mag). Williams et al. (1987), from their extensive infrared photometric study of a large number of Wolf–Rayet stars, find WR104 to be one of the few WR stars in which a

★E-mail: soumen@prl.ernet.in (SM); chandra@prl.ernet.in (TC)

© 2002 RAS

© Royal Astronomical Society • Provided by the NASA Astrophysics Data System

2002MNRAS.334..143M

Table 1. Previous high angular resolution measurements.

Date of Obs.	Method	λ ($\Delta\lambda$) in μm	UD (mas)	Ref.[a]
1980	speckle interferometry	2.2 (0.4)	130 ± 15	1
Aug. 1981	speckle interferometry	2.2 (0.4)	130	2
Oct. 1981	speckle interferometry	3.8 (0.7)	250 ± 70	2
Jun. 1982	speckle interferometry	4.8 (0.5)	310 ± 50	2
Apr. 1998 – Jun. 2000	Keck I aperture-masking	1.67 (0.33) & 2.27 (0.16)	130	3, 4
May 2001	Lunar occultation	2.2 (0.4)	86 ± 5	5

[a]1. Allen et al. 1981, 2. Dyck et al. 1984, 3. Tuthill et al. 1999, 4. Tuthill et al. 2002, 5. This work.

substantial fraction (~60 per cent) of the luminosity of the star is reradiated in the infrared by the dust shell. They derive from modelling of the ground-based infrared measurements and extinction data, for WR104, an inner edge radius of the dust shell of 48 au, adopting a distance of 1.58 kpc and a shell temperature of 1110 K. In deriving the inner edge radius, Williams et al. (1987) assume the binary equivalent of a WC9 star, with a radius 1.5 times that of a single WC9 star, or 22 $R_\odot$. They also estimate the extent of the dust shell in their best-fitting model to be 4800 au.

WR104 is suggested to be a binary by Cohen & Kuhi (1977), as the optical emission lines from WR104 are weaker than those from other WC9 stars due to dilution by a companion. A RCB-type visual fading by ~1.1 mag with the disappearance of high-ionization spectral features has been recently reported by Crowther (1997). The fading has been attributed to dust cloud condensation with measured dimensions $\geq 20\,R_*$ taking place beyond 300 $R_\odot$ or 100 R_*, with the permanent dust shell at a radius of 3000–300 000 R_*. This behaviour is interpreted in terms of an obscuration of the inner Wolf–Rayet wind by dust cloud condensations. It is also noted that Crowther derives a stellar radius $R_* = 3\,R_\odot$, which is 5 times smaller than the model-dependent value for a single WC9 star used by Williams et al. (1987).

High angular resolution observations for WR104 are summarized in Table 1. One-dimensional speckle interferometry (Allen, Barton & Wallace 1981) with the 3.9-m Anglo-Australian Telescope at 2.2 μm yielded a uniform disc (UD) diameter of 130 ± 15 milliarcsecond (mas). Multiband one-dimensional speckle observations (Dyck, Simon & Wolstencroft 1984) using the 2.2-m telescope of the Mauna Kea Observatory yielded UD diameters of 130, 250 ± 70 and 310 ± 50 mas at 2.2, 3.8 and 4.8 μm respectively. The UD values at 3.8 and 4.8 μm are larger than at 2.2 μm by a factor ~2. It may be noted that no asymmetric structures in the dust shell were resolvable by the early efforts.

Recently, by aperture-masking interferometry at the Keck I 10-m telescope, it has been possible to resolve structures in the dust shell around WR104 (Tuthill, Monnier & Danchi 1999). The dust emission was observed to be distributed in a rotating 'pinwheel' structure, which can be explained by wind interactions between the WR and OB-type companion in a short-period binary system. Subsequently, another stellar 'pinwheel' system was also observed in the Wolf–Rayet star WR98a by the aperture-masking method at the Keck I telescope (Monnier, Tuthill & Danchi 1999). The aperture-masking technique can retrieve spatial information up to the diffraction limit of the Keck I telescope, which at 2.2 μm is 50 mas. The two images of Tuthill et al. (1999) separated by about 3 months taken at 1.65 and 2.27 μm clearly show that the pinwheel structure is rotating with a period of 220 ± 30 d. The size of the pinwheel dust envelope is 130 mas. More recently, using four *K*-band images of WR104 spread over a period of more than 2 years (Tuthill, Monnier & Danchi 2002), the parameters of the system have been refined. The period is better determined as 243.5 ± 3.0 d, the viewing angle as 11° ± 7°, and the angular velocity of dust outflow as 111 ± 9 mas yr^{-1}. Using the angular velocity and the estimated terminal velocity of 1220 ± 300 km s^{-1} (Howrath & Schmutz 1992) from spectral linewidths, the distance to WR104 can be placed at 2.3 ± 0.7 kpc. This value is higher than earlier estimates of 1.58 ± 0.4 kpc (Lundstrom & Stenholm 1984) or 1.91 kpc (Cohen et al. 1975).

In this paper we present high angular resolution observations obtained in the *K* band centred at 2.2 μm by the method of lunar occultations. The occultation observation provided an opportunity of comparing the one-dimensional high angular resolution results obtained by relatively simple means with those obtained by a sophisticated aperture-masking technique at a large telescope. Lunar occultation (LO) observations provide a high spatial resolution (typically ~2 mas) one-dimensional scan of the source in the direction of occultation. An earlier LO observation of the Wolf–Rayet star WR 112 has been reported by Ragland & Richichi (1999). Recently, a lunar occultation of the thick dusty shell surrounding the carbon-rich Mira IRC+10216 (CW Leo) has been observed at 2.2 μm by Chandrasekhar & Mondal 2001. Analysis of the occultation light curve has shown asymmetric and extremely clumpy dust structure in the dust shell. In the present paper a similar method of analysis is followed for deriving the brightness profile (BP) of the dusty nebula surrounding WR104 observed at 2.2 μm.

3 OBSERVATIONS

A unique opportunity to observe the lunar occultation of the Wolf–Rayet star WR104 occurred in 2001 May at the 1.2-m Infrared Telescope of Gurushikhar Observatory, Mt. Abu, India (latitude: 24° 39′ 8.8″ N, longitude: 72° 46′ 47.47″ E, altitude: 1680 m). The circumstances of the occultation event are listed in the Table 2. The event was a reappearance under excellent sky conditions. Fig. 1 shows the schematic geometry of the reappearance event. It was recorded using a single-element InSb detector cooled by liquid nitrogen and in the standard broad *K* band ($\lambda = 2.2$ μm, $\Delta\lambda = 0.4$ μm) filter. Details of the instrument regularly used for lunar occultation observational work can be found elsewhere (Ashok et al. 1994; Mondal et al. 1999). The light curve was sampled at 1 millisecond, and no chopping was used. The detector's pre-amplifier output was digitized using 16-bit analog-to-digital converter and recorded in a PC. The telescope was made to track a nearby (within 3°) unocculted star until ~5 min before the event time, and then it was precisely switched to the position of the

© Royal Astronomical Society • Provided by the NASA Astrophysics Data System

2002MNRAS.334..143M

Table 2. Circumstances of the occultation event.

Date	10 May 2001
Event type	Reappearance
Event time (UT)	$23^h\ 2^m\ 17^s$
Position angle (NESW)	252°
Contact angle	159°
Altitude	39°
Predicted velocity component of Moon in direction of occultation ($km\,s^{-1}$)	−0.5534
Predicted angular velocity component in direction of occultation ($arcsec\,sec^{-1}$)	−0.2922
Lunar phase (days after new Moon)	17.25
Data sampling rate	1 ms
Photometer diaphragm on the sky (arcsec)	26
Wavelength of observation (λ)	2.2 μm
Bandwidth $\Delta\lambda$ (FWHM)	0.4 μm
K magnitude (Williams et al. 1987)	2.37

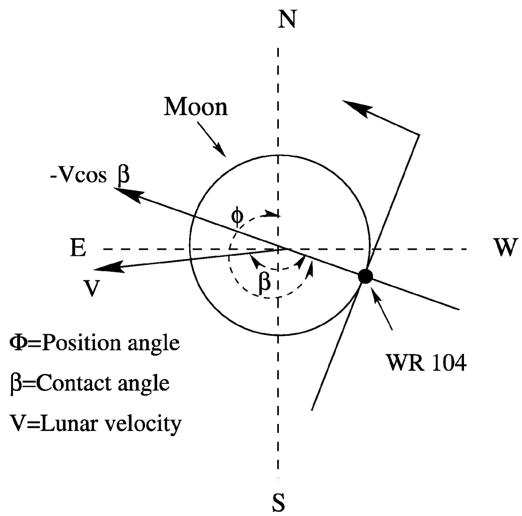

Figure 1. The schematic geometry of the lunar occultation event of WR104 observed on 2001 May 10 from the Gurushikar Observatory.

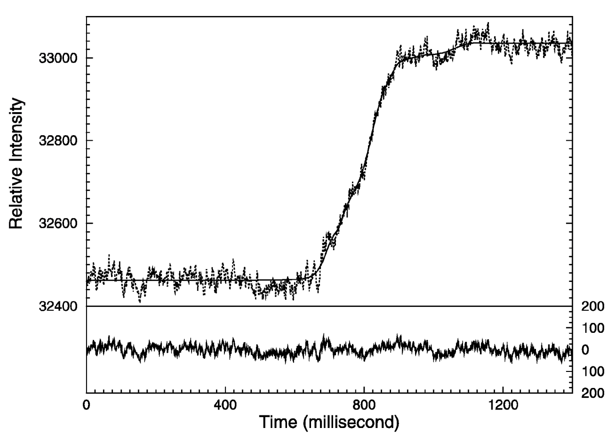

Figure 2. Upper Panel: *Dotted line*: The observed lunar occultation light curve of WR104 in the K band. *Solid line*: The best fit obtained by the MIA analysis. **Lower Panel:** The residual (data−model) of the best fit shown expanded.

occulted star. The event occurred 10 s after the predicted time. The occultation light curve is shown in Fig. 2.

4 ANALYSIS

The conventional method of analysis of the LO light curve involves a χ^2-minimization technique to obtain the best estimates of the five free parameters: (i) the geometric time of occultation; (ii) the stellar signal in counts; (iii) the sky-background in counts; (iv) the velocity component of the Moon in the direction of occultation, and (v) the UD angular diameter. The analysis procedures are based on the standard non-linear least-squares (NLS) method introduced by Nather & McCants (1970). The point-source Fresnel diffraction pattern modulated by the finite spectral bandwidth of the system, the finite telescope aperture, the instrument time response and the extended angular size of the source are taken into consideration for fitting of the above-mentioned parameters. The resolution limit of the LO technique determined by studying occultations of a number of bright, point sources is ~2 mas (Chandrasekhar 1999). In the case of WR104, the source is embedded in a thick dust shell which is so extended that the usual diffraction effects are negligible. The conventional NLS analysis for this occultation light curve yields a UD size of 86 ± 5 mas. However, there are clear departures of the light curve from a uniform disc which merit further investigation. For this purpose we have employed the model-independent algorithm (MIA) introduced by Richichi (1989) and used earlier by us (Chandrasekhar & Mondal 2001). MIA is a composite algorithm which makes use of the NLS method and the Lucy deconvolution algorithm (Lucy 1974), wherein usually the UD profile is assumed as a initial guess profile and is modified iteratively to obtain the best fit of the observed data points. The averaging effects arising from the finite optical filter bandwidth and the telescope aperture have also been accurately taken into account.

For a proper comparison of Keck images with our LO data we have reduced the 2.27-μm Keck images to one dimension along the direction of our occultation. To achieve this reduction, we need to know the orientation of the dust envelope at the epoch of our observation. The rotation period of the dust envelope as deduced by Tuthill et al. (1999) from their two images is 220 ± 30 d. We have generated one-dimensional scans of the recent Keck images observed on 2000 June 25 along the direction of our occultation for various rotation periods ranging from 200 to 250 d covering the error zone of Tuthill et al.'s estimation of the period of WR104. These are shown in Fig. 4. To achieve this reduction, each of the Keck images is rotated appropriately to match the epoch of our observation, and then integrated perpendicular to the direction of occultation to produce a one-dimensional profile. It can be noted from Fig. 4 that the resulting one-dimensional scans are quite sensitive to the rotation rate. In comparison with the results of our MIA program, we find that rotation periods between 240 and 250 d provide the best-fitting one-dimensional reduction of Keck images. This results is in good agreement with the recent refined measurement of the rotation rate of 243.5 ± 3 d reported by Tuthill et al. (2002).

The one-dimensional BP derived from the MIA program as well as the corresponding best fit to the occultation light curve are shown in Figs 2 and 3 respectively. Several uniform disc starting profiles from 100 to 200 mas were tried out during the MIA analysis. The best convergence was reached for a starting UD of 170 mas which resulted in the final profile (Fig. 3).

The reduced one-dimensional six-epoch Keck profiles along the

© Royal Astronomical Society • Provided by the NASA Astrophysics Data System

2002MNRAS.334..143M

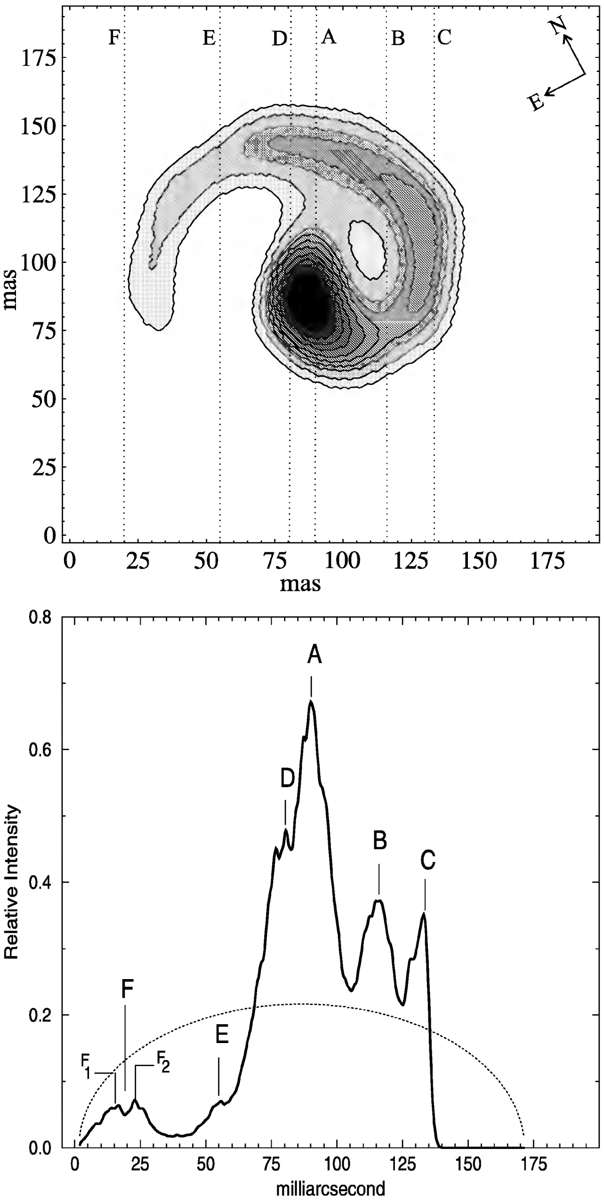

Figure 3. Lower Panel: The *solid line* is the brightness profile of WR104 recovered from the model-independent algorithm (MIA) program, and the *dotted line* is the uniform disc (UD) profile with a diameter of 170 mas given as a input to MIA. **Upper Panel :** Keck I image of WR104 taken in 1998 April. The direction of occultation is along the *x*-axis.

direction of our occultation, along with our derived BP from LO analysis, is shown in Fig. 5. Overall, a remarkable similarity between the two profiles is apparent. Many structures are not seen in the Keck profiles, as their spatial resolution is 50 mas. The LO profile exhibits a lot of fine structure consistent with its higher angular resolution along the direction of occultation. In order to compare the LO profile with 1D Keck profiles at the same resolution, we have systematically degraded our brightness profile by taking running averages of 70, 80, 90 and 100 points (corresponding resolutions are 70, 80, 90 and 100 mas). We find that with a running average of 90 points, our smoothed profile corresponds reasonably well with the 1D Keck profiles. There are, however, some differences which could be real, resulting from temporal changes taking place in the dust shell in one or two rotations.

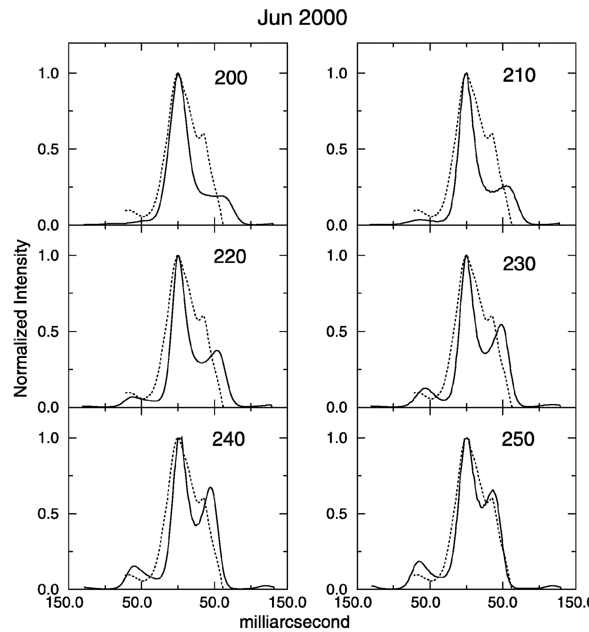

Figure 4. Comparison of Keck I image of WR104 taken on 2000 June 25 reduced to one dimension along the direction of occultation (*solid line*) with the 90-point running average of the brightness profile obtained from lunar occultation (*dotted line*). Different periods of rotation from 200 to 250 d are considered. It can seen that the best-fitting rotation period lies between 240 and 250 d.

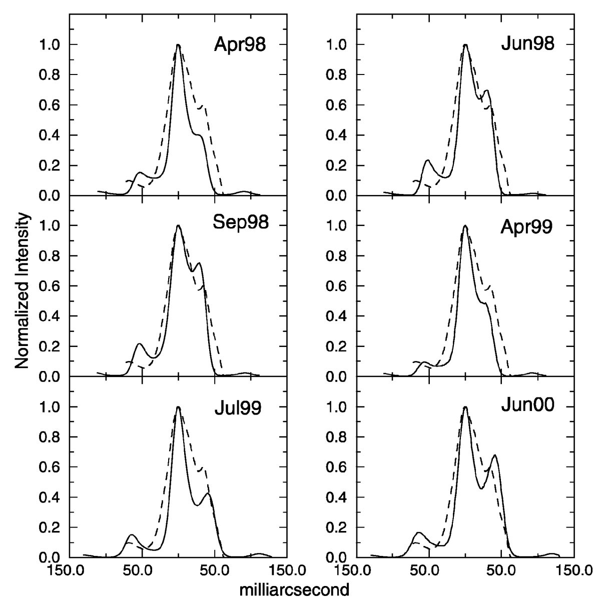

Figure 5. One-dimensional brightness profile (BP) along the direction of occultation obtained for each of the six-epoch Keck I images of WR104 (*solid line*). A rotation period of 243.5 d has been assumed. Superposed on each figure is the smoothed (90-point running average) brightness profile of WR104 obtained from the lunar occultation (*dashed line*).

5 RESULTS AND DISCUSSION

Fig. 5 shows the one-dimensional six-epoch Keck profiles plotted along the direction of occultation. It can be seen that both the Keck profiles have similar features – two large peaks and a distinctly smaller one. Further fine structures are not seen in the reduced

© Royal Astronomical Society • Provided by the NASA Astrophysics Data System

2002MNRAS.334..143M

Table 3. Relative positions of features observed by LO and Keck I profiles.

Features	Unit	A	B	C	D	E	F
BP from LO	mas	0.0	26.3	43.07	−9.5	−34.6	−70.0
May 2001	AU	0.0	60.0	99.0	−22.0	−79.0	−160.0
Nor. Intensity		1.0	0.554	0.523	0.712	0.104	0.107
90 mas avg. LO	mas	0.0	34.0				−68.0
May 2001	AU	0.0	78.0				−156.0
Nor. Intensity		1.0	0.603				0.098
Keck I 1D	mas	0.0	27.0				−53.0
Apr 1998	AU	0.0	62.0				−122.0
Nor. Intensity		1.0	0.401				0.15
Keck I 1D	mas	0.0	30.0				−52.0
Jun 1998	AU	0.0	68.0				−119.0
Nor. Intensity		1.0	0.675				0.233
Keck I 1D	mas	0.0	29.0				−54.0
Sep 1998	AU	0.0	66.0				−124.0
Nor. Intensity		1.0	0.753				0.218
Keck I 1D	mas	0.0	28.0				−56.0
Apr 1999	AU	0.0	64.0				−129.0
Nor. Intensity		1.0	0.486				0.095
Keck I 1D	mas	0.0	40.0				−64.0
Jul 1999	AU	0.0	92.0				−147.0
Nor. Intensity		1.0	0.425				0.153
Keck I 1D	mas	0.0	41.0				−63.0
Jun 2000	AU	0.0	94.0				−145.0
Nor. Intensity		1.0	0.679				0.166

Keck profiles as the angular resolution achievable is the diffraction limit of the Keck telescope (~50 mas). In comparison, the BP generated by the MIA program which provides the best fit to the occultation data has a similarity with the 1D Keck profiles but exhibits a lot of fine structure. There is a smaller peak (F) at −70 mas, followed by three large peaks A, B and C. There are also a lot more fine structures in the profile which can be identified as E, D, F_1 and F_2 (in Fig. 3). The position of the dominant peak (A) coincides with the centre of the dust nebula. Relative to A, the positions of other peaks B, C, and F and also the fine structures D and E are given in Table 3. The 90 mas averaged LO profile does not show the features C, D and E, and is similar to the 1D Keck profiles. The corresponding Keck positions are also given in the Table 3. Considering the distance to WR104 of 2.3 ± 0.7 kpc adopted by Tuthill et al. (1999), our 1D resolution of 2 mas corresponds to ~4.6 au. The separation between the features in linear units (au) is also given in Table 3.

If we identify the rotation period of the pinwheel with the orbital period of the binary system, then assuming a combined mass in the range 20–50 $M_\odot$ (Moffat, Niemela & Marraco 1990) results in a binary separation of ~2 au, which at this distance is only ~1 mas. This is at the limit of our achievable angular resolution, but as emission of the circumstellar dust predominates over the stellar component at near-infrared wavelengths, the binary signature does not show in the BP. The fine structure that we see in this profile is all attributable to the circumstellar dust shell surrounding WR104.

In Fig. 3 we have marked also the positions corresponding to our structures A, B, C, D, E and F by appropriate lines in the Keck images of 1998 April, appropriately rotated to epoch of our observations. Unfortunately, due to the one-dimensional nature of the resolution derived by lunar occultation and also the lower resolution of the Keck images (~50 mas at 2.2 μm), it is not possible to pinpoint a specific location in the nebula corresponding to a feature.

The time-scale of the dust formation and its features is another aspect to be considered. The pinwheel structure clearly indicates that dust ejected one rotation earlier does not contribute to the observed geometry. The old dust is eclipsed in the orbital plane by the newly formed dust and cools rapidly. It may, however, be seen at far-infrared wavelengths. For an outflow velocity of 1220 km s^{-1} the distance covered by dust in one rotation is ~170 au. So, in comparing our observations with Keck observations taken one to three years earlier, we may be actually comparing different generations of dust. This time evolution of the dust could explain the additional peak C and features D and E not seen in the reduced Keck profiles. The difference between the Keck profiles and our smoothed profiles could also be due to minor differences in the pinwheel structure from one rotation to the next. However, the overall picture is not greatly altered, suggesting that time evolution of the dust shell with different orbits is not a strong effect. Continued high angular resolution observations of WR104 would be invaluable in studying finer details of dust production and dissipation in an WR system.

In conclusion, our lunar occultation observations of WR104 trace out remarkably well, in one dimension, the pinwheel dust structure surrounding the star seen earlier by the aperture-masking techniques at the Keck telescope. Additional fine structures not seen in Keck data are also noted in the one-dimensional high angular resolution LO profiles, and these could be due to real but small temporal changes in the dust structure. However, over the time period of a few years, large-scale changes in the dust shell are not observed.

ACKNOWLEDGMENTS

We thank Dr Sam Ragland for providing the MIA program. We are particularly grateful to the referee, Dr P. G. Tuthill, for kind

© Royal Astronomical Society • Provided by the NASA Astrophysics Data System

2002MNRAS.334..143M

permission to download his Keck images of WR104 and compare them with our data, and also for his valuable comments and suggestions which have greatly improved the paper. This work is supported by the Dept. of Space, Govt. of India.

REFERENCES

Allen D. A., Harvey P. M., Swings J. P., 1972, A&A, 20, 333
Allen D. A., Barton J. R., Wallace P. T., 1981, MNRAS, 196, 797
Ashok N. M., Chandrasekhar T., Sam Ragland, Bhatt H. C., 1994, Exp. Astron., 4, 177
Chandrasekhar T., 1999, Bull. Astron. Soc. India, 27, 43
Chandrasekhar T., Mondal S., 2001, MNRAS, 322, 356
Cohen M., Kuhi L. V., 1977, MNRAS, 180, 37
Cohen M., Barlow M. J., Kuhi L. K., 1975, A&A, 40, 291
Crowther P. A., 1997, MNRAS, 290, L59
Dyck H. M., Simon T., Wolstencroft R. D., 1984, ApJ, 277, 675
Gehrz R. D., Hackwell J. A., 1974, ApJ, 194, 619
Hackwell J. A., Gehrz R. D., Smith J. R., 1974, ApJ, 192, 383
Howrath I. D., Schmutz W., 1992, A&A, 261, 503
Lucy L. B., 1974, AJ, 79, 745
Lundstrom I., Stenholm B., 1984, A&AS, 58, 163
Moffat A. F. J., Niemela V. S., Marraco H. G., 1990, ApJ, 348, 232
Mondal S., Chandrasekhar T., Ashok N. M., Kikani P. K., 1999, Bull. Astron. Soc. India, 27, 335
Monnier J. D., Tuthill P. G., Danchi W. C., 1999, ApJ, 525, L97
Nather R. F., McCants N. M., 1970, AJ, 75, 963
Ragland S., Richichi A., 1999, MNRAS, 302, L13
Richichi A., 1989, A&A, 226, 366
Smith L. F., 1968, MNRAS, 140, 409
Torres A. V., Massey P., 1987, ApJS, 65, 459
Tuthill P. G., Monnier J. D., Danchi W. C., 1999, Nat, 398, 487
Tuthill P. G., Monnier J. D., Danchi W. C., 2002, in Moffat A. F. J., St-Louis N., eds, ASP Conf. Ser. Vol. 260, Interacting Winds from Massive Stars. Astron. Soc. Pac., San Francisco, p. 321
Usov V. V., 1991, MNRAS, 252, 49
van der Hucht K. A., 1992, A&AR, 4, 123
van der Hucht K. A. et al., 1996, A&A, 315, L193
Veen P. M., Van Genderen A. M., van der Hucht K. A., Li A., Sterken C., Dominik C., 1998, A&A, 329, 199
Williams P. M., van der Hucht K. A., 1992, in Drissen L., Leitherer C., Nota A., eds, ASP Conf. Ser. Vol. 22, Non-isotropic and Variable Outflows from Stars. Astron. Soc. Pac., San Francisco, p. 269
Williams P. M., van der Hucht K. A., Thé P. S., 1987, A&A, 182, 91
Williams P. M., van der Hucht K. A., Pollock A. M. T., Florkowski D. R., van der Woerd H., Wamsteker W. M., 1990, MNRAS, 243, 662
Zubko V. G., 1998, MNRAS, 295, 109

This paper has been typeset from a TEX/LATEX file prepared by the author.

© Royal Astronomical Society • Provided by the NASA Astrophysics Data System