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A compact, variable radio nebula around P Cygni

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ABSTRACT

We present high spatial resolution images, at a wavelength of 6 cm, of the luminous blue variable star P Cygni. The images fully resolve the core of the stellar wind, and show that it is very clumpy. Two images were taken, separated in time by approximately a month, during which the structure in the wind has changed radically. The total flux observed has also changed significantly. We show that the clump sizes and electron densities are consistent with the radio variability being due to recombination of the ionized gas within the clumps, after key cooling lines become optically thin, causing the free–free emission to disappear. This is the first time that resolved radio images of a hot star wind have been obtained. It also represents important confirmation of a previous observation that thermal free–free wind emission can vary rapidly in a hot stellar wind.

Key words: stars: early-type – stars: imaging – stars: individual: P Cygni.

1 INTRODUCTION

The luminous blue variables (LBVs: Conti 1984; Humphreys 1989) are hot stars (spectral types O–A, effective temperatures 8000–30 000 K), which exhibit variability on a variety of time-scales, and show evidence in their emission line-dominated spectra for substantial ongoing mass loss. They probably (Crowther & Willis 1994) represent a phase of the post-main-sequence evolution of the most massive stars, with initial masses greater than 30 $M_\odot$.

The best known and observed of the LBVs is P Cyg, largely because, unlike most of the others, it is located in the northern sky and relatively nearby. P Cyg exhibits most of the major properties usually associated with LBVs. It is optically variable on quite short time-scales with small amplitude, as well as on much longer time-scales (Lamers & de Groot 1992). During an outburst in AD 1600 it brightened from being too faint for naked eye observation to third magnitude, and was denoted a nova by the astronomers of the time. It has recently been found to possess an optical nebula, both spectroscopically (Johnson, Barlow & Drew 1992) and via direct and coronographic imaging (Leitherer & Zickgraf 1987; Barlow et al. 1994; Nota, Livio & Clampin 1995). It is undergoing significant mass loss, at a current rate estimated to be 2.2×10^{-5} $M_\odot$ yr^{-1} (Barlow 1991). The mass loss is continuous, and there appear to be additional sporadic ejections of somewhat denser shells (Lamers, Korevaar & Cassatella 1985).

P Cyg was one of the first stars found to be a thermal radio source (Wendker, Baars & Altenhoff 1973). The radio emission has been resolved by the VLA (White & Becker 1982) and, although the VLA's baseline was insufficient to allow an image of the emission to be constructed, the derived brightness temperature confirmed the thermal free–free nature of the source. P Cyg's radio flux varies on unexpectedly short time-scales (a month or less: van den Oord et al. 1985). Amongst all hot stars, these observations make P Cyg very unusual at radio wavelengths.

Simple models of the radio emission of P Cyg suggest that its wind, emitting in the radio by means of free–free emission, should present an optically thick radio photosphere with a diameter of about 0.10 arcsec at 6 cm (Wright & Barlow 1975).

2 OBSERVATIONS

We observed P Cyg at a wavelength of 6 cm with MERLIN (the Multi-Element Radio Linked Interferometer Network). MERLIN has a maximum baseline of about 250 km, providing a spatial resolution at 6 cm of ≈ 40 milliarcsec (mas), well suited to stellar radio astronomy. However, as it has only six telescopes, in order to obtain adequate *uv* phase-coverage it is necessary to use Earth rotation synthesis, allowing planetary rotation to fill in the many baselines that would be missing in a short 'snapshot' observation.

We obtained images on 1992 June 24 and August 4. Each observation lasted about 16 h. A nodding phase referencing technique was employed, in which 8-min integrations on P Cyg were interleaved with 2-min integrations on the nearby phase calibrator 2005+403. 3C 286 was the primary amplitude calibrator, and the

Table 1. Parameters of P Cyg from MERLIN images.

Parameter	June 24 1992	August 04 1992
S_ν [mJy]	$4.76(^{+0.46}_{-0.20})$	$3.80(^{+0.10}_{-0.29})$
rms noise [mJy beam^{-1}]	0.105	0.099
Beamsize [mas]	51×48	51×48
Size of emitting region [arcsec]	0.2×0.15	0.17×0.17

point sources 0552+398 and OQ208 were used to calibrate instrumental phases. Assuming a spectral flux density of 7.23 Jy for 3C 286, spectral flux densities of 2.75 and 2.71 Jy were derived for 2005+403 at the times of the June and August observations, respectively. Corrections for the heights of the telescopes, the polar motions and the diurnal aberration were carried out. The baselines are known to 60 mm, i.e. to one wavelength at 6 cm, and the accuracy of the phase referencing process is better than 2 mas. For each observation the beam was found to be a $51 \times 48\,\mathrm{mas}^2$ ellipse. Components of the source significantly more extended than about 1.0 arcsec will not have been detected by MERLIN.

Intensity maps were produced using natural weighting. The rms noise levels were 63 μJy beam^{-1} for the June 24 observation and 47 μJy beam^{-1} for the August 4 observation. The resulting images are presented in Figs 1 and 2. Dramatic changes have occurred on a time-scale of 40 d. To see whether the integrated fluxes, as well as the overall structure, have varied, further images were made with

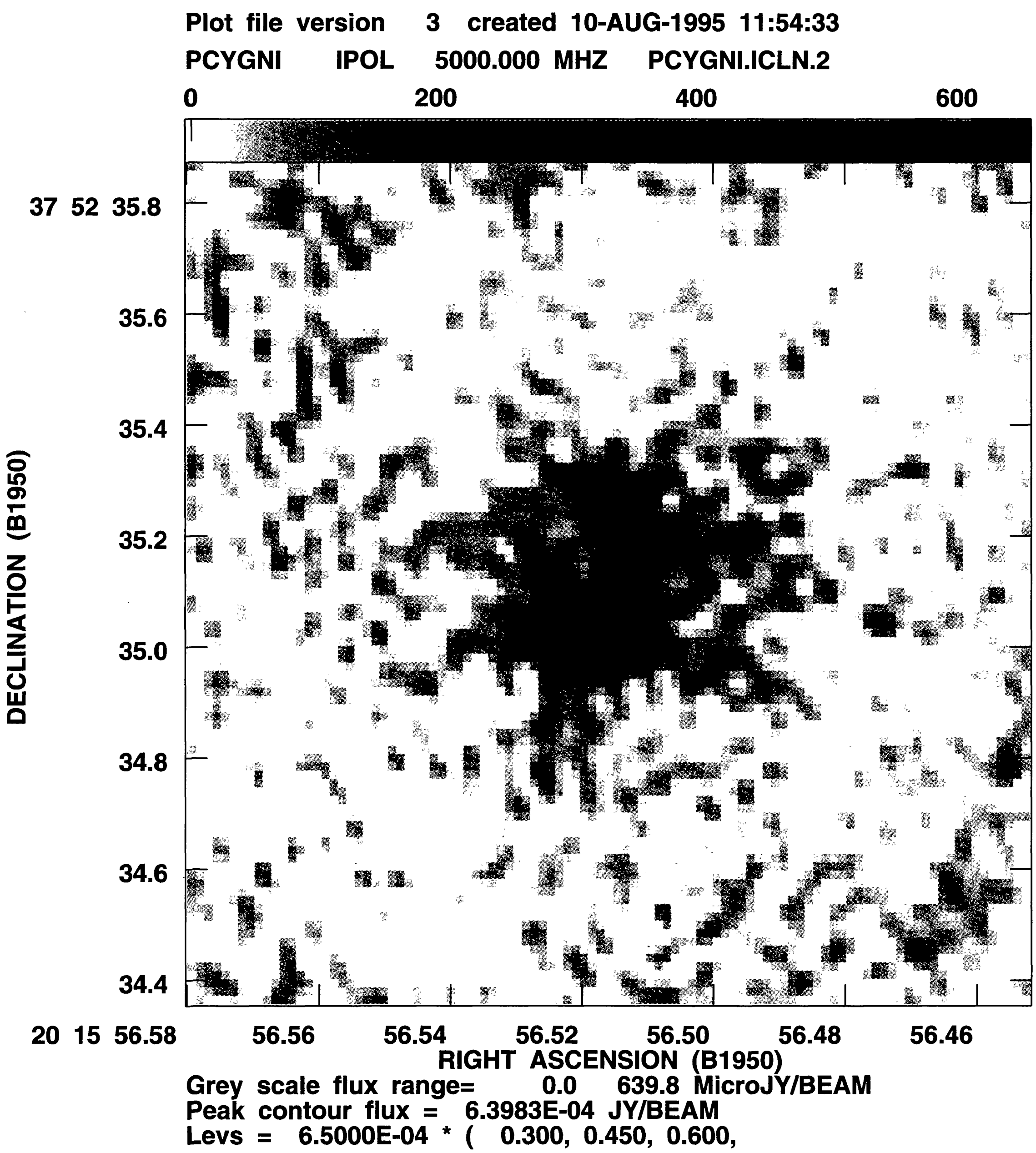

Figure 1. 6-cm MERLIN image of P Cyg obtained on 1992 June 24. The beam is an ellipse of size $48 \times 51\,\mathrm{mas}^2$. Contours are plotted at intervals of 0.0447 Jy arcsec^{-2}, with the base level at 0.0894 Jy arcsec^{-2}, corresponding to a brightness temperature T_b of 4950 K. The highest contour corresponds to 0.2682 Jy arcsec^{-2} (T_b = 14 850 K) and the peak intensity on the map corresponds to T_b = 16 510 K. The rms noise level is 0.055 Jy arcsec^{-2}.

the beam tapered to a 0.3-arcsec circle. The derived fluxes are listed in Table 1. The flux indeed changed, from 4.8 mJy on June 24 to 3.8 mJy on August 4. Although some flux will have been lost by MERLIN, these values fall within the range of 2–11 mJy previously measured at 6 cm over a five-year period (van den Oord et al. 1985).

3 DISCUSSION

The MERLIN images, even individually, suggest that P Cyg's wind is somewhat chaotic. The brighter parts of the nebula, the contours of which have changed shape and location radically between the two images, are detected at signal-to-noise ratios (S/N) of between 6σ and 9σ, and it is highly unlikely that the differing appearances of the nebula in the two images are the result simply of poor S/N. The flux variability adds support to this.

Time-scales for variability in P Cyg's wind have been discussed previously by van den Oord et al. (1985), who also found that significant variations could occur on a time-scale as short as a month. The wind terminal velocity for P Cyg is 206 km s^{-1} (Lamers et al. 1985), and our images suggest a radius of order 0.05–0.1 arcsec for the 6 cm emitting zone, which for a distance of 1.8 kpc indicates that mass-loss variations would take about 2 yr to alter the 6-cm flux substantially, compared with the 40 d we find to be an upper limit for the time-scale.

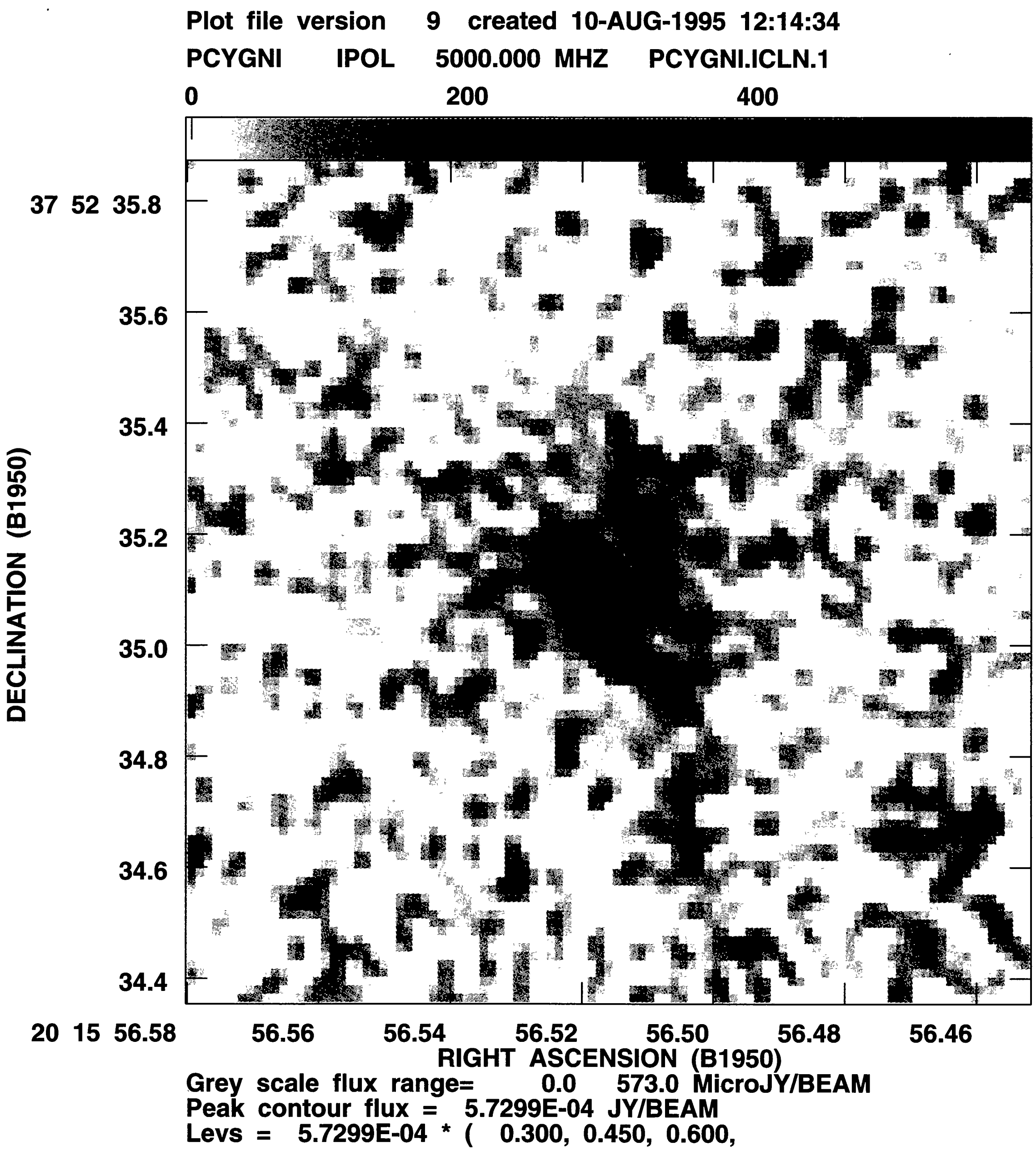

Figure 2. As Fig. 1, but the image taken on 1992 August 4. Contours are plotted at intervals of 0.0507 Jy $arcsec^{-2}$. The base level is at 0.1014 Jy $arcsec^{-2}$ (T_b = 5620 K). The highest contour level plotted corresponds to 0.3042 Jy $arcsec^{-2}$ (T_b = 16 860 K) and the peak intensity on the map corresponds to T_b = 18 430 K. The rms noise level is 0.052 Jy $arcsec^{-2}$.

From our images, the characteristic 6-cm angular radius is 0.07 arcsec. For an electron density of n_e cm^{-3}, the recombination time-scale for hydrogen atoms is $1.2 \times 10^5/n_e$ yr, so for a characteristic n_e of 2.8×10^5 cm^{-3} at 0.07 arcsec (Wright & Barlow 1975) the recombination time-scale is about 160 d. Thus clumps with densities of about four times the mean value could in principle recombine, varying the free–free emission, on the required time-scale of 40 d.

Assuming that the brightest emission peaks in our MERLIN maps correspond to optically thick free–free emission, the brightness temperatures T_b observed at the peaks indicate the clump electron temperatures. The peak brightness temperatures of 14 000–18 000 K are consistent with thermal emission from the wind material around P Cyg, which has $T_{eff} \sim 2 \times 10^4$ K. If we assume that the depth of a clump's emitting region is the same as its observed diameter (1.35×10^{15} cm for an angular diameter of 0.05 arcsec) then a free–free optical depth of unity corresponds to an electron density of 6.4×10^5 cm^{-3}, similar to the mean wind density derived above. Denser clumps would have shorter recombination time-scales, with free–free optical depths of unity closer to their surfaces. The sizes measured for the brightest clumps are near MERLIN's resolution limit. If higher resolution observations were to indicate that the clumps actually have significantly smaller diameters, then a non-thermal emission mechanism would be required. However, all current evidence suggests that thermal free–free emission is the sole mechanism.

Although we have shown that the clump electron densities are probably sufficiently high for recombination to explain the observed variability time-scale of about a month, a mechanism to cause such recombination needs to be identified. Dense shells appear to be ejected by P Cyg at intervals of about a year (Lamers et al. 1985). Van den Oord et al. (1985) suggested that an optically thick shell would temporarily shield the outer part of the wind from ionizing photons so that the wind would recombine. However, the electron density in P Cyg's wind is maintained by ionization out of the $n = 2$ level of hydrogen by near-UV photons shortwards of the Balmer jump (Drew 1985). Ejected shells should not influence the degree of ionization in the wind due to increased opacity in the hydrogen Lyman continuum, since this continuum is already optically thick. Furthermore, hydrogen Lyα photons are unlikely ever to become optically thin in the radio-emitting regions, so this is not a means of causing the $n = 2$ population and ionization of hydrogen to collapse (Drew 1985). Instead, since the $n = 1$ and $n = 2$ level populations of hydrogen are in Boltzmann equilibrium, a decrease in the electron temperature should cause a decrease in the $n = 2$ population and thus a decrease in the ionization (Drew 1985). Since collisionally excited heavy element forbidden and semi-forbidden lines will cool the wind rapidly once the lines become optically thin, we suggest that the escape probabilities are low for these lines within the denser clumps, leading to relatively high local electron temperatures, but that once key cooling lines become optically thin the clumps rapidly cool and recombine, causing the free–free emission to disappear.

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