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R CORONAE BOREALIS STARS AND PLANETARY NEBULAE

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ABSTRACT

IRAS observations of R Coronae Borealis type stars (R CrB's) suggests that a subset of these are inside planetary nebulae (PNs). In most cases, the PN is confirmed by the finding of a visible nebula around the star. These nebular R CrB's are identified as being the results of a final helium shell flash on the central star of old PNs. The majority of the R CrB's formed after the coalescence of a binary consisting of CO and He white dwarfs. Also presented in this paper are the results of a survey of 52 R CrB's. The normal R CrB's have power-law spectra which imply that the grain absorption coefficient varies linearly with frequency. It is estimated that R CrB's eject ~ 300 clouds per year, each of which subtend an angle of ~ 30 deg^2.

Subject headings: infrared: sources — nebulae: planetary — stars: circumstellar shells — stars: evolution — stars: R Coronae Borealis

I. INTRODUCTION

R Coronae Borealis type stars (R CrB's) are a rare and peculiar class of variable star. The members of this class are usually nearly constant at some maximum brightness, yet on random occasions will precipitously drop in brightness for some indeterminate length of time before it recovers its old maximum light. These minima are presumed to be caused by obscuration of the supergiant type star by a dust cloud which condenses out of gas ejected by the star along the line of sight to Earth (Loreta 1934; O'Keefe 1939). Payne-Gaposhkin (1963) proposed that the grains were formed just above the photosphere. This proposal has severe trouble with the observed infrared excesses as well as the survivability of the grains in a hot environment (Alexander *et al.* 1972; Hartmann and Apruzese 1976). Since the obscuring cloud must be far from the star, Stein *et al.* (1969) hypothesized a uniform shell which would also account for the infrared excess. However, the infrared luminosity does not change in antiphase with the visual luminosity, as is required by a uniform shell model, so Wing *et al.* (1972) and Forrest, Gillett, and Stein (1972) proposed blotchy cloud models. Wing *et al.* (1972) said that these obscuring clouds are part of an ensemble of clouds orbiting the star. This suggestion cannot account for the asymmetry of the light curve and the color evolution during minimum (Feast and Glass 1973). Humphreys and Ney (1974) then claimed that the infrared emission and dust clouds are produced by a cool companion star. However, the associated radial velocity variations are not seen and the infrared pulsations seen by Feast *et al.* (1977) demonstrate that the infrared emission is derived from the visible star. Hecht *et al.* (1984) used the color evolution during minimum to argue for a decrease in particle size (due to collisions); however, Pugach (1984) offers an alternative explanation for the color changes.

Our current understanding of the R CrB mechanism (summarized, for example, by Hartmann and Apruzese 1976 or Pugach 1984) is remarkably close to that originally given by O'Keefe (1939). The obscuring dust is formed from metals condensing out of a stream of matter ejected from the star in the general direction of the Earth. The cause for this ejection is related to the semiregular pulsation which all R CrB's must undergo (Trimble 1972) and are observed to undergo (Pugach 1984). Minimum light occurs when the ejecta has reached a distance from the star where amorphous carbon particles with a radius $\sim 10^{-6}$ cm (Hecht *et al.* 1984) are formed and the cloud has expanded so as to cover the star (Pugach 1984). At this time, the star will suffer greater extinction than the extended chromosphere, and a sharp emission line spectrum will appear (Pugach 1984).

Perhaps the most important unanswered question about R CrB's concerns their position in the evolutionary sequence of dying stars. So far, several evolutionary tracks have been proposed (Iben and Tutukev 1984, 1985; Iben *et al.* 1983; Webbink 1984) for which stars with properties similar to R CrB's are found. An observable distinction of the track proposed by Iben *et al.* (1983) is that the R CrB's should be inside old planetary nebulae (PNs).

This paper will address the questions of the evolution of R CrB's and the structure of the ejected dust clouds. The new observational data comes from the recent all sky survey by *IRAS* (Neugebauer *et al.* 1984) in four broad-band filters between 12 and 100 μm. This greatly extends the previous infrared observations (Stein *et al.* 1969; Lee and Feast 1969; Forrest, Gillett, and Stein 1971, 1972; Wing *et al.* 1972; Lee 1973; Feast and Glass 1973; Humphreys and Ney 1974; Webster and Glass 1974; Strecker 1975; Feast *et al.* 1977; Glass 1978) which cover only a dozen stars, mostly for wavelengths shorter than 5 μm.

II. DATA

The *IRAS* point source catalog (Neugebauer *et al.* 1984) was searched for infrared emission from any of 52 sources claimed to be R CrB's. Not all of these stars are necessarily true members of the R CrB class because stars without published spectra and with poor light curves may easily be mistakenly placed in this class. Of the stars examined, 21 were not present in the catalog (DZ And, UX Ant, XX Cam, V425 Cas, ρ Cas, V504 Cen, CC Cep, LO Cep, AE Cir, V1405 Cyg, V638 Her, W Men, V973 Oph, V1773 Oph, MT Pup, CL Sge, V589 Sgr,

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TABLE 1

IRAS OBSERVATIONS OF R CrB STARS

Star	f_ν(12 μm)	f_ν(25 μm)	f_ν(60 μm)	f_ν(100 μm)	α or T	Class of R CrB
S Aps	2.7	1.1	...	...	0.75	Normal
U Aqr	0.9	<0.4	...	...	1	Normal
UV Cas	3.6	1.3	...	...	1.25	Normal
UW Cen	7.2	5.3	8.6	5.7	0.0	Normal
DY Cen	0.89	0.85	<0.46	...	0.0	Normal
Z Cir	7.4	3.5	0.74	...	1.0	Normal
V CrA	4.6	2.0	~ 0.4	...	1.0	Normal
WX CrA	2.0	0.7	0.9	...	0.5	Normal
R CrB	29.9	13.4	3.3	1.8	1.3	Normal
V482 Cyg	0.78	0.35	...	...	1.0	Normal
SY Hyi	0.77	0.43	...	...	0.5	Normal
Y Mus	0.82	0.29	...	...	1.0	Normal
RT Nor	0.78	0.40	...	...	0.75	Normal
RZ Nor	2.9	1.5	...	...	0.75	Normal
LR Sco	9.5	7.8	3.4	~ 7.0	0.25	Normal
SV Sge	3.0	1.4	...	...	1.0	Normal
RY Sgr	59.0	20.5	4.5	4.2	1.25	Normal
VZ Sgr	0.90	<0.49	...	...	1	Normal
GU Sgr	0.88	~ 0.6	<0.44	...	0.0	Normal
V3795 Sgr	3.5	~ 1.5	...	...	0.75	Normal
SU Tau	7.6	3.4	1.5	2.8	1.0	Normal
RS Tel	1.3	0.60	...	...	0.75	Normal
RZ Vul	1.8	1.2	...	...	0.5	Normal
BG Cep	1.5	1.7	0.66	...	200 K	Hot normal
MV Sgr	~ 0.9	1.5	0.66	...	200 K	Hot normal
NGC 2346	0.49	0.89	7.8	13.0	-1.0	Final flash
V352 Aql	0.49	1.0	5.4	11.7	-1.5	Nebular
V605 Aql	3.9	35.5	40.4	17.4	90 K	Nebular
V1860 Sgr	1.4	3.7	9.0	...	-1.25	Nebular
V348 Sgr	4.7	2.6	2.6	...	0.5	Hot nebular
VY Mon	34.3	66.8	110.4	212.9	-0.75	T Tauri[a]

[a] Cohen and Kuhi (1979) show VY Mon to be spectroscopically a T Tauri star, while I find VY Mon's light curve from the Harvard collection of archival plates not to be that of an R CrB star.

V618 Sgr, V732 Sco, VZ Tel, and CT Vul). Typical limits for detection are 0.25, 0.4, 0.6, and 1.0 Jy for the 12, 25, 60, and 100 μm filters, respectively. These limits can vary widely with position on the sky because of different coverage and background source density. The color-corrected fluxes for the detected sources are given in Table 1. The color correction was accomplished with the procedure of Beichman *et al.* (1985) and the power law or backbody parameter given in Table 1.

Additional near infrared observations of several R CrB's were made with the Infrared Telescope Facility in Hawaii. The data for four stars are presented in Table 2. The fluxes are in janskys.

The 0.9 m telescope at the Cerro Tololo Inter-American Observatory was used in a search for nebulosity around V1860 Sgr and CT Vul. The search was made with a CCD detector and interference filters centered on the rest wavelengths of Hα and O III (with bandpasses of 73 and 14 Å, respectively). Ninety minutes of exposure at Hα was obtained for V1860 Sgr. One hour of exposure on CT Vul was obtained in both Hα and O III. Detailed analysis reveals no nebulosity around either star. The sensitivity of the search depends strongly on the assumed size of the nebula. Roughly, a nebula with a flux of 1 rayleigh and a diameter of 1′ would be detected with a signal-to-noise ratio of 3.

TABLE 2

NEAR-INFRARED OBSERVATIONS OF R CrB STARS

Star	log $f_\nu(J)$	log $f_\nu(H)$	log $f_\nu(K)$	log $f_\nu(L)$
DZ And	-0.12	-0.05	-0.24	...
CL Sge	-0.36	-0.13	-0.23	...
V1860 Sgr	-0.172	-0.66	-0.62	...
CT Vul	-2.10	-1.78	-1.58	-1.27

III. NORMAL R CrB STARS

The majority of R CrB's have *IRAS* spectra for which the flux decreases with wavelength. I will call this subset of R CrB's as the "normal R CrB's," which will be distinguished from other subsets of R CrB's as discussed later. The brightest example of this class of stars is R CrB itself. In Figure 1, I have constructed a flux spectrum for R CrB with data for log $\nu > 13.5$ (collected from the literature) and log $\nu < 13.5$ (as reported in this paper). The spectrum is dominated by flux from two sources. The first source is the F-type supergiant and is associated with the blackbody peak in the visible. The second source is associated with the blackbody-like peak in the infrared and is caused by thermal emission from dust grains around the supergiant. The luminosity of the dust varies by a factor of 3—which presumably reflects short-term changes in the mass ejection rate by the supergiant.

The *IRAS* data provides a first look at the long wavelength portion of the dust spectrum, which can be characterized as a power law with $F_\nu \propto \nu^{1.3}$. The reason for the departure from a Rayleigh-Jeans spectrum is that extra long wavelength flux is contributed by dust far away from the star which is much cooler. The precise slope of this power law can provide information on the emission properties of the dust grains. Following Rees *et al.* (1969), the flux should be

$$F_\nu \propto \nu^\zeta, \; \zeta = \tfrac{1}{2}[2 + \alpha - (4 + \alpha)(2 - \beta)] \; , \qquad (1)$$

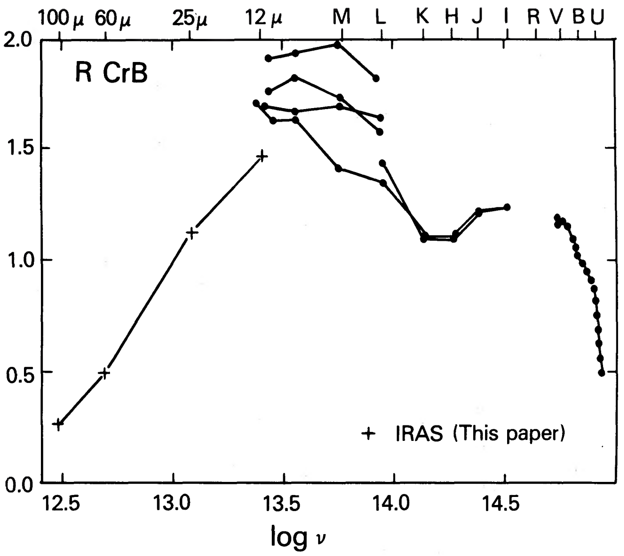

FIG. 1.—Spectrum of R Coronae Borealis. The spectrum is dominated by two peaks at log $\nu_{\rm max}$ of 14.6 and 13.7, caused by blackbody emission from the central star and surrounding dust, respectively. The flux in the infrared peak varies considerably with time because of short-term changes in the rate of mass ejection (and, hence, dust formation). The *IRAS* observations show a power-law spectrum with $F_\nu \propto \nu^{1.3}$. The deviation from a Rayleigh-Jeans spectrum is because cooler dust at large distances from the star contribute significantly to the far infrared flux. The slope of the power spectrum implies that absorption coefficient for the grains varies as $\nu^{0.6}$. The data for wavelengths shorter than 12 μm was taken from Patterson, Fix, and Neff (1976), Humphreys and Ney (1974), Glass (1978), Forrest, Gillett, and Stein (1972), and Stein *et al.* (1969).

where the grain number density varies as

$$\rho \propto r^{-\beta} \tag{2}$$

and the absorption coefficient varies as

$$Q \propto \nu^{\alpha} . \tag{3}$$

For R CrB's with a steady mass-loss rate, β will be 2. The *IRAS* spectrum determines ζ as 1.3. Hence, α must be 0.6. Pure graphite would have α equal 2.0; however, amorphous carbon with impurities will have a lower value (Koike, Hasegawa, and Manabe 1980). For RY Sgr, the value for α is 1.2. Apparently, for normal R CrB's, a typical value of α is unity.

The infrared flux can also be used to make an *order of magnitude estimate* of the frequency of cloud ejections and the size of individual clouds for R CrB. The first step is to estimate the total number of dust grains in a cloud (N_g) in terms of the amplitude of the light curve, A, the star's radius, R_*, and the dust grain radius, S. At minimum light, the cloud will have a cross section similar to that of the star (Pugach 1984) while the column density is given by equation 5-240 of Lang (1978). So

$$N_g = 0.92 \times r^2 \times A \times R_*^2/S^2 \approx 4.10^{39} , \tag{4}$$

for $A = 8$, $R_* = 100\ R_\odot$ (Hartmann and Apruzese 1976) and $S = 10^{-6}$ cm (Hecht *et al.* 1984). Here, the value of r is the ratio of the mean cloud radius to the star's radius. The factor of r^2 in equation (4) is to allow for the possibility that minimum does not occur when the cloud is exactly along the line of sight. The observation of chromospheric lines at minimum implies that the edge of the cloud is significantly smaller than the star's radius. In addition, it is plausible that the width of the cloud's edge is a significant fraction of the cloud's radius. Hence, the value of r cannot be much greater than unity. I will assume that on average r^2 is 10. The grains relatively close to the star will be hot enough so that they will contribute to the peak of infrared flux with $\nu_{\rm max} \approx 5 \times 10^{13}$ Hz (see Fig. 1). The flux (f_ν) at $\nu_{\rm max}$ for a single cloud will be

$$f_\nu = Q N_g \nu_{\rm max}^3 (S/D)^2 (2.4 \times 10^{-48} \text{ ergs s}^3 \text{ cm}^{-2}) \tag{5}$$

from equations (3) and (4) above and equations 1–119, 122, and 130 of Lang (1978). For a distance, D, to R CrB of 1 kpc [$m_v - M_v = 6 - (-4) = 10$] and $Q \approx 0.003$ (Gilman 1974), the total flux at $\nu_{\rm max}$ will be 4×10^{-2} Jy. Since the observed maximum flux is $\sim$40 Jy (see Fig. 1), the total number of clouds (N_c) contributing to the infrared peak must be of order 10^3. The grain temperature in each of these clouds must be greater than $\sim$500 K for the cloud to contribute to the infrared peak. The solution of the energy balance equation for an individual grain (Clayton and Wickramasinghe 1976) gives the distance, R, from a star of luminosity L and temperature T_* for which the grains will have a temperature of T_g. So

$$R^2 = \frac{LQ_1}{16\pi\sigma T_g^4 Q_2} \approx (2 \times 10^{15} \text{ cm})^2 , \tag{6}$$

where $L = 10^4\ L_\odot$, $\sigma = 5.6 \times 10^{-5}$ ergs cm^{-2} K^4 s, $T_g = 500$ K, and $Q_1/Q_2 \approx T_*/T_g \approx 10$ since α was found to be unity. Since the clouds are ejected from a star with a velocity, V, of $\sim$200 km s^{-1} (Hartmann and Apruzese 1976; Alexander *et al.* 1972; Payne-Gaposhkin 1963) the frequency of cloud ejection is

$$F = N_c\, V/R \approx 300 \text{ yr}^{-1} . \tag{7}$$

To reproduce the observed frequency of minima ($F_{\rm min}$) of 0.2 yr^{-1}, the solid angle of an individual cloud as seen from the star will be

$$\Omega = 4\pi F_{\rm min}/F \approx 30 \text{ deg}^2 . \tag{8}$$

The mass-loss rate in grains can be estimated from

$$\dot{M}_g = F N_g S^3 \rho 4\pi/3 \approx 5 \times 10^{-9}\ M_\odot \text{ yr}^{-1} , \tag{9}$$

where ρ is an assumed grain density of 2.0 gm cm^{-3}. It must be remembered that the quantities given in equations (4)–(9) are only approximate. For example, it is possible that A is much larger than 8 if the optical light at minimum has a scattered component (see Hecht *et al.* 1984). The values of V and r^2 are also uncertain.

The most likely evolutionary channel for normal R CrB's is that proposed by Webbink (1984) which is illustrated schematically in Figure 2. In this scenario, normal R CrB's form from the coalescence of He/CO white dwarf binaries and turn into non–DA white dwarfs. While the star is an R CrB, it will evolve to higher temperature (at a constant luminosity) on a time scale of 10^4 yr. Hence, we should find a subset of normal R CrB's which are hotter than usual.

MV Sgr (Herbig 1964; Hoffleit 1958) is a likely candidate for this "hot R CrB" class. It displays R CrB–like variability, has a high temperature, and an absolute bolometric magnitude only slightly fainter than other R CrB's. Herbig has commented that "the spectrum is much like that to be expected if R CrB were to be raised to a temperature of about 20,000°K." The emission lines are caused by the $\sim 10^2\ L_\odot$ of ionizing radiation with which MV Sgr is illuminating the recently ejected material. MV Sgr is one of the least active of all R CrB's (Glasby 1970; Glass 1978; Pugach 1984) which suggests that it is an old and small R CrB gradually turning off its mass ejection. This view is possibly supported by the *IRAS* spectrum which indicates a relative paucity of dust near the star. The observed value of $\zeta = -1$ for $13.0 < \log \nu < 14.5$ along with the previously deduced value of $\alpha \approx 1$ implies that β is unity. This is consistent with a mass-loss rate falling off inversely with time.

BG Cep is the other star which I identify as a member of the hot R CrB class. BG Cep is similar to MV Sgr in that it has a B8 spectral type and a $\log \nu_{\max} \approx 13.0$. However, my examination of the archival plate collection at Harvard shows that, unlike MV Sgr, BG Cep's minima are not rare. It is striking that all normal R CrB's (with a temperature of less than 7000 K) have $\log \nu_{\max} \approx 13.5$ while the two hot R CrB's (with a temperature of $\sim$20,000 K) have $\log \nu_{\max} \approx 13.0$.

The scarcity of hot R CrB's when compared to normal R CrB's has two causes. First, the evolution for temperatures above 10,000 K is quite fast when compared to the time at which the star lingers at low temperatures (Iben and Tutukov 1985). Second, the possible low frequency of minima is a strong selection effect against the discovery of hot R CrB's.

V. NEBULAR R CrB STARS

Iben *et al.* (1983) have pointed out that some R CrB's may have evolved along a different track than the normal R CrB's. Specifically, they calculate that stars with R CrB–like properties will result when the central star of an old PN undergoes a final helium shell flash. After this final flash, the star will expand to giant proportions with temperature, luminosity, and composition similar to those measured in R CrB's. The star will then evolve to higher temperatures (at a constant luminosity) and become a large high-excitation PN of which A30 and A78 are the prototypes. The ultimate fate of these stars is to decrease in size and follow cooling track as a non–DA white dwarf (WD). The various stages in this evolutionary scenario are schematically represented in Figure 2. One of the main difficulties is that R CrB's were not seen to be in PNs.

However, the *IRAS* data does select out three R CrB's as apparently being in PNs. These stars (V605 Aql, V1860 Sgr, and V352 Aql) have spectra whose flux is rising rapidly into the far-infrared. This is a qualitatively different behavior from the majority of R CrB's. The three stars have *IRAS* spectra which are indistinguishable from those of PN (Pottasch 1984). This is suggestive that these stars are indeed inside PNs (see van der Hucht *et al.* 1985).

Two of these stars have a visible planetary nebula around it. V605 Aql is surrounded by the planetary cataloged as A58 or PK 037−05°1 (van den Bergh 1971; Ford 1971; Bidleman 1971). V352 Aql is inside the planetary K3-25 = PK 037−03°3 (Kohoutek 1965). V1860 Sgr has no apparent nebulosity; however, this can be because the nebula has had time to recombine (see below).

The presence of PN infrared spectra and visible nebulosity confirms that there is a subset of R CrB's surrounded by planetary nebulae. I will name this class "nebular R CrB's." These stars are identical in the properties required by Iben *et al.* (1983) for supergiants formed by a final flash.

Additional evidence that the nebular R CrB's are on the evolutionary track of Iben *et al.* (1983) comes from the indications that the central stars were recently much hotter than is now observed. This is because the central stars are presently much too cool to excite their nebulae. Evolutionary calculations suggest that the central star had a $\log T_*$ of greater than 4.7 within the last 10^3 yr. Over this period, the nebula would not have had time to recombine. Tylenda (1979) gives the hydrogen recombination time scale as 120,000 yr cm^{-3} divided by the electron number density. Ford (1971) gives an electron density of ~ 100 cm^{-3} for V605 Aql, which implies that the nebula will remain visible for the $\sim 10^3$ yr duration of the giant phase.

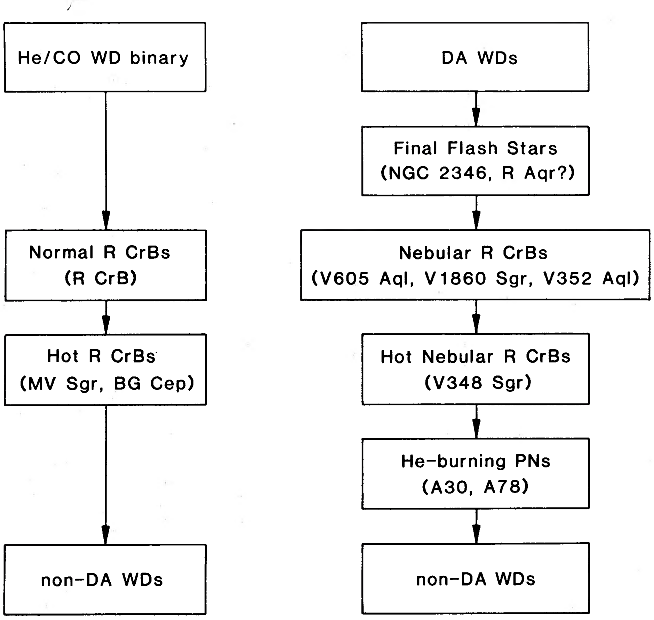

FIG. 2.—Schematic evolutionary tracks for R CrB's. Track on the left illustrates the evolutionary scenario of Webbink (1984) which produces the majority of R CrB's. Track on the right illustrates the proposal of Iben *et al.* (1984) for producing R CrB's from final helium shell flashes on central stars of old planetary nebulae. In this paper I assign stars to membership in the newly defined classes of "hot R CrB's," "final flash stars," "nebular R CrB's", and "hot nebular R CrB's". The nebular R CrB's are distinguishable by the surrounding nebula visible at either optical or infrared frequencies.

Other places along the evolutionary track of Iben *et al.* (1983) have already been identified with actual stars. NGC 2346 has been recognized as a final flash star by Schaefer (1985) because of its position on the H-R diagram, the large nebula, and its R CrB–like light curve. V348 Sgr is suggested (Dahari and Osterbrock 1984) to be a hot nebular R CrB because of its double-shelled planetary nebula, high effective temperature, abundance anomalies, and R CrB–like light curve. (It is mysterious why the visible PN does not have any associated cold dust.) The He-burning PNs are identified by Iben *et al.* (1983) as the large high-excitation PNs (Kaler 1981) which include A30 and A78.

The relative numbers of normal R CrB's versus nebular R CrB's can be estimated from the numbers given in Iben and Tutukov (1985). The ratio of the two class's populations will be the ratio of the birthrate times the lifetime. The birthrates and lifetimes are ~ 0.006 yr^{-1} and ~ 0.06 yr^{-1} and $10^{4.5}$ yr and 10^3 yr for normal and hot R CrB's, respectively. Hence, the normal R CrB's are dominant in our galaxy by a factor of 3. The observed numbers will differ from this because of selection effects on the luminosities. The normal R CrB's are 3 times brighter than the nebular R CrB's, so variable star searches will cover a 5 times larger volume in our galaxy. So the ratio of observed stars on the two evolutionary tracks should be ~ 15, which is comparable to the observed ratio.

TABLE 3

CLASSES OF R CrB STARS

Class	Prototype	log (ν_m)	log (T_*)	log (L)	Nebula?	R CrB–like Variability?
Normal R CrB's	R CrB	13.5	3.8	4	No	Yes
Hot R CrB's	MV Sgr	13.0	4.3	4	No	Yes
Final flash stars	NGC 2346	$\lesssim 12.5$	4.9	1.5	Yes	Yes
Nebular R CrB's	V605 Aql	$\lesssim 12.5$	3.8	4	Yes	Yes
Hot nebular R CrB's	V348 Sgr	$\lesssim 12.5$?	4.3	4	Yes	Yes
He-burning PNs	A30	$\lesssim 12.5$	4.9	4	Yes	No

V. CONCLUSIONS

As detailed in the introduction, infrared observations have frequently proved decisive in arriving at our current understanding of R CrB's. This paper reports the first long wavelength measurements of R CrB's by surveying all known members of the class in the *IRAS* data base. The infrared emission can be understood as radiation of a clouds whose density falls off as r^{-2} and whose grain absorption coefficient varies as ν^1. To a first approximation, the star emits several hundred clouds a year—each of which subtends ~ 30 square degrees. Each R CrB will contribute $\sim 5 \times 10^{-9}$ $M_\odot$ yr^{-1} of grains to the interstellar medium.

The *IRAS* observations also distinguish a subset of R CrB's which are in planetary nebulae. These nebular R CrB's are identified as being on a separate evolutionary track from the majority of R CrB's. The characteristics of classes of stars along the two tracks are summarized in Table 3 and Figure 2.

Based on the work presented here, I can advance several predictions. (1) None of the normal R CrB's will be found to have a visible surrounding nebula. (2) The atmospheric composition of the nebular R CrB's should be systematically different from the normal R CrB's because of their different evolutionary history. (3) The nebula around the nebular R CrB's will show evidence for the coexistence of both high- and low-excitation features. (4) No hot compact object will be found which can illuminate the nebulae around the nebular R CrB's. (5) High-resolution far-infrared spectra of the nebular R CrB's will be indistinguishable from ordinary planetary nebulae.

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