THE SPATIAL, TEMPORAL, and PHOTOMETRIC PROPERTIES OF AGB STARS

S. G. Kleinmann
University of Massachusetts

The Two Micron Sky Survey (Neugebauer & Leighton 1969;TMSS) provides a census of AGB stars which is relatively insensitive to interstellar or circumstellar reddening, temporal variations, or differences in photospheric temperature. This paper summarizes results from recent analyses of all carbon, S type, and mass-losing M stars in the TMSS, including local surface densities, scale heights, and mass loss rates. All three groups are concentrated toward the plane; the mass-losing M stars appear least concentrated toward the plane but most strongly concentrated toward the galactic center. Results from the IRAS survey were used to determine the range of infrared colors of stars in each class, and to estimate their mass loss rates. Carbon stars have relatively higher 60 μm flux densities than oxygen-rich stars, and have relatively higher mass loss rates. The total mass loss rate is dominated by a small fraction of the stars in this sample. IRAS photometry and IRAS Low Resolution Spectometer data do not unambiguously distinguish carbon-rich and oxygen-rich stars in this sample. Future searches for stars with the greatest mass loss rates might concentrate on sources found to be variable in the IRAS survey, since a large fraction of the TMSS stars with the most massive envelopes are known Miras or infrared variables.

INTRODUCTION

The Asymptotic Giant Branch (AGB) of the Hertzsprung-Russell diagram (B-V > 0.5 mag., 0<M(V)<-3) is associated with the final phases of nuclear burning in stars having masses between 1 and 6 M☉. Though stars in this branch are quite luminous and can be seen to large distances, they are rare because their lifetime in this phase is strongly limited by their rapid mass loss rates (up to 10^{-4} M☉ yr^{-1}). Unfortunately, since stars in this mass range are concentrated toward the plane of the Milky Way, interstellar obscuration limits the range over which they can be detected in optical surveys. Interest in obtaining an accurate census of these stars is stimulated by the goals of measuring their range of lifetimes in the AGB phase, and the extent to which they dominate the chemical evolution of the Galaxy.

Infrared surveys carried out in the past two decades are far less sensitive to interstellar dust obscuration and far more sensitive to dust emission from warm circumstellar envelopes than previous surveys of

https://doi.org/10.1017/S0252921100062576 Published online by Cambridge University Press

the sky at shorter wavelengths. The infrared surveys will therefore provide a far more accurate picture of the types and distribution of mass-losing stars than was previously available.

In order to exploit infrared sky surveys, it is necessary first to have some minimal information on the classification of stars found in the survey, since stars in different classes have different luminosities, and may have very different spatial distributions. For example, it is necessary to distinguish the evolved mass-losing stars from those which are bright in the infrared simply because they are nearby or because they are reddened by interstellar dust. It is also necessary to distinguish the evolved mass-losing stars from very young stars whose infrared-bright circumstellar envelopes are a remnant of their birth rather than a product of their old age. Finally, it is important to distinguish stars belonging to specific sub-classes, such as Carbon stars (O/C < 1), S stars (O/C ~ 1), and M stars (O/C > 1), in order to test and measure the standard scenario for chemical evolution among these stars (M -> MS -> S -> SC -> C).

The necessary classification information is only just now becoming available for the stars found twenty years ago in the Two Micron Sky Survey (Neugebauer & Leighton 1969). This survey covered the sky between $-33^{o} < \delta < +82^{o}$ to a limit of m(K) = +3.0 mag. (39 Jy) at 2.2 μm, and obtained simultaneous measurements of each star in a second broad band with an effective wavelength near 0.9 μm. The total number of stars found in this survey was 5612, and the average surface density is about the same as the surface density of stars listed in the Bright Star Catalog, which contains sources brighter than V = 6.5 mag.

This review summarizes recent studies of carbon stars, S stars, and mass-losing M stars in the TMSS presented by Claussen et al. (1987), Jura (1988), and Kleinmann et al. (1988) respectively. These authors combined data from the Bidelman's (1980) catalog of spectral classes of sources in the TMSS with photometry presented in the TMSS and the IRAS Point Source Catalog (1985) and temporal information given in the General Catalog of Variable Stars (Kholopov 1985; hereafter GCVS) to learn the space distribution and mass loss rates of the various classes of AGB stars detected in the TMSS. The results of these studies are summarized in Table 1. One of the major conclusions of these analyses, and of a more recent study of very rapidly mass-losing stars in the solar neighborhood (Jura & Kleinmann 1988), is that only a few of the stars found in the TMSS make a significant contribution to the total rate of mass return to the interstellar medium.

The IRAS Sky Survey provides a far more sensitive probe of stars losing mass rapidly. Unfortunately, classifications based on high resolution spectra are unavailable for many IRAS sources at this time, which has led to the use of low-resolution spectra and broad-band photometric data to identify these stars. The adequacy of these techniques is addressed here, by reviewing the IRAS colors and spectral characterizations of stars found in the TMSS. Infrared source variability is discussed as an alternative means of identifying the stars in the IRAS survey that are losing mass most rapidly.

CARBON STARS IN THE TWO MICRON SKY SURVEY

Using spectral classifications given in Bidelman's (1980) catalog and in a compilation made by C. Payne Gaposchkin, Claussen et al. (1987) obtained a list of all known carbon stars in the TMSS. (Dr. Bidelman subsequently pointed out that at least one of the objects included in that list -- TMSS -10433 -- is a K-type supergiant, and not a carbon star.) The total number of carbon stars in this flux-limited sample (m(K) < +3.0 mag.) is 214. The Yale Bright Star Catalog lists fewer than one-tenth as many carbon stars.

The low median galactic latitude of carbon stars (6.6^{0}) implies that, even at the relatively high flux levels of the TMSS, they must be being viewed at distances that are large compared to their scale height. Distances to individual carbon stars could be deduced by adopting the mean absolute K magnitude for carbons stars in the Magellanic Clouds, (M(K) = -8.1 mag.), since Frogel et al. (1980) found the dispersion in in this value is relatively small, ~0.5 mag. (It remains to be seen, however, whether the same mean and dispersion apply to carbon stars in the neighborhood of the sun, where stars are relatively richer in metals than in the Magellanic Clouds.) In most cases, the total fluxes and derived distances indicated total luminosities $\sim 10^{4}$ Lo. For a few objects, namely those where F(12 μm) > F(2.2 μm), circumstellar extinction depresses the observed 2.2 μm continuum, so that distances derived by assuming a constant K-band luminosity are uncertain for these objects. However even with the assumption of a constant K-band luminosity, only one object -- TMSS +10216 -- would have appeared to have a total luminosity far exceeding an AGB limit of $\sim 3 * 10^{4}$ Lo. This object is the most heavily obscured carbon star in the sample. No stars as red as TMSS +10216 have been detected in the nearby dwarf ellipticals in Draco and Sculptor (Jura 1986).

With the derived distances, and making allowance for interstellar dust obscuration amounting to ~ 0.2 K mag./kpc (Jura et al. 1989), we deduced that the carbon stars seen in the TMSS must be being observed out to a distance of ~1.5 kpc. This value is, as expected, much larger than their scale height. Thus, we can accurately estimate the surface density of carbon stars projected onto the galactic plane: it is N = ~ 40 kpc^{-2}. (In deriving this number, a 25% correction was made for the incomplete sky coverage of the TMSS.) The distribution of stars perpendicular to the disk is well fit with an exponential, and the derived scale height is ~ 200 pc. This implies a local number density of ~ 100 kpc^{-3}.

A comparison of the TMSS and the Case survey (Stephenson 1973) showed that the TMSS missed a large fraction of the carbon stars found in the optical survey. Analyses of these stars suggests that they must belong to another class of carbon stars which is at least 10 times less luminous in the near-infrared than the average carbon star sampled in the TMSS.

On the other hand, the Case survey missed ~7% of the carbon stars that were found in the TMSS survey. The missing stars have extremely red colors; over half of them are brighter at 12 μm than at 2.2 μm. It

https://doi.org/10.1017/S0252921100062576 Published online by Cambridge University Press

seems plausible to assume that this redness is due to obscuration by circumstellar dust in massive envelopes; this obscuration hindered their detection in the shorter-wavelength Case survey.

The Revised Air Force Four-Color Infrared Sky Survey (Price & Murdock 1983) lists nearly 50 infrared-bright carbon stars that were not detected in the TMSS (Kleinmann et al. 1981). Kinematic distances to these objects, derived from the velocities of the line centers of their strong CO J = 1-0 emission lines, suggest that about a third of them lie within the 1.5 kpc radius sampled by the TMSS. As indicated below, these objects play a major role in the rate of mass return by carbon stars in the solar neighborhood.

A two-color diagram of the IRAS colors of carbon stars in the TMSS is shown in Figure 1a. The stars are seen to exhibit strong long-wavelength excesses due to emission by dust in their circumstellar envelopes. The median mass loss rate for carbon stars, computed from their 60 μm IRAS fluxes according to a prescription given by Jura (1987), and assuming an average outflow velocity of 15 km sec^{-1} (Knapp & Morris 1985; Zuckerman et al. 1986) is ~2 x 10^{-7} M⊙ yr^{-1}. Only ~10% of the carbon stars in the TMSS have mass loss rates higher than ~2 x 10^{-6} M⊙ yr^{-1}; yet these stars contribute 85% of the mass returned by carbon stars to the interstellar medium. This fraction is really a lower limit, since heavily dust-enshrouded carbon stars detected in the Air Force survey and the IRAS survey make a contribution to the rate of mass return that is twice the total rate lost by all of the carbon stars in the TMSS (Jura & Kleinmann 1988).

S STARS IN THE TWO MICRON SKY SURVEY

Jura (1988) studied all 65 of the stars in the TMSS that were classified as type S by Wing & Yorka (1977). The completeness of this list is not well known. Stars having transitional spectral classes of MS and SC were excluded.

The space distribution of the S stars studied by Jura (1988) is similar to that of the carbon stars in the TMSS. The median galactic latitude of the S stars is 6.0^{o}, essentially the same as the carbon stars in the TMSS. If the S type stars seen in the TMSS have a scale height that is roughly comparable to that of the carbon stars, then they are being viewed at comparable distances; i.e., they must have the same average K-band luminosity as the TMSS carbon stars. Thus, as Jura (1988) pointed out, the TMSS samples more luminous S stars than those found in globular clusters (Lloyd Evans 1984).

The IRAS two-color diagram for S stars in the TMSS is shown in Figure 1b. In the range 12 μm to 60 μm, these stars appear to have continua that more closely resemble those of the carbon stars, than of the mass-losing M stars in the TMSS (see below). Relatively fewer S stars than carbon stars have strong far-infrared excesses. Also, most of the S stars in this sample have mass loss rates lower than the median mass loss rate of carbon stars in the TMSS (Jura 1988). Only two S stars in this sample have mass-loss rates exceeding 2 x 10^{-6} M⊙ yr^{-1}. No heavily dust-enshrouded S stars have been identified from the IRAS

https://doi.org/10.1017/S0252921100062576 Published online by Cambridge University Press

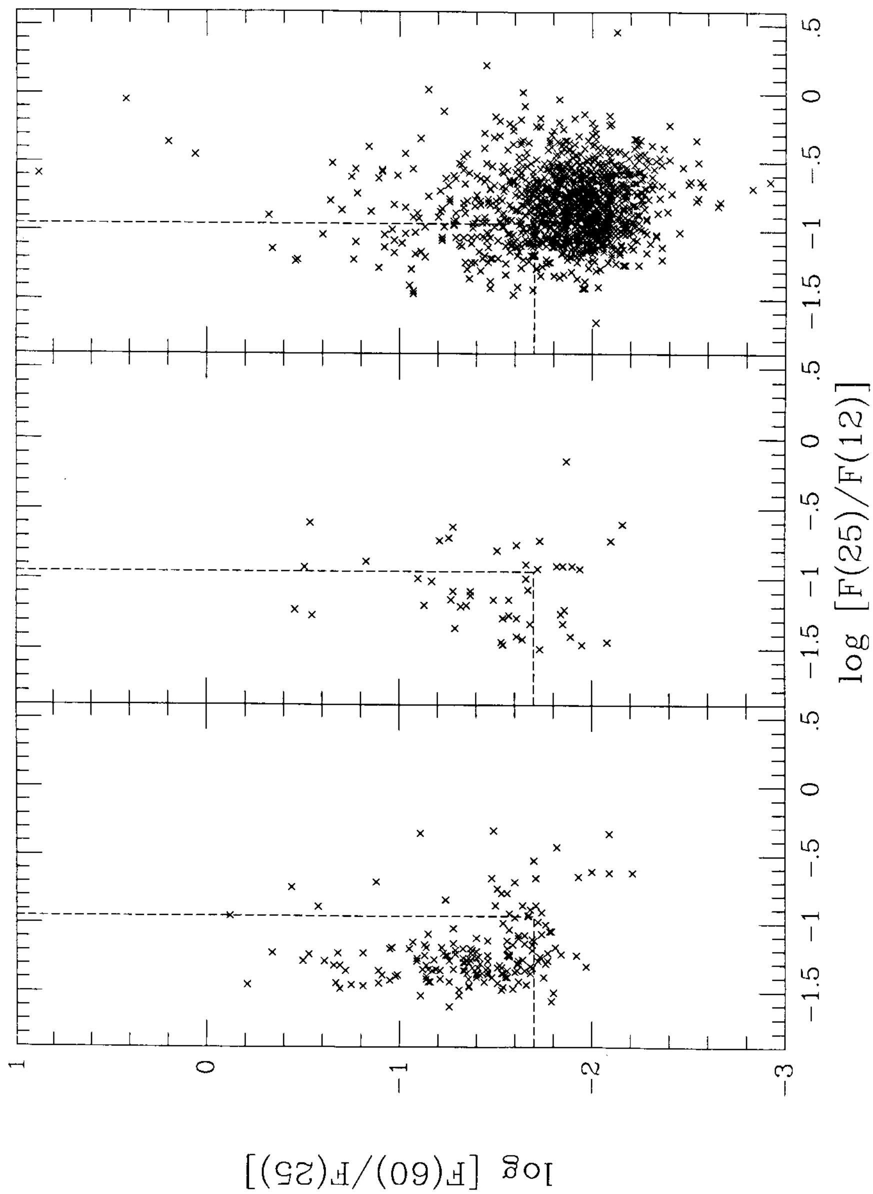

Figure 1. A two-color diagram of stars in the TMSS. Flux densities at 12, 25, and 60 μm were taken from the PSC, Version 2; they were not color-corrected. A 4000 K blackbody would lie at −0.61, −0.77 in these plots. Left: Carbon stars; Middle: S Stars; Right: Mass-losing M stars.

https://doi.org/10.1017/S0252921100062576 Published online by Cambridge University Press

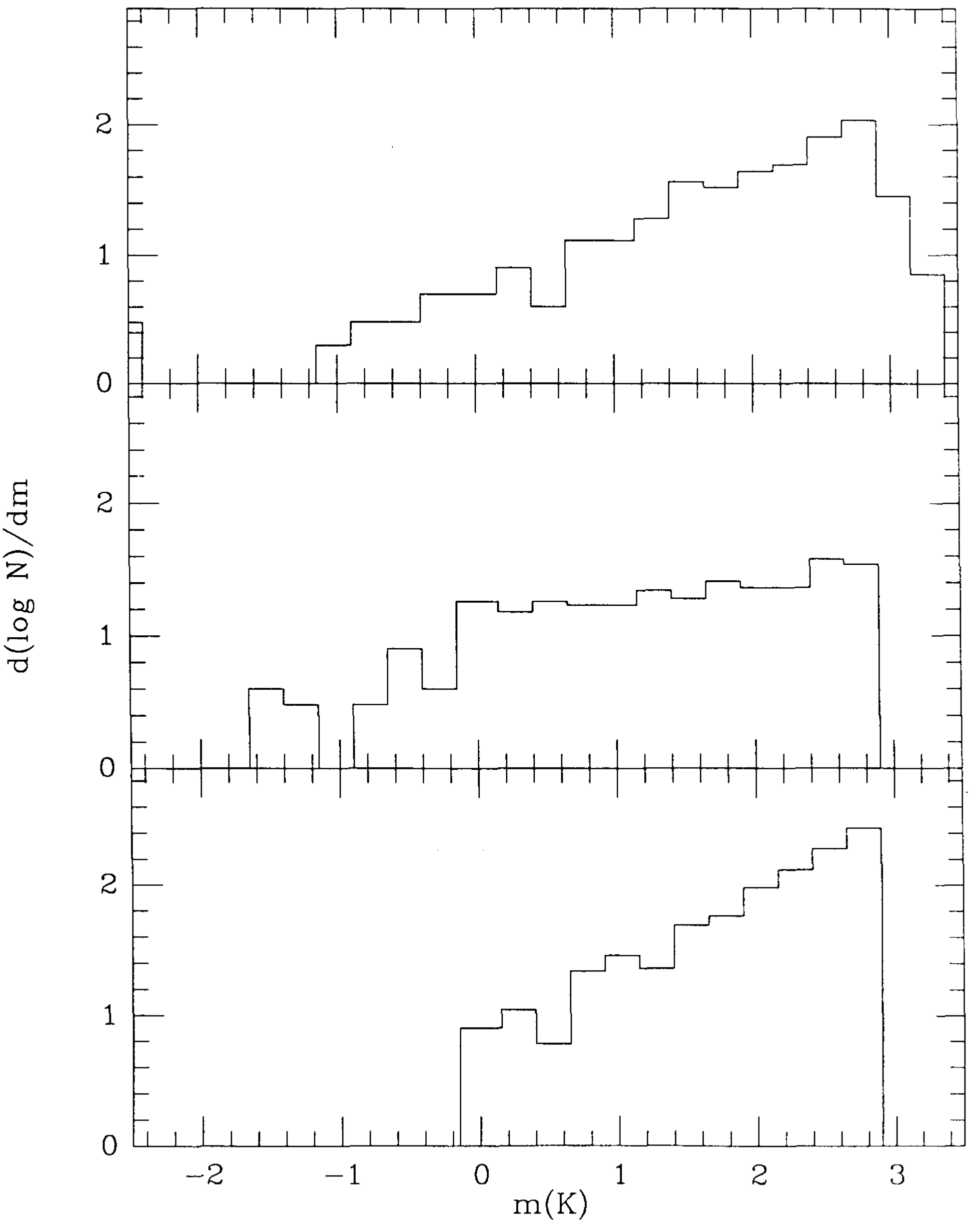

Figure 2. Distribution of mass-losing M stars in the TMSS vs. m(K). Top: Known Mira variables and infrared variables not identified with stars in the GCVS; Middle: Known Semi-Regular variables; Bottom: Irregular variables and stars not identified with known variables.

https://doi.org/10.1017/S0252921100062576 Published online by Cambridge University Press

survey. It is not clear at what level this is a selection effect, i.e., that the spectroscopic criteria distinguishing an S star from a carbon or M star are masked by strong circumstellar absorption.

M STARS IN THE TWO MICRON SKY SURVEY

Kleinmann et al. (1988) have reviewed the properties of AGB M stars detected in the TMSS. In this study, the assumption was made that the AGB stars could be distinguished from the first ascent giant branch M stars by their high mass loss rates. A significant infrared excess at $\lambda>10$ μm was taken as an indicator of the presence of a massive circumstellar envelope.

The distribution of colors among carbon stars were used as a guide in selecting the mass-losing M stars in the TMSS. The carbon stars have uncorrected colors (K - m[12]) as low as 0.9 mag., which is the expected uncorrected color for a 4000 K blackbody. All stars having colors redder than this, but not known to be carbon or S stars, were taken to be mass-losing M stars. Stars with peculiar spectral types (e.g., Wolf-Rayet stars, early-type emission line stars), or peculiar variable types (e.g., symbiotic stars) were eliminated from this list. Supergiants listed in Bidelman's (1980) catalog were also eliminated. Finally, 8 objects listed in Bidelman's (1980) catalog with spectral classes of M0 or earlier were eliminated. The remaining list numbered 1705 stars.

Studies of M stars in the Magellanic Clouds indicate that they are not characterized by a constant luminosity; rather, the Miras appear to follow a period-luminosity relationship. Thus, a knowledge of the temporal properties of the sample is critical to an understanding of their spatial distribution. Comparison of the sample of mass-losing M stars with the GCVS shows that ~52% of the sample are known variables. The TMSS and PSC provide an independent measure of source variability; those sources which appeared to vary in the infrared during the course of multiple observations made in these surveys are flagged in the catalogs. There are 523 such infrared variables among the mass-losing M stars. Of these, 413 are identified with variables in the GCVS; most of these previously known variables are Miras. Since Miras have larger amplitudes than Semi-Regulars or Irregulars (the only other variable classes in the sample), and since Miras have smaller amplitudes at infrared than at optical wavelengths, it seems reasonable to assume that most of the remaining 110 infrared variables are also Miras; these stars might not have been recognized as optical variables, since they are heavily enshrouded in thick circumstellar envelopes (as indicated by their extremely red colors).

The lack of temporal information for all of the M stars in our sample leads to significant selection effects. The brightness distribution of the Miras and the infrared variables (shown in Figure 2a) is consistent with that expected for stars confined to a disk whose thickness is small compared to the maximum distance of stars in the sample. On the contrary, the brightness distribution of the Semi-Regular stars (Figure 2b) increases less rapidly at faint flux levels than would be expected for such a distribution. The Irregular variables (Figure 2c) (including the unidentified stars which are not infrared variables) increase more rapidly than expected even for stars

https://doi.org/10.1017/S0252921100062576 Published online by Cambridge University Press

being viewed at distances small compared to their scale height. The deficiency of faint Semi-Regular stars, and the excess of faint Irregular stars and stars not identified with variables, suggest that many of the Irregulars and stars not identified with variables may be unrecognized Semi-Regular variables. The brightness distribution derived by combining the Semi-Regulars with the Irregulars and the stars not identified with variables is the same as the distribution of the Miras, i.e., consistent with a flux-limited sample of stars being seen at distances that are large compared to their scale height.

The distribution of periods among known variables in the sample is bimodal; 80% of the stars with $P \geq 250$ days are Miras, while 89% of the stars with $P < 250$ days are Semi-Regulars. The median period for all identified Miras in the sample is 360 days, while the median period for all identified Semi-Regulars is 150 days. If the period-luminosity relationship given by Glass et al. (1987) were applied both to Miras and Semi-Regulars, then the Miras would have a median absolute K magnitude of -8.1, similar to the carbon stars, and the Semi-Regulars would have a median absolute K magnitude of ~ -6.7.

This expectation is in marked contrast to the observed distribution of galactic latitudes among the Miras (including the infrared variables) and the Semi-Regulars (including Irregulars and stars not identified with variables). The median galactic latitude of the former class is 14.5^{o}, while the median galactic latitude of the latter class is actually less, only 11.4^{o}. If the Semi-Regulars had the same scale height as Miras, their median galactic latitude should be nearly twice as large, since the TMSS should detect them at distances only about half as great as the faintest Miras in the sample. Lacking any obvious reason why the Semi-Regulars should be more confined to the galactic plane than the Miras, we deduce from their proximate median latitudes that they must have a comparable K-band luminosities. In this case, the TMSS samples mass-losing M stars and carbon stars to comparable distances, ~1.5 kpc. The surface density of all mass-losing M stars is then 320 kpc^{-2}.

Table 1 shows that the carbon stars appear more closely confined to the galactic plane than the mass-losing M stars (either the Miras or the Semi-Regulars). If the K-band luminosities of these stars are comparable, then the scale height of M-type Miras must be about twice that of the carbon stars, i.e., ~ 400 pc. This result implies that the progenitors of most of the mass-losing M stars in this sample may be somewhat less massive than the progenitors of the carbon stars.

A check on the luminosities of M stars in our sample can be obtained by considering their longitude distribution. If the TMSS views these stars to distances ~1.5 kpc, and if these stars are distributed in an exponential disk with a scale length of ~3.5 kpc (like the integrated light from other well-studied spirals), then there should be an apparent concentration of these sources toward the galactic center. Figure 3 shows the longitude distribution for the all TMSS carbon stars, Mira-type M stars (including infrared variables), and Semi-Regular M stars (including Irregulars and stars not identified with variables), in the brightness range $3 \leq K < 2$. (The "dip" between $220^{o} < l < 360^{o}$ is due to the fact that the TMSS was limited to $\delta > -33^{o}$, and therefore did not sample all galactic latitudes at these longitudes.) With the

https://doi.org/10.1017/S0252921100062576 Published online by Cambridge University Press

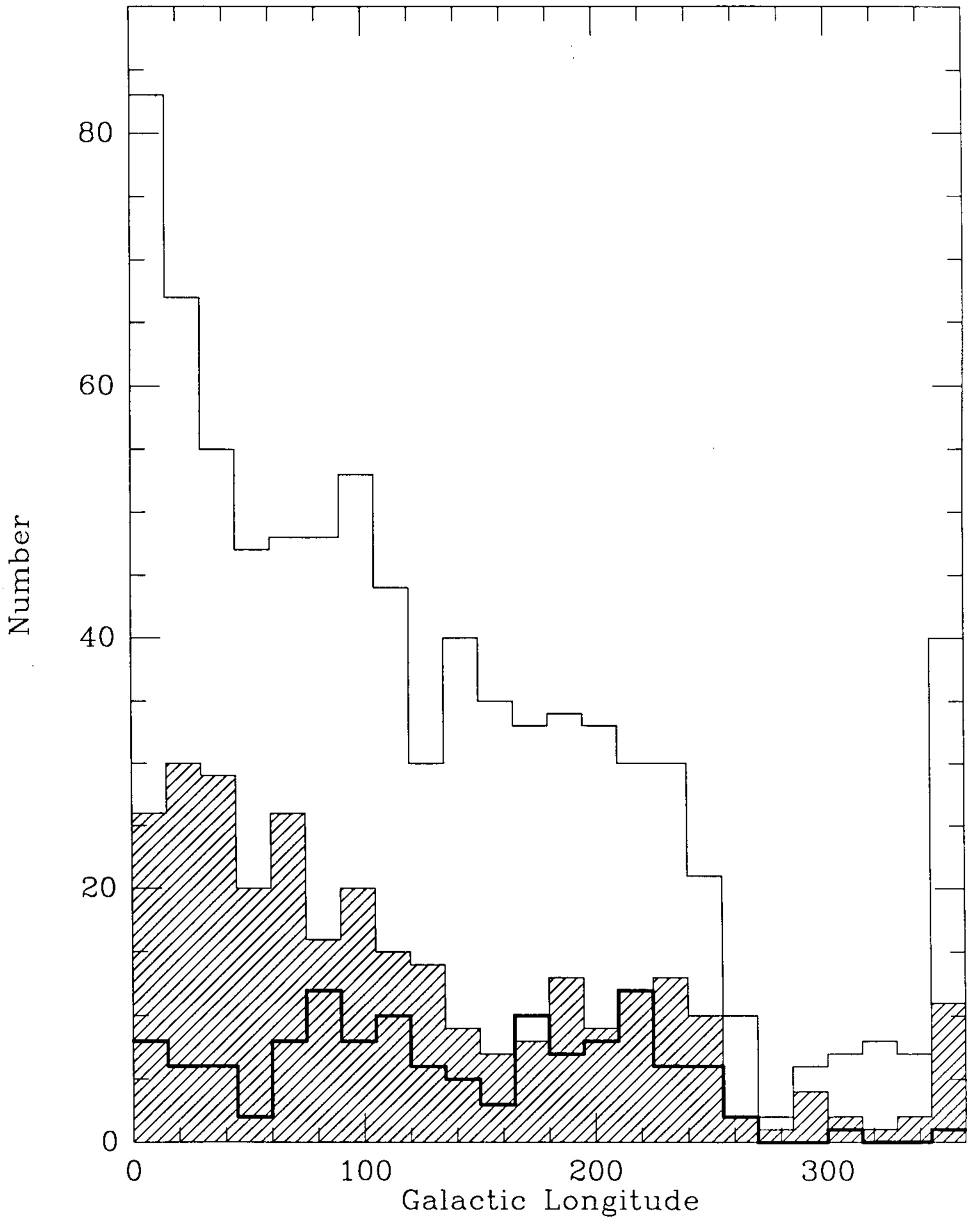

Figure 3. The distribution of certain classes of AGB stars in the TMSS vs. galactic longitude. The heavy line denotes carbon stars. The hatched area denotes Semi-Regular variable, mass-losing M stars (including Irregular variables and stars not identified with known variables). The thin line denotes Mira variables and infrared variables not identified with stars in the GCVS among the mass-losing M stars. Only stars having $3 \leq m(K) < 2$ are included in the Figure. The TMSS covered only a fraction of the sky for longitudes between $235^{o} < l < 15^{o}$.

https://doi.org/10.1017/S0252921100062576 Published online by Cambridge University Press

TABLE 1
AGB Stars in the TMSS

	C	S	M
Number	214	65	1705
Miras	38	22	354
IR Variables	13	2	110
Semiregulars	79	14	331
Irregulars	53	14	210
Others	31	13	700
Median Galactic Latitude	6.6^{o}	6.0^{o}	12.4^{o}
Fraction Within $330^{o} < l < 30^{o}$	0.13	0.21	0.19
Surface Density (kpc^{-2})	40	12	320
Scale Height (pc)	200	200	400
Median Mass-Loss Rate (10^{-7} M☉ yr^{-1})	2.0	0.1	1.5
Total Projected Mass-Loss Rate (10^{-4} M☉ yr^{-1} kpc^{-2})	0.3	0.03	1.0

TABLE 2
LRS Characterizations for AGB Stars in the TMSS

Index Range	Description	C	S	M
10 - 19	Featureless Blue Continuum	33	17	572
20 - 29	Blue Continuum with 10 μm Emission	14	7	409
30 - 39	Blue Continuum with 10 μm Absorption	2	1	12
40 - 49	Blue Continuum with 11 μm Emission	88	2	21
50 - 59	Featurless Red Continuum	1	0	4
60 - 69	Red Continuum with 10 μm Emission	0	0	2
70 - 79	Red Continuum with 10 μm Absorption	0	0	1

https://doi.org/10.1017/S0252921100062576 Published online by Cambridge University Press

assumptions stated above, the number of stars should be greater, roughly by a factor of 2, between longitudes centered at $l = 0^o$ and the anti-center direction. Just such an increase is observed for both Miras and Semi-Regulars. The sharp increase in the number of Semi-Regulars at $l < 30^o$ may be due to unrecognized supergiants in the 5 kpc ring.

Interestingly, the carbon stars show no such variation with longitude, although their numbers in the TMSS are too small to make a definitive assessment. Jura et al. (1989) have, however, studied the carbon stars found in Fuenmayor's (1981) deep I-band survey near the galactic anti-center. They found no difference between the local density of carbon stars and the density of carbon stars at the deepest levels of Fuenmayor's survey (which samples distances out to ~ 4 kpc beyond the solar circle). These results imply that the density of carbon stars falls much less steeply with galacto-centric radius than the density of other stars, an effect which might be attributed to the higher incidence of carbon stars among low-metallicity populations.

The fractions of all carbon, S, and mass-losing M stars in the TMSS that are concentrated in the direction of the galactic center, $330^o < l < 30^o$ are summarized in Table 1. The overall average ratio of mass-losing M stars to carbon stars within the volume sampled by the TMSS is 8. Since the M stars appear to be more concentrated toward the galactic center than do the carbon stars, and since the TMSS missed a large fraction of the galactic plane near the galactic center, this ratio is a lower limit.

As shown in Figure 1, the median infrared colors of mass-losing M stars in the TMSS differ significantly from those of the carbon stars. This difference was first noted by Hacking et al. (1985), in their analysis of the brightest high-latitude 12 μm sources. The average color, F(60)/F(K), of mass-losing M stars in the TMSS is lower than that of the carbon stars. Thus, if their outflow velocities and K-band luminosities are similar, then their inferred mass loss rates must be lower. The median, $\sim 1.5 \times 10^{-7}$ M$_\odot$ yr^{-1}, is ~25% lower than the median for carbon stars in the TMSS; some of this discrepancy may be due to differences in the properties of the dust grains (Zuckerman and Dyck 1986). Only 5% of the mass-losing M stars in the TMSS have mass loss rates exceeding $\sim 2 \times 10^{-6}$ M$_\odot$ yr^{-1}, about half the fraction of carbon stars that are losing mass rapidly. Though the number of M stars is much greater than that of carbon stars, longer-wavelength infrared surveys (e.g., the RAFGL) failed to show that the number of heavily dust-enshrouded M stars significantly exceeds that of heavily dust-enshrouded carbon stars. This result is in substantial agreement with the recent analysis by Jura & Kleinmann (1988) showing that carbon and M stars contribute about equally to the local rate of mass return to the interstellar medium.

DEEPER INFRARED SURVEYS

The IRAS survey offers an opportunity to obtain a census of heavily mass-losing stars at distances much greater than those sampled by the RAFGL or TMSS. In analyzing the IRAS data, it will be necessary to distinguish between carbon-rich and oxygen-rich stars because of their different spatial distributions. Unfortunately, the IRAS data do not provide a robust means of making this distinction. Though there is a significant difference in the median colors of carbon stars and M stars, as seen in Figure 1, there is also a large degree of overlap in the colors of stars belonging to different spectral subclasses. Thronson et al. (1987) attempted to find the carbon stars in the PSC by selecting those within the region bounded by the dotted lines in Figure 1. More than 25% of the TMSS carbon stars, including +10216, lie outside the region used by Thronson et al. (1987) to select carbon stars; it seems reasonable to imagine that a survey at a longer wavelength would detect a relatively higher fraction of extremely red stars like those not in the Thronson et al. sample. More than 50% of the TMSS sources lying within the bounded region are, in fact, not carbon stars. This fact emphasizes the difficulty in using IRAS broad-band colors to deduce spectral classifications.

It is instructive to determine whether the classifications provided by the Low Resolution Spectrometer (LRS) experiment in IRAS might usefully distinguish between carbon-rich and oxygen-rich stars. Unfortunately, LRS classifications are only available for the brightest stars in the IRAS survey, and therefore samples only a small fraction of the volume represented in the PSC. For example, the LRS provides classifications for only 60% of the AGB stars in the TMSS. These results are summarized in Table 2: the number of sources in each of 8 ranges of classification are given for carbon stars, S stars, and M stars. Fewer than half of the stars classified by the LRS exhibited any infrared spectral feature. The LRS classes assigned to the remaining objects are sometimes discordant from the optical spectral classifications. For example, 20% of the sources with 11 μm emission, often attributed to SiC dust and commonly seen in carbon stars, have been classified M or S on the basis of optical spectra. Of the sources with 10 μm emission or absorption, often attributed to silicate dust and commonly seen in M stars, 4% have been classifed as carbon stars on the basis of optical spectra.

Will it take decades of optical and near-infrared spectroscopy to exploit the IRAS data to learn the distribution of mass-losing stars? Maybe not. Analyses of the carbon stars and mass-losing M stars in the TMSS shows that the stars with high infrared variability typically have the highest mass loss rates. Of the 214 carbon stars in the TMSS, 24 were found to vary (probability of variability $\geq$ 90%) during the IRAS survey. These stars (11% of the all the TMSS carbon stars) contribute nearly half of the mass loss rate by carbon stars in the TMSS. Similary, 10% of the mass-losing M stars in the TMSS were found to be variables by IRAS, and these stars account for nearly 40% of the mass loss rate by AGB M stars in the TMSS. Thus, studies focussed just on the infrared variable sources in the PSC might provide good estimates of the numbers and distribution of mass-losing stars in the Galaxy to distances of at least 5 kpc.

ACKNOWLEDGEMENTS

This work benefitted from helpful discussions with M. Jura. This work was supported by the AFOSR, under grant No. 88-0070, and by the National Aeronautics and Space Administration under JPL contract No. 958046.

REFERENCES

Bidelman, W. P. 1980, Pub. Warner and Swasey Obs., 2, No. 6.
Claussen, M. J., Kleinmann, S. G., Joyce, R. R., and Jura, M. 1987, Ap. J. Suppl., 65, 385.
Frogel, J. A., Persson, S. E., and Cohen J. G. 1980, Ap. J., 239, 495.
Fuenmayor, F. J. 1981, Rev. Mexicana Astr. Ap., 6, 83.
Glass, I. S., Catchpole, R. M., Feast, M. W., Whitelock, P. A., and Reid, I. N. 1987, in Late Stages of Stellar Evolution, ed. S. Kwok and S. R. Pottach (Dordrecht: Reidel), p. 51.
Hacking, P. et al. 1985, Pub. A.S.P., 97, 616.
IRAS Point Source Catalog. 1985, Joint IRAS Science Working Group (Washington, DC: GPO) (PSC).
Jura, M. 1986, Ap. J., 301, 624.
Jura, M. 1987, Ap. J. 313, 743.
Jura, M. 1988, Ap. J. Suppl., 66, 33.
Jura, M., Joyce, R. R., and Kleinmann, S. G. 1989, Ap. J., in press.
Jura, M., and Kleinmann, S. G. 1988, Ap. J., submitted.
Kholopov, P. N. 1985-1987, General Catalogue of Variable Stars, Vols. 1-3, (4th ed.; Moscow: Nauka Publishing House) (GCVS).
Kleinmann, S. G., Jura, M., Joyce, R. R., and Claussen, M.J. 1988, in preparation.
Kleinmann, S. G., Gillett, F. C., and Joyce, R. R. 1981, Ann. Rev. Astr. Ap., 19, 411.
Knapp, G. R. and Morris, M. 1985, Ap. J., 292, 640.
Lloyd Evans, T., 1984, M.N.R.A.S., 209, 825.
Neugebauer, G., and Leighton, R. B. 1969, Two Micron Sky Survey (NASA SP-3047) (TMSS).
Price, S. D., and Murdock, T. L. 1983, The Revised AFGL Infrared Sky Survey Catalog (AFGL-TR-83-0161).
Stephenson, C. B. 1973, Pub. Warner and Swasey Obs., 1, No. 4.
Thronson, H. A., Jr., Latter, W. B., Black, J. H., Bally, J., and Hacking, P. 1987, Ap. J., 322, 770.
Wing, R. F., and Yorka, S. B. 1977, M.N.R.A.S., 178, 383.
Zuckerman, B. and Dyck, H.M. 1986, Ap. J. 311, 345.
Zuckerman, B., Dyck, H. M., and Claussen, M. J. 1986, Ap. J., 304, 401.

https://doi.org/10.1017/S0252921100062576 Published online by Cambridge University Press