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MASS RETURN TO THE INTERSTELLAR MEDIUM FROM HIGHLY-EVOLVED CARBON STARS

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1. INTRODUCTION

Carbon stars play a central role in the evolution of the interstellar medium, returning highly-processed material during a period of extensive mass loss. In addition, they represent a major period in the advanced evolution of moderate-mass stars. Since these stars are often very bright at mid- and far-infrared wavelengths, an extensive survey for them is possible using the data produced by the Infrared Astronomical Satellite.

2. SELECTION CRITERIA

We began our study by plotting visually-identified carbon stars in the 12 μm/25 μm/60 μm color-color diagram, along with the location of a number of mass-losing stars that lie near the location of the carbon stars, but are not carbon rich. Carbon stars were found to be heavily concentrated in one part of the diagram (e.g., Hacking *et al*. 1985, Zuckerman and Dyck 1986, Thronson *et al*. 1986), while oxygen stars are more widely distributed. Models show that this part of the color-color diagram is populated largely by circumstellar emission from amorphous carbon. Our first selection was to search through the *IRAS* Point Source Catalog (PSC) for objects that fell within the central box in the figure. Only objects were included in our sample that had high-quality detections by the satellite. About half of this sample had either a good *IRAS* Low Resolution Spectrum or a reliable visual spectral classification, which allowed us to both remove non-carbon-rich objects and to estimate the contamination in our final sample. This final sample consists of 619 objects, which we estimate is contaminated by 7% non-carbon-rich objects.

To estimate the mass return rate for *all* evolved circumstellar envelopes, both oxygen- and carbon-rich, we also searched the PSC for the entire class of stars with excess emission (in particular, $4.57 > F_\nu(12\ \mu m)/F_\nu(25\ \mu m) > 2.4$, $4.79 > F_\nu(25\ \mu m)/F_\nu(60\ \mu m) > 1$, while excluding hot photospheres).

3. THE DISTRIBUTION OF CARBON-RICH SHELLS IN THE MILKY WAY

Plotted on the plane of the sky, we find that the number of carbon-rich objects appears to decline toward the center of the Galaxy. Some of this decrease is due to incompleteness in our sample as a consequence of source confusion in the PSC.

We have constructed a statistical distribution of these objects in the galactic plane by adopting an average 12 μm "luminosity", L (12 μm) = $4 \pi R^2 F_\nu$ (12 μm) = 3 x 10^9 Jy-pc^2, for all the objects in our sample. This value was found by combining the data in Knapp and Morris (1985) for many well-studied objects with the PSC flux densities. This value is accurate to a factor of 4. We applied it to our sample to calculate average distances and found that the distribution of objects in the plane of the Galaxy is extremely uniform, with a surface density of about 6.5 kpc^{-2}. There is no clear concentration toward the center. This is in sharp contrast with reported distributions of oxygen-rich stars, but is in general agreement with that reported for visually-identified carbon stars.

For a uniform distribution in the Galaxy, we estimate a total number of infrared-emitting carbon-rich stars of 4600 x [R^2/15], where R is the radius of the Galaxy in units of kpc.

4. MASS-LOSS RATES, LIFETIMES, AND BIRTHRATES FOR EVOLVED STARS

Data in Knapp and Morris (1985) and in the PSC shows that the mass-loss rate for both carbon and oxygen stars may be estimated from the ratio [S] of the 12 μm to 60 μm *IRAS* flux densities, log[$\dot{M}$ ($M_\odot$ yr^{-1})] = -4 - 0.112 x log[S]. Applied to the carbon-rich envelopes in our sample, the mass-return rate for the galaxy is 0.04 $M_\odot$ yr^{-1}. For our sample of *all* circumstellar envelopes, the mass return rate is 0.3 $M_\odot$ yr^{-1}. Both calculations assume a radius of the Milky Way of 15 kpc.

An approximate average lifetime for the carbon-rich objects may be estimated from $(M_a-1.4)/\dot{M}$, where M_a is the average stellar mass (about 3 $M_\odot$ for this sample) and $\dot{M}$ is the average mass-loss rate (1.4 x 10^{-5} $M_\odot$ yr^{-1}). Our average calculated lifetime is 10^5 yrs.

The birthrate may likewise be estimated by dividing the mean lifetime into our estimated total number, giving 0.05 star yr^{-1}.

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