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A VERY FAST MOLECULAR OUTFLOW FROM THE PROTO–PLANETARY NEBULA CRL 618

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ABSTRACT

Observations of the CO(2–1) and CO(3–2) lines from the highly evolved carbon star/proto–planetary nebula CRL 618 show the presence of a very high velocity molecular outflow with $V_0 > 190$ km s^{-1}.

Subject headings: molecular processes — nebulae: planetary — nebulae: structure — stars: carbon — stars: winds

I. INTRODUCTION

Several post–asymptotic giant branch (AGB) stars evolving toward the planetary nebula stage have been identified in recent years. These are strong infrared sources with extended molecular envelopes produced by red giant mass loss at speeds like 20 km s^{-1} which have optical or radio emission from ionized gas in the central regions. Sensitive molecular line observations of these protoplanetary nebulae (PPNs) made recently with the Caltech Submillimeter Observatory (CSO) show that several such sources have not only slow red giant molecular winds but also much faster molecular winds which may be instrumental in shaping the subsequent planetary nebula (Knapp *et al.* 1989). In this *Letter* we describe the most spectacular such wind found to date, that from CRL 618, with a speed of at least 190 km s^{-1}.

II. OBSERVATIONS

Observations of the CO(2–1) line at 230.5 GHz were made using the 10.4 m telescope of the Caltech Submillimeter Observatory on Mauna Kea, Hawaii, in 1988 August and November and 1989 January. The telescope half-power beamwidth is 32″, and the main beam efficiency 72% at this frequency. The CO(3–2) line at 345.8 GHz was observed in 1989 January; the half-power beamwidth is 21″, and the main beam efficiency is 60%. Both receivers (Ellison 1989) used liquid helium–cooled SIS mixers in double-sideband mode, with receiver temperatures of 200–250 K. The calibration was performed using observations of an ambient temperature chopper. The resulting antenna temperatures are corrected for antenna losses and atmospheric opacity and a final correction is applied to give the main-beam brightness temperature.

The spectral line back end is an acousto-optic spectrograph (Masson 1982) with 1024 channels over a bandwidth of 500 MHz, with effective velocity resolutions of 1.3 km s^{-1} at 230 GHz and 0.9 km s^{-1} at 345 GHz. The observations were made in position-switched mode at $\alpha = 04^h39^m34^s$, $\delta = +36°01'15''$ (1950) (Westbrook *et al.* 1975).

A high-sensitivity CO(1–0) line profile for CRL 618 was measured using the AT&T Bell Laboratories 7 m telescope in 1989 February with a half-power beamwidth of 100″. No high-velocity emission was seen, with an upper limit of 1 K × km s^{-1} over the velocity intervals -200 to -42 km s^{-1} and 2 to 144 km s^{-1}; i.e., the mean wing brightness temperature is less than 0.01 K for the CO(1–0) line.

III. RESULTS

The CO(2–1) line profile from 1988 November and the CO(3–2) profile from 1989 January are shown in Figure 1. In both cases, linear baselines have been fitted to the parts of the profile judged to be free of line emission and subtracted from the profile. Two components are seen, the parabolic circumstellar envelope line of width ~40 km s^{-1} at zero intensity, and weaker line wings of very large velocity extent (see Table 2). The CO(2–1) line agrees well with those observed in 1988 August (Knapp *et al.* 1989) and in 1989 January. The general features of the high-velocity CO emission shown in Figure 1 agree with IRAM observations by Cernichero, Guelin, Martin-Pintado, and Mauersberger, reported by Martin-Pintado *et al.* (1988) and Lucas (1989). The total velocity extent of the CO(2–1) line is ~250 km s^{-1} to zero intensity while that of the CO(3–2) line is ~380 km s^{-1}. The maximum outflow speed of this fast wind is at least 190 km s^{-1}; if the fast wind region has the inclination derived from the nebula itself of 45° (Carsenty and Solf 1982), its deprojected outflow speed is >270 km s^{-1}.

The CO(2–1) line was mapped in 1989 January at the half-beamwidth spacing of 15″. The profiles at equal offsets from the central position were averaged and the integrated line brightness found for the main line and for the wings. The results are shown in Figure 2. The main line emission is peaked at the source position, as expected for a centrally heated object, and extended at low levels (comparison with maps of Mars shows that this extension is real), while the wide wing appears to have an angular size smaller than that of the beam, 32″. The flattening of the CO(3–2) profile and the similarity of the peak CO(2–1) and (3–2) temperatures also suggests that the circumstellar envelope is extended.

Table 1 lists the results of parabolic fits to the red giant wind components of the CO(1–0), (2–1), and (3–2) lines. The central velocities and terminal outflow velocities are in good agreement for the three lines. The CO(1–0) intensity agrees well with the value measured 6 years ago using the same telescope by Knapp and Morris (1985), and we therefore do not confirm the increase in the source brightness temperature suggested by Thronson and Mazurkewich (1983) and Bachillar *et al.* (1988).

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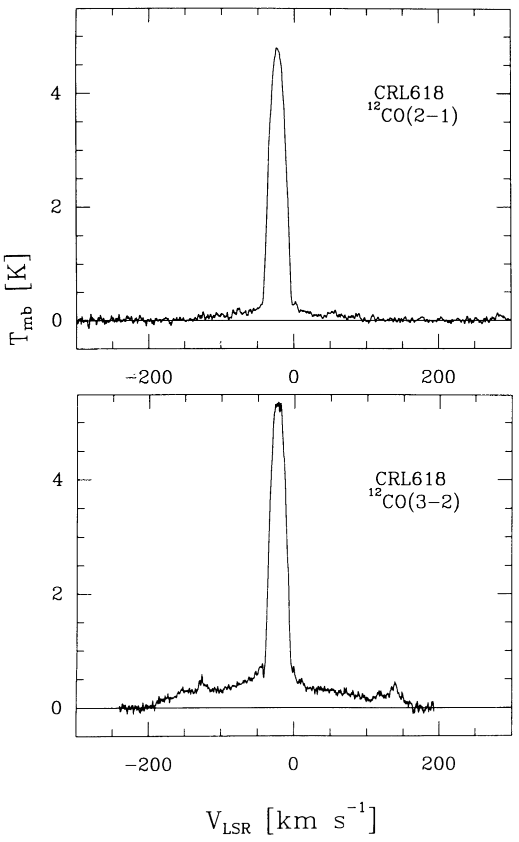

FIG. 1.—*Upper panel*: ^{12}CO(2–1) line profile of CRL 618 observed with the Caltech Submillimeter Observatory in 1988 November. The ordinate is main beam brightness temperature in K; the abscissa velocity with respect to the LSR. *Lower panel*: ^{12}CO(3–2) line profile for CRL 618. The weak feature near −130 km s^{-1} is probably emission in the CS(7–6) line at 342.883 GHz from the main circumstellar component of CRL 618 in the image sideband (2.4 GHz below the signal sideband). The weak feature near +135 km s^{-1} is probably emission in the HC_3N(38–32) line at 345.610 GHz from the main component of CRL 618.

We use a distance of 1300 pc estimated from the observations of Westbrook *et al.* (1975) and an assumed bolometric luminosity of 10^4 $L_\odot$. With a relative CO abundance $n(\mathrm{CO})/n(\mathrm{H_2})$ of 8×10^{-4}, the CO(1–0) data give a mass-loss rate on the AGB of $\sim 8 \times 10^{-5}$ $M_\odot$ yr^{-1}. The radial intensity distribution depicted in Figure 2 suggests that the envelope radius is ~60″ or 10^{18} cm. The total envelope mass is then about 1.5 $M_\odot$.

The radial profile shown in Figure 2 suggests that the wide wing region is smaller than the extended mass-loss envelope. The CO(3–2) line profile in Figure 1 shows a dip at −41.3 km s^{-1} which is at the extreme blueshifted velocity expected for gas in the extended circumstellar envelope (cf. Table 1), also suggesting that the extent of the circumstellar envelope is greater than that of the fast outflow. The width of the absorption dip, ≤0.9 km s^{-1}, gives an upper limit on the radius of the fast wind region of ~20″.

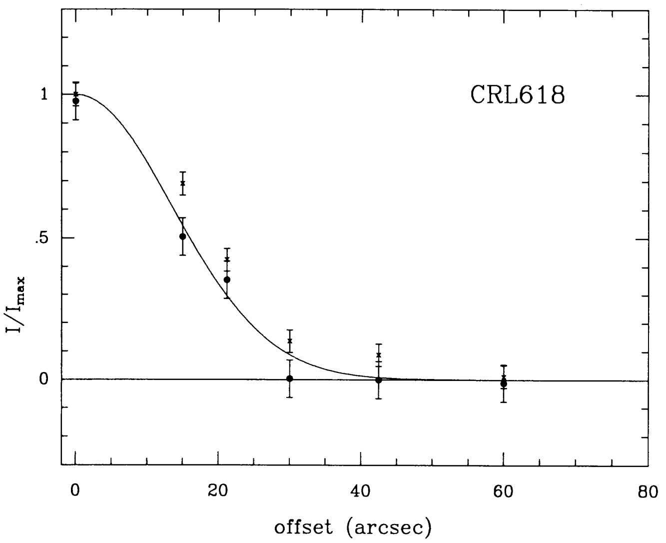

FIG. 2.—Radial dependence of the normalized velocity-integrated intensity for the main CO line for CRL 618 (*crosses*) and for the wings (*dots*).

If a CO line source is optically thin, in thermal equilibrium at temperature T_k and unresolved by the telescope beam, the total mass is

$$\dot{M} \sim 5.7 \times 10^{-4} \sum T_a^* \Delta V D^2 (\mathrm{kpc})\, M_\odot \qquad (1)$$

for the CO(2–1) line observed with a telescope of beamwidth 32″, assuming that the CO/H_2 ratio is 8×10^{-4}. This formula is correct to about a factor of 2 over a temperature range of 15–200 K (cf. also the discussion of Huggins and Healy 1989). The mass of the fast wind source from the CO(2–1) observation (Fig. 2) is then ≥0.06 $M_\odot$. The large-velocity-gradient model of Morris (1980) (with constant outflow velocity, spherical symmetry, CO/H_2 = 8×10^{-4}, $n \sim r^2$ and convolved with Gaussian beams) suggests that the source is unresolved by the CO(3–2) beam and therefore has $r \leq 10''$. The best-fit model has $M \sim 0.1$ $M_\odot$ and $r = 5''$, giving a dynamical age of about 140 yr. This radius is extremely poorly constrained, however. The time scale for the fast wind of 140 yr is similar to the brightening time for the optical object of >50 yr found by Gottlieb and Liller (1976) and the expansion time of the central H II region of ~100 yr measured by Kwok and Bignell (1984).

IV. DISCUSSION

As the observations described above show, CRL 618 has two molecular outflows; a slow, "red giant" outflow with a speed of 20 km s^{-1} and a second much faster outflow with a speed of >190 km s^{-1}. The slow wind region is larger than the fast wind region, showing that the fast molecular wind is emitted after the end of the red giant mass loss phase.

TABLE 1

OBSERVATIONS OF CRL 618 CIRCUMSTELLAR ENVELOPE

Line	HPBW	T_{mb}*(peak) (K)	V_c (km s^{-1})	V_0 (km s^{-1})
CO(1–0)	100″	0.41 ± 0.02	−22.3 ± 0.1	19.7 ± 0.2
CO(2–1)	32	4.8 ± 0.2	−22.6 ± 1.0	19.1 ± 0.8
CO(3–2)	22	5.4 ± 0.4	−22.2 ± 2.0	18.9 ± 1.2

TABLE 2

OBSERVATIONS OF FAST MOLECULAR WIND FROM CRL 618

Line	T^*_{mb} (K)	V_c (km s^{-1})	V_0 (km s^{-1})
CO(2–1)	0.36	−15	125
CO(3–2)	0.75	−19	190

Strong H_2 emission is seen from this nebula (Beckwith, Beck, and Gatley 1984) indicating the presence of shocked molecular gas; the H_2 line also shows a large velocity extent (Burton and Geballe 1986). One possible interpretation of these observations is that the high-velocity molecular gas is material from the circumstellar molecular cloud shock-accelerated by a fast ionized wind from the central star; such winds have been proposed to shape the subsequent planetary nebula (Kwok 1987). However, shock acceleration of molecular gas to speeds greater than 50 km s^{-1} results in the destruction of the molecules (e.g., Draine 1983). Further, CRL 618 is an optical bipolar nebula whose lobes are separated by about 7″ (similar to the diameter of the fast molecular wind region suggested by our observations), and the H_2 emission peaks on the eastern lobe, not at the position of the central star (Beckwith, Beck, and Gatley 1984). Shock-produced forbidden line emission is also seen from the lobes (Schmidt and Cohen 1981). These observations suggest that the shocks are occurring in the lobes and not the vicinity of the star and are due to the interaction of a fast *molecular* wind with the previous slow molecular wind.

Morris (1981) has proposed that the morphology of evolved bipolar nebulae can be explained by the gravitational influence of a companion main-sequence star in an asynchronous binary system with the red giant. The velocity of 200–300 km s^{-1} of the fast molecular wind in CRL 618 suggests that it may be ejected from the vicinity of the companion star. However, it could also be identified with the final stage of mass loss from the red giant itself just before it evolves from the AGB. This ejection could be the result of the final thermal pulse of the star which causes the envelope to leave the star and the star to evolve from the AGB (Härm and Schwarzschild 1975); it remains to be explored whether this ejection is gentle enough to preserve the gas in molecular form.

Models of the final stages of AGB eveolution (e.g., Paczyński 1971; Schönberner 1983; Kwok 1987) suggest that the evolution time of a star between the AGB phase and when it becomes hot enough to ionize the surrounding circumstellar envelope is $\sim$1–2 × 10^3 yr, as the final H-burning shell is consumed. If the mass loss which produces the circumstellar envelope ceases at the end of the AGB phase, the envelope continues to coast at its ejection speed of 20 km s^{-1}, and after 200 yr has reached a distance of about 6″ from the central star. However, the central H II region in CRL 618 measures 0″.4 × 0″.2 (Kwok and Bignell 1984) showing the presence of dense gas close to the star and suggesting that the evolution between the cessation of mass loss and the beginning of nebular ionization is considerably shorter than 2000 yr. We suggest that this rapid evolution is accomplished by the ejection of the remains of the envelope in the form of a fast, high-density molecular wind as the star begins to contract and heat up. This wind may itself be bipolar due to the increased rotational frequency of the contracting star. Indeed, the presence of a similar high-velocity wind in the Egg nebula CRL 2688 (Kawabe *et al.* 1987; Young *et al.* 1989), whose central star is of type F, shows that the high-velocity molecular flow begins *before* the central star is hot enough to begin ionizing the nebula. CRL 618 appears to be at the stage of beginning to ionize both the fast and slow molecular winds, as shown by the shapes of the millimeter-wavelength recombination lines (Martin-Pintado *et al.* 1988) and the width of the Hα line (Carsenty and Solf 1982).

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