Pinwheels in the Quintuplet Cluster

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The five enigmatic cocoon stars after which the Quintuplet cluster was christened have puzzled astronomers since their discovery (*1*). Hundreds of stars have now been identified within the cluster (*2*, *3*), placing it among the most massive in our Galaxy, yet the nature of the five extremely red stars at the heart of the Quintuplet has remained elusive. Their extraordinary cool, featureless thermal spectra [~780 to 1315 K (*3*)] have been attributed to various stellar types from young to highly evolved, whereas their absolute luminosities place them among the supergiants (10^4 to 10^5 times the luminosity of the Sun). We present diffraction-limited images from the Keck 1 telescope, which resolves this debate with the identification of rotating spiral plumes characteristic of colliding-wind binary "pinwheel" nebulae. These have previously been reported in dust shells around luminous hot Wolf-Rayet stars (*4*, *5*).

By using high-resolution speckle techniques in the near-infrared (*6*), we (at least partially) resolved all five cocoon stars and recovered images of the two presenting the largest apparent size, Q 2 and Q 3 (Fig. 1). Outflow plumes depicted follow the form of an archimedean spiral, thereby establishing the presence of circumstellar dust formed in a colliding-wind binary system. These rare pinwheel nebulae result when dust condensation in the stellar wind is mediated by the presence of a companion star, as established in the prototype systems WR 104 (*4*) and WR 98a (*5*). Dust nucleation is enabled by the wind compression associated with the bowshock between the stellar winds. Newly formed hot dust streaming into the wake behind the companion is wrapped into a spiral by the orbital motion as it is embedded within the expanding Wolf-Rayet wind.

With high-resolution images available from two epochs separated by 357 days, we fitted the dust plume of star Q 3 to an archimedean spiral model with winding angle 110 ± 10 milliarc sec per turn and with an inclination of the rotation axis to the line of sight of 26° (not well constrained; adequate fits are possible in the range 0° to 36°). The proper motion of structures between the two epochs indicates a rotation period of the spiral, and hence the colliding-wind binary, of 850 ± 100 days. Assuming an 8000-pc distance to the Quintuplet (*7*), these measurements constrain the Wolf-Rayet wind velocity to be v_∞ = 1800 ± 300 km/s, which is typical for a late-type carbon-rich (WC-spectrum) star (*8*).

Simple models fall short of reproducing all structures (Fig. 1), particularly near the bright core where multiple knots and streams can exist. This problem has also been noted in WR 98a (*5*), where extra complexity was attributed to optical depth and line-of-sight effects from a three-dimensional (3D) structure (*9*). Q 2 appears to have parameters similar to those of Q 3, although a second image epoch is required to measure the rotation rate. Partially resolved objects Q 1, Q 4, and Q 9 (*6*) (table S1) exhibit colors and surface brightness similar to those of Q 2 and Q 3, and we therefore suggest that they are also pinwheels but with tighter winding angles (shorter periods) or less favorable inclinations. Furthermore, the prototype pinwheel WR 104, with a period of 243 days, would give an apparent size in close accord with measured sizes of Q 1, Q 4, and Q 9 if it were removed to the distance of the Quintuplet.

Given the extreme visible extinction [A_v = 29 ± 5 (*2*)], small separation of the central binary stars (likely ~0.6 milliarc sec or 5 astronomical units), and presence of high-luminosity circumstellar dust shells, it would be extremely difficult to detect or study these systems with other techniques. The most luminous stars in our Galaxy are often surrounded by dusty shells, and the implication that most, if not all, of these harbor massive binaries (not single stars) has important implications for the high-mass tail of the stellar initial mass function. Binarity is also a key element to studies of type Ib/c and type IIb supernovae. There are recent indications that explosion light curves can be modified by the imprint of circumstellar matter, carrying an encoding of the mass-loss history of the supernova precursor star system (*10*, *11*).

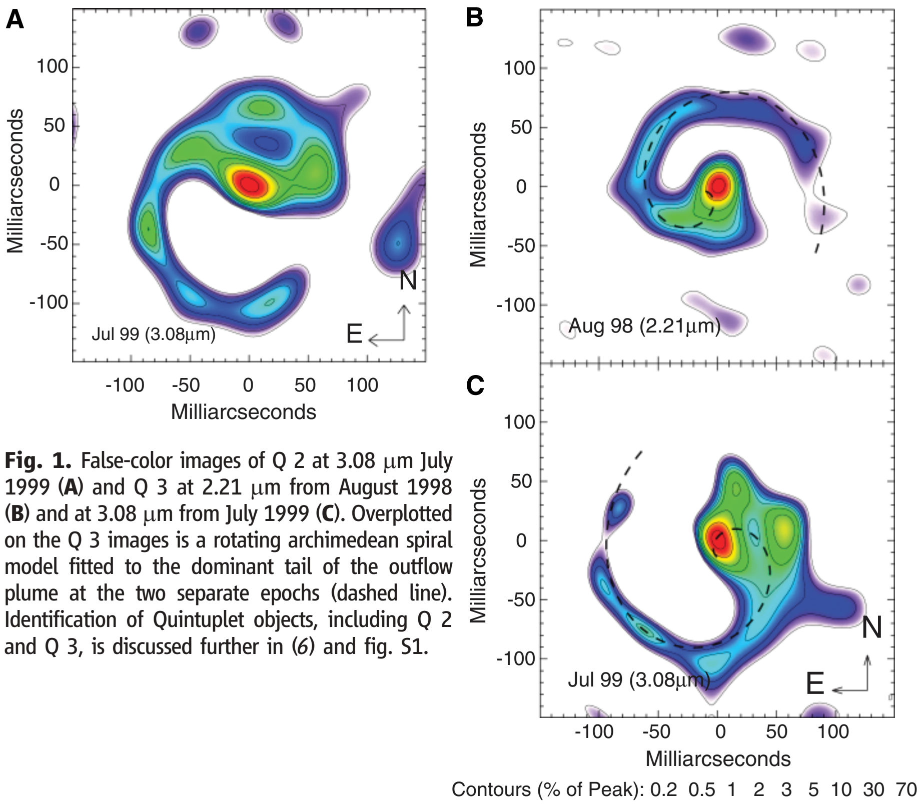

Fig. 1. False-color images of Q 2 at 3.08 μm July 1999 (**A**) and Q 3 at 2.21 μm from August 1998 (**B**) and at 3.08 μm from July 1999 (**C**). Overplotted on the Q 3 images is a rotating archimedean spiral model fitted to the dominant tail of the outflow plume at the two separate epochs (dashed line). Identification of Quintuplet objects, including Q 2 and Q 3, is discussed further in (*6*) and fig. S1.

References and Notes

1. H. Okuda *et al.*, *Astrophys. J.* **351**, 89 (1990).
2. D. F. Figer, I. S. McLean, M. Morris, *Astrophys. J.* **514**, 202 (1999).
3. D. F. Figer *et al.*, *Astrophys. J.* **525**, 750 (1999).
4. P. G. Tuthill, J. D. Monnier, W. C. Danchi, *Nature* **398**, 487 (1999).
5. J. D. Monnier, P. G. Tuthill, W. C. Danchi, *Astrophys. J.* **525**, L97 (1999).
6. Materials and methods are available on *Science* Online.
7. M. J. Reid, *Annu. Rev. Astron. Astrophys.* **31**, 345 (1993).
8. I. D. Howarth, W. Schmutz, *Astron. Astrophys.* **261**, 503 (1992).
9. T. J. Harries, J. D. Monnier, N. H. Symington, R. Kurosawa, *Mon. Not. R. Astron. Soc.* **350**, 565 (2004).
10. J. A. Moran, D. E. Reichart, *Astrophys. J.* **632**, 438 (2005).
11. S. D. Ryder *et al.*, *Mon. Not. R. Astron. Soc.* **349**, 1093 (2004).
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Supporting Online Material

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Materials and Methods
Fig. S1
Table S1
References

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