THE ASTROPHYSICAL JOURNAL, 341:359–366, 1989 June 1

DUST-ENSHROUDED ASYMPTOTIC GIANT BRANCH STARS IN THE SOLAR NEIGHBORHOOD

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Received 1988 August 11; accepted 1988 November 7

ABSTRACT

Using available infrared catalogs, we take an inventory of the AGB stars losing large amounts of mass ($>2 \times 10^{-6}$ $M_{\odot}$ yr^{-1}) within ~ 1 kpc of the Sun. We estimate a surface density of these stars of ~ 25 kpc^{-2} projected onto the plane of the Galaxy. Of these stars, about one-half are oxygen-rich while the other half are carbon-rich.

The total mass-loss rate from AGB stars into the interstellar medium is probably between 3 and 6×10^{-4} $M_{\odot}$ kpc^{-2} yr^{-1}. Within the uncertainties, this is in reasonable agreement with an estimated net loss rate of $\sim 8 \times 10^{-4}$ $M_{\odot}$ kpc^{-2} yr^{-1} for main-sequence stars with initial masses between 1 and 5 $M_{\odot}$ as they evolve to white dwarfs. However, it is possible that there are important sources of mass loss that we have not yet identified.

In the solar neighborhood, about one-half of all ~ 1.2 $M_{\odot}$ main-sequence stars spend $>3 \times 10^4$ yr in a carbon-star phase where they lose 1–2×10^{-5} $M_{\odot}$ yr^{-1} and then become white dwarfs with ~ 0.7 $M_{\odot}$.

Subject headings: stars: circumstellar shells — stars: evolution — stars: horizontal branch — stars: mass loss — stars: white dwarfs

I. INTRODUCTION

In the standard model, luminous (typically 10^4 $L_{\odot}$) stars on the asymptotic giant branch evolve from intermediate-mass stars (initially 1 $M_{\odot} < M_{\rm star} <$ 5–8 $M_{\odot}$ on the main sequence; Iben and Renzini 1983) that are undergoing extensive mass loss, and they are in the final stages of stellar evolution before becoming a planetary nebula and then a white dwarf (see Zuckerman 1980; Olofsson 1985). According to this scenario, during the AGB, a star may lose more than half of its initial mass, and this mass loss is important both for replenishing the interstellar medium and in the evolution of the star. The goal of this paper is to develop a more quantitative understanding of the mass loss from the local AGB stars, to determine how well the standard model reproduces the data.

With improvements in millimeter and infrared technology, considerable progress has been made in understanding the mass-loss process from red giants during the past 20 yr. The mass-losing stars display outflows that have been extensively studied both by their molecular emission from species such as CO (Morris 1985), and by their infrared emission associated with dust produced in the outflows (Jura 1986). These data indicate that AGB stars lose between 10^{-8} and 10^{-4} $M_{\odot}$ yr^{-1}. The total of all the mass loss from these stars is dominated by the relatively few objects with high mass-loss rates rather than the more plentiful objects with low mass loss rates (Knapp and Morris 1985; Claussen *et al.* 1987). Therefore, it is important to make a quantitative study of the objects losing large amounts of mass.

Because AGB stars are intrinsically cool and because they have large amounts of circumstellar dust, they are primarily infrared sources; they are not very prominent, for example, in the *Yale Bright Star Catalogue* (Hoffleit and Jaschek 1982). Therefore, it is possible to use the *Two Micron Sky Survey* (TMSS) (Neugebauer and Leighton 1969) and the *IRAS* data base to identify and study the local AGB stars. Using the *Two Micron Sky Survey*, the carbon-rich, S-type and oxygen-rich AGB stars have been listed and their spatial properties discussed by Claussen *et al.* (1987), Jura (1988), and Kleinmann, Jura and Joyce (1989), respectively. However, since these studies were directed toward stars found in the *Two Micron Sky Survey*, it did not lead to a comprehensive picture of the stars which are losing a large amount of mass, such as RAFGL 3068 and RAFGL 5379, where most of the flux emerges at longer infrared wavelengths. Because such stars dominate the total return of mass to the interstellar medium, it is important to develop a comprehensive survey of such stars.

As discussed by Claussen *et al.* (1987) and Kleinmann, Jura, and Joyce (1989), the *Two Micron Sky Survey* is complete for stars with $L = 10^4$ $L_{\odot}$ that mainly emit in the near-infrared to approximately 1 kpc in the northern hemisphere ($82° > \delta > -33°$). In this paper, we aim to make a complete sample of all the mass-losing stars in this volume. This is a useful region to consider because (1) it is large enough that we have an adequate number of stars to study, but (2) small enough that gradients in the galactic distribution of AGB stars (see, for example, Jura, Joyce, and Kleinmann 1989) are not too large, and (3) because good kinematic information is available for stars within this volume using catalogs of OH/IR stars by Engels (1979) and Hekkert *et al.* (1989) and carbon stars by Zuckerman and Dyck (1988) and Lucas, Guilloteau, and Omont (1988). While previous studies of selected subsamples of the AGB stars in the *IRAS* data base such as carbon stars (Thronson *et al.* 1987) and OH/IR stars (van der Veen and Habing 1988), this paper is the first survey to use the bolometric fluxes rather than only the *IRAS* colors of the AGB stars and therefore aims to establish a more unbiased survey.

Since *IRAS* surveyed more than 95% of the sky and because we have identified three out of 63 sources not in the *IRAS* catalog that otherwise meet our selection criteria (see Table 1), our sample is probably reasonably complete.

II. THE SAMPLE OF VERY DUSTY STARS

Our first goal is to identify mass-losing stars. The mass-loss rate from these objects can be measured by their flux at 60 μm (Jura 1986, 1987), and therefore, we consider objects with large fluxes at this wavelength. According to Jura (1987), we may write for the mass loss rate from both carbon-rich and oxygen-rich stars, dM/dt, that

$$dM/dt = 1.7 \times 10^{-7} v_{15} r_{\rm kpc}{}^2 L_4{}^{-1/2} F_\nu(60) \lambda_{10}{}^{1/2}\ M_\odot\ {\rm yr}^{-1} . \quad (1)$$

In equation (1), v_{15} is the outflow velocity in units of 15 km s^{-1}, $r_{\rm kpc}$ is the distance to the star in units of kpc, L_4 is the luminosity of the star in units of $10^4\ L_\odot$, $F_\nu(60)$ is the flux at 60 μm in units of Jy, and λ_{10} is the average wavelength of the light emitted from the star and circumstellar shell together, in units of 10 μm. If we are interested in those stars with unusually high mass-loss rates, say those with rates at least 10 times greater than the typical value of $2 \times 10^{-7}\ M_\odot$ yr^{-1} found by Claussen *et al.* (1987) for most carbon stars which are within 1 kpc of the Sun, then we require:

$$F_\nu(60) > 10 \text{ Jy} . \quad (2)$$

We therefore use equation (2) as one criterion for our selection of objects. We also include stars near the galactic plane which are subject to confusion at the longer wavelengths in the *IRAS* survey and for which only upper bounds to the 60 μm flux are measured if they meet the other criteria discussed below (for example, -20454).

The frequency distribution of infrared emission from a circumstellar shell is very sensitive to the spatial distribution of the dust grains around the star (see, for example, Sopka *et al.* 1985). In most mass-losing carbon stars, dM/dt and v apparently do not change dramatically with time and therefore we expect the density to vary approximately as r^{-2}. In this case, we expect that either or both

$$F_\nu(12) > F_\nu(60) \quad (3a)$$

and/or

$$F_\nu(25) > F_\nu(60) \quad (3b)$$

We use equations (3a) and (3b) as a second selection criteria for our objects. There are a few rapidly evolving post–AGB stars where criteria (3a) or (3b) are not satisfied (Likkel *et al.* 1987), but none of them are known to lie within 1 kpc of the Sun and satisfy equation (2).

Because we are interested only in objects which lie in the same spatial zone as the *Two Micron Sky Survey*, we consider only objects such that:

$$82° > \delta(1950.0) > -33° . \quad (4)$$

According to Iben and Renzini (1983), most carbon stars have a luminosity near $10^4\ L_\odot$. If we are to consider a volume within 1 kpc of the Sun, we therefore require that

$$F = \int F_\nu d\nu > 3.2 \times 10^{-7} \text{ ergs cm}^{-2}\text{ s}^{-1} . \quad (5)$$

To measure the total flux from a star we must supplement the *IRAS* data with ground-based observations. Extensive observations have been obtained by many different observers, and are cataloged by Gezari, Schmidt, and Mead (1987); we use the data in their catalog to determine the total flux from a star.

To allow for source variability, photometric inaccuracy, and interstellar extinction at K (perhaps 0.15 mag kpc^{-1}; Jura, Joyce, and Kleinmann 1989) our criterion on the total flux was relaxed to $F > 2.5 \times 10^{-7}$ ergs cm^{-2} s^{-1}. We assume $K = 0.0$ mag corresponds to 620 Jy (Beckwith *et al.* 1976).

Our estimated averaged fluxes are listed in Table 1; the *IRAS* data are not color-corrected nor have we made any corrections for interstellar reddening. If a star is variable either in the TMSS or at >90% probability level in the *IRAS* data, it is denoted as v in Table 1. Most of the stars with high mass loss rates are known variables: 80% of the 49 stars in Table 1 that were detected in the TMSS were found to be variable in the survey.

Finally, because we are interested in stars that are losing large amounts of mass, we require that there is substantial emission by the circumstellar shell relative to the amount of emission by the stellar photosphere. Since these stars are generally quite cool, they emit much of their total energy near 2 μm. Therefore, we require

$$F_\nu(12\ \mu\text{m}) > F_\nu(2\ \mu\text{m}) . \quad (6)$$

By using equation (6), we eliminate from consideration those stars with large bolometric fluxes that happen to be close to Earth but are not losing a very large amount of mass such as R Leo or W Hya. That is, we effectively require a high luminosity at 60 μm; not merely a high flux.

In Table 1, we list all the stars in the sky found from the TMSS, the AFGL survey (Kleinmann, Gillett, and Joyce 1981) or the *IRAS* Point Source Catalog that satisfy the criteria given in equations (2)–(6).

There are a few stars which satisfy criteria (2)–(6), but are thought to be supergiants and descended from stars with initial main sequence masses $>10\ M_\odot$ rather than AGB stars. The stars that we have excluded from Table 1 are VY CMa, S Per, PZ Cas, AH Sco, +10420 and NML Cyg (see Engels 1979; Morris and Jura 1983) and additionally IO Per, KW Sgr, UY Sct and KY Cyg (Kleinmann *et al.* 1989).

There are some unusual stars listed in Table 1. The optical counterpart to -30099 is 3 Pup, an A supergiant (Kleinmann *et al.* 1989). It could well be a star, similar to F supergiants such as 89 Her, which are thought to be undergoing the transition from being a red AGB star to being the central star of a planetary nebula (Parthasarathy and Pottasch 1986). RAFGL 5379 is a very strong infrared source and apparently has a very high mass-loss rate, yet it has not been extensively studied. We estimate a distance to the well-studied star +10216 of only 130 pc, consistent with the value given by Zuckerman and Dyck (1986*b*), but considerably smaller than the previously assumed value of 200 pc or even 290 pc.

III. PHYSICAL PROPERTIES OF THE AGB STARS

In order to determine the physical properties of these stars, it is necessary to infer their distances. As a first approximation, we assume that all the stars have a luminosity of $10^4\ L_\odot$. From the measured total flux, F, we can then determine a distance, D, and we write:

$$D = [L/(4\pi F)]^{1/2} . \quad (7)$$

The assumption that $L = 10^4\ L_\odot$ for all the very dusty AGB stars is very uncertain. Zuckerman and Dyck (1989) have

TABLE 1

VERY DUSTY AGB STARS

IRAS Star	TMSS	RAFGL	$F_\nu(2)$ (Jy)	$F_\nu(12)$ (Jy)	$F_\nu(25)$ (Jy)	$F_\nu(60)$ (Jy)	F (10^{-7} ergs cm^{-2} s^{-1})	Name
00042+4248..........	+40004	14	61	480	320	58	2.9	KU And
01037+1219..........	+10011	157	140v	1200	970	220	8.0	WX Psc
01159+7220..........	+70024	194	150v	340	200	27	3.5	S Cas
02270−2619..........	−30021	337	190	250	75	16	4.8	R For
02316+6455..........	+60092	349	53v	480	310	46	3.3	...
02351−2711..........	−30023	357	220v	420	260	34	4.1	...
03229+4721..........	+50096	489	83v	540v	200	40	5.8	...
03507+1115..........	+10050	529	1900	4600	2400	330	43	NML Tau
04307+6210..........	+60144	595	95	250v	92	17	3.4	...
04566+5606..........	+60150	664	580v	1600v	630	130	25	TX Cam
05073+5248..........	+50137	700	51v	230v	270	72	2.8	NV Aur
05411+6957..........	+70066	811	150	800v	410	52	6.7	...
05559+7430..........	+70067	849	160v	200v	110	17	3.4:	V Cam
06176−1036..........	...	915	27	420	460	170	2.6	Red Rectangle
06300+6058..........	+60169	956	180v	300v	210	45	5.2	...
06500+0829..........	+10143	1028	280v	600v	360	110	8.0:	GX Mon
07418−2850..........	−30099	1181	66	260	150	25	2.5	3 Pup
08088−3243..........	...	1235	17	350	160	31	3:	...
09116−2439..........	...	5254	<39	740	400	83	3:	...
09429−2148..........	−20197	5259	160	600	500	71	3.8	IW Hya
09452+1330..........	+10216	1381	190v	48000v	23000	5700	190	...
10131+3049..........	+30219	1403	210v	3300	1200	270	20	CIT 6
... .	−10236	1406	56	...	...	...	4.3	...
10491−2059..........	−20218	1439	900v	1100	460	98	24	V Hya
12447+0425..........	+00224	1579	69v	230	69	13	3.5	RU Vir
17049−2440..........	...	1922	8	790v	500	120	3.5	...
17119+0859..........	+10322	1940	200v	460v	320	41	5.8	V2108 Oph
17297+1747..........	+20326	1977	55v	560v	410	73	4.3	
17360−3012..........	...	1992	43	220v	320	73	2.5	OH 358.2+0.5
17411−3154..........	...	5379	<39	1300v	2700	1400	5:	...
17513−2313..........	−20397	2024	200	210	150	27	5.3	V774 Sgr
18009−2019..........	−20424	2054	270v	420v	290	46	5.8	...
18040−0941..........	−10396	2067	66v	210v	85	20	2.5	FX Ser
18135−1641..........	−20454	2103	280	350	230	<170	5.3	...
18194−2708..........	...	2135	13	680v	260	70	3.2	...
18204−1344..........	−10414	2139	300	500	320	73	6.3	...
18240+2326..........	...	2155	3	730	450	88	3.0	...
18333+0533..........	...	2199	47	300v	320	76	2.6	...
18348−0526..........	...	2205	2	360v	630	460	2.6	OH 26.5+0.6
18349+1023..........	+10365	2206	310v	720v	320	66	7.9	V1111 0ph
18397+1738..........	+20370	2232	110v	530v	240	60	5.7	...
18398−0220..........	+00365	2233	53v	560v	240	52	3.5	...
18413+1354..........	+10374	2241	75v	230v	150	21	2.6	...
18560−2954..........	−30398	2289	110v	640v	330	63	4.4	V3953 Sgr
19008+0726..........	+10401	2310	43v	450	180	37	4.4	...
19059−2219..........	−20540	2330	80v	290v	210	34	2.6	V3880 Sgr
19093−3256..........	−30404	5556	210v	320v	210	33	4:	V342 Sgr
19126−0708..........	−10497	2349	290v	1600v	670	110	13	W Aql
19175−0807..........	−10502	2368	99v	380v	190	48	40	...
19321+2757..........	+30374	2417	43v	330v	170	39	3.8	V1129 Cyg
20077−0625..........	−10529	2514	54v	1300	1100	220	8.2	V1300 Aql
20396+4757..........	+50338	2632	290v	660	230	49	12	V Cyg
20440−0105..........	+00490	2646	140v	210v	120	17	3.4	...
20570+2714..........	...	2686	36	280v	150	31	2.5	...
... .	...	2688	...	...	...	...	...	Egg Nebula
21032−0024..........	+00499	2702	160v	310v	120	22	4:	RV Aqr
NGC 7027............	...	2713	...	...	...	...	...	...
21286+1055..........	+10498	2775	150v	160	110	18	2.8	UU Peg
21320+3850..........	+40485	2781	95v	260	94	20	5.8	V1426 Cyg
21456+6422..........	+60328	2808	130v	180	110	17	3.8	RT Cep
23166+1655..........	...	3068	0.4	710	780	250	3.2	...
23320+4316..........	+40540	3116	63v	960	470	110	5.9	...
23496+6131..........	+60427	3165	170v	370	250	45	4.2	...

shown that stars with higher outflow velocities lie closer to the galactic plane than do stars with lower outflow velocities. It is quite plausible that for the carbon stars, as with the oxygen-rich stars (Jones, Hyland, and Gatley 1983; Jura 1984), there is a correlation between outflow velocity and luminosity. On the basis of galactic rotation, Nguyen-Q-Rieu *et al.* (1987) also argue that some carbon stars have luminosities appreciably greater than 10^4 $L_{\odot}$. However, it is straightforward to show that (1) as long as the stars are distributed in a flattened disk and (2) our survey penetrates considerably further than the thickness of the disk, then the mass loss rates per unit area projected onto the galactic disk are independent of the assumed luminosity of the mass-losing stars (Knapp and Morris 1985).

In Table 2, we list all the stars in Table 1 with their inferred or measured total flux, the inferred distance, their galactic latitude and longitude, [C]/[O] type, their distance from the galactic plane, their measured outflow velocity when available from molecular observations, and, from equation (1), their inferred mass-loss rate. Relevant references to the data employed for each star are also listed. With these data in Table 2, it is possible to estimate the density distribution and mass loss rates from this sample of stars.

There are 63 stars listed in Table 2; 29 are carbon-rich, 32 are oxygen-rich, and 2 are S type. The fraction of carbon stars is about 0.5, a much higher percentage of carbon-rich objects than are found in the *Two Micron Sky Survey* (Claussen *et al.* 1987; Kleinmann *et al.* 1989).

Let ρ denote the density of stars in the plane of the Milky Way. We assume a distribution locally such that

$$\rho = \rho_0 \exp(-|z|/H) , \tag{8}$$

where H is the exponential scale height perpendicular to the galactic plane. In Figure 1, we show a comparison between the inferred distribution of $|z|$ taken from Table 2 with the model given in equation (8) for H = 100, 200, and 300 pc. The best agreement between the data and the calculations is for the model with H = 200 pc. Claussen *et al.* (1987) and Jura (1988) also derive exponential scale heights of carbon stars and S stars of 200 pc. The inferred exponential scale height of $\sim$200 pc implies that the typical progenitor main sequence mass of the currently observed AGB stars is $\sim$1.5 $M_{\odot}$ (Claussen *et al.* 1987), although, of course, there are some more massive stars that evolve into AGB stars. As can be seen from the tabulation of Miller and Scalo (1979), we expect that most AGB stars have main sequence progenitors between 1 and 1.5 $M_{\odot}$.

In Figure 2 we plot the spatial distribution of the AGB stars in Table 1 projected onto the galactic plane. There may be an excess of stars in the direction of the galactic center compared to the anticenter direction. It has been known for many years that OH/IR stars are concentrated toward the center of the Galaxy (Bowers 1978; Baud *et al.* 1981), but this is not true for carbon stars (Jura, Joyce, and Kleinmann 1989). In any case, assume that the surface density of stars, σ, follows that of exponential disk such that

$$\sigma = \sigma_0 \exp(-r/r_{\rm disk}) . \tag{9}$$

We expect that if $r_{\rm disk}$ = 3.5 kpc (see, for example, Mihalas and Binney 1981) and if we observe out to 1 kpc, then there should be a difference factor of 1.8 in the surface density between $l = 0°$ and $l = 180°$. Such a variation is roughly consistent with the data shown in Figure 2.

It should be recognized that there is some uncertainty in our estimated mass loss rates, and they could well be systematically in error. Equation (1) was derived by comparing the dust loss rate in terms of a simple model for the infrared emission (Jura 1987) with the integrated CO brightness measured by Knapp and Morris (1985). We must assume a ratio for H_2/CO as well as employ a specific model for the CO radio emission. Olofs-

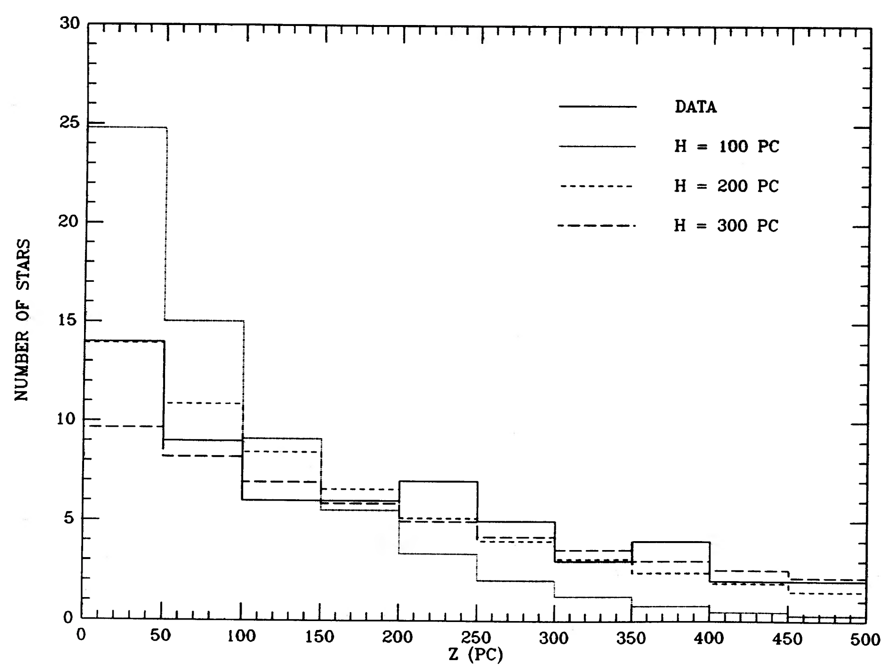

FIG. 1.—Histogram of the $|z|$ distribution of the AGB stars (*solid line*) in Table 2 compared to models with H = 100, 200, and 300 pc, respectively, corresponding to dotted, short-dashed, and long-dashed lines. All the theoretical curves are normalized to 63 stars.

TABLE 2

PHYSICAL PROPERTIES OF VERY DUSTY STARS

Star	D (pc)	Class	l	b	v_∞ (km s^{-1})	$\lvert Z \rvert$ (pc)	dM/dt (10^{-5} $M_\odot$ yr^{-1})	References
00042+4248	1100	O	114°3	−19°0	24	360	1.9	1
01037+1219	630	O	128.6	−50.1	23	480	2.3	1
01159+7220	960	S	125.1	9.9	15	170	0.42	2
02270−2619	820	C	215.8	−68.1	17	760	0.21	2, 3
02316+6455	980	O	133.6	4.5	17	77	0.85	4
02351−2711	880	O	218.7	−66.5	12	810	0.36	2
03229+4721	740	C	148.2	−7.6	17	98	0.42	1
03507+1115	270	O	178.0	−31.4	22	140	0.60	1
04307+6210	970	C?	146.0	9.9	20	170	0.36	1, 5
04566+5606	360	O	152.8	8.6	13	54	0.25	1
05073+5248	1100	O	156.4	7.8	15	150	1.5	1
05411+6957	690	O	143.4	20.1	21	240	0.59	1
05559+7430	970	O	139.4	22.9	12	380	0.22	6
06176−1036	1100	C	219.0	−11.8	10?	220	2.3	7, 8
06300+6058	780	O	154.3	21.5	17	290	0.53	1
06500+0829	630	O	205.6	4.1	19	45	0.94	2
07418−2850	1100	O	244.4	−2.5	...	48	0.51	
08088−3243	1000	C	250.7	−0.4	21	7	0.74	2
09116−2439	1000	C	252.8	16.2	13	280	1.2	2
09429−2148	920	O	255.8	23.4	14	370	0.95	2
09452+1330	130	C	221.4	45.1	15	92	1.6	1, 2
10131+3049	400	C	197.7	56.0	17	330	0.83	1, 2
−10236	860	C	256.3	33.9	11	480	0.4:	1
10491−2059	370	C	269.0	33.6	21	200	0.32	1, 9
12447+0425	960	C	300.3	67.0	17	880	0.23	1
17049−2440	960	C	358.8	9.3	17	160	2.1	4, 10
17119+0859	740	O	29.9	25.6		320	0.38	
17297+1747	860	O	40.8	25.3	18	370	1.1	1, 5
17360−3012	1100	O	358.2	0.5	20	10	2.0	11
17411−3154	800	O	357.3	−1.3	21	18	21	12
17513−2313	780	O	5.9	1.2		16	0.28	
18009−2019	740	O	9.5	0.8		10	0.43	
18040−0941	1100	C	19.2	5.3	27	100	0.74	6
18135−1641	780	O	14.2	−0.1		2	0.5?	
18194−2708	1000	C	5.6	−6.2	14	110	1.1	10, 13
18204−1344	710	O	17.5	−0.1	10	1	0.42	14
18240+2326	1000	C	51.6	15.8	15	270	1.5	1
18333+0533	1100	C	36.1	6.0	8	110	0.83	1
18348−0526	1100	O	26.5	0.6	14	12	8.8	11, 15, 16
18349+1023	640	O	40.7	7.8	17	87	0.52	1
18397+1738	750	C	47.8	10.0	16	130	0.61	1, 12
18398−0220	960	C	29.9	1.0	35	19	2.2	4
18413+1354	1100	O	44.6	8.0	19	150	0.55	4
18560−2954	850	O	6.6	−14.7	13	220	0.67	12
19008+0726	850	C	41.0	0.8	17	12	0.52	4
19059−2219	1100	O	14.7	−13.6	22	260	1.0	12
19093−3256	890	O	4.8	−18.4	15	280	0.44	17
19126−0708	500	S	29.3	−8.5	20	74	0.62	1
19175−0807	890	C	29.0	−10.0	23	150	0.99	2, 10
19321+2757	920	C	62.6	4.0	24	64	0.90	2
20077−0625	620	O	36.4	−20.4	16	220	1.5	1
20396+4757	520	C	86.5	3.8	12	34	0.18	1, 2
20440−0105	970	O	46.1	−25.8	15	420	0.27	6
20570+2714	1100	C	72.6	−12.0	24	230	1.0	2
RAFGL 2688	750	C	80.2	−6.5	20	85	4.1	1, 16, 18
21032−0024	890	C	49.6	−29.6	16	440	0.32	1, 3
NGC 7027	940	C	84.9	−3.5	18	57	6.3	1, 18, 19
21286+1055	1100	O	64.3	−28.2	7	520	0.16	20
21320+3850	740	C	86.3	−9.4	15	120	0.19	1
21456+6422	920	O	8.5	21.0		330	0.25	
23166+1655	1000	C	93.5	−40.4	12	650	3.4	1, 4
23320+4316	740	C	108.5	−17.1	15	220	1.0	1, 4
23496+6131	870	O	116.0	−0.3	14	5	0.54	3, 6

NOTE.—If no outflow velocity is measured, we assume $v = 15$ km s^{-1}

REFERENCES.—(1) Knapp and Morris 1985; (2) Zuckerman and Dyck 1986*a*; (3) Olofsson *et al.* 1988; (4) Zuckerman, Dyck, and Claussen 1986; (5) Claussen *et al.* 1987; (6) Zuckerman and Dyck 1989; (7) A. Omont 1988, private communication; (8) Ney *et al.* 1975; (9) Kahane, Maizels, and Jura 1988; (10) Knapp 1986; (11) Jones, Hyland, and Gatley 1983; (12) Zuckerman and Dyck 1986*b*; (13) Zuckerman *et al.* 1978; (14) Kolena and Pataki 1977; (15) Bowers, Johnstone, and Spencer 1983; (16) Werner *et al.* 1980; (17) Knapp *et al.* 1989; (18) Jura 1983; (19) Masson 1986; (20) Fix and Weisberg 1978.

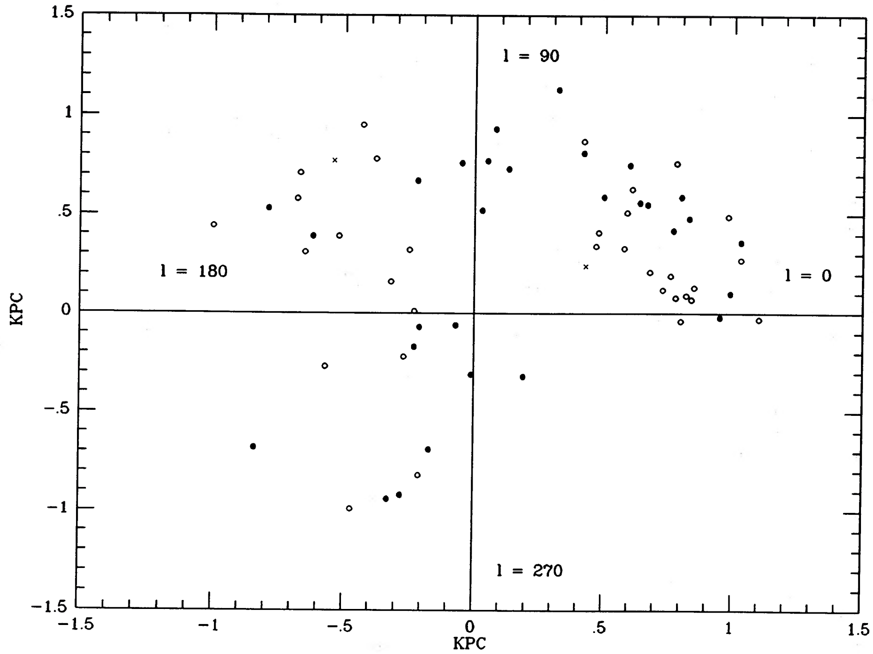

FIG. 2.—Plot of the spatial distribution of the stars in Table 1 projected onto the galactic plane. The carbon stars are filled circles, the oxygen-rich stars are plotted as open circles, and the S stars as crosses. The lower right quadrant has essentially no stars present because it lies at southern declinations.

son, Eriksson, and Gustafsson (1987, 1988) have measured the CO emission from a large number of nearby, bright carbon stars, and they have estimated mass-loss rates on the basis of their measurements. Olofsson, Eriksson, and Gustafsson (1987, 1988) usually derive mass loss rates about a factor of 2 greater than predicted by equation (1). Because they assume that they resolved their observed sources in their 20 m telescope beam while Knapp and Morris (1985) did not in the beam of the 7 m telescope that they used, Olofsson, Eriksson, and Gustafsson (1987, 1988) scaled the mass-loss rates derived from Knapp and Morris by nearly a factor of 2. It is not certain that this correction should in fact be applied in all cases. In Figure 3, we display a comparison of the mass-loss rate inferred by Olofsson, Eriksson, and Gustafsson (1987, 1988) from their CO data and the mass-loss rate inferred from the 60 μm flux, the outflow velocity and distance given by Olofsson, Eriksson, and Gustafsson (1987, 1988) and equation (1). [For stars with $F_\nu(2\,\mu\text{m}) > F_\nu(12\,\mu\text{m})$ we assume that $\lambda_{10} = 0.22$; otherwise we assume $\lambda_{10} = 1.0$.] The distances given by Olofsson, Eriksson, and Gustafsson (1987, 1988) are derived on the basis of the brightness of the stars at 2 μm and are within 10% of the values given by Claussen *et al.* (1987). The mass-loss rates given by Olofsson, Eriksson, and Gustafsson (1987, 1988) are consistently higher than those given by the equation (1). If, however, the CO-inferred loss rates are reduced by a factor of 2 or the 60 μm-inferred loss rates are increased by a factor of 2, then the agreement is much improved.

There are a number of reasons why the mass-loss rates derived from equation (1) may be too low on the average by a factor of 2. There are uncertainties in the absolute scaling of the CO and infrared data to the total mass-loss rate because of unknown dust-to-gas ratios, and there are also uncertainties in the infrared emissivity of the grains. Furthermore, the consequences of the simplifications used in the models to reproduce the CO data may be significant. The calculations for the intensity of the CO radio emission (Morris 1985) assume spherical outflows with constant outflow velocity and constant mass loss rate, a fixed kinetic temperature profile in the outflowing gas (see Jura, Kahane, and Omont 1988), a fixed value of the turbulent line broadening in the gas, and a fixed rate of the infrared pumping of the CO molecule. Finally, the oxygen-rich and carbon-rich stars may behave differently. These approximations may produce some error in determining the total mass loss rate.

We can also compare the momentum in the mass outflow, $v\,dM/dt$ to that available from radiation pressure, L/c. In most cases, the mass outflow momentum is less than or comparable to the radiation pressure, consistent with the view that radiation pressure on the grains helps drive the mass loss (see Jura 1986). There are some stars in Table 2 where $v\,dM/dt$ is significantly larger than L/c. This could occur if a rapid decline in the star's luminosity (Jura 1983) resulted in a current value of L/c that is much lower than the value when the currently emitting CO gas was expelled from the star.

IV. IMPLICATIONS FOR STELLAR EVOLUTION

Our results can now be used to constrain the effects of mass loss from AGB stars on stellar evolution and the replenishment of the interstellar medium. If we sum all the mass loss for the stars listed in Table 2 and we correct for the fraction of sky not covered in this survey, we estimate a total mass-loss rate from these stars of $4 \times 10^{-4}\ M_\odot\ \text{kpc}^{-2}\ \text{yr}^{-1}$. However, one poorly studied object, RAFGL 5379, contributes nearly 25% to this total. Furthermore, the mass-loss rate inferred from the CO emission measured by Zuckerman and Dyck (1986*b*) is much less than that inferred from the 60 μm flux, and so the mass-loss rate quoted in Table 2 may be too large. More conservatively, it seems that the total mass return rate is $3 \times 10^{-4}\ M_\odot\ \text{kpc}^{-2}\ \text{yr}^{-1}$. Approximately one-half of this mass loss comes from the carbon stars and about one-half from the oxygen-rich stars. Also, more than one-half of the mass-loss results from stars not listed in the *Two Micron Sky Survey*. Finally, if we were to recalibrate our mass loss rates using the results from Olofsson, Eriksson, and Gustafsson (1987, 1988), we would find a total

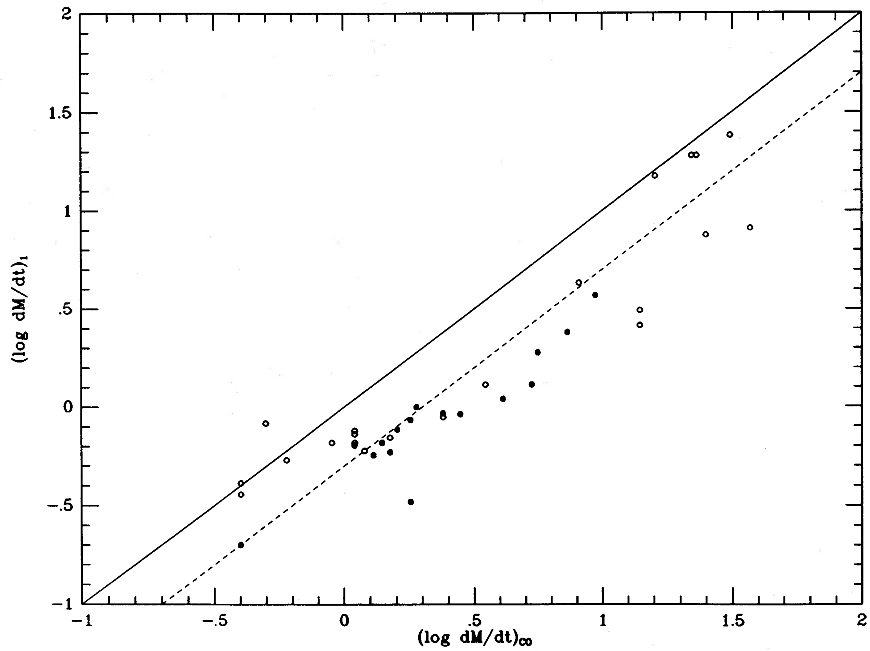

FIG. 3.—Plot of the mass-loss rates derived from eq. (1) and those estimated by Olofsson *et al.* (1987, 1988) from CO radio emission in units of $10^{-7}\ M_\odot\ \mathrm{yr}^{-1}$. The filled circles are from data acquired at Onsala, while the open circles are from data acquired at SEST. The solid line is the fit if the two mass-loss rates equal each other; the dashed line is the fit if all the CO-inferred loss rates are reduced by a factor of 2.

mass-loss rate that would be increased by a factor of 2, up to $6 \times 10^{-4}\ \mathrm{kpc}^{-2}\ \mathrm{yr}^{-1}$.

From the compilation of Miller and Scalo (1979) for the density, scale height, and lifetimes of local stars, we find that there should be a net loss of $8 \times 10^{-4}\ M_\odot\ \mathrm{kpc}^{-2}\ \mathrm{yr}^{-1}$ if all the main-sequence stars that are initially between 1 and 5 $M_\odot$ ultimately become white dwarfs with a mass of 0.7 $M_\odot$ (Liebert 1980). Given the uncertainties (Mazzitelli and d'Antona 1986), there is no strong disagreement between the expected and inferred summed mass loss rates.

In this paper, we use the results of Miller and Scalo (1979) for the local distribution of stars, but they could be in error. For example, Bienaymé, Robin, and Crézé (1987) estimate that there are about twice as many main-sequence stars with lifetimes between 2×10^9 and 8×10^9 yr in the solar neighborhood as given by Miller and Scalo (1979).

As suggested a number of years ago by Zuckerman *et al.* (1976, 1978); perhaps half of all AGB stars that are losing large amounts of mass and that are pre–planetary nebulae are carbon stars. More recently, Zuckerman and Aller (1986) find that over half of all planetary nebulae are carbon-rich. Our results strongly support the hypothesis that about half of the mass loss from AGB stars is produced from carbon-rich objects in agreement with the previous study by Knapp and Morris (1985) and in disagreement with the study by Thronson *et al.* (1987). (Both of these previous studies used samples of stars different from that employed here.) Therefore, it is clear that the carbon star phase of evolution is quite common in the evolution of stars with an initial main sequence mass similar to that of the Sun. In the region within the 1 kpc region near the Sun north of $-33°$, there are 29 carbon stars listed in Tables 1 and 2. This implies that the surface density in the disk of the Milky Way of the high mass-loss rate carbon stars is 12 kpc^{-2} compared to 40 kpc^{-2} for the low mass-loss rate carbon stars (Claussen *et al.* 1987).

For the stars with low mass-loss rates, we did not know whether there were relatively few stars which spent a long time as carbon stars or whether most stars become carbon stars but spend a relatively short time in this phase. In contrast, by comparing the numbers of oxygen-rich and carbon-rich stars with high mass loss rates, it is clear that about one-half of all main-sequence stars of initial mass between 1 and 1.5 $M_\odot$ become carbon stars. The death rate of such stars is $\sim 2.5 \times 10^{-4}$ stars $\mathrm{kpc}^{-2}\ \mathrm{yr}^{-1}$ (Miller and Scalo 1979). If there are ~ 12 very dusty carbon stars kpc^2, this implies a lifetime in the carbon star phase losing a large amount of mass of about 5×10^4 yr. However, if stars with masses between 1 and 5 $M_\odot$ instead of only those with masses between 1 and 2.5 $M_\odot$ become carbon stars, then the duration of the very dusty carbon star phase need only be 3×10^4 yr. As can be seen from Table 2, the typical mass-loss rate from these stars is $\sim 10^{-5}\ M_\odot\ \mathrm{yr}^{-1}$. Therefore, we expect that these stars lose $\sim 1\ M_\odot$ in the high mass-loss rate phase, consistent with the view that 1.5–2 $M_\odot$ stars ultimately become white dwarfs of $\sim 0.7\ M_\odot$ (Liebert 1980).

Finally, approximately 15% of all optically bright carbon stars are very rich in ^{13}C in the sense that $^{13}\mathrm{C}/^{12}\mathrm{C} > 0.25$ (Jura, Kahane, and Omont 1988). It will be important to determine if a similar fraction of the carbon stars losing large amounts of mass also have such an unusually high fraction of their carbon as ^{13}C. The answer to this question is very important for determining the evolutionary history of this isotope in the Milky Way galaxy (see, for example, Hawkins and Jura 1987).

V. CONCLUSIONS

1. We have identified 63 AGB stars that are losing mass rapidly ($> 10^{-6}\ M_\odot\ \mathrm{yr}^{-1}$) within 1 kpc of the Sun. These stars

appear to be returning between 3 and $6 \times 10^{-4}\ M_\odot$ kpc^{-2} yr^{-1} into the interstellar medium, in reasonable agreement with the expectation that stars between 1 and 5 $M_\odot$ are losing approximately $8 \times 10^{-4}\ M_\odot$ kpc^{-2} yr^{-1}.

2. With an assumed luminosity of $10^4\ L_\odot$, the inferred exponential scale height of these stars is about 200 pc. This implies that the main-sequence progenitors are typically 1.5 $M_\odot$.

3. Approximately one-half of all the mass-losing AGB stars are carbon-rich, and they account for about one-half of the mass loss in the solar neighborhood. Therefore, the carbon-star phase occurs in about one-half of all main-sequence stars between 1 and 1.5 $M_\odot$.

4. The typical mass-loss rate from a very dusty carbon star is about $1\text{–}2 \times 10^{-5}\ M_\odot$ yr^{-1}, and this phase lasts for $> 3 \times 10^4$ yr. This mass-loss episode is consistent with the view that most main sequence stars with initial masses of 1.5 $M_\odot$ evolve into white dwarfs which have masses of about 0.7 $M_\odot$.

This work has been partly supported by NASA. S. G. K. was also supported by AFOSR under grant 88-0070.

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