

Pinwheels in the Quintuplet Cluster

Peter Tuthill,¹ John Monnier,² Angelle Tanner,³
Donald Figer,⁴ Andrea Ghez,⁵ & William Danchi,⁶

Correspondance to Peter Tuthill: gekko@physics.usyd.edu.au

ABSTRACT

The five enigmatic “Cocoon stars” after which the Quintuplet cluster was christened have puzzled astronomers since their discovery. Their extraordinary cool, featureless thermal spectra have been attributed to various stellar types from young to highly evolved, while their absolute luminosities places them among the supergiants. We present diffraction-limited images from the Keck 1 telescope which resolves this debate with the discovery of rotating spiral plumes characteristic of colliding-wind binary “pinwheel” nebulae. Such elegant spiral structures, found around high-luminosity Wolf-Rayet stars, have recently been implicated in the behavior of supernovae lightcurves in the radio and optical.

The five enigmatic “Cocoon stars” after which the Quintuplet cluster was christened have puzzled astronomers since their discovery (8). Hundreds of stars have now been identified within the cluster (1, 2), 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 ($\sim 780\text{--}1315\text{ K}$ (1)) have been attributed to various stellar types from young to highly evolved, while their absolute luminosities places them among the supergiants ($10^{4\text{--}5} L_{\odot}$). We present diffraction-limited images from the Keck 1 telescope which resolves this debate with the discovery 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 (11, 6).

Using high-resolution speckle techniques in the

near-infrared (13), all five Cocoon stars were (at least partially) resolved, and images recovered of the two presenting the largest apparent size, Q 2 and Q 3, (Fig. 1). Outflow plumes depicted follow the form of an Archimedian 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 (11) and WR 98a (6). 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, the dust plume of star Q 3 was fitted to an Archimedian spiral model with winding angle 110 ± 10 mas/turn and with an inclination of the rotation axis to the line-of-sight of 26° (not well constrained; adequate fits possible in the range $0\text{--}36^{\circ}$). 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 (9), these measurements constrain the Wolf-Rayet wind velocity to

¹School of Physics, University of Sydney, NSW 2006, Australia

²Univ. Michigan Astronomy Dept., 500 Church Street, Ann Arbor, MI 48109-1090, USA

³JPL/Caltech, Mail Code 100-22, 770 South Wilson Ave, Pasadena, CA 91125 USA

⁴COS/Ctr for Imaging Sci, 54 Lomb Memorial Dr, RIT, Rochester, NY 146235604, USA

⁵Astronomy, UCLA, Los Angeles, CA 90095-1547, USA

⁶NASA Goddard, Code 667, Greenbelt, MD 20771, USA

be $v_\infty=1800\pm 300$ km/sec, which is typical for a late-type Carbon-rich (WC-spectrum) star (4).

Simple models fall short of reproducing all structures (Fig. 1), particularly near the bright core where multiple knots and streams can exist. This has also been noted in WR 98a (6) where extra complexity was attributed to optical depth and line-of-sight effects from a 3-D structure (3). Q2 appears to have similar parameters to Q3 although a second image epoch is required to measure the rotation rate. Partially-resolved objects Q1, Q4 and Q9 (see 13 and Table S1 for observational results) exhibit similar colors and surface brightness to Q2 & Q3, and we therefore suggest that they are also pinwheels but with tighter winding angles (therefore 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 Q1, Q4 and Q9 if it were removed to the distance of the Quintuplet.

Given the extreme visible extinction ($A_v=29\pm 5$ (2)), small separation of the central binary stars (likely ~ 0.6 mas or 5 AU), 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 ramifications for the high-mass tail of the stellar Initial Mass Function (IMF). Binarity is also a key element to studies of Type Ib/c and Type IIb supernovae. There are recent indications that explosion lightcurves can be modified by the imprint of circumstellar matter, carrying an encoding of the mass-loss history of the supernova precursor star system (7, 10).

References and Notes

1. Figer, D. F., McLean, I. S., & Morris, M. 1999, *ApJ*, **514**, 202
2. Figer, D. F., Kim, S. S., Morris, M., Serabyn, E., Rich, R. M., & McLean, I. S. 1999, *ApJ*, **525**, 750
3. Harries, T. J., Monnier, J. D., Symington, N. H., & Kurosawa, R. 2004, *MNRAS*, **350**, 565

4. Howarth, I. D., & Schmutz, W. 1992, *A&A*, **261**, 503
5. Moneti, A., Glass, I. S., & Moorwood, A. F. M. 1994, *MNRAS*, **268**, 194
6. Monnier, J. D., Tuthill, P. G., & Danchi, W. C. 1999, *ApJ*, **525**, L97
7. Moran, J. A., & Reichart, D. E. 2005, *ApJ*, **632**, 438
8. Okuda, H., et al. 1990, *ApJ*, **351**, 89
9. Reid, M. J. 1993, *ARA&A*, **31**, 345
10. Ryder, S. D., Sadler, E. M., Subrahmanyam, R., Weiler, K. W., Panagia, N., & Stockdale, C. 2004, *MNRAS*, **349**, 1093
11. Tuthill, P. G., Monnier, J. D., & Danchi, W. C. 1999, *Nature*, **398**, 487
12. We thank Stuart Ryder, Charles Townes, Eric Becklin, and Seth Hornstein for contributions to this paper. This work has been supported by the Australian Research Council and the U.S. National Science Foundation. Data presented here were obtained at the W.M. Keck Observatory.
13. Observational methods and discussion are available in *Science* online: www.sciencemag.org (contents: Observations and Discussion, Table S1 and Fig. S1) For Astro-PH, this material follows in the next section.

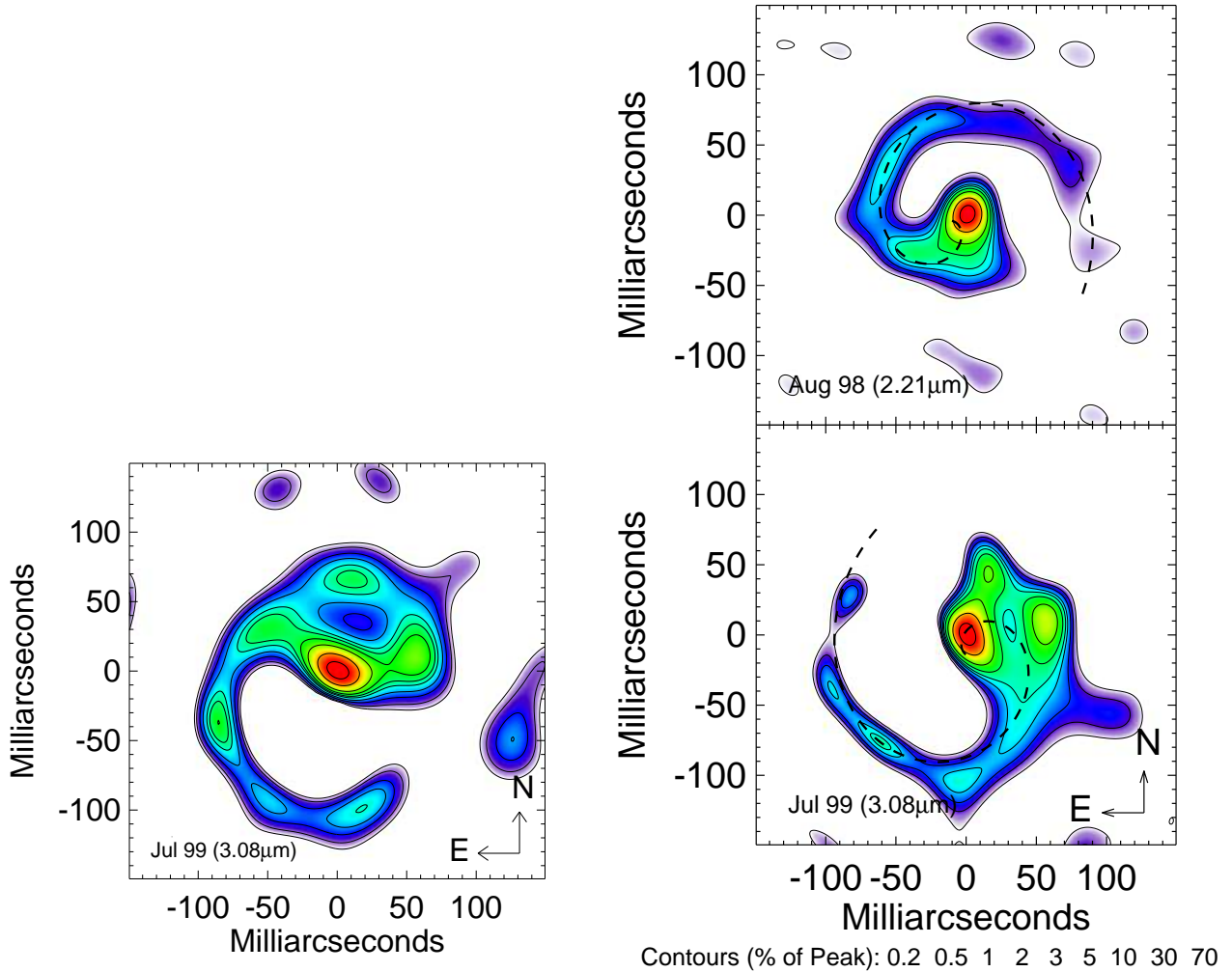


Fig. 1.— False-color images of Q2 at $3.08\ \mu\text{m}$ 1999 July (left panel) and Q3 at $2.21\ \mu\text{m}$ from 1998 Aug (upper right panel) and $3.08\ \mu\text{m}$ from 1999 July (lower right panel). Overplotted on the Q3 images is a rotating Archimedian spiral model fitted to the dominant tail of the outflow plume at the two separate epochs (dashed line). Identification of Quintuplet objects including Q2, Q3 is discussed further in the supporting online material and Fig. S1.

Supporting On-line Material

1. Observations and Discussion

Observations of the Quintuplet cluster are listed in Table S1 and were made with the near-infrared NIRC camera on the Keck 1 telescope. The nomenclature of Moneti et al.(5) is adopted here, identifying the dusty red Quintuplet proper members, or cocoon stars, as Q 1, Q 2, Q 3, Q 4 and Q 9. Locations of each of these stars within the cluster as imaged by the Hubble Space Telescope is given in Fig. S1, which also depicts our diffraction-limited Keck images of Q 2, Q 3 overlaid with graphical indication of the relative spatial scale.

The high angular resolution imaging utilized rapid-exposure speckle interferometry techniques from a number of long-standing experiments at the Keck 1 (8). Typical datasets entailed from one to a few hundred short-exposures (~ 0.14 sec) with the NIRC camera operating in a high-magnification (0.0206 arcsec/pixel) mode. Interleaved observations of galactic-center object IRS 7 were used to calibrate the telescope-atmosphere point-spread function (the unresolved nature of this object was itself checked against stars HD 159255 and HD 163042).

All five Quintuplet cocoon stars were found to be spatially resolved to some degree. The full-width at half-maximum (FWHM) of best-fitting circular Gaussian functions, used here to give an estimate of apparent size, are given in Table S1. Images of stars Q 2 and Q 3, recovered with Fourier techniques(8) and presented earlier in Fig. 1, show that complex and asymmetric structures exist within the dust shells surrounding these stars. The complexity of these visibility functions resulted in poor fits for the Gaussian model, and we therefore limited the fit range to low spatial frequencies/short baselines where visibility excursions are not yet strongly manifest ($< 2 \times 10^6$ and 1×10^6 rad $^{-1}$ for 2.21 and 3.08 μ m respectively; equivalent to $\lesssim 4.5$ and 3.1 m).

By implication, if similar physics is assumed to pertain to the remaining three of the five Quintuplet cocoon stars, then the utility of fitting Gaussian shells may appear limited. Despite this, for objects which are only partially resolved, the fitting of such simple functional forms to interfer-

ometer data gives a good estimate of the overall size, and permits quantitative comparison with models. Furthermore, this allows sizes for morphologically complex objects Q 2 and Q 3 to be compared against measurements of the partially-resolved Q 1, Q 4 and Q 9, and against other dusty Wolf-Rayets observed with high resolution techniques. Note also that FWHM in the range 10–15 mas are only marginally resolved with this experiment; relative errors in these cases are correspondingly high.

Apparent sizes have been combined with flux measurements to yield estimates of surface brightness in our two filter bandpasses for the target stars. Correction for the $A_v = 29 \pm 5$ visible extinction was made using the optical dust constants of Mathis(4). Surface brightnesses were then derived following Monnier et al.(6), which also gives a comparison population of Galactic dusty Wolf-Rayets with similarly measured surface brightnesses. For both filter bandpasses, the Quintuplet cocoon stars showed surface brightnesses within the range spanned by the WR population studied in Monnier et al.(6). In particular, for Q 4 and Q 9 the color temperature between 2.21 and 3.08 μ m appeared to be in reasonable accord with similar measurements from the Galactic population. This finding was found to be generally robust against variations in the extinction correction over the expected range.

However, in some regards the Quintuplet WRs, and in particular Q 2 and Q 3, did appear to be distinct from the Galactic population. The observed increase in size between 2.21 and 3.08 μ m which approaches a factor of ~ 2 in the Quintuplet, is found to be a more modest ~ 1.4 elsewhere(9; 6). Such changes of size (and surface brightness) with wavelength reflect the fact that dust with a range of temperatures contributes to the near-IR emission. The dramatic enlargement between 2.21 and 3.08 μ m argues for a flatter thermal profile in the Quintuplet dust shells: plausibly due to external heating from stars in the dense central region of the cluster. The comparison population of Galactic WRs were in far less crowded regions where the outer dust shell likely receives little or no energy except that originating with the central WR star.

Perhaps the simplest way to test the hypothesis that the remaining 3 cocoon stars are also pinwheels is by photometric monitoring. Variabil-

ity of these sources has already been noted(2), although not with sufficient coverage to reveal a cyclic change consummate with any rotational period(3). The ~ 2.5 yr periods inferred from the imaging extend the confirmed operation of continuous dust formation by the pinwheel mechanism to significantly longer periods/larger binary separations than previously known, with implications for models of these processes.

This finding of late-type WC binaries in the Quintuplet means that WC (Carbon rich) outnumber WN (Nitrogen rich) Wolf-Rayets by 11:6, and furthermore all WC stars are dusty. This makes an interesting contrast to the massive young WR-rich cluster Westerlund 1 where the WC:WN ratio is reversed to 7:12, with none of the WC's exhibiting dust. Clearly, the close binaries at the heart of the Pinwheel systems can be responsible for significant modification of the stellar evolutionary path, in which mass-transfer or envelope-stripping events might precipitate the WC phase. This entanglement of binarity, mass-loss history, and evolutionary path has the potential to skew population distributions, although it is unclear exactly what conditions resulted in the abundance of Pinwheels in this cluster.

REFERENCES

- 1 Figer, D. F., Kim, S. S., Morris, M., Serabyn, E., Rich, R. M., & McLean, I. S. 1999, *ApJ*, 525, 750
- 2 Glass, I. S., Matsumoto, S., Carter, B. S., & Sekiguchi, K. 2002, *MNRAS*, 336, 1390
- 3 Kato, T., Haseda, K., Yamaoka, H., & Takamizawa, K. 2002, *PASJ*, 54, L51
- 4 Mathis, J. S. 1990, *ARA&A*, 28, 37
- 5 Moneti, A., Glass, I. S., & Moorwood, A. F. M. 1994, *MNRAS*, 268, 194
- 6 Monnier, J. D., Tuthill, P. G., Danchi, W. C., Murphy, N. M., & Harries, T. J. 2006, *ApJ*, Submitted
- 7 Okuda, H., et al. 1990, *ApJ*, 351, 89
- 8 Tuthill, P. G., Monnier, J. D., Danchi, W. C., Wishnow, E. H., & Haniff, C. A. 2000, *PASP*, 112, 555
- 9 Tuthill, P. G., Monnier, J. D., & Danchi, W. C. 2002, *ASP Conf. Ser. 260: Interacting Winds from Massive Stars*, 260, 321

This 2-column preprint was prepared with the AAS L^AT_EX macros v5.2.

TABLE S1
OBSERVING LOG AND APPARENT SIZES

Source(5)	Alt. Name(7)	Date	2.21 μm FWHM (mas)	3.08 μm FWHM (mas)
Q 1	GCS 3-4	1998 Aug 06	18 \pm 3	–
Q 2	GCS 3-2	1998 Aug 06	35 \pm 2	–
		1999 May 04	38 \pm 3	–
		1999 Jul 29	37 \pm 3	77 \pm 2
Q 3	GCS 4	1998 Aug 06	41 \pm 2	–
		1999 Jul 29	40 \pm 2	75 \pm 2
Q 4	GCS 3-1	1998 Aug 06	13 \pm 4	–
		2002 Jul 23	15 \pm 3	20 \pm 3
Q 9	GCS 3-3	1998 Aug 06	13 \pm 4	–
		2002 Jul 23	< 11	21 \pm 3

NOTE.— Log of observations of the five cocoon stars. Observations in the K band at 2.21 μm were made at all epochs, but longer wavelength data at 3.08 μm were only secured on the four occasions listed. The FWHM of a circular Gaussian profile fit to the visibility data is also given, together with the estimated uncertainty, as a measure of the overall apparent size.

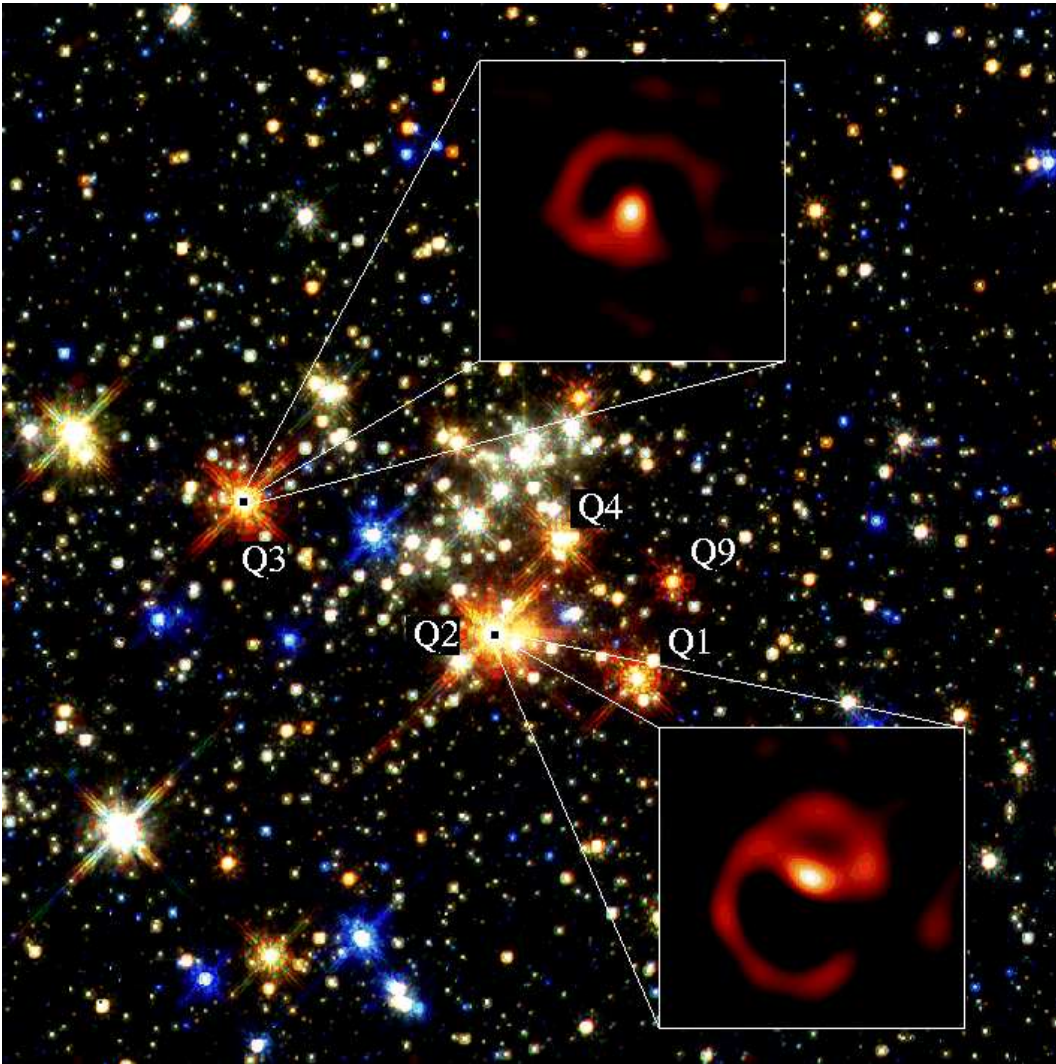


Fig. S1– The background star-field is from multi-wavelength Hubble Space Telescope (NICMOS) near-infrared imaging. Further details and discussion of this image can be found in Figer et al. (1). The five dusty red cocoon stars are labelled according to the nomenclature of Moneti et al. (5). Inset images of Q2 and Q3 recovered with our Keck imaging experiments (see also Fig. 1) are overlaid, with graphical indication showing the relative scaling between the Hubble and Keck imaging.