Circumstellar Molecular Gas of PV Cephei Observed with the OVRO Millimeter Array

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Introduction

The peculiar pre-main sequence object PV Cephei (HBC 696; IRAS 20453+6746) is located in L1158, near NGC 7023, at a distance of 500 pc. This variable star is associated with a large fan-shaped nebula (designated GM 29) which was absent from the first Palomar sky survey and which has varied widely in brightness and morphology since its discovery in 1977 (Gledhill, Warren-Smith, and Scarrott MNRAS 229 643 1987). PV Cephei has been classified as a Herbig Ae star (A5e+shell) in the catalog of Thé et al. (A.A.Suppl. 104 315 1994); however, Hamann and Persson (Ap.J. 394 628 1992) assign it a spectral type of F2. The system luminosity is estimated to be 80-100 $L_\odot$. PV Cephei is the source of a strong bipolar CO outflow which is aligned roughly north-south and which extends a total distance of $10'$ (1 pc; Levreault Ap.J. 277 634 1984). Anglada *et al.* (Ap.J. 395 494 1992) detected a 3.6 cm continuum source at the stellar position using the VLA, and interpreted it as evidence for an ionized wind near the star. An H_2O maser has also been found $5''$ south of the star by Rodriguez *et al.* (A.A. 186 319 1987). Very recently Whitney and Gomez have discovered a collimated jet of optical [S II] emission along the outflow axis at a distance of $4'$ from the star, evidence suggestive of an episodic outflow process.

Several studies have addressed the circumstellar material of PV Cephei. The spectral energy distribution rises steeply from 3 μm to 100 μm, defining PV Cep as a "class I" young stellar object accompanied by substantial amounts of warm dust. Natta *et al.* (Ap.J. 406 674 1993) find that the 100 μm source is unresolved in a $20''$ KAO beam. There are between 3 and 10 magnitudes of visual extinction toward the star (Van Citters and Smith A.J. 98 1382 1989; Hamann and Persson 1992), and a very large stellar polarization of 16% (Scarrott, Rolph, and Tadhunter MNRAS 249 131 1991). The latter, along with the large ratio of infrared to optical luminosity (9), suggests that PV Cephei may be seen via reflection at optical wavelengths as has recently been found to be the case for HL Tauri (Stapelfeldt *et al.*

Ap.J. 449 888 1995). The star has a moderately strong 3 μm ice absorption feature in its spectrum (Van Citters and Smith 1989). Levrault (1984) proposed that a circumstellar disk could collimate the outflow and produce the observed shape of GM 29. Recent models of YSO infrared spectral energy distributions and reflection nebula morphology suggest that PV Cephei should possess an extended circumstellar envelope within which a circumstellar disk might lie. No circumstellar NH_3 emission was detected by Torreles *et al.* (Ap.J. 307 787 1986), and until now no CO interferometry had been done.

Observations

PV Cephei was observed at OVRO during the 1994-1995 season with six 10.4 m telescopes. Continuum measurements were obtained at 110 GHz (2.7 mm) with a bandwidth of 1 GHz. Spectral line observations were made simultaneosly in ^{13}CO 1-0 (110.2 GHz) and C^{18}O 1-0 (109.8 GHz) using a digital correlator which provided 64 channels of width 0.08 km s^{-1} for each emission line. The resulting maps have a $1'$ field of view. The field was centered on the optical stellar position (Herbig and Bell, Lick Obs. Bull. 1111 1 1988). Two telescope configurations with largest baselines 200 m E-W and 100 m N-S yielded a synthesized beam of $3.9''$x$3.2''$ elongated at PA 278°. Spectral line observations were made over the VLSR range 0.0-5.0 km s^{-1}.

Results: Continuum Emission

A single unresolved millimeter continuum peak is present at the stellar position. The location of this peak is $\alpha = 20^h45^m23.32^s, \delta = +67°07'35.8''$. It is coincident with the 3.6 cm continuum peak reported by Anglada *et al.* 1992 and less than $0.2''$ from the reported optical position of PV Cephei (Levreault Ap.J.Suppl. 67 283 1988). The continuum emission must arise within a region less than 1000 AU in diameter in order for it to remain unresolved at PV Cephei's distance of 500 pc. The 2.7 mm flux density is 38±4 mJy. This is much greater than would be expected by extrapolating the 3.6 cm flux density (0.2 mJy) to higher frequencies using a power law appropriate to free-free emission (F$\propto \nu^{0.6}$.) Most likely this flux originates in thermal dust emission, as is typical for young stellar objects at 3 mm. In this case an approximate circumstellar material mass can be calculated: assuming optically thin emission, a 2.7 mm mass opacity of 0.01 cm^2 gr^{-1}

(corresponding to an opacity spectral index $\beta = 1$), and a characteristic circumstellar temperature of 40 K, the circumstellar mass would be 0.3 $M_\odot$. There is also strong 1.3 mm continuum emission from PV Cephei (208$\pm$15 mJy; Osterloh and Beckwith Ap.J. 439 288 1995). The continuum slope between 1.3 mm and 2.7 mm follows a shallow spectral index of only -2.32, suggesting that the millimeter continuum emission is optically thick.

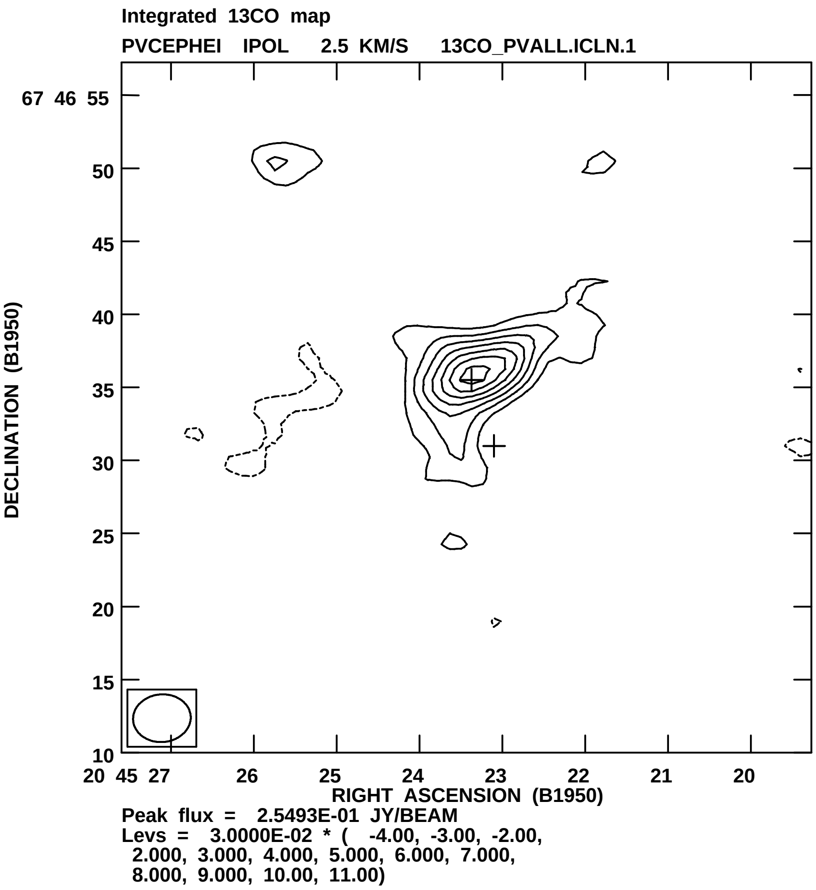
Results: ^{13}CO and C^{18}O Line Emission

The ^{13}CO isotope emission peaks at the same position as the continuum emission. It is spatially resolved, with a deconvolved source size of 2600 AU at PA 120° and unresolved in the perpendicular direction. Morphologically similar but much weaker C^{18}O emission is seen at the same position. ^{13}CO emission is seen over the VLSR velocity range 1.8-4.3 km sec^{-1}, but vanishes at the intermediate velocity 2.6-3.0 km sec^{-1}. This appears to be self-absorption from a highly optically thick line; a similar behavior is seen in millimeter interferometry of embedded YSOs. The circumstellar emission appears NW of the star at the lower velocities (1.9-2.2 km sec^{-1}), and SE of the star at higher velocities (3.2-3.6 km sec^{-1}). At the velocity extrema (1.9 and 4.3 km sec^{-1}) the emission lies very close to the stellar position. In addition to the circumstellar emission, there is widespread extended ^{13}CO between 2.0-2.4 km sec^{-1}. The C^{18}O emission brightness was too low to facilitate good channel maps, although this weak emission was concentrated in the velocity range 2.6-3.0 km sec^{-1} where the ^{13}CO is self-absorbed.

The long axis of the circumstellar CO isotope emission is aligned only 40° from the axis of GM 29 and the recently discovered optical jet. If the flattened CO emission structure seen here does trace an extended disk, then its outer parts do not extend perpendicular to the outflow axis. This unexpected result might be explained by a warped disk whose symmetry plane near the source is more nearly perpendicular to the jet axis. Exploration of this possibility will require observations with a spatial resolution several times better than the current dataset.

Discussion and Conclusions

Recent IRAM interferometry of five AeBe stars by Di Francesco *et al.* (BAAS 48 14 1995) revealed that the single dish detections of their sources were due to nearby embedded objects and not the AeBe stars themselves. PV Cephei does not fit into this pattern. It shows instead that Ae stars can possess massive amounts of circumstellar material, probably disks, at the earliest evolutionary stages associated with strong bipolar outflow. The implication of these observations is that circumstellar matter dissipates rapidly among AeBe stars, and thus less time is available for planet formation in these systems than in the case of lower mass stars.



In figure above, the upper cross marks the location of the 2.7 mm continuum peak; the lower cross marks the position of the H_2O maser found by Rodriguez *et al.* (1987).