Discovery of Extremely Large-Amplitude Quasi-Periodic Photometric Variability in WC9-Type Wolf-Rayet Binary, WR 104

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Abstract

We discovered that the Wolf-Rayet (WR)+OB star binary, WR 104, renowned for its associated "dusty pinwheel nebula" recently spatially resolved with infrared interferometry, exhibits strong quasi-periodic optical variations with a full amplitude of 2.7 mag. Such a large-amplitude, continuous variation has been unprecedented in a WR star. The optical quasi-period (∼241 d) is in almost perfect agreement with the interferometric period (243.5±3 d). The remarkable agreement of the dominant period in optical variability with the orbital period supports that the strongly varying dust obscuration is physically related to the binary motion, rather than sporadic dust-forming episodes. Considering the low orbital inclination (11±7°) and the nearly circular orbit inferred from the interferometric observations, the strongly variable line-of-sight extinction suggests that the highly structured extinction can be being formed via an ejection of dust in the direction of the binary rotation axis. Another viable explanation is that the three-dimensional structure of the shock front, itself is the obscuring body. Depending on the geometry, the dusty shock front near the conjunction phase of the binary can completely obscure the inner WR-star wind and the OB star, which can explain the amplitude of optical fading and the past observation of remarkable spectral variation.

KeyWords: stars: Wolf-Rayet — stars: variables — stars: winds, outflows — stars: individual (WR 104)

1 Introduction

Wolf-Rayet (WR) stars are massive, luminous, hot stars which have blown away the hydrogen envelope, and are considered to be immediate precursors of some kinds of supernovae. Carbon-rich, late-type subclass of WR stars (WCL) are known as one of the most efficiently dust-productive stellar environments (for recent reviews, see Williams 1995,1997ab). The dust production in these stars not only highlights the problems of the dust formation mechanism in a very hot environment (Williams, 1997a), but also plays an important role in the chemical enrichment in galaxies (Esteban, Peimbert (1995); Schaerer, Vacca (1998)). In addition to the strong infrared emission in WCL stars, which is considered to arise from persistent dust shells, there has been emerging evidence of episodic dust formation in these stars. Veen et al. (1998) reported transient optical fadings in several WCL stars, attributable to temporary condensations of dust clouds.

Crowther (1997) reported remarkable weakening of the WR-type spectral feature, together with a possible 1.1 magnitude photometric fading, in a WR+OB binary WR 104, which was interpreted as a temporary obscuration of the inner Wolf-Rayet wind by a dust cloud. On the other hand, recent interferometric imaging of WR 104 by Tuthill et al. (1999) revealed the amazing "dusty pinwheel nebula". This extended structure which rotates with a period of 220±30 d [Tuthill et al. (2002) further reported a refined the period to be 243.5±3 d] is believed to be formed by the colliding winds of the WR star and companion OB-star. The relation between occasionally reported obscuration episodes and the persistent dusty pinwheel structure, however, remained a mystery Tuthill et al. (1999,2002)[1].

In 2001 April, one of the authors (KH) serendipitously discovered a new variable star named HadV82 (Haseda, 2001), which was subsequently identified with WR 104. This led to a discovery of dramatic photometric variation in WR 104, with an unprecedented amplitude and frequency of fadings among all WR stars. The variation has a quasi-period close to the reported binary period, which provides an essential clue to understanding the relation between the formation of dust and the role of binarity.

[1] More recently, WR 98a and perhaps WR 112 are known to have a "dusty pinwheel nebula" (Monnier et al. (1999); Marchenko et al. (2002)), though neither of them are yet known to be as highly variable as WR 104.

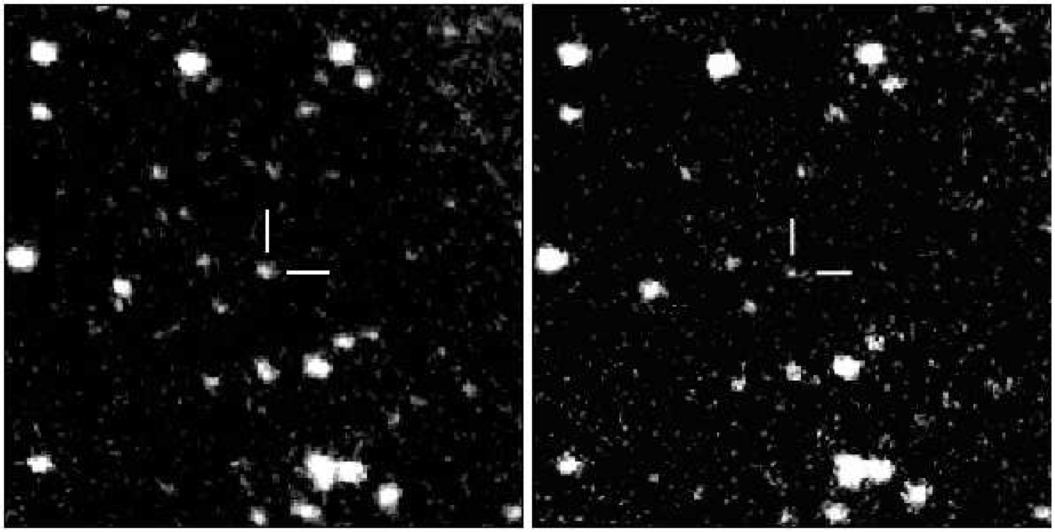

Figure 1: The variation of WR 104 = HadV82, recorded with photographs taken by one of the authors (KH). The left panel was taken on 1998 March 2, when the object was at 12.0 magnitude. The right panel was taken on 1998 April 25, when the object was at 13.8 magnitude. Such dramatic variability of a Wolf-Rayet star is quite exceptional.

2 Observation and results

A total of 176 observations were done between 1994 May 12 and 2001 April 26, with twin patrol cameras equipped with D=10cm f/4.0 telephoto lens and unfiltered T-Max 400 emulsions, located at two sites in Toyohashi, Aichi (KH) and Saku, Nagano (KT). The passband of observations covers the range of 400–650 nm. Photographic photometry was done using neighboring comparison stars whose V-magnitudes were calibrated by T. Watanabe. The overall uncertainty of the calibration and individual photometric estimates is 0.2–0.3 mag, which will not affect the following analysis.

The resultant light curve is presented in figure 2. The star showed an overall range of variability between 11.8 and fainter than 14.5 magnitudes, making the full amplitude greater than 2.7 magnitudes. The raw data are available at ⟨ ftp://vsnet.kusastro.kyoto-u.ac.jp/pub/vsnet/WR/WR104/wr104obs.jd ⟩.

Such a large variation in visible light far exceeds previously known variations of WR-type stars (Veen et al., 1998), which only occasionally show temporary fadings having depths less than 1 magnitude. Faint phases of WR 104 typically last an order of months, which is strikingly longer than any known transient episodes of WR-type variable stars (Veen et al., 1998), which usually last days to weeks. The most remarkable feature is the existence of a quasi-period of 200–400 d, superimposed on a long-term trend, which may be attributed to slow changes of optical depth of the line-of-sight extinction. The result of period analysis using the Phase Dispersion Minimization technique (Stellingwerf, 1978) is presented in figure 3. The strongest period in the range of 50–500 d is 241 d, which is in almost perfect agreement with the suggested orbital period of 243.5±3 d (Tuthill et al., 2002). Figure 4 shows a phase-averaged light curve with this period. The mean orbital light curve is characterized by a rather sharp minimum and a broader maximum.

3 Discussion

The previously known most striking evidence of variability in WR 104 is the temporary remarkable weakening of the spectroscopic feature of the WR-type star (Crowther, 1997). Crowther (1997) suggested that occultation by a dust cloud condensation, analogous to R CrB stars, is responsible for the phenomenon. The coincidence of the the remarkable weakening of the WR-type spectral feature and the optical fading supports the idea that the WR-type star was almost entirely obscured at the time of the observation by Crowther (1997).

The remarkable agreement of the dominant period in optical variability with the orbital period supports that at least a considerable fraction of varying dust obscuration is physically related to the binary motion. We mainly discuss on implications of the remarkable coincidence between the period of large-amplitude optical variation and the binary period.

First, the reported low binary inclination of $11\pm7^{\circ}$

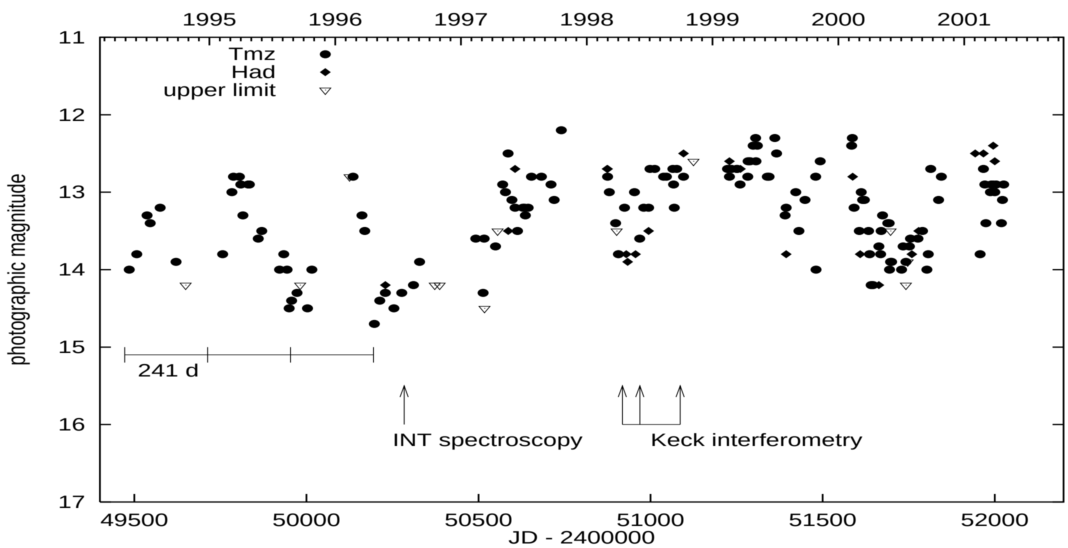

Figure 2: Light curve of WR 104. Filled circles and squares represent observations by Takamizawa (Tmz) and Haseda (Had) , respectively. Open triangles represent upper limits. The epochs of the INT spectroscopy (Crowther, 1997), when the weakening of the WR-type spectral feature was observed, and Keck interferometry (Tuthill et al., 1999), which led to the discovery of the "dusty pinwheel nebula", are marked with arrows. The coincidence of the the remarkable weakening of the WR-type spectral feature and the optical fading supports that the WR-type star was almost entirely obscured at the time of the observation, and that the WR-type star emits most of the visual light. The 241-d cycle was prominently seen for the period of 1994–1996, as shown with a tick-marked line. (The tick marks correspond to the phase zero in Tuthill et al. (2002)). The object slightly brightened in 1997–1999, when the rigid periodicity became less marked. Recurring fading episodes with time scales of 200–400 d, however, persisted up to 2001. The light curve is completely unique among all previously known WR-type variable stars (Veen et al., 1998).

(Tuthill et al., 2002) makes unlikely that the tail of the dust spiral is directly responsible for the variation. A possible explanation is the periodic enhancement of dust production in the WR-star wind at the passage of the companion star though an elliptical orbit. This effect is most pronounced in an episodic dust producer, WR 140 (Williams et al., 1990) and presumably WR 137 (Williams et al., 2001). The evidence for this scenario in WR 104 is less convincing, in its little infrared variability (van der Hucht et al., 1996), and in its continuous appearance of the dust spiral Tuthill et al. (1999,2002), and the lack of evidence of a large orbital eccentricity (Tuthill et al., 2002), all of which were considered against episodic dust production around periastron. Further full-orbit interferometric observation, together with contemporaneous visual and infrared photometry will be key information in testing the hypothesis.

The other possibility is that the varying obscuration is of geometrical origin, e.g. varying extinction as a consequence of rotating binary seen through a gradient of absorption near the line of sight. This explanation is similar to an idea to explain the unique variability of the binary central star of the planetary nebula, NGC 2346 (Roth et al. (1984); Costero et al. (1986)). This explanation would require an extremely strong gradient or a sharply defined dense obscuring body in the line of sight. The observed amplitude (more than 2.7 magnitudes) could only be explained if the WR-type component emits about 90% of the visual light, and the star is almost completely eclipsed by this obscuring structure. However, this assumption may not be consistent with its weaker WR-type spectral feature even in the high state than in other WC9 stars (Cohen et al., 1975). Such apparent discrepancies were also observed in WR 137 (Williams et al., 2001), which may be a rather common phenomenon seen in WCL+OB wind collision binaries.

Considering the total line-of-sight absorption of $A_{\rm V}$=6.5 magnitude (Pendleton et al., 1994), about 4.5 mag of which (after subtracting the interstellar absorption) is likely to be attributed to past mass-loss events of the progenitor, rather than the present dust formation (Cohen et al. (1975), Tuthill et al. (1999)), such a large fraction (2.7/4.5) of variable line-of-sight extinction seems to be difficult to reconcile with the past, presumably more spherical mass-loss episodes. The present discovery of strongly variable extinction may alternately suggest that the highly structured extinction can be being formed via an ejection of dust in the direction of the binary rotation axis. Such a possibility may be tested by a future development of full three-dimensional treatment of dust formation and ejection in a colliding-wind binary.

Another viable explanation is that the three-dimensional structure of the shock front, where the compressed gas is considered to effectively form dust grains (Usov, 1991), itself is the obscuring body. Depending on the geometry, the dusty shock front near the conjunction phase of the binary can completely obscure the inner WR-star wind, as well as the OB star, both are required to explain the spectral variation (Crowther, 1997) and the observed amplitude of optical fading. This explanation would require a higher inclination angle than was reported, or a sufficient vertical structure to obscure the stellar component viewed even nearly pole-on. Detailed high-resolution, full-orbit observation is again indispensable to discriminate the possibilities.

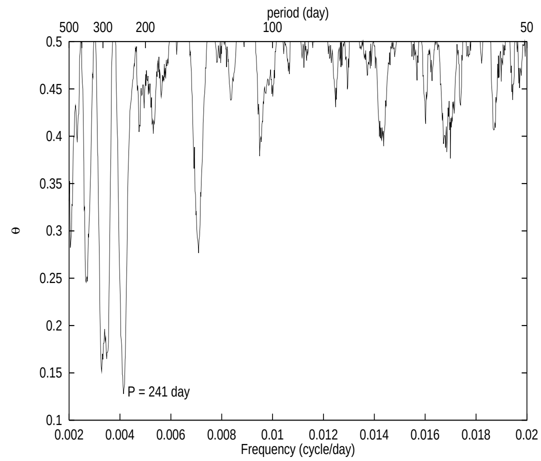

Figure 3: Period analysis. Lower theta values represent stronger periodicities. The period of 241 d is the strongest period between 50 and 500 d (please note that some of the weaker signals are sidelobes due to sampling). The period almost perfectly agrees with the period determined with interferometry (Tuthill et al., 2002). This agreement suggests that the semi-periodic obscuration of the WR-type component is strongly associated with the binary motion.

The present discovery of quasi-periodic, highly variable visual obscuration in WR 104 proposes a new class and mechanism of light variability in WR-type stars. With the advent of sub-milliarcsecond optical and infrared interferometry, and the coming era of Atacama Large Millimeter Array (ALMA), WR 104 would provide a powerful tool in geometrically resolving the heart of dust production in the most efficiently dust-productive stellar environments.

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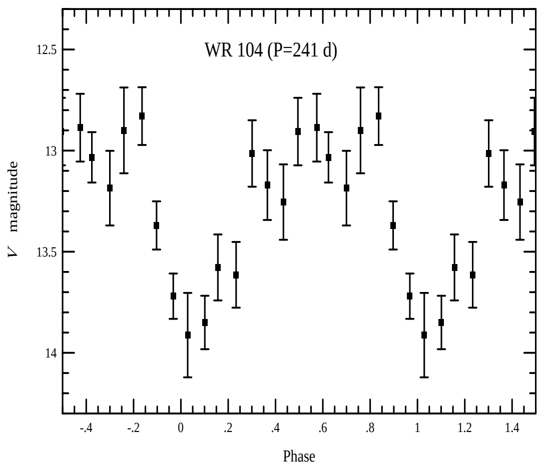

Figure 4: Phase-averaged light curve of WR 104. The phase zero corresponds to the phase zero in Tuthill et al. (2002) (1998 April 14). The mean orbital light curve is characterized by a rather sharp minimum and a broader maximum.

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