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PROPER MOTIONS OF DUST SHELLS SURROUNDING NML CYGNI

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ABSTRACT

The distribution of dust emitted by the supergiant star NML Cygni has been resolved by interferometry at 11 μm wavelengths at various times over a period of 6 yr. Results show there are two discrete dust shells, which have both moved away from the star approximately the same amount during the 6 yr period. This allows determination of the time between ejection of material forming the two shells to be 65 ± 14 yr. Assuming the radial outflow velocity can be derived from Doppler-measured velocities of masers surrounding the star, its distance can be calculated from the observed angular motion to be 1220 ± 300 pc. This decreases the luminosity of the star by about 1 mag over that deduced from the distance 1900 pc previously assumed.

Subject headings: circumstellar matter — infrared: stars — stars: individual (NML Cygni) — techniques: interferometric

1. INTRODUCTION

NML Cyg is believed to be a supergiant surrounded by an optically thick envelope of dust and molecules. The composition and velocity of this envelope have been much studied at infrared and radio frequencies, with Doppler velocities and apparent motions of water masers observed over approximately a decade (cf. Richards, Yates, & Cohen 1996). Blöcker et al. (2001) have recently provided an extensive analysis of dust around NML Cyg, including new interferometric measurements at near infrared wave lengths. Initial models of dust outflow were based on a single spherical shell with density decreasing as r^{-2}, where r is the distance from the star (Rowan-Robinson & Harris 1983). Subsequent visibility measurements with the Berkeley Infrared Spatial Interferometer (ISI) on Mount Wilson indicated two discrete shells, representing episodic emission by the star with a time separation between shell creation of about 80 yr (Monnier et al. 1997). We report a new series of ISI measurements, a 11 μm wavelength with improved precision, which show outward motions of the two shells indicated previously. The observed movement of the shells is reasonably consistent with previous information, but yields an improved and somewhat different measurement of the distance to NML Cyg and of the time between emission of the two shells.

2. EXPERIMENTAL OBSERVATIONS

The ISI uses two movable 65 inch telescopes and heterodyne detection to provide a spatial interferometer for mid-IR radiation. The equipment and its operation are described in detail by Hale et al. (2000). Telescope separations ranging from 4 to 32 m have been used to measure visibilities of NML Cyg over the 6 yr period from 1993 to 1999. The measurements made are listed in Table 1.

NML Cyg varies somewhat irregularly with a period of approximately 940 days as determined from variations in mid-IR intensity over the time period 1981–1996 (Monnier et al. 1997). The phases listed in Table 1 are derived from these measurements, with $\phi = 0$ corresponding to peak IR intensity of the circumstellar dust, which may not coincide precisely with the peak in stellar luminosity. Furthermore, the phase in recent years was obtained by extrapolating earlier measurements which ended in 1994 (Monnier et al. 1997) and may be inaccurate. The intensity variation with phase is not large, being about 0.4 mag in the mid-IR, but nevertheless it is large enough to have some effect on the visibility. At the higher stellar luminosities the fraction of IR radiation from more distant dust compared with that from very near the star increases, which results in a lower visibility whenever the dust is partially resolved. Such changes are not large for this star, but are indicated in the curves of visibilities and the experimental points shown in Figure 1. These changes are not critical to determination of the motion of the two shells but do affect their relative intensities substantially.

Visibility values of Table 1 for the years 1993, 1994, and 1996 were previously published (Monnier et al. 1997), but with a somewhat different calibration from that used here. The earlier calibration assumed that the fraction of total stellar intensity which occurred within approximately 2″ beamwidth of the ISI telescopes was the same for NML Cyg as it was for α Orionis. Careful measurement of this fraction for α Orionis shows that it is 0.879. The actual fraction of total intensity of NML Cyg falling within this angular field of view is not known. But for the present calibration, it is assumed to be unity rather than 0.879, which makes the present visibilities 1/0.879 times larger than those previously published (Monnier et al. 1997). This change in calibration has no affect on the shape of the visibility curve from ISI data and, hence, has no significant effect on the distribution of relative intensities as a function of distance which is derived from this shape. It affects only the relative values of data at a very low resolution obtained by Dyck &

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TABLE 1

SUMMARY OF NML CYG VISIBILITY MEASUREMENTS BY THE ISI

Date	Phase of Luminosity Cycle with Phase = 0 at Mid-IR Maximum	Spatial Frequency (10^5 rad^{-1})	Amplitude of Visibility	Position Angle (degrees east of north)
1993 Sep 30	0.70	6.19	0.25 ± 0.02	93
1993 Sep 30	0.70	6.73	0.22 ± 0.02	97
1993 Jul 27	0.64	8.50	0.067 ± 0.03	140
1994 Jul 8, 9, 14	0.00	27.5	< 0.08	130
1994 Sep 22	0.08	2.73	0.60 ± 0.02	50
1994 Sep 15	0.08	2.99	0.51 ± 0.07	58
1996 Oct 10	0.88	2.81	0.49 ± 0.03	50
1996 Sep 23 and Oct 10	0.88	2.95	0.53 ± 0.03	56
1996 Sep 23 and Oct 10	0.88	3.05	0.50 ± 0.02	60
1996 Sep 23 and Oct 7, 10	0.88	3.13	0.49 ± 0.3	63
1996 Oct 7, 10	0.88	3.21	0.48 ± 0.02	66
1996 Oct 7, 10	0.88	3.31	0.46 ± 0.01	70
1997 Aug 14	0.20	2.77	0.65 ± 0.03	47
1997 Aug 2	0.20	2.94	0.53 ± 0.02	55
1997 Aug 2	0.20	3.08	0.51 ± 0.01	60
1997 Oct 19	0.28	11.20	0.005 ± 0.03	108
1997 Oct 19	0.28	12.77	0.00 ± 0.03	114
1998 Aug 7, 19	0.59	5.875	0.240 ± 0.006	92
1998 Aug 7, 18, 19	0.59	6.202	0.198 ± 0.008	95
1998 Jul 30 and Aug 7, 18, 19	0.59	6.529	0.167 ± 0.010	97
1998 Jul 30 and Aug 7, 18, 19	0.59	6.776	0.155 ± 0.011	98
1998 Jul 30 and Aug 7, 18, 19	0.59	6.990	0.145 ± 0.004	100
1998 Jul 30 and Aug 7, 18, 19	0.59	7.232	0.114 ± 0.004	102
1998 Jul 30 and Aug 7, 18, 19	0.59	7.486	0.089 ± 0.009	105
1998 Aug 12, 19	0.59	7.670	0.051 ± 0.016	107
1998 Jul 29 and Aug 19	0.59	8.526	0.026 ± 0.013	122
1998 Oct 18	0.67	3.086	0.548 ± 0.016	60
1998 Oct 23	0.67	3.177	0.542 ± 0.014	63
1998 Oct 23	0.67	3.322	0.540 ± 0.016	70
1999 Jun 10, 12, 19	0.92	3.258	0.468 ± 0.022	69
1999 Jun 19, 25, 26	0.92	3.491	0.465 ± 0.014	79

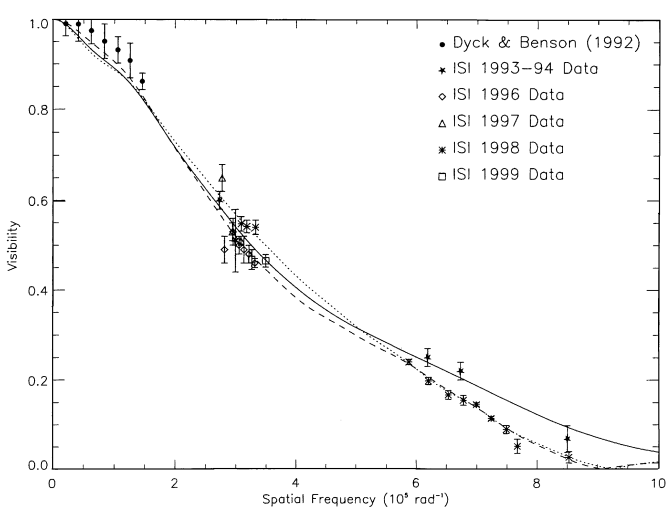

FIG. 1.—Visibility of NML Cyg at 11.15 μm wavelength as a function of spatial frequency, showing variations between 1993 and 1999. The solid curve fits data of 1993 and 1994 when luminosity was near maximum. The dotted curve fits data of 1998 when it was near minimum. The dashed curve fits data of 1996, 1997, and 1999 near maximum luminosity in the spatial frequency range (2–4) × 10^5 rad^{-1}. For higher spatial frequencies, the dashed curve for the years 1996, 1997, and 1999 is fitted to data of 1998, which are at a different luminosity phase but provide a reasonable approximation for the curve in this range of spatial frequencies.

Benson (1992) compared with the higher resolution ISI data.

The orientation of interferometric resolution across the star and dust shells is given in the column labeled "Position Angle" in Table 1. The position angle is not very different for most of the measurements, so any asymmetry in intensity distribution probably does not have a large effect on the measured visibility curve, although it may affect some details. Most important, however, is the fact that position angles in 1993 and 1998 are identical for spatial frequencies in the range (6–10) × 10^5 rad^{-1}, so that the position change of the inner shell, which is largely determined by measurements in this range, is rather well evaluated regardless of any asymmetry which might affect details in the shape of this part of the visibility curve. The phases were also quite similar during these particular measurements. The third telescope recently constructed for the ISI, and phase closure which can be obtained with three telescopes, will be important in determining any asymmetries present and allow more detailed mapping of the mid-IR intensity distribution.

Measured visibilities are plotted in Figure 1, with theoretical curves fitted to them based on models of intensity distribution which are shown in Figure 2. The intensity distribution model for data of 1993–1994 (*solid curve*) is very similar to that of Monnier et al. (1997), who showed

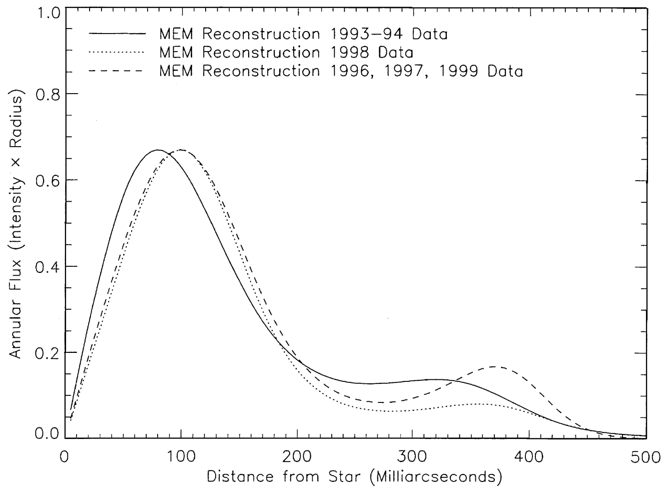

FIG. 2.—Three radial intensity distributions which produce the visibility curves of Fig. 1, fitting data of various epochs. Intensities plotted are proportional to radiation from an entire circle around the star at a fixed radius, as indicated by the ordinate of this figure. The solid curve fits data of 1993–1994 when the luminosity was near maximum; the dotted curve data of 1996, 1997, and 1999 when the star was near minimum; and the dashed curve data of 1998 when it was near maximum luminosity. As noted in Fig. 1, however, the curve for 1996, 1997, and 1999 uses high-resolution data of 1998, which determine characteristics of the inner peak of intensity. Both peak intensities, representing two dust shells, have moved outward during the approximately 5 yr between data obtained for the solid and the dashed curves.

there are two major shells of dust with optical depths approximately 1.9 for the inner one and 0.33 for the outer. Figure 1 shows there was clearly a change in visibility in the range of (6–10) $\times$ 10^5 rad^{-1} between the 1993 and 1998 measurements, which implies motion of material around the star. There is also a small change in visibility near 3×10^5 rad^{-1}, which is attributable to differences in phase of the star. Such changes due to phase occur because, as the star changes luminosity or temperature and hence changes the temperature of surrounding dust, the mid-IR intensity changes approximately linearly with temperature, whereas the IR intensity from the cooler dust changes experientially (cf. Danchi et al. 1990). Phases for the measurements are listed in Table 1. As a rough approximation, measurements in 1994, 1996, 1997, and 1999, involve phases near 1 or 0 (but actually range from 0.88 to 0.20) and hence may be considered to be near peak luminosity. Those of 1993 and 1998, ranging from 0.59 to 0.70, are nearer minimum luminosity (phase = 0.5). The difference in visibilities in the range (6–10) $\times$ 10^5 rad^{-1} cannot therefore be attributed to a change in luminosity as can the small variations near 3×10^5 rad^{-1}. The changes are in any case much larger than would be produced by luminosity variations even if the two sets of data came from completely different phases. The dashed curves in Figures 1 and 2 correspond to data of 1996, 1997, and 1999 near maximum luminosity, and the dotted curves correspond to data of 1998, near minimum luminosity. The solid curves correspond to data of 1993 and1994. Visibility values in Figure 1 for the low-resolution range (0–2) $\times$ 10^5 rad^{-1} were measured on a single telescope by Dyck & Benson (1992) in 1988–1989 at a position angle of 0°. The stellar phase for these low-resolution measurements was not published.

Sudol et al. (1999) have made recent visibility measurements in the low spatial frequency range (0–1.6) $\times$ 10^5 rad^{-1} with a single telescope at a position angle of 90°. These differ as much as 50% from the earlier data at 0°. If correct, this indicates a very large deviation from spherical symmetry, and the visibility is so low at a spatial frequency of 1.6×10^5 rad^{-1} that it appears inconsistent with our own measurements at spatial frequencies (2.7–3.0) $\times$ 10^5 rad^{-1}. Because of this apparent inconsistency, we have not accepted the measurements at Sudol et al. (1999), but we have plotted the earlier data of Dyck & Benson (1992) as a better approximation for extrapolating the visibility curve to low resolutions. Even if incorrect, this low-resolution part of the curve has little effect on intensity distributions very near the star, in particular on the clear evidence for motion of the inner shell, which will be discussed below. The report of Sudol et al. (1999) does emphasize, however, the importance of having coeval and consistently calibrated visibilities at more than one position angle, and it is our expectation that such measurements will be made using the third telescope recently constructed for our interferometer system. It also makes clear the importance of using essentially the same baseline orientation, as is the case for the measurements reported here in the (6–10) $\times$ 10^5 rad^{-1} range, if motion or changes in the intensity distribution are to be detected.

The measured visibility values were fitted by models of radial intensity assuming spherical symmetry and using the maximum entropy method (MEM; cf. Monnier et al. 1997). The resulting radial intensity curves for data taken during the periods 1993–1994 and 1996–1999 are shown in Figure 2. The visibility curves predicted from these distributions and their agreement with measurements are shown in Figure 1. The clearest and most important difference between these two intensity distributions is the change in position of the innermost intensity peak. This change is primarily determined by the change in visibility curves between the years 1993–1994 and 1998 in the spatial frequency range of (6–10) $\times$ 10^5 rad^{-1}, shown in Figure 1. In addition, the outer intensity peak has moved approximately the same amount as has the inner intensity peak and, as expected, is considerably weaker during minimum luminosity than it is during maximum luminosity. The visibility data leaves considerably more uncertainty in the position change of this outer peak than that of the inner, more intense peak.

3. INTERPRETATION OF MEASUREMENTS

Peaks of the two dust shells shown in Figure 2 have changed location by 19 ± 1 mas over approximately 5 yr, indicating their expansion. Since this figure represents fits to visibility measurements which have potential errors, the actual uncertainly in motion is probably as much as several milliarcseconds. Change in position of the inner shell in Figure 2 is more accurately determinable than that for the outer one because it is much more intense and, hence, less affected by the other shell; the apparent position of the latter may be somewhat distorted by uncertainties in slope of the outer part of the inner peak. However, both shells appear to have moved by the same amount.

Expansion velocities of gas clouds surrounding NML Cygnus have been estimated from measurements of associated H_2O and OH masers by a number of observers. Bowers et al. (1983) found an expansion velocity of 27.7 km

s^{-1}, Morris & Jura (1983) a value 29.4 ± 2.5 km s^{-1}, and Wolf & Carlson (1982) a value 27.5 ± 1.3 km s^{-1}. More recently, Richards et al. (1996) give an average expansion velocity of 22.3 km s^{-1} and also were able to measure a proper motion for H_2O masers of 1.9 ± 0.4 mas yr^{-1}, which they note is consistent with a transverse velocity of 19 ± 4 km s^{-1} if the distance is 2 kpc. The distance to NML Cyg has been previously estimated as approximately 2.0 kpc from its apparent association with Cyg OB2 (Herbig & Zappala 1970; Abbott et al. 1981; Knapp et al. 1982; Morris & Jura 1983). Bowers et al. (1981) measured an outflow velocity of 23 km s^{-1} and adopted a distance of 1800 pc.

SiO masers generally occur much closer to a star than do H_2O masers, and recent observations by Boboltz & Marvel (2000) have revealed an approximately elliptical distribution of SiO masers at a radius of approximately 16.5 mas with a distribution of velocities which suggest they may be in orbit around the star. Bobolitz and Marvel obtain a period of 73 sin θ yr for such a possible orbit, where θ is the inclination angle of the orbital axis. This may suggest that changes in the visibility curve reported here are partly due to rotation of a nonsymmetric cloud of dust rather than radial motion outward. For the distance 1220 pc, which appears more correct than the previously assumed value, the rotation period is reduced to 44.5 sin θ yr. The closest dust shell observed by the ISI is approximately 100 mas distant than the star, or 6 times farther away than the SiO masers. If angular momentum is conserved and similar, this would make the period of rotation of this shell 267 sin θ yr, giving a change in angular position during the 5 yr between 1993 and 1998 observations of only 6.7/sin θ deg. It is unlikely that sin θ is very small, so any angular rotation of the dust around the star is probably not more than a few times $6\overset{\circ}{.}7$. Hence, although extreme asymmetry and some rotation may contribute a part of the apparent radial motion of the inner dust shell around NML Cygni, most of the change in apparent radial distance is probably due to actual radial motion.

The present measurement of proper motion is probably more accurate than those of the H_2O masers and is appropriate for an estimate of distance to NML Cyg. A combination of Richard's average measured outflow velocity of 22.3 km s^{-1} (Richards et al. 1996), assuming it represents the transverse velocity of the dust shells observed with the IR interferometer, and the measured proper motion of the inner dust shell of 19 mas in approximately 4 yr and 11 months gives a distance to the star of 1220 pc. This distance is substantially less than previous estimates, and hence possible errors need to be considered. First, the inner dust shell may not expand at the same velocity as the H_2O masers, some of which are substantially farther away from the star. But normal expectations are that material speeds up as it becomes more distant from the star, and if a slower velocity were assumed for the inner dust shell the stellar distance determined would be still smaller than 1220 pc. Proper motion of the outer dust shell measured by the ISI is essentially the same as that of the inner one, although less accurately known. Uncertainty in the proper motion measured by the ISI is probably not greater than about 25%, based on the probable errors in measurement of visibility which are indicated in Figure 1 by vertical bars. This represents an expansion of 3.86 mas yr^{-1} as compared with the H_2O maser apparent motions of 1.9 ± 0.4 mas yr^{-1}. Perhaps the H_2O masers, presumably associated with shock waves, are not always at the same location in the expanding gas, or perhaps expansion velocities have changed with time and proper motion of the H_2O masers, measured at distances of about 250 mas from the star, are slower than the inner dust shell. But the most likely explanation is that the masers may not be in a plane perpendicular to the line of sight so their projected velocities are slower than the actual expansion.

If the maximum expansion velocity around NML Cyg estimated in a previous publication as 29.4 km s^{-1} (Morris & Jura 1983) is used, the resulting distance to NML Cyg obtained from ISI measurements would be 1600 rather than 1220 pc. However, it appears that the value 22.3 km s^{-1} obtained from the results of Richards et al. (1996) is probably correct to within about 10%. The dominant error in this distance hence probably comes from the approximately 25% uncertainty in expansion of the dust shell as measured by the ISI. In view of the above, the distance to NML Cyg is probably substantially less than the previously accepted value of 1900 pc. With estimated errors, the distance appears to be 1220 ± 300 pc. This reduced distance reduces previous estimates of the star's luminosity by approximately 1 mag.

Present measurements provide a determination of the time between the emission of the two shells which is not dependent on previously estimated expansion velocities or on the stellar distance. Since the measured proper motion of the shells is 3.86 mas yr^{-1} and their separation is 250 mas, the time between their emission is 65 ± 14 yr, somewhat shorter than the 80 yr estimated by Monnier et al. (1997) from information previously available.

4. SUMMARY

Proper motion of the double shell structure of dust clouds around NML Cyg has been observed over a period of 5 yr by interferometry in the mid-infrared using two movable telescopes. More telescopes would be very desirable to obtain a richer variety of baselines and to determine any asymmetry in distribution of material emitted by the star, and a third telescope will soon be added to the system. However, the present results clearly indicate two shells of dust around the star with the inner one having moved a distance 19 ± 4.5 mas during the 5 yr. The angular distance between the two shells and their observed motion show that the time between formation of the two shells, and of peak material emissions from NML Cygni which produced them, was approximately 65 yr. The measured proper motion, combined with previous observations of Doppler velocities for H_2O masers surrounding the star, also allows determination of the distance to the star as 1220 ± 300 pc, which decreases the stellar luminosity about 1 mag compared with that deduced from the distance 1900 pc previously assumed.

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