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CRL 2688: A POST–CARBON-STAR OBJECT AND PROBABLE PLANETARY NEBULA PROGENITOR

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ABSTRACT

We observed millimeter-wavelength emission toward CRL 2688 from $H^{12}CN$, $H^{13}CN$, CS, and HC_3N. The similarity of this emission and that from the molecular envelope of the carbon star IRC +10216 establishes, beyond a reasonable doubt, that CRL 2688 is a post–carbon-star object. It appears probable that both of these objects will evolve into planetary nebulae. An evolutionary sequence leading from carbon stars to planetary nebulae is outlined.

Subject headings: infrared: spectra — stars: carbon — stars: evolution — nebulae: planetary

I. INTRODUCTION

CRL 2688, an infrared source discovered during the AFCRL rocket survey, has been intensively investigated during the past year (Ney *et al.* 1975; Crampton, Cowley, and Humphreys 1975; Forrest *et al.* 1975). Despite a variety of optical and infrared observations, these groups were unable to decide on the evolutionary state of the object; that is, both pre– and post–main-sequence interpretations appeared possible. The observed C_3 absorption features (Crampton, Cowley, and Humphreys 1975) indicate a very low molecular excitation temperature somewhere in the envelope, and we therefore decided to search for radio emission from carbon-containing molecules.

II. EQUIPMENT AND OBSERVATIONS

We used the 36 foot (11 m) telescope of the National Radio Astronomy Observatory equipped with a dual polarization cooled 80–120 GHz mixer receiver and 256 channel filter banks. For our HCN observations no difference in intensity between the two orthogonal polarizations (position angles ~80° and ~170°) was evident. For some of the observations, (see col. [2] in Table 1), a filter was used to reject the unwanted sideband of the mixer receiver (Wannier *et al.* 1975). Data were obtained by switching the telescope in position every 30 s between CRL 2688 and a reference position 10′ away and subtracting the off-source spectra from the on-source spectra. The results for $H^{12}CN$, $H^{13}CN$, CS, HC_3N, SiS, and HCO^+ are shown in Figure 1 and/or summarized in Table 1. T_B is the peak brightness temperature above the background continuum averaged over the main beam of the telescope and corrected to outside of the atmosphere, v_{lsr} is the radial velocity with respect to the local standard of rest, and Δv is the full line width at half-maximum intensity.

A 5-point map of the HCN emission showed no evidence that the source is extended (source diameter $<90''$; telescope beamwidth $\sim80''$). The map did suggest, however, that we might have been slightly mispointed when the $H^{12}CN$ spectrum shown in Figure 1 was obtained. Therefore, the peak T_B might be as much as 1.5 times larger than the value given in Table 1. For HC_3N, Δv and especially v_{lsr} appear to disagree with the values given for the other three molecules in Figure 1. It is unlikely that the discrepancy can be explained away by the poor signal-to-noise ratio in the HC_3N spectrum, as this spectrum is an average of two different spectra taken on successive days and shifted by 9 MHz with respect to each other. Each day's spectrum shows a line having similar v_{lsr} and Δv. One possible explanation for the discrepant v_{lsr} is a nonuniform distribution of HC_3N in the molecular envelope around CRL 2688.

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III. INTERPRETATION OF SPECTRA

We believe that CRL 2688 is an object that recently evolved from a carbon star. We conclude this on the basis of (*a*) the optical spectra and appearance of CRL 2688; (*b*) our millimeter-wavelength spectra which suggest that the molecular envelope of CRL 2688 is carbon-rich and (*c*) the fact that CRL 2688 (and similar objects such as IRC +10216 and CIT 6) are not located in regions of obvious star formation and therefore are unlikely to be young. Arguments that establish the carbon star ancestry of CRL 2688 are given in the present section; its evolutionary state is considered in § IV.

The C_3 absorption bands observed in CRL 2688 (Crampton, Cowley, and Humphreys 1975) have previously been seen only in late N-type carbon stars and comets. The C_2 Swan bands observed (in emission) in CRL 2688 are seen (in absorption) only in stars where C/O > 1. Also the carbon star IRC +10216 (Herbig and Zappala 1970; Morris *et al.* 1975) shows the C_2 Phillips bands in absorption (Gilra 1975*b*). (Unfortunately, IRC +10216 is too faint at shorter wavelengths to have shown the C_3 features or the C_2 Swan bands.)

The published C_3 spectrum of CRL 2688 shows that the excitation temperature of the molecules is considerably lower than the effective temperature of the star. For example, at a temperature ~3000 K the C_3 electronic spectrum in the 4000 Å region would show a continuum with a few broad features superposed on it (Brewer and Engleke 1962) mainly because of the low bending frequency of C_3 (Gausset *et al.* 1965). Only at very low temperatures does one see unblended features without a strong continuum. The C_3 spectrum in CRL 2688 matches very well with that of Gausset *et al.* which was taken at about room temperature in a flash photolysis experiment. Similarly, the presence of the (0, 0) and (0, 1) Swan bands of C_2 but the apparent absence of the (1, 0) and (1, 1) bands is consistent with a low excitation temperature. The excitation temperatures of

TABLE 1

MOLECULAR OBSERVATIONS OF CRL 2688

Molecule	Sideband Filter	Transition	T_B (K)	v_{lsr}* (km s^{-1})	Δv (km s^{-1})
$H^{12}CN$....	Yes	$J=1\to0$	0.46†	-30.0 ± 1	25.5
$H^{13}CN$....	Yes	$J=1\to0$	0.20	-29.5 ± 1	28.0
CS.......	Yes	$J=2\to1$	0.12	-31.3 ± 2	24
HC_3N.....	No	$J=10\to9$	0.11	-38 ± 4†	32†
SiS.......	No	$J=5\to4$	<0.07		
HCO^+....	No	$J=1\to0$	<0.10		

* To correct to $V_{\rm heliocentric}$, add -16 km s^{-1}.
† See remarks in text.

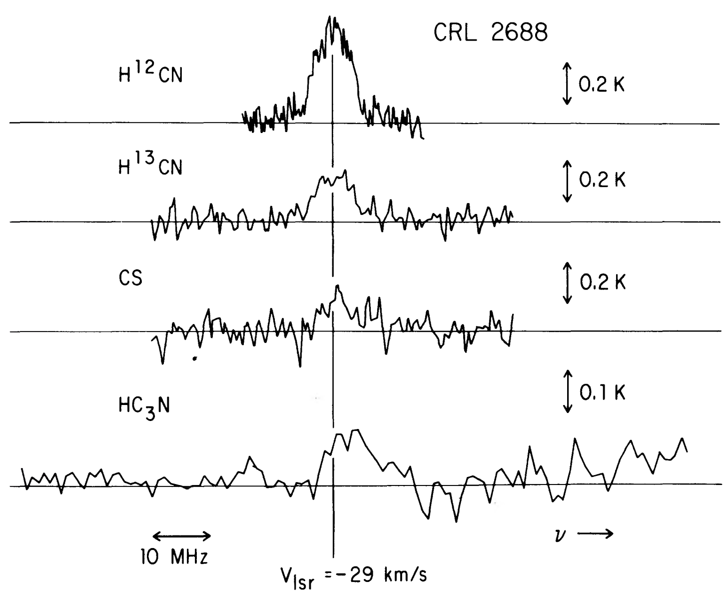

FIG. 1.—Spectra of $H^{12}CN$, $H^{13}CN$, CS, and HC_3N in CRL 2688. The ordinate is brightness temperature, T_B, as defined in the text; the abscissa is frequency. The zero point of the frequency scale corresponds to $v_{lsr} = -29$ km s^{-1}. Frequency increases to the right. 10 MHz corresponds to 34, 35, 31, and 33 km s^{-1} in radial velocity, and the spectral resolutions were 250, 500, 500, and 1000 kHz for $H^{12}CN$, $H^{13}CN$, CS, and HC_3N, respectively.

these two molecules might therefore be about the same as the dust temperature, $\sim$150 K (Ney *et al.* 1975; Forrest *et al.* 1975).

Our observations show that the millimeter-wavelength spectra of CRL 2688 are very similar to those of IRC + 10216. The sources are both small, and the line widths are large and comparable. The ratios of line intensities for $H^{12}CN$, $H^{13}CN$, CS, and HC_3N (Table 1) and ^{12}CO and ^{13}CO (Lo and Bechis 1976) are not very different from the corresponding ratios in IRC +10216 (Wilson, Schwartz, and Epstein 1973; Turner *et al.* 1973; Morris *et al.* 1975). Also, the shapes of the $H^{12}CN$ and $H^{13}CN$ lines are (to within the noise) parabolic and rectangular, respectively, in both sources (Fig. 1 and Gottlieb 1974), indicating that if the molecular envelopes are expanding in an approximately spherically symmetric manner then the $H^{12}CN$ and $H^{13}CN$ lines are optically thick and thin, respectively, in both sources (Morris 1975). HCO^+ (Woods *et al.* 1975) produces strong emission lines in most galactic molecular clouds where HCN and CS are seen, but is not observed in either IRC +10216 (Hollis *et al.* 1975) or CRL 2688 (Table 1). A conclusive demonstration that CRL 2688 is a carbon star, i.e., $C/O > 1$, based solely on millimeter-wavelength radio data, requires a measurement of the SiS/SiO ratio. This ratio, which has been measured in IRC +10216, is expected to be greater than 1 only if $C/O > 1$ (Morris *et al.* 1975). If $C/O > 1$ is observed, then mixing of material from a helium-burning zone is strongly implied. (In a hydrogen-burning region, $C/O > 1$ only at $T \gtrsim 50 \times 10^6$ K, but then the mass fractions of both C and O are very low [Cowan 1975].) A small $^{12}C/^{13}C$ ratio or a large $C^{13}/^{15}N$ ratio (Morris *et al.* 1971) is not a definitive test for $C/O > 1$ since such isotope ratios may be altered relatively easily in mere hydrogen-burning as well as in helium-burning zones.

All in all, the combined optical and radio spectra indicate that CRL 2688 is a post–carbon-star object.

IV. CARBON STAR TO PLANETARY NEBULA?

Although others have alluded to the possibility that objects like IRC +10216 and CRL 2688 are progenitors of planetary nebulae, we are now in a position to strengthen the connection considerably. First, we briefly outline the evolutionary sequence that we envisage. The picture begins with a luminous carbon star, possibly of type R or early N, with no observable infrared excess. The star then evolves into a late N-type carbon star completely surrounded by dust that displays a (remarkable) violet opacity and a shell expanding at 12–15 km s^{-1} (Gilra 1975*a*). At present, no molecular radio emission has been detected from such stars (Wilson, Schwartz, and Epstein 1973; Frogel, Dickinson, and Hyland 1975). Next, an object such as IRC +10216 or CIT 6 (Wilson, Schwartz, and Epstein 1973) is produced: the infrared-emitting dust shell is generally resolvable, and the molecular envelope is now large enough to be detectable at millimeter wavelengths. In the fourth stage, represented by CRL 2688, a symmetric pair of reflection nebulosities are visible, illuminated by the central star through two "holes" in the expanding dust envelope. The central star, which is presumably evolving rapidly to the left on the H-R diagram, is still too cool to ionize hydrogen in the surrounding cloud (e.g., CRL 2688 presently has spectral type F5 Ia). During this and following stages the thermodynamic conditions in the envelope are changing; therefore, there are probably significant changes in the overall composition of dust and molecules. As the surface temperature of the central star increases, objects like HD 44179 (Cohen *et al.* 1975) or M1-92 (Herbig 1975), both of which have B-type central stars, might be produced. (However, there are reasons [see below] to suspect that these two objects have not evolved from carbon stars and, therefore, might not belong to the sequence we are discussing.) Eventually the central star becomes hot enough to ionize the inner portions of the surrounding cloud and to produce a very compact planetary nebula such as CRL 618 (Westbrook *et al.* 1975). Finally the ionized region increases in size, and a bona fide planetary nebula, such as NGC 7027, results.

As in § III where we compared CRL 2688 and IRC +10216, connections among all the various objects listed above may be established from similarities in their optical, infrared, and radio appearances and spectra. The visual appearances of CRL 2688, HD 44179, M1-92, and CRL 618 are similar. The optical and/or infrared spectra of CIT 6, IRC +10216, CRL 2688, CRL 618, NGC 7027, and HD 44179 all show evidence of carbon richness. The first three objects are or were carbon stars. Reliable C/O abundance ratios in planetary nebulae such as NGC 7027 are not yet obtainable optically (but might be established by ultraviolet measurements [Bohlin, Marionni, and Stecher 1975]). However, the detection of carbonate but not silicate grains in NGC 7027 and one other planetary (Gillett, Forrest, and Merrill 1973; Bregman and Rank 1975) suggests that the material surrounding the central stars in these planetaries is carbon-rich. (The 11 μ spectrum of HD 44179 also indicates the presence of carbonate grains [Cohen *et al.* 1975].) The near-infrared spectra of NGC 7027 and CRL 618 contain lines of [C I] (Kolotilov and Noskova 1974; Danzinger and Goad 1973; Westbrook *et al.* 1975). We are not aware of any other galactic objects with forbidden lines of *neutral* carbon in their spectra. The presence of a considerable abundance of C I near such hot stars is not easy to understand. (Perhaps C_3 and/or C_2 are photodissociated by diffuse nebula continuum radiation near 6 eV or by Lα to produce C I which is shielded from the direct stellar flux by pockets of neutral gas and dust.) HD 44179, on the other hand, displays enhanced blue-green absorption lines of C I that are not seen in the spectrum of any other late B star (Cohen *et al.* 1975) but are, however, enhanced in the spectrum of the carbon star R CrB (see, e.g., Searle 1961).

The radio molecular spectra of IRC +10216, CIT 6, CRL 2688, CRL 618, and NGC 7027 are similar. All five objects show broad ($\Delta v \sim 30$ km s^{-1}) CO emission lines (Wilson, Schwartz, and Epstein 1973; Lo and Bechis 1976; Mufson, Lyon, and Marionni 1975). The first three objects show broad HCN lines (Wilson, Schwartz, and Epstein 1973; Table 1). (It is difficult to estimate accurately the mass of the molecular envelope around objects like IRC +10216, CRL 2688, and NGC 7027 due to uncertainties in fractional molecular abundances in the envelope and an uncertain C/H abundance ratio.)

If IRC +10216 and CRL 2688 have luminosities ($>10^4 L_\odot$) typical of a late-type carbon star and an F supergiant, respectively, then their implied distances (Herbig and Zappala 1970; Crampton, Cowley, and Humphreys 1975) require that they be 200 and 110 pc from the Galactic plane. (CIT 6 is near the North Galactic Pole and is therefore also well out of the Galactic plane.) The average $|Z|$ for 41 planetaries within 1 kpc of the Sun is 150 pc (Osterbrock 1974). Furthermore the typical planetary in Cygnus has a blueshifted radial velocity (Osterbrock 1974), and the lsr radial velocity of CRL 2688 is ~ -30 km s^{-1} (Table 1; Crampton, Cowley, and Humphreys 1975), which is more negative than that of the other CO (Wilson *et al.* 1974) and OH (Turner 1976) clouds in the Cygnus region.

Thus, although there is a danger in arguments based on only a small number of objects, there is substantial observational evidence for associating some luminous carbon stars with the progenitors of planetary nebulae. There are also a few indirect arguments which suggest that IRC +10216, CIT 6, and CRL 2688 will evolve into planetary nebulae. For example, it is difficult to imagine any other evolutionary sequence for these objects. Their carbon richness and isolated spatial positions rule out pre–main-sequence interpretations. Their carbon richness and radio spectra argue strongly against their association with oxygen-rich long-period (Mira) type variables or with semiregular or irregular variables. Indeed, association of these carbon-rich objects with a pre–planetary-nebula phase supplies a plausible explanation for a question recently raised by Frogel, Dickinson, and Hyland (1975). These authors point out that "calculations by Tsuji (1964) show that the partial pressure of CO is similar in the photospheres of both oxygen- and carbon-rich stars and, further, its value is close to that of the H_2O partial pressure for the oxygen-rich stars. Why, then, has CO [radio] emission not been detected in the oxygen-rich stars that are H_2O, [OH, and SiO] sources?" Since the rate of mass loss is less than 10^{-5} yr^{-1} from oxygen-rich stars (Gehrz and Woolf 1971) but greater than 10^{-5} $M_\odot$ yr^{-1} in planetary nebulae, the CO projected densities in the pre-planetary phase will undoubtedly be significantly greater than in oxygen-rich Mira variables. However, various people (e.g., Feast 1968) have noted that the distribution and kinematics of oxygen-rich Miras and planetary nebulae are remarkably similar. It is conceivable that after Miras have shed their (oxygen-rich) outer envelopes at a relatively leisurely pace, at least some will reveal (carbon-rich) lower envelopes which might then be shed more rapidly in the form of planetary nebulae. If the luminosities of IRC +10216 and CRL 2688 are greater than 10^4 $L_\odot$, mass ejection is possible by all three of the mechanisms suggested for forming planetary nebulae (e.g., Miller 1974). In particular, in the models of Rose (1967) and Smith and Rose (1972), relaxation oscillations in the envelopes of luminous red giants may cause rapid mass loss. It appears plausible that, for stars somewhat more massive than those considered by Rose (i.e., the stars we are considering), helium shell flashes and mixing of some of this material to the surface might account for both the carbon richness and mass ejection.

The absence of detectable OH maser radiation from known planetary nebulae (Turner 1971) including NGC 7027 (Turner 1976) is well established. To determine if OH is detectable in the suggested progenitors we used the 140 foot (43 m) telescope of NRAO to search for all four ground-state lines toward CRL 2688, IRC +10216, CRL 618, and M1-92. Results for the first three objects were negative (M1-92 is discussed below), further establishing the similarity between carbon-rich objects and planetary nebulae.

Although the optical appearance of M1-92 and HD 44179 suggests that they may be evolving into planetary nebulae, they appear to be of a somewhat different nature from CRL 2688, IRC +10216, CIT 6, and CRL 618. The luminosities of M1-92 and HD 44179 appear lower ($<10^4$ $L_\odot$ [Herbig 1975; Cohen *et al.* 1975]), and their shell masses may be lower since they do not show CO emission (Lo and Bechis 1976). Also, M1-92 appears to be associated with a peculiar OH maser source detected by Lépine and Rieu (1974). They found that its right ascension agreed with that of M1-92 to within 3^s; our measurements show that the declination of the OH maser is within $4'$ of that of M1-92. Thus a physical association is likely. If so, M1-92 is probably oxygen- rather than carbon-rich. (Another mysterious OH maser source, OH 231.8+4.2, which is not located in a region of star formation, displays a broad 1667 MHz emission line similar to that in M1-92. If OH 231.8+4.2 is a pre–planetary nebula, that would be ironical since Turner (1971) originally misidentified it with the bona fide planetary NGC 2438.)

V. CONCLUSIONS

We have argued that IRC +10216, CIT 6, and CRL 2688 are carbon-rich (C/O > 1) progenitors of planetary nebulae and that CRL 618 and NGC 7027 are carbon-rich planetaries. The cases of M1-92 and HD 44179 are not yet as clear; but if they are also progenitors of planetary nebulae, then at least M1-92 is probably oxygen-rich (O/C > 1). An obvious question is: Do most planetary nebulae pass through a carbon star phase, or do only a small minority (for example, those that have evolved from rather massive stars)? Since the typical pre-planetary main-sequence star is believed to have a mass ~ 1.5 $M_\odot$ (Miller 1974) while carbon stars are believed to have evolved from main-sequence stars with masses $\gtrsim 2$ $M_\odot$ (Rose 1975), one might expect that only a minority of planetary nebulae go through a carbon star stage. There are 41 known planetaries and $\gtrsim$ four carbon-rich pre-planetaries (we include IRC +40540; Frogel, Dickinson, and Hyland 1975) within 1 kpc of the Sun. (The number of carbon-rich progenitors might be significantly larger than 4 since many of the unidentified AFCRL infrared sources are probably late-type carbon stars [Merrill 1975], some of which might have a substantial molecular envelope.) Uncertainties in the relative lifetimes of the planetary and pre-planetary phases together with the possibility of multiple outbursts in either or both phases make it impossible at this time to decide whether most or only a small fraction of planetaries pass through a carbon star phase. The size and structure of and the carbon to oxygen ratio in shells around planetary nebulae and suspected progenitors might be clarified by observations of the 21 cm line of H or the 9 cm lines of CH which might reveal extensive low-density envelopes that would not be detectable in molecules like CO or HCN which are harder to excite. (We have begun observations of the 21 cm line with the 300 foot NRAO antenna and have already obtained preliminary upper limits of 2.0, 0.5, 0.5, and 0.2 K antenna temperature from M1-92, CRL 2688, NGC 7027, and IRC +10216, respectively.) In most galactic clouds $OH/CH \gg 1$ (Zuckerman and Turner 1975). The nondetection of OH from planetary nebulae might be explained if $C/O > 1$. If so, CH/OH might be greater than 1 in neutral shells around planetary nebulae.

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