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CRL 2688 AND CRL 618: PROTO–PLANETARY NEBULAE?

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ABSTRACT

Emission from the $J = 1 \rightarrow 0$ transition of $^{12}C^{16}O$ has been detected at 2.6 mm from the peculiar infrared objects CRL 2688 (the Egg Nebula) and CRL 618. The observed parabolic line-shape can be interpreted as optically thick emission from a uniformly expanding molecular envelope with a size smaller than the telescope beam. The line width indicates an expansion velocity on the order of 20 km s^{-1}. Other molecular lines similar to those observed in the envelope of the carbon star IRC +10216 are also observed in CRL 2688, even though the central star in CRL 2688 has a relatively early spectral type (F5 Ia). In CRL 618, the existence of an expanding molecular envelope around a central star with spectral type B0 implies that the central star has evolved within a very short time ($<10^4$ years) from a cool, perhaps carbon-rich, star. The presence of mass loss and the rapid evolution of the central stars suggest that CRL 2688 and CRL 618 may be proto–planetary nebulae. It is noted that IRC +10216, CRL 2688, CRL 618, and the planetary nebula NGC 7027 may represent different stages of an evolutionary sequence. Other peculiar objects such as M1-92 (Minkowski's Footprint), HD 44179 (the Red Rectangle), OH 0739−14, and HD 200775 have also been searched for circumstellar CO emission, but no emission greater than 0.2 K (5 σ) was detected.
Subject headings: molecular processes — nebulae: planetary — stars: carbon — stars: circumstellar shells

I. INTRODUCTION

Millimeter-wavelength emission lines from circumstellar molecular envelopes have been observed in only a few carbon-rich stars such as IRC +10216 and CIT-6 (e.g. Wilson, Schwartz, and Epstein 1973). However, analysis of such emission lines, when combined with optical and infrared observations, forms a powerful tool for probing the physical conditions: the temperature, the densities, the chemical compositions, the kinematics, and the dynamics of the molecular envelope (e.g., Morris 1975). In this *Letter*, we report on the molecular envelopes around two infrared objects to which such analysis can be applied and which may be progenitors of planetary nebulae.

Recently, a few infrared sources with a roughly biconical visual appearance have been studied intensively at various wavelengths. They are CRL 2688, the Egg Nebula (Ney *et al.* 1975; Crampton, Cowley, and Humphreys 1975); HD 44179, the Red Rectangle (Cohen *et al.* 1975); M1-92, Minkowski's Footprint (Herbig 1975); and CRL 618 (Westbrook *et al.* 1975). The models proposed to explain the observations of these objects all include a dense dust disk surrounding a central star of early spectral type, with the biconical nebula being due to reflected starlight escaping along the paths of minimum extinction. The nature of the evolutionary state of these objects is, however, unknown. Furthermore, it is uncertain that they are similar to each other.

Other objects of interest are OH 0739−14 (Turner 1971; Wynn-Williams, Becklin, and Neugebauer 1974) and HD 200775 (Lépine and Rieu 1974) which together with M1-92 are characterized by their unusual 1667 MHz OH emission spectrum, with a narrow feature superposed on a weaker and very broad ($\lesssim$75 km s^{-1}) emission feature. HD 200775 is a B3e shell star (Herbig 1960) while OH 0739−14 is an extended infrared source without an identified optical counterpart.

The above objects were searched for $^{12}C^{16}O$ $J = 1 \rightarrow 0$ emission, and in some cases, also for $^{13}C^{16}O$ $J = 1 \rightarrow 0$ and $^{12}C^{14}N$ $K = 1 \rightarrow 0$ emission.

II. OBSERVATIONS

The observations were carried out on the NRAO[1] 36 foot (11 m) telescope at Kitt Peak with the 80–120 GHz dual-channel cooled mixer receiver. Only one channel was used, and the received signal was split and fed into two filter-banks each of 256 channels. The filter-banks had filter bandwidth and channel separation of 250 kHz and 500 kHz. The spectra were obtained in the total power mode in which the telescope was moved between the source and a reference position (usually west in right ascension by $1^m/\cos \delta_s$) every 60 seconds.

The system temperature, the antenna beam efficiency,

[1] The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under contract with the National Science Foundation.

TABLE 1

Parameters of Observed Lines

Parameter	CRL 2688	CRL 618	HD 200775
α (1950)	$21^h00^m20^s$	$04^h39^m34^s$	$21^h00^m59.7$
δ (1950)	36°29′44″	36°01′15″	67°57′56″
V_{LSR} (km s^{-1})	-34.5 ± 1	-25.0 ± 3, 4.6 ± 1	4.0 ± 1
$T_A^*(^{12}CO)$ (K)	1.0 ± 0.05	0.35 ± 0.05, $0.25\dagger\pm0.05$	$5.3\ddagger\pm0.1$
$T_A^*(^{13}CO)$ (K)	0.16 ± 0.05	... , ...	$0.56\ddagger\pm0.1$
T_A^* (CN)	<0.1	<0.15, <0.15	...
V_{LSR}(optical) (km s^{-1})	-28 ± 8[a]	-50 ± 20[b]	...

† Possible narrow interstellar component.
‡ Spatially extended, narrow line-width CO emission, most likely to be interstellar in origin.
[a] Crampton *et al.* 1975.
[b] Westbrook *et al.* 1975.

and the atmospheric attenuation were calibrated following the procedures outlined by Ulich and Haas (1976). The corrected antenna temperature (T_A^*) quoted in this paper is then the excess antenna temperature due to the line emission that one would measure outside the atmosphere with a lossless antenna.

III. RESULTS

Observations of the emission lines from CRL 2688, CRL 618, and HD 200775 are summarized in Table 1 which gives the coordinates, the LSR radial velocity of the CO emission, the T_A^* of the various transitions or the 5 σ upper limits, and the V_{LSR} of the objects derived from optical spectra. For CRL 618, the V_{LSR} (optical) derived from fairly low dispersion spectra (Westbrook *et al* 1975) can be taken as equal to the V_{LSR}(CO) within the errors. CO emission from the vicinity of HD 200775 has already been reported by Loren, Vanden Bout, and Davies (1973) and is presumably interstellar in origin.

The CO spectra from CRL 2688 and CRL 618 are shown in Figures 1 and 2, respectively. The line widths are large (>30 km s^{-1}). In the case of ^{12}CO emission from CRL 2688, a parabolic line-shape has been fitted by inspection to the observed spectrum. It has been shown that optically thick line emission from an unresolved uniformly expanding spherical gas cloud has a parabolic line-profile (Sobolev 1960; Morris 1975). The expansion velocity of the molecular envelope of CRL 2688 deduced from fitting the parabolic line profile to the observed profile is ~19.3 km s^{-1}. The ^{13}CO spectrum from CRL 2688 is consistent with being flat-topped, as expected from optically thin line emission from an unresolved, uniformly expanding gas sphere. The negative results of observations at points 1′ away from the central position show that the ^{12}CO emission region to be smaller than 1′.

The spectrum of the ^{12}CO emission from CRL 618 appears to consist of two components, at 4.6 km s^{-1} and -25 km s^{-1}. The broad emission at -25 km s^{-1} also suggests optically thick emission from a molecular envelope expanding or contracting at a velocity of ~20 km s^{-1}.

The $^{12}C^{14}N$ $K = 1 \rightarrow 0$ transition was also searched for from CRL 2688 and CRL 618, but no emission above

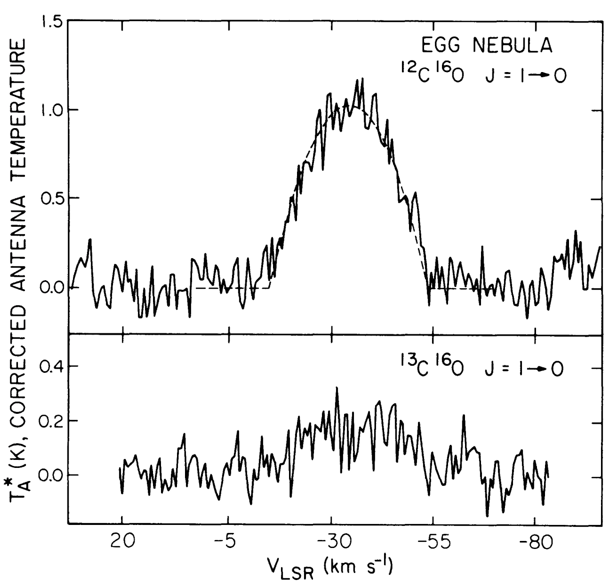

Fig. 1.—Spectra of CO emission from CRL 2688 at a frequency resolution of 250 kHz. The $^{12}C^{12}O$ spectrum was obtained with a total integration time of 80 minutes. The dashed curve is parabolic, with the form $T_A^* = T_0[1 - (V_{LSR}/V)^2]$. It is fitted to the CO line profile by inspection, with the parameters $T_0 = 1$ K and $V = 19.3$ km s^{-1}. The ^{13}CO spectrum was obtained with a total integration time of 160 minutes. No fitting was attempted because of the poor signal-to-noise ratio.

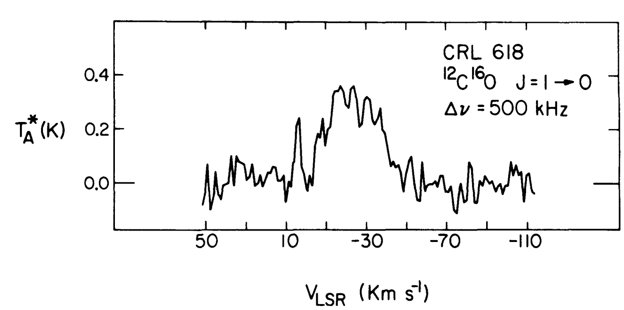

Fig. 2.—Spectrum of the ^{12}CO emission from CRL 618 at a frequency resolution of 500 kHz. T_A^* is the corrected antenna temperature.

0.15 K was detected (cf. Table 1). However, in IRC +10216, T_A* of CN is twice that of ^{13}CO.

M1-92, HD 44179, and OH 0739−14 were searched for ^{12}CO emission, but the results were negative. Table 2 gives the coordinates, the V_{LSR} corresponding to the center of the filter-banks, and the 5 σ upper limits to ^{12}CO emission.

IV. DISCUSSION

The large line-width and the parabolic line-shape of the ^{12}CO emission from CRL 2688 and CRL 618 suggest that the emission arises from a uniformly expanding or contracting molecular envelope. The absence of CO emission at points 1′ away from the central position and the apparent lack of obscuring matter around CRL 2688 make mass-inflow or a contracting molecular envelope an unlikely process. Similarly, there is no evidence of nebulosity surrounding CRL 618, as shown by the lack of narrow CO emission lines typical of that from nebulosity associated with stars (Loren, Vanden Bout, and Davies 1973) at the optical velocity. Hence, we conclude that the molecular envelopes around CRL 2688 and CRL 618 are expanding and presumably originate from the central stars. Such expanding envelopes resemble that around IRC +10216 (Solomon *et al.* 1971; Morris 1975). In particular, millimeter lines of HCN, H^{13}CN, HC$_3$N, and CS have been observed from CRL 2688 (Zuckerman *et al.* 1976). A very important difference between IRC +10216 and CRL 2688 and CRL 618 is, however, that the latter two objects have central stars of relatively early spectral type—F5 Ia in CRL 2688 and B0 in CRL 618.

From the CO observations of CRL 2688, we can make estimates of the physical quantities of the molecular envelope. Assuming a constant mean excitation temperature $\bar{T}_{ex}$, we determine from the intensity of the ^{12}CO line and the source size of $<1'$ that $\bar{T}_{ex}$ is higher than 4 K. From the ^{13}CO and ^{12}CO line ratio, adopting an envelope radius similar to that in IRC+10216 (2.5×10^{17} cm, equivalent to a source size θ of 33″ at a distance D of 1 kpc), a total particle density $N(r) = kr^{-2}$, and assuming constant $\bar{T}_{ex}$, we get $k = 1.4 \times 10^{33}/f$ cm^{-1}, where f is the fractional abundance of ^{13}CO molecules in the envelope. Taking $f(^{12}\mathrm{CO}) = 1.7 \times 10^{-3}$ from the computations of Tsuji (1965) for a carbon-rich supergiant and a mean ^{12}C/^{13}C ratio of 30, determined from 12 K giants and subgiants (Dearborn, Lambert, and Tomkin 1975), we estimate $f(^{13}\mathrm{CO}) = 6 \times 10^{-5}$. This assumed value of f is quite uncertain. The total envelope mass is $4\pi k D \theta m_{H_2}$ which for the parameters assumed is equal to $M/M_{\odot} = 0.1$. The mass-loss rate is $4\pi k V m_{H_2}$, where V is the expansion velocity, and equals 3×10^{-5} $M_{\odot}$ yr^{-1}. The quantities derived are dependent on the assumed parameters of θ, D, and $f(^{13}\mathrm{CO})$ and should be taken as indicative values only.

Although detailed abundance ratios in the CRL 2688 molecular envelope are not yet available, the existence of CO, HCN, HC$_3$N, and CS indicates that the C/O ratio is greater than 1 (Tsuji 1965). Crampton, Cowley, and Humphreys (1975) attributed anomalous absorption features and some emission in the CRL 2688 spectrum to C$_3$ and C$_2$, respectively. All this suggests that the F5 Ia central star in CRL 2688 is in, or has recently (within the envelope expansion time scale of a few thousand years) passed through, the stage of a carbon star. Crampton, Cowley, and Humphreys (1975) also pointed to the similar spectroscopic appearance of CRL 2688 to that of the young stars V1057 Cyg and FU Ori. However, our CO studies of V1057 Cyg (Bechis and Lo 1975) and FU Ori (Bechis and Lo 1976) indicate that the CO emission orginates from the gas in the general neighborhood of the stars, and that no broad emission from expanding envelopes is present. Its spatial isolation, the difference of its CO emission from that of young stars, the carbon richness, the presence of mass outflow, and the possible rapid evolution of the central star all suggest that CRL 2688 is at a late stage of stellar evolution.

The ^{12}CO emission from CRL 618 is very weak, and its spatial extent has not been determined. However, lines from other molecules such as HCN, HC$_3$N, CS, SiS, and SiO should be searched for, especially since a central infrared source favorable to the excitation of the molecules is present. Nonetheless, the mere existence of an expanding molecular envelope around a central star of spectral type B0 in CRL 618 has several interesting implications, all of which point to the rapid evolution of the central star. First, the central star must have evolved within the expansion time scale of the envelope ($\lesssim 10^4$ years) from a cool, perhaps carbon-rich star which produced all the molecules in its atmosphere. Second, the lifetime of CO against photodissociation near a B0 star is very short (<700 years at a distance of 5×10^{16} cm from the star, with 3 mag of visual extinction, assuming 0.01 for the quantum efficiency of decomposition; cf. Stief *et al.* 1972). Third, from the diameter of the region of ionized gas (0.″25; cf. Westbrook *et al.* 1975) around the central star, we estimate the age of the H II region from the expansion time of the ionization front to be less than $100 \times (D/\mathrm{kpc})$ years. In short, the above considerations indicate that the central star could not have been a B0 star for very long.

An alternate model to explain the broad CO emission from CRL 618 is that there is a binary stellar system consisting of a B0 star which dominates the optical light and a late-type star which is not prominent in the optical but is responsible for the maintenance of the molecular envelope. This may eliminate the argument for a short envelope expansion time scale, but the short time scales posed by the photodissociation life-

TABLE 2

NEGATIVE RESULTS

Source	α(1950)	δ(1950)	V_{LSR} (km s^{-1})	T_A*(^{12}CO) (K)
M1-92..........	19^{h}34^{m}20^s	29°26′04″	0.0	<0.1
			−530.0	<0.2
HD 44179*.....	06^{h}17^{m}37^s	−10°36′52″	27.0	<0.1
OH 0739−14...	07^{h}39^{m}59^s	−14°35′43″	25.0	<0.1

* The Red Rectangle.

time of CO and the age of the H II region could still be strong arguments for a rapid evolution of the B0 star.

From the high electron density, the compact nature, large dust optical depth, and spatial isolation, Westbrook *et al.* (1975) suggested that CRL 618 is an extremely young planetary nebula, perhaps still in the process of formation. This proposal is supported by the rapid evolution of the central star inferred from the CO observation reported here. Furthermore, the presence of molecular envelopes in extremely young planetary nebulae is perhaps to be expected since broad emission has been detected from NGC 7027, a bona fide planetary nebula (Mufson, Lyon, and Marionni 1975). Another check of this proposal is to determine the surface gravity g of the central star and compare it with the typically high g of a planetary nebula nucleus.

The existence of mass loss, the rapid evolution of the central star, the similarity of the expansion velocity to that in planetary nebulae, and envelope mass close to the mass of planetary nebulae suggest that CRL 2688 and CRL 618 may represent some intermediate stage between red giants and planetary nebulae. In particular, the central stars of CRL 2688 and CRL 618 may be identified with points along the theoretical stellar evolutionary track of the transitions from a red giant to a blue nucleus after ejection of a planetary nebula (Härm and Schwarzschild 1975). If IRC +10216, CRL 2688, CRL 618, and the planetary nebula NGC 7027, in the order of progressively earlier spectral type of the central stars, mark different points along an evolutionary sequence, then the similarity of the molecular envelopes raises the question whether all planetary nebulae pass through the carbon-star stage (Zuckerman *et al.* 1976). In this context, it is important to establish the carbon richness of the CRL 618 molecular envelope[2] and to search for and study molecular envelopes in other cool stars, supergiants, and peculiar infrared objects.

[2] The presence of [C I] λλ9823, 9849 in the CRL 618 spectrum (Westbrook *et al.* 1975) does not necessarily imply carbon richness.

If we accept that CRL 2688 and CRL 618 are at transitory stages before becoming planetary nebulae, we also need to consider the relationship between the molecular envelopes and the optical planetary nebulae. During the formation of the planetary nebula, the circumstellar molecular envelope may be swept out by the ejected outer envelope of the central star and form a shell external to the optical nebula, as is observed perhaps in NGC 7027. Since planetary nebulae must be ejected from extreme giants, most likely red giants (Abell and Goldreich 1966), CRL 2688 and CRL 618 with early-type central stars must be at some stage after the outer stellar envelope has been ejected. However, in the absence of visual evidence of such ejected envelopes in CRL 2688 and CRL 618, either the rapidly cooled ejected matter is identified with the obscuring matter immediately around the central star or it has become the inner stratum of the molecular envelope. Stratified structure in the molecular envelope should be looked for with high angular resolution, and better determinations of the size and mass of the molecular envelope mass and of the mass-loss rate are important for verifying such inferences.

The absence of CO emission from M1-92, HD 44179, and OH 0739−14 may be taken to indicate that they are isolated in space and are unlikely to be in an early stage of stellar evolution like the Orion population stars. Although M1-92 and HD 44179 require similar models as CRL 2688 and CRL 618 to explain the visual and infrared observations, their relationship to planetary nebulae is not yet established.

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Note added in proof.—E. W. Gottlieb and W. Liller (private communication) have obtained light curves from inspection of the Harvard plates for CRL 2688 and CRL 618. For CRL 2688, the mean light curve can be described as a slow rise in brightness (~0.05 mag/yr) beginning at some time before 1920 to about 1958 when it reached more or less constant magnitude. CRL 618 has apparently increased in brightness by ~2 mag since 1940 (~0.06 mag/yr). For future references, the CO spectra in this paper were taken at 1975.8.

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