A dusty pinwheel nebula around
the massive star WR 104

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Wolf-Rayet (WR) stars are luminous massive blue stars thought to be immediate
precursors to the supernova terminating their brief lives. The existence of
dust shells around such stars has been enigmatic since their discovery some 30
years ago; the intense radiation field from the star should be inimical to dust sur-
vival [1]. Although dust-creation models, including those involving interacting
stellar winds from a companion star [2], have been put forward, high-resolution
observations are required to understand this phenomena. Here we present re-
solved images of the dust outflow around Wolf-Rayet WR 104, obtained with
novel imaging techniques, revealing detail on scales corresponding to about
40 AU at the star. Our maps show that the dust forms a spatially confined
stream following precisely a linear (or Archimedian) spiral trajectory. Images
taken at two separate epochs show a clear rotation with a period of
220 ± 30 days.
Taken together, these findings prove that a binary star is responsible for the
creation of the circumstellar dust, while the spiral plume makes WR 104 the
prototype of a new class of circumstellar nebulae unique to interacting wind
systems.

Observations of WR 104 were made with the Keck I telescope on 14 April and 4 June
1998, and employed the technique of aperture masking interferometry in order to recover
information out to the diffraction limit of the 10 m Keck aperture [3, 4]. We present, in
Figure 1, reconstructed images taken at 1.65 & 2.27 µm (Δλ = 0.33 & 0.16 µm respectively)
for both observing epochs. As infrared emission from the hot circumstellar dust dominates
the infrared region of the spectrum, we may interpret the highly asymmetric curved plumes
evident in the maps as tracing the distribution of this material. Previous high-resolution
efforts have been restricted to partially-resolved one-dimensional visibility curves interpreted
in the context of spherically symmetric outflow models [7, 8]. As a comparison with these
earlier results, we have fitted a uniform-disk model to our visibilities, azimuthally averaged
and cropped to the resolutions then obtained, finding perfect agreement with the 130 mas
diameter disk reported in 1981 [7]. This similarity over a timescale of decades is in accord
with the inclusion of WR 104 in the small handful of ‘persistent’ dust producing WR’s [4].
Additional interferometric observations at 3.08 µm (Δλ = 0.1 µm) show no evidence of the
marked enlargement towards longer wavelengths reported by Dyck et. al. [8]. However, as
Figure 1: Maps of WR 104. Maximum-Entropy image reconstructions of WR 104 at 1.65 (left) and 2.27 μm (right) taken over two separate epochs: April (upper) and June (lower) 1998 (JD 2450918 & JD 2450969 respectively). Contour levels are 0.5, 2, 4, 6, 8, 10, 12, 15, 20, 25, 30, 50 & 70% of the peak. Overplotted on each map is the best-fit Archimedian spiral model (dashed line). Observations utilized an annulus shaped pupil mask to form the interference pattern, which was recorded on a fast-readout (130 ms) infrared array and subsequently processed to extract Fourier amplitudes and closure phases. Bispectral information constituting about 700 baselines and 7000 closing triangles enabled high-quality images to be produced from an algorithm based on the maximum entropy method [5, 6]. Although these images are at the heart of our discussion, it is important to note that clear and systematic signals betraying the presence of the final image morphology are directly visible in the calibrated Fourier data themselves.
is apparent from Figure 1, the images do not show even remote similarity to a uniform disk, and we hereafter abandon further consideration of circularly symmetric models.

The maps of Figure 1 consist of two components; a bright central core which appears elongated, and a curved tail which seems to emerge from one end of the elongation. This spiral structure dominates the morphology at both colors, and maps taken in April and June 1998 show a high degree of similarity with the striking exception of a clear rotation of the image. The hypothesis of dust formation mediated by the orbital motion of a companion star and subsequently swept outwards by the stellar wind unifies the spiral structure and the $-83^\circ$ rotation apparent between our two epochs into a simple, elegant geometry. A schematic of our model is shown in Figure 2, showing the WR+OB binary, the dust formation zone associated with the collision front between the stellar winds [2], and the resultant curved outflow plume as this dust ‘nursery’ is carried with the orbital motion. Although the idea of a binary nature for WR 104 is not new, it is only very recently that the presence of an OB companion was confirmed from detection of hydrogen Balmer absorption features and optical emission-line dilution [10, 11].

Figure 2: Schematic diagram of the WR 104 binary system. The illustration shows the WR star, the OB companion, wind-wind collision front, and the resultant dust outflow plume (not to scale). The spiral shape is a consequence of material being swept radially outwards by the WR wind from a rotating dust nucleation zone associated with the shock front where the stellar winds collide.
We have overplotted, also in Figure 1, the results of fitting a simple geometrical model consisting of an Archimedian spiral where the free parameters are the winding rate and the viewing angle to the observer. These modelling results were obtained by finding a global best fit to all four maps simultaneously, but allowing for a rotation of the spiral structure about the model-derived axis between the two epochs. Implicit in the assumption of an Archimedian spiral model is the hypothesis that the material in the spiral is moving out at a uniform velocity, and that new material feeding into the flow insertion point does so at a uniform angular velocity. Although such a model contains the fewest free parameters and yet gives excellent fits to our data, it is important to note that a more complex model may be required if the plume is in a zone where it is being accelerated, or if the orbit of the companion presumed to be mediating the flow is eccentric (e.g. [9]).

The physical geometry of the system, as derived directly from our model, is a spiral plume rotating with a period of $220 \pm 30$ days viewed at an angle of $20 \pm 5^\circ$ from the pole and with an outflow velocity of $111 \pm 17$ mas yr$^{-1}$ in the plane of the orbit. If we identify this rotation as the orbital period of a binary stellar system, then assuming a combined mass in the range of $20 - 50 M_\odot$ [4] results in a separation of $1.9 - 2.6$ AU. As this corresponds to a separation of only $\sim 1$ mas on the sky, our images lack the resolution to show such detail directly, and furthermore the infrared flux is so dominated by thermal emission from the warm dust [3] that it is unlikely that we have detected the central stars in our maps at all. It is interesting to compare our binary parameters with those of the famous ‘episodic’ dust producer WR 140 which is known to undergo dramatic bouts of dust creation coincident with the passage of a companion star through periastron in a highly elliptical orbit [9]. At periastron, the separation between the stars is $\sim 2.5$ AU, raising the possibility that the physical conditions favoring copious dust formation fall within a confined range of companion distances for WC+OB binaries.

We may make use of the $1220$ km s$^{-1}$ wind outflow velocity [14] combined with our proper motion to derive an independent estimate of $2.3 \pm 0.7$ kpc as the distance to WR 104, where the dominant error arises from a $\sim 25\%$ uncertainty in outflow velocities found by comparing the results of various line-profile studies [15] (velocities as high as 1600 km s$^{-1}$ have been reported for this star [16]). Our distance is somewhat further than earlier estimates of 1.6 kpc derived from a possible association with Sgr OB1 [17], however the discrepancy is within the estimated errors. Alternatively if the closer distance is preferred, then our measurements imply an outflow velocity of $845$ km s$^{-1}$ for the dust component. Our geometrical solution solves for the projected viewing angle of the observer, and thus we avoid the usual $\sin(i)$ uncertainty. We note that although isolated dust grains should be momentum-coupled to the flow [1], the outflow velocities in the wake of the passage of the OB stellar companion could be significantly perturbed and thus the behavior of the plume may not act as a good tracer of the bulk motion of the stellar wind. With additional observations covering an entire orbit, we will be able to greatly refine our estimates of the physical geometry of this system.

It is apparent from Figure 1 that the outflowing material presents a relatively smooth, spatially confined stream without strong clumping out to a radius of some $\sim 65$ mas ($\sim 150$ AU) from the star, by which time the outflow has rotated through about $360^\circ$. We
believe that the finding of a single complete turn in the spiral arm is not coincidental, as we detect only dust heated by radiation from the central stars, and therefore lying along a direct line of sight. Material in the second and further coils of the outflow will, of course, be eclipsed by newer material closer in, and will therefore cool rapidly resulting in the relatively sharp cutoff we see. Although there is some evidence for brightness variations along the arm at a level of a few percent of the peak, especially apparent in the maps taken at 1.65 \( \mu m \), the overall behavior points to a continuous and smooth dust creation process, in accord with the classification of WR 104 as a ‘persistent’ dust producer with a constant IR flux \[18\]. Again it is interesting to compare this behavior with that of WR 140 whose elliptical orbit results in episodic dust production. The contrasting characteristics of WR 104 argue against a high degree of orbital eccentricity, giving some justification to our choice of the Archimedian spiral model in this case.

For WR 104, our observations confine the IR excess emission from the dust to lie in a narrow, spatially confined outflow which rotates synchronously with a period of 220 days – a plausible period for a wind-interacting binary system. No spherically symmetric or diffuse component to the dust nebula was detected to within a few percent of the peak flux. We are therefore able to reject dust-formation models resulting in spherical or disk shaped outflows such as the clumpy spherical outflows of \[19\] or equatorial density enhancements \[20\] in favor of the binary wind-wind model.

The viewing angle to the observer of 20\( \pm \)5\( ^\circ \) is well constrained by these measurements. This finding of an almost face-on system contradicts previous attribution of high circumstellar extinction \[21\] and spectral variability \[11\] to an edge-on viewing angle. Some of these observations may be explained as WR 104 is thought to lie behind a heavily obscuring cloud \[17\] with further extinction possibly arising from material created in past mass-loss events of the progenitor star.

As the dust comprises only a very small fraction of the total mass loss, it therefore acts as a visible tracer in the outflow enabling the fascinating possibility of dynamical studies of the wind itself. Detailed numerical modelling is needed to determine if the high degree of initial collimation and subsequent confinement of the dust plume can be explained with simple models of the wind-wind interaction \[2\], or whether more detailed three-dimensional calculations such as those of Walder \[22\], are required. Spectral studies of the plume, beyond the scope of this letter, should reveal the thermal and chemical evolution of the dust as it is swept outwards into the interstellar medium, and also yield information on processes underlying the binary-mediated dust creation mechanism. With a handful of dusty WR systems open to study with this novel method for the detection of binary stars, wider questions of dust formation in this class of objects can now be addressed.

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