PROTO-PLANETARY NEBULAE

B. Zuckerman
University of Maryland, California Institute of Technology,
and University of California at Los Angeles

1. INTRODUCTION

Although rare, planetary nebulae have been extensively studied by astronomers. This affection is certainly due in part to the beauty of the gaseous nebulae but it is also due to the belief that many, probably most, stars of intermediate mass (1-4 $M_\odot$) become planetary nebulae at least once during their lifetimes. If the planetary nebula is an (almost) inevitable stage in stellar evolution, it is important to determine its evolutionary precursors and followers. The latter are likely to be the white dwarfs and the former are generally believed to be red giants. With the advent of infrared and radio techniques it now appears possible, for the first time, to specify the immediate progenitors of planetary nebulae.

In the following discussion a "proto-planetary nebula" or a "planetary nebula progenitor" is the term we use to describe those objects that are losing mass at a rate $\gtrsim 10^{-5}$ $M_\odot$/year (i.e. comparable to mass loss rates in planetary nebulae with ionized masses $\gtrsim 0.2$ $M_\odot$) and which, we believe, will become planetary nebulae themselves within $\lesssim 10^5$ years. We will see from the following discussion that most proto-planetary nebulae appear to us as very red objects although a few have been "caught" near the middle of the Hertzsprung-Russell diagram. The precursors of these proto-planetaries are the general red giant population, more specifically probably Mira and semi-regular variables as discussed by, e.g., Feast (1968), Cudworth (1974), Wood and Cahn (1977), and below.

2. PROPERTIES OF PROTO-PLANETARY NEBULAE

There are ∿ 41 optically-thin planetary nebulae within 1 kpc of the sun (Osterbrock, 1974; Cahn and Wyatt, 1976). The exact number depends on some uncertain quantities including, for example, the distance scale for planetary nebulae. Because rapid mass loss must have taken place while these planetary nebulae were still red giants

Yervant Terzian (ed.), Planetary Nebulae, Observations and Theory, 305-313.

(e.g. Abell and Goldreich, 1966; Härm and Schwarzschild, 1975) it is logical to look for planetary nebulae progenitors as luminous, very red stars. If the dust to gas ratio in the molecular envelopes surrounding red giants is not much less than in the ordinary interstellar medium, many of these progenitors will not be visible stars. For example, for a mass loss rate, $\dot{M}$, $\sim 10^{-5}$ $M_\odot$/year, the hydrogen projected density between the photosphere ($R_* \sim 3\times10^{13}$ cm) and infinity is $\sim 10^{24}$ cm^{-2}. In the interstellar medium this would correspond to $A_V \sim 1000$! Therefore, taking our cue from observations of regions of star formation where comparable extinctions are believed to exist, it is logical to search for proto-planetaries at infrared and radio wavelengths.

In the infrared a large stellar mass loss is manifest as a very low color temperature or possibly a spectral feature such as, for example, 10μ silicate absorption (e.g. Evans and Beckwith, 1977). In the radio domain, CO emission from an expanding molecular envelope is probably the most reliable way to determine large mass-loss rates. In Table 1 we list stars with detectable emission from the J=1→0 rotational transition of the CO molecule. We give for each star the corrected CO antenna temperature, T_A^*, as defined, for example, in Zuckerman et al. (1977a). Because of the very large dispersion in distances to these and other evolved stars, T_A^* is not by itself a good measure of $\dot{M}$. A better first approximation to $\dot{M}$ is obtained by assuming that all red giants have the same intrinsic luminosity, which is probably true to within an order of magnitude. T_A^* is then normalized by the integrated stellar flux, F, received at the Earth. This procedure was carried out by Zuckerman et al. (1977a), who found that some very bright nearby red giants, such as Mira and W Hya, are not examples of stars undergoing extreme mass loss. Redder, i.e. cooler, objects, such as IRC+10216 and IRC+10011, have much larger mass loss rates. $\dot{M}$ for these two stars is estimated to be $\sim 2\times10^{-5}$ $M_\odot$/year (Goldreich and Scoville, 1976; Kwan and Hill, 1977). For the other stars in Table 1, $\dot{M}$ is likely to be within a factor of 3 of this value, although for a few, e.g. NGC 7027, it might be ~ 10 times larger.

Most of the objects in Table 1 were first discovered in the infrared, consistent with the argument given above that proto-planetary nebulae will not be prominent visual stars. A clear majority of the objects are either carbon-rich (C/O > 1) or S-type (C/O $\sim$ 1) stars. Carbon-rich stars also comprise a majority of the CRL objects studied in the infrared by Merrill and Stein (1976b), although there may be significant selection effects involved here. An infrared study likely to be free of selection effects was carried out by Strecker and Ney (1974), who examined $\sim$ 230 sources in the IRC catalogue that were first classified by Vogt (1973). Whereas Vogt found that the fraction of carbon-rich stars in this sample was comparable to the percentage (5-10%) of carbon stars in the general red giant population, Strecker and Ney found that 20% of the 30 stars with large infrared excesses are carbon-rich. The probable reason that this percentage is smaller than the percentage of carbon-rich stars in Table 1 or in the CRL

TABLE 1

SUGGESTED PROTO-PLANETARY NEBULAE

OBJECT	T_A^*(K)	V_{exp} (km/s)	C/O[†]	Ref.
IRC+10216	4.2	15.0	C	1
CIT6	2.0	15.0	C	2
NGC 7027[#]	2.0	12.5	C	3
CRL 2688	1.0	13.0	C	4
CRL 3068	0.55	9.5	C	5
IRC+40540	0.55	10.5	C	5
IRC+20370	0.50	10.5	C	5
χ Cyg	0.50	10.5	S	6
V Cyg	0.45	10.0	C	5
R Scl	0.40	11.5	C	5
CRL 865	0.40	13.5	C	5
W Aql	0.40	12.5	S	7
CRL 618[#]	0.35	20.0	C	4
IRC+10011	0.30	14.5	O	5
V Hya	0.30	13.0	C	5
IRC+50096	0.25	13.0	C	5
IRC+20326	0.25	10.0	O	6
NML Tau	0.20	20.0	O	5
R And	0.20	10.5	S	6
CRL 2135	0.20	14.0	C?	7
CRL 2155	0.20	14.0	C?	7
CRL 2199	0.20	10.5	C?	7
IRC-10236	0.17	7.0	C	7
IRC+60150	0.15	13.0	O	7

[†] C indicates carbon-rich (C/O > 1); S indicates C/O ∿ 1;
O indicates oxygen-rich (O/C > 1).

[#] Very young planetary

1. Kuiper *et al.* 1976
2. Mufson and Liszt 1975
3. Mufson *et al.* 1975
4. Lo and Bechis 1976
5. Zuckerman *et al.* 1977a
6. Lo and Bechis 1977
7. Zuckerman *et al.* 1977b

catalogue is that the reddest objects are not conspicuous even at 2μ wavelength.

M-type supergiants are not prominent CO sources. Among the supergiants searched by Lo and Bechis (1977) and by Zuckerman et al. (1977a), only RS Cnc has been detected for certain. Even here, Lo and Bechis find a CO linewidth of only 10 km/s, which is about 40% of the width of typical CO lines from objects listed in Table 1. According to Merrill and Stein (1976a), RS Cnc is a borderline S-type star. These results suggest that M-type supergiants are not undergoing extreme mass loss unless their envelopes are mainly atomic rather than molecular gas (which seems unlikely).

Although not all appropriate objects in the General Catalog of Variable Stars and the IRC and CRL catalogues have yet been searched for CO, it is clear from the references given in Table 1 and observations of oxygen-rich, late-type giant stars by Gilmore and Bowers (1977) that a majority of red giants with $\dot{M} \gtrsim 10^{-5}$ $M_{\odot}$ have C/O $\gtrsim$ 1. We therefore predict that a majority of the planetary nebulae within 1-2 kpc of the Earth (see below) will be carbon-rich.

Distances to the objects in Table 1 may be estimated from measured values of F, assuming stellar luminosities $\sim 10^4$ $L_{\odot}$. Typical distances are $\sim$ 1 kpc with all objects likely to lie within $\lesssim$ 2 kpc of the Earth. Their average galactic latitude, 22°, corresponds to an average distance from the galactic plane, $|Z|$, which is somewhat larger than the $|Z|$ value for the 41 local planetaries mentioned above (Osterbrock, 1974; Cahn and Wyatt, 1976). Because of contamination by interstellar CO, molecular envelopes are more difficult to detect around stars in the galactic plane than stars that are outside of it. We, therefore, expect that a complete sample of planetary nebula progenitors within 2 kpc of the Earth will have a smaller average $|Z|$ than the mean value for stars in Table 1. There is no doubt that the population of stars that we are studying is considerably less confined to the galactic plane than extreme population I objects, such as H II regions. Since we expect that the total number of proto-planetaries eventually found within 2 kpc of the Earth will be no more than three times the number given in Table 1, we conclude that, within this volume, the number of planetary nebula progenitors is less than or comparable to the number of planetaries. Note that the above discussion of proto-planetaries and planetaries only pertains to the Northern 75% of the sky (Cahn and Wyatt, 1976).

Little information is presently available on the detailed nature of the outflow during the proto-planetary phase. Does the matter flow out continuously, or is it ejected in a series of puffs? How long does a red-giant star of a given main-sequence mass support outflow rates $\gtrsim 10^{-5}$ $M_{\odot}$/year? Is long-period variability always associated with such high mass loss rates? Do red, oxygen-rich progenitors such as IRC+10011, evolve into red, carbon-rich stars before they become planetary nebulae? Are intervals of rapid mass loss interspaced with relatively quiescent periods as, for example, might be the case if rapid mass ejection is due to helium shell flashes and the time between flashes is $\gtrsim 3\times10^4$ years (e.g. Trimble and Sackmann, 1977)? For stars for which this is the case, some of which might be included in Table 1, the definition of proto-planetary nebula given in §1 would not be quite appropriate. These objects might not become planetaries within 10^5 years.

Final resolution of these problems will require high spatial resolution observations in both the infrared and radio domains. To date, CO envelopes around only IRC+10216 and NGC 7027 have been spatially resolved, and then only barely, with the NRAO 11-m antenna (Wilson et al. 1973; Mufson et al., 1975). The infrared structure of IRC+10216 is fairly well understood, thanks to two lunar occultations (Toombs et al., 1972) and high resolution 4.7μ CO observations (Geballe et al., 1973). Combination of the radio and infrared observations of IRC+10216 suggests that at least two, and perhaps many, shells of gas have been ejected during the past 10^4 years. The innermost shell of 2" diameter has a mass $\sim10^{-2}$ $M_\odot$ and is expanding at 20 km/s, which is slightly faster than the average expansion velocity, $\sim$ 15 km/s, of the > 2' diameter molecular cloud seen in CO. Most of the molecules observed around IRC+10216, such as HCN, CS, SiS, and HC_3N, are excited mostly by the near infrared flux from the central star, whereas CO is mainly excited by collisions with H_2 molecules (Morris, 1975; Kwan and Hill, 1977). Fairly extensive optical, infrared, and radio observations also exist for CRL 618 and 2688 (Ney et al., 1975; Crampton et al., 1975; Westbrook et al., 1975; Lo and Bechis, 1976; Zuckerman et al., 1976; Cohen and Kuhi, 1977).

The primary constituent in the envelopes around evolved stars is probably either H or H_2. Both are difficult to observe directly, although detection of the 21-cm line from planetary and proto-planetary nebulae has been attempted with the NRAO 300-ft. and the Arecibo 1000-ft. antennae (Zuckerman et al., 1976 and 1977c). An advantage of the 21-cm line over the $J=1\rightarrow0$ line of CO is that the former is excited at much lower densities and we might, therefore, hope to detect very extended envelopes indicative of mass loss rates over the past $\sim 10^5$ years (contrasted with the $\sim 10^4$ years sampled by CO observations). With the possible exception of α Ori, which is not a CO source (Vanden Bout and Lambert, 1976; Lo and Bechis, 1977), and one planetary nebula, no 21-cm lines were evident. Then for objects such as IRC+10011, IRC+10216, and NML Tau, if the total mass in the envelope is $\gtrsim 0.1$ $M_\odot$, the bulk of the hydrogen is in the form of H_2 rather than H.

3. COMPARISON WITH PLANETARY NEBULAE

In the preceding section we estimated that within $\sim$ 1 kpc of the Earth the volume density of observable proto-planetary nebulae is comparable to, or less than, the volume density of observable optically thin planetary nebulae. If we assume that IRC+10216 is typical, the observable lifetime of a single shell of ejected molecular gas is $\sim 5\times10^3$ years ($\sim$ 0.1 pc at $\sim$ 15 km/s). Similarly, for a typical planetary the observable lifetime of a single shell is ∿ 2×10^4 years (∿ 0.7 pc at ∿ 25 km/s). Therefore, it appears that, very roughly, the average number of shells ejected during the planetary and proto-planetary phases are comparable. The relative volume densities are still too imprecisely known to make a good estimate. The time spent crossing the H-R diagram from cool, red giant to hot, O-type central star must be very short as only CRL 2688 (F-type star) and CRL 618 (B-type star) appear as likely "transit" candidates. However, even for crossing time scales as short as $3\text{-}5\times10^3$ years (Härm and Schwarzschild, 1975) we would expect to see rather more objects in transit unless the average number of observable shells per planetary is 3 or more. Since this seems unlikely, perhaps there are more interesting objects like CRL 618 and 2688 yet to be discovered and/or properly classified.

One may also compare the lifetime of a proto-planetary nebula with the lifetime of a typical Mira variable. According to Wood and Cahn (1977) there are ∿ 511 Miras within 1.5 kpc of the sun. Since this is ∿ 10-20 times the number of proto-planetaries within a comparable volume, either (a) only a small fraction of Mira variables become proto-planetaries, as defined in §1 above, or (b) the lifetime in the Mira phase is (∿ 10 times) longer than the lifetime as a proto-planetary, or some combination of (a) and (b). Wood and Cahn estimate that the typical Mira phase lasts between 7×10^4 and 7×10^5 years. The lifetime of the proto-planetary phase must be $\lesssim 10^5$ years for even the most massive stars that become planetaries and even shorter for stars near 1.5 $M_\odot$, based on simple considerations of the total mass available in the envelope of a red giant.

We noted in §2 that the small inner shell in IRC+10216 appears to be expanding more rapidly than the bulk of the much older and larger molecular envelope. This may be a manifestation of a more general phenomenon: the later in time is the ejection event, the more rapid is the ejection velocity. This regularity is suggested by comparison of the expansion velocities, V_{exp}, of the 24 objects listed in Table 1 with measured expansion velocities for 21 planetaries (Osterbrock, 1973). The average expansion velocity for the proto-planetaries is ∿ 13 km/s and for the planetaries ∿ 23 km/s. Many explanations of this difference appear conceivable including, for example: successively more violent ejection events as a function of time; ejection from a smaller radius for the later events; or acceleration of the planetary nebula material after ejection.

The planetary nebula progenitors listed in Table 1 probably originate from main-sequence stars of initial mass $\gtrsim 1.5\ M_\odot$ (Zuckerman et al., 1977b). Stars of lower mass (say ∿ 1.1 $M_\odot$) such as those found in globular clusters, the galactic halo, and the nuclear bulge are unlikely to produce the "classical" kind of planetary nebulae that we have been discussing. Planetary nebulae from population II stars are apt to be ∿ 100 times less massive than classical planetaries and may be mostly oxygen-rich, rather than carbon-rich (Wood and Cahn, 1977; Zuckerman et al., 1977b).

SUMMARY

The observation and identification of proto-planetary nebulae appears reasonably well established. Continued study of such objects promises to help our understanding of stellar evolution including, for example, the physical mechanism(s) responsible for the ejection of planetary nebulae. The elemental composition of these planetaries and their progenitors helps to regulate the chemical evolution of the galaxy.

The author gratefully acknowledges his various radio astronomical colleagues for their contributions to the work described above and especially Dr. Daya Gilra for his contagious enthusiasm. I have enjoyed fruitful discussions with many astronomers, especially Drs. S.G. Kleinmann, W.K. Rose, M. Jura, and P. Harrington. The author is a John S. Guggenheim Foundation Fellow. This research was partially supported by National Science Foundation grant AST 76-17600 to the University of Maryland.

REFERENCES

Abell, G.O. and Goldreich, P.: *Publ. Astron. Soc. Pacific*, **78**, 232.
Cahn, J.H. and Wyatt, S.P.: 1976, *Astrophys. J.*, **210**, 508.
Cohen, M. and Kuhi, L.V.: 1977, *Astrophys. J.*, **213**, 79.
Crampton, D., Cowley, A.P., and Humphreys, R.M.: 1975, *Astrophys. J.*, **198**, L135.
Cudworth, K.M.: 1974, *Astron. J.*, **79**, 1384.
Evans, N.J. and Beckwith, S.: 1977, *Astrophys. J.*, (in press).
Feast, M.W.: 1968, in D.E. Osterbrock and C.R. O'Dell (ed), *IAU Symp. #34, Planetary Nebulae*, Reidel, Dordrecht, p. 433.
Geballe, T., Wollman, E., and Rank, D.: 1973, *Astrophys. J.*, **183**, 499.
Gilmore, W., and Bowers, P.F.: 1977, (private communication).
Goldreich, P.A. and Scoville, N.Z.: 1976, *Astrophys. J.*, **205**, 144.
Härm, R. and Schwarzschild, M.: 1975, *Astrophys. J.*, **200**, 324.
Kuiper, T.B.H., Knapp. G.R., Knapp, S.L., and Brown, R.L.: 1976, *Astrophys. J.*, **204**, 408.
Kwan, J. and Hill, F.: 1977, *Astrophys. J.*, (in press).
Lo, K.Y. and Bechis, K.: 1976, *Astrophys. J.*, **205**, L21.
Lo, K.Y. and Bechis, K.: 1977, (in preparation).
Merrill, K.M. and Stein, W.A.: 1976a, *Publ. Astron. Soc. Pacific.*, **88**, 285.
Merrill, K.M. and Stein, W.A.: 1976b, *Publ. Astron. Soc. Pacific.*, **88**, 874.
Morris, M.: 1975, *Astrophys. J.*, **197**, 603.
Mufson, S.L. and Liszt, H.S.: 1975, *Astrophys. J.*, **202**, 183.
Mufson, S.L., Lyon, J., and Marionni, P.A.: 1975, *Astrophys. J.*, **201**, L85.
Ney, E.P., Merrill, K.M., Becklin, E.E., Neugebauer, G., and Wynn-Williams, C.G.: 1975, *Astrophys. J.*, **198**, L129.

Osterbrock, D.E.: 1973, in Mem. Soc. Roy. Sci. Liege, 6th Series, 5, 391.
Osterbrock, D.E.: 1974, Astrophysics of Gaseous Nebulae, Freeman, San Francisco, pp 220-222.
Strecker, D.W. and Ney, E.P.: 1974, Astron. J., 79, 797.
Toombs, R.I., Becklin, E.E., Frogel, J.A., Low, S.K., Porter, F.C., and Westphal, J.A.: 1972, Astrophys. J., 173, L71.
Trimble, V., and Sackman, I.J.: 1977, (preprint).
Vanden Bout, P.A. and Lambert, D.: 1976, (private communication).
Vogt, S.S.: 1973, Astron. J., 78, 389.
Westbrook, W.E., Becklin, E.E., Merrill, K.M., Neugebauer, G., Schmidt, M., Wilner, S.P., and Wynn-Williams, C.G.: 1975, Astrophys. J., 202, 407.
Wilson, W.J., Schwartz, P.R., and Epstein, E.E.: 1973, Astrophys. J., 183, 871.
Wood, P.R. and Cahn, J.H.: 1977, Astrophys. J., 211, 499.
Zuckerman, B., Gilra, D.P., Turner, B.E., Morris, M., and Palmer, P.: 1976, Astrophys. J., 205, L15.
Zuckerman, B., Palmer, P., Gilra, D.P., Turner, B.E., and Morris, M.: 1977b, Astrophys. J., (submitted).
Zuckerman, B., Palmer, P., Morris, M., Turner, B.E., Gilra, D.P., Bowers, P.F., and Gilmore, W.: 1977a, Astrophys. J., 211, L97.
Zuckerman, B., Silverglate, P., Terzian, Y., and Wolff, M.: 1977c, (in preparation).

DISCUSSION

Seaton: What criteria are used to determine whether progenitors are carbon-rich?

Zuckerman: Near infrared spectroscopy or visual work for the stars which are optically observed. Sometimes radio observations can see enough molecules to tell whether the object is carbon rich or oxygen rich.

Feldman: I have not been able to detect continuum radio emission from CRL 2688, but have recently been able to detect an optically thick cm-wavelength radio source associated with CRL 618. It becomes optically thin by 9.0 GHz where the radio flux ($\sim$270m Jy) indicates that the H_β flux has been underestimated by a factor of 9.

Do I understand you correctly to imply that V1016 Cyg is not a proto-planetary nebula? This object underwent a large optical outburst in 1964-65, developed an optical line spectrum like that of a dense planetary nebula, and exhibits a mass loss of $\sim 10^{-5} M_\odot yr^{-1}$. However, Marionni and Mufson have been unable to detect CO ($T_A < 0.15$ K). So, by your criteria, this would not be a proto-planetary.

Zuckerman: Yes, that is one object that does not fit my definition.

Aller: Do you feel that there is any evidence that so-called combination variables (e.g., R.W. Hydrae, BF Cyg, CI Cyg, Z And, and AX Persei) are evolving into planetaries? They are associated with M-type stars and thus presumably O-rich objects.

Zuckerman: Without checking the infrared characteristics or looking for CO, I don't know the answer.

Finzi: If proto-planetaries evolve into planetaries, there should be some objects whose properties are intermediate.

Zuckerman: There are some such as CRL618.

Tinsley: On the question of the galactic population type, why do you believe that supergiants do not become planetaries?

Zuckerman: They may, but they are not protoplanetary nebulae according to my definition. The mass loss rates are less than 10^{-5} $M_{\odot}yr^{-1}$ on the average by a factor of about 10.