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LONG-PERIOD OXYGEN-RICH OPTICAL MIRAS IN THE SOLAR NEIGHBORHOOD

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ABSTRACT

We use available surveys and the *K*-band period-luminosity relationship to determine the spatial distribution of oxygen-rich Miras with periods longer than 400 days in the neighborhood of the Sun. We restrict the analysis to "optical" Miras, stars with $F_\nu(12\ \mu\text{m})/F_\nu(2.2\ \mu\text{m}) < 1.0$. We identify a total of 48 such stars within 1 kpc of the Sun and argue that this sample is probably better than 80% complete.

We derive an exponential scale height of these long-period Miras of ~240 pc and a surface density projected onto the Galactic plane of 18 kpc^{-2}. The derived scale height indicates a main-sequence progenitor population with masses ~1.1 $M_\odot$ and appears to be the same as that of the intermediate-period oxygen-rich Miras ($400 > P \geq 300$ days). The data are consistent with the hypothesis that the intermediate-period Miras in the solar neighborhood evolve into long period Miras in ~5×10^5 yr.

From the observed spatial distribution and estimates of the death rates of the progenitor main-sequence stars, we estimate a lifetime of the local long-period Miras ($P \geq 400$ days) of 30,000 yr. The typical mass-loss rate is ~$4 \times 10^{-7}\ M_\odot$ yr^{-1}, with a total mass loss during this phase of ~0.01 $M_\odot$. The suggestion that the relatively short lifetime of the long-period Miras is a consequence of the development of very rapid mass loss in these stars is qualitatively consistent with the relative numbers of intermediate- and long-period Miras, but does not seem to agree in detail with our estimates for the mass-loss rates.

There is a marked contrast between the Mira population at ~1 kpc from the Galactic center where there are nearly as many long-period oxygen-rich Miras as intermediate-period oxygen-rich Miras, and the local, solar neighborhood population of oxygen-rich Miras where the fraction of Miras of intermediate period is much greater. We suggest that at ~1 kpc from the Galactic center, the main-sequence stars with masses larger than 1 $M_\odot$ have higher metallicities than main-sequence stars with the same masses in the solar neighborhood. In the solar neighborhood such main-sequence stars become carbon rich on the AGB; in the region near the Galactic center, we propose that they become long-period oxygen-rich Miras.

Subject headings: Galaxy: stellar content — infrared: stars — stars: evolution — stars: mass loss — stars: variables: other (long-period variables)

1. INTRODUCTION

The mass loss from red giants is both critical in their evolution as stars and for the replenishment of the interstellar medium. We are studying the local red giants to understand better the spatial distribution and lifetimes of these stars and their contributions to the evolution of the Galaxy.

Previously, we have studied carbon stars (Claussen et al. 1987), S-type stars (Jura 1988), "very dusty stars" losing mass at large rates (Jura & Kleinmann 1989), luminous red supergiants (Jura & Kleinmann 1990), oxygen-rich Miras with periods less than 400 days (Jura & Kleinmann 1992a) and Semiregulars and Irregulars (Jura & Kleinmann 1992b). In this paper, we discuss oxygen-rich Miras with $P \geq 400$ days.

In our previous work on the space distribution of short- and intermediate-period Miras, we only considered the half of the sky with $|b| \geq 30°$. This procedure was employed because Miras are identified from their optical light curves, and we hoped to minimize the effects of incompleteness caused by interstellar extinction. However, we cannot rely exclusively upon this procedure for the optical Miras with $P \geq 400$ days since there are only 20 such stars at $|b| \geq 30°$ in the General Catalog of Variable Stars, the GCVS (Kholopov et al. 1985). Because the longer period Miras are luminous in the infrared, we have used available infrared sky surveys to attempt to identify essentially all the long-period Miras within 1 kpc of the Sun. It may be insightful to compare our results for the local stars with those of more distant regions such as the stars at ~1 kpc from the Galactic center (Lloyd Evans 1976; Whitelock, Feast, & Catchpole 1991).

Previously (Jura & Kleinmann 1989), we have cataloged the nearby "very dusty" stars; objects where there is so much circumstellar dust that

$$F_\nu(12\ \mu\text{m}) \geq F_\nu(2.2\ \mu\text{m}) \tag{1}$$

Many of these stars are very long period variables, typically with $P \geq 450$ days (see Jones et al. 1990). In this paper, we only consider "optical" stars where equation (1) is not satisfied.

2. THE SAMPLE OF STARS

2.1. *The Stars within 1 Kiloparsec*

To develop a complete sample of stars with a sufficiently large number of objects to perform an analysis of their statistical properties, we have tried to identify all long-period Miras within 1 kpc of the Sun. We estimate the distances to optical Miras from the period-luminosity relationship for the

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Large Magellanic Cloud (Feast et al. 1989) corrected to the metallicity of the local Milky Way (Wood 1990) and applied to the time-averaged value of M_K:

$$M_K = -3.47 \log (P) + 1.26 . \quad (2)$$

From Kholopov et al. (1985) we have considered all the Miras, defined to be long-period red variables with $\Delta m \geq 2.5$ mag where Δm refers to the range of optical variation. We derive distances from published infrared data and include the star within Table 1 if it appears to be within 1 kpc of the Sun on the basis of equation (2). We ignore interstellar extinction, because even at $b = 0°$, it is only $\sim$0.15 K mag kpc^{-1} (Jura, Joyce, & Kleinmann 1989).

Our first choice for a source of infrared magnitudes is the Two Micron Sky Survey (hereafter TMSS; Neugebauer & Leighton 1969) which was complete to $m_K = 3.0$ mag over 75% of the sky. From equation (2), we expect that a Mira with $P \geq 400$ days has $M_K \leq -7.78$. Therefore, a Mira at 1 kpc will be at least as bright as $m_K = 2.2$ mag, and thus it must have been detected in the TMSS.

For the region of the sky not covered by the TMSS, in many cases we can use measured fluxes at 2.2 μm as reported in the survey of ground-based data by Gezari, Schmitz, & Mead (1987). If there is not any published measurement of the 2.2 μm flux, we extrapolate from the *IRAS* survey data (non–color-corrected) at 12 to 2.2 μm. With the calibration of the K-band magnitudes given by Beckwith et al. (1976), we find for the stars in Table 1 for which there are measured fluxes at both 2.2 μm from the TMSS and 12 μm from *IRAS*, that on average

$$F_\nu(12\ \mu\mathrm{m})/F_\nu(2.2\ \mu\mathrm{m}) = 0.45 . \quad (3)$$

This average value for flux ratio found for the oxygen-rich Miras with $P \geq 400$ days is substantially larger than the ratio of 0.31 found for the intermediate-period ($400 > P \geq 300$ days) Miras and 0.25 found for the short-period (300 days $> P$) Miras (Jura & Kleinmann 1992a). We assume that equation (3) obtains for all the Miras with $P \geq 400$ days and therefore, from the observed 12 μm flux we estimate a flux at 2.2 μm from equation (3) and then a distance from equation (2).

We list in Table 1 all the Miras which satisfy the above criteria and our estimates of their distances from the Sun. We include V2059 Sgr, SV Lib, U Tel, and EK CrA in Table 1 even though the lower bounds to their optical variations are less than 2.5 mag. It is likely that these stars in fact are Miras rather than Semiregulars because the fraction of long-period variables with $P > 200$ days that are Miras rather than Semiregulars is substantially larger than 0.5 (Jura & Kleinmann 1992b; Kerschbaum & Hron 1992). Because it meets all the other criteria, we also include UZ Per in Table 1, even though its period of 927 days is much longer than that of any star on our list. Because their periods reported in the GCVS are probably twice their true periods (Feast 1963; Feast et al. 1982), we omit R Nor and R Cen from Table 1.

2.2. *Completeness*

Since 53% of the long-period Miras listed both in Table 1 and the TMSS are denoted as variable at K in that survey, we may investigate the completeness of our sample of Miras by considering that subset of sources in the TMSS that are known to be variable at K. There are 5612 sources in the TMSS of which 342 are flagged as variable at K. We have examined these 342 stars to determine if they are possibly unrecognized oxygen-rich Miras (with $\Delta m \geq 2.5$ mag) with $P \geq 400$ days. Spectral classifications of nearly all the stars in the TMSS exist (Bidelman 1980) and can be used to determine which are oxygen-rich. We consider all such stars that (1) do not have measured periods in the GCVS, (2) exhibit $m_K \leq 2.2$ mag so they may be closer than 1 kpc if they have $P \geq 400$ days, and (3) display

$$1.0 \geq F_\nu(12\ \mu\mathrm{m})/F_\nu(2.2\ \mu\mathrm{m}) \geq 0.20 . \quad (4)$$

The upper of this flux ratio is chosen because if $F_\nu(12\ \mu\mathrm{m})/F_\nu(2.2\ \mu\mathrm{m}) \geq 1.0$ then we describe the object as "very dusty" and it is listed by Jura & Kleinmann (1989). The minimum bound in equation (4) is derived from the long-period Miras in Table 1 for which all but one star displays $F_\nu(12\ \mu\mathrm{m})/F_\nu(2.2\ \mu\mathrm{m}) \geq 0.20$. Using these criteria, there are only three objects in the TMSS (-30013 = AD Scl, -30121 = NN Pup and -10348) which may be candidates for inclusion in Table 1. Possibly +30475 may belong in Table 1 as well; however, it is not listed in the *IRAS* catalog, so we do not know if equation (4) is satisfied. Neither is +10510 listed in the *IRAS* catalog, but the results of Hacking et al. (1985) indicate that $F_\nu(12\ \mu\mathrm{m})/F_\nu(2.2\ \mu\mathrm{m}) = 1.3$ for this star, and therefore it is not an "optical" Mira under our definition. Thus, since there are only four candidates from the TMSS for inclusion in Table 1 beyond the 17 variable stars in the TMSS which are already known to be long-period, oxygen-rich, optical Miras, we argue that our sample of stars is complete to better than 80%.

2.3. *The High-Latitude Stars*

Following our earlier work, we list in Table 2 all the known oxygen-rich Miras listed in the GCVS with $P \geq 400$ days which satisfy equation (4) and which lie at $|b| \geq 30°$. There are 20 such stars. WX Ser and IK Tau are "very dusty" stars and are not included in Table 2 while we suspect that SW Eri also is "very dusty" since it was not detected in the TMSS [hence $m_K \geq 3.00$ mag or $F_\nu(2.2\ \mu\mathrm{m}) < 39$ Jy] yet the flux at 12 μm measured by *IRAS* is 40 Jy. Because the vast majority of stars listed in Table 2 display $F_\nu(12\ \mu\mathrm{m}) \geq 30$ Jy and because Hacking et al. (1985) have categorized all the 12 μm *IRAS* sources brighter than 28 Jy at $|b| \geq 30°$ and there are no additional candidates for long-period optical rich Miras, it seems unlikely that we have omitted many high-latitude, long-period optical Miras in Table 2.

3. SPATIAL DISTRIBUTION

We assume that the density of long-period Miras, n, can be represented as

$$n = n_0 \exp(-R/R_0) \exp(-|Z|/Z_0) , \quad (5)$$

where R measures Galactocentric radius and Z the distance from the Galactic plane. The parameters R_0 and Z_0 denote the scale length and scale height, respectively. We write for the surface density of stars projected onto the Galactic plane, σ, that

$$\sigma = 2nZ_0 . \quad (6)$$

If we consider two imaginary cones defined as the zones with $|b| \geq 30°$, then (see Jura & Kleinmann 1992a), the number of stars contained within these two cones, N_* is given by

$$N_* = 6\pi\sigma Z_0 . \quad (7)$$

Because it is a relatively well determined quantity, we first estimate the surface density of stars projected onto the Galac-

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TABLE 1

OPTICAL MIRAS WITH $P \geq 400$ DAYS WITHIN 1 KILOPARSEC OF THE SUN

Star	IRC Number	P (days)	l	b	$F_\nu(2.2)$ (Jy)	$F_\nu(12)$ (Jy)	Δm (mag)	m_K (mag)	D (pc)
VV Sgr	−20403	402	9°59	2°66	100	84	≥2.7	1.97v	890
V2059 Sgr	−20524	405	13.81	−9.97	120	65v	≥1.9	1.76v	810
Z Sgr	−20555	450	16.95	−15.38	130	31v	7.6	1.71	850
FQ Sgr	−20538	434	19.39	−11.16	140	85	≥5.9	1.60v	790
RS Aql	−10527	410	33.50	−18.61	97	32v	6.7	2.01v	920
U Her	+20298	406	35.35	40.35	820	500v	7.0	−0.31v	310
RT Oph	+10342	426	36.91	17.19	160	59	6.9	1.50	750
RU Her	+30283	485	41.98	45.61	430	170	7.5	0.40v	490
RX Vul	+20490	457	68.43	−13.44	240	72	4.0	1.02v	630
SX Cyg	+30423	411	69.80	−2.19	90	33	7.0	2.10v	960
SX Vul	+30440	425	70.19	−7.11	86	24v	4.8	2.14	1000
AU Cyg	+30426	435	72.90	−0.86	210	100v	5.8	1.19	660
RS Peg	+10514	415	75.19	−33.18	240	...	6.5	1.04v	590
KZ Cyg	+40420	406	79.38	1.54	110	41v	6.0	1.84v	840
DG Cyg	+40442	458	82.86	0.44	180	...	4.9	1.34v	730
SS Peg	+20532	425	87.15	−28.59	250	86	5.6	1.00	590
CL Lac	+50448	414	105.05	−6.32	85	14	2.8	2.16	990
R Cas	+50484	430	114.56	−10.62	3400	1300	8.8	−1.84	160
Y Cas	+60001	413	116.14	−6.56	190	98	6.6	1.27	660
T Cas	+60009	445	118.95	−6.86	1500	430	6.1	−0.97v	250
U Lyn	+60172	434	155.66	21.94	220	110v	6.2	1.12	630
UZ Per	+30061	927	156.23	−21.07	260	64	≥3.1	0.96	1000
R Aur	+50141	458	156.37	8.97	1500	460v	7.2	−0.94	260
SZ Aur	+40136	454	171.07	4.58	220	61	4.6	1.13	660
RU Aur	+40135	466	171.99	3.59	170	150v	7.0	1.39v	750
U Aur	+30126	408	176.96	0.99	250	120v	8.0	0.98	570
X Ori	+00080	422	205.92	−17.19	150	96v	≥4.1	1.55	760
S Ori	+00074	414	207.60	−20.45	690	150	6.8	−0.11v	350
SY Mon	+00119	422	212.58	−3.73	150	150v	7.4	1.51v	740
Z Pup	−20133	509	235.90	−0.68	120	120v	8.1	1.77v	960
S Pic	...	428	254.84	−36.29	440$^{\mathrm{a}}$	200v	7.5	...	440
R Hor	...	408	265.46	−57.38	1700$^{\mathrm{b}}$	730v	9.6	−1.10	220
RS Vel	...	410	271.76	1.02	700$^{\mathrm{b}}$	200v	≥3.5	−0.13	340
RW Vel	...	443	271.81	0.15	850$^{\mathrm{b}}$	240	≥4.2	−0.34	330
Y Vel	...	450	274.64	−0.79	230$^{\mathrm{b}\prime}$	82	6.2	1.06	630
Z Vel	...	411	278.65	0.05	270$^{\mathrm{b}}$	82	7.0	0.89	550
CL Car	...	513	289.22	−1.39	130$^{\mathrm{b}}$	72	2.5	1.68	920
U Men	...	407	295.61	−32.22	580$^{\mathrm{b}}$	340v	2.9	0.08	380
V370 Cen	...	403	296.93	16.03	140$^{\mathrm{a}}$	61v	≥3.5	...	770
R Oct	...	405	299.11	−28.39	410$^{\mathrm{b}}$	91v	6.8	0.45	440
ST Cru	...	440	299.72	2.71	350$^{\mathrm{b}}$	130	3.0	0.61	510
OS Cen	...	433	307.54	3.20	120$^{\mathrm{a}}$	55	≥5.0	...	850
SS Tel	...	415	338.60	−19.87	330$^{\mathrm{a}}$	150v	4.2	...	500
SV Lib	−30236	403	341.85	23.20	110	34	≥1.3	1.89v	860
S Gru	...	402	345.90	−54.77	380$^{\mathrm{b}}$	130v	9.0	0.54	460
WW Sco	−30264	431	347.91	12.13	90	33	≥4.1	2.09	990
U Tel	...	445	348.22	−22.70	470$^{\mathrm{a}}$	210v	≥2.4	...	440
EK CrA	...	435	354.41	−6.87	270$^{\mathrm{a}}$	120v	≥1.7	...	580

NOTE.—We use " v " to denote variability either in the TMSS or at the ≥90% level in the *IRAS* Point Source Survey.

[a] Estimated from the *IRAS* measurement of the 12 μm flux and equation (3).

[b] Flux taken from the data compilation by Gezari et al. (1987).

tic plane. We list 48 stars within 1 kpc of the Sun in Table 1. In addition, there are eight stars listed in Table 2 (SY Scl, V393 Her, AI Her, S Psc, WZ Eri, T Crv, T Com, R Tel) that are further than 1 kpc from the Sun, but whose distance from the Sun projected onto the Galactic plane is less than 1 kpc. Therefore, since there are 56 known stars inside an imaginary cylinder of radius 1 kpc oriented perpendicular to the Galactic plane, the surface density near the Sun is 18 kpc^{-2}.

According to Table 2, $N_* = 20$; that is, there are 20 long-period optical Miras at $|b| \geq 30°$. Therefore, from the inferred value of $\sigma = 18$ kpc^{-2} and equation (7), we find that $Z_0 = 240$ pc. This is the same value for the scale height as that derived for the intermediate-period Miras by Jura & Kleinmann (1992a) and very close to the value of 250 pc derived by Kerschbaum & Hron (1992). Using equation (6), we derive a local density of these long-period Miras of $n = 38$ kpc^{-3}. In contrast, the local density of intermediate-period oxygen-rich Miras in the solar neighborhood is 210 kpc^{-3}.

We have found that locally, the number density of long-period oxygen-rich Miras is $\sim\frac{1}{6}$ of the number density of

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TABLE 2

OPTICAL MIRAS WITH $P \geq 400$ DAYS AT $|b| \geq 30°$

Star	IRC Number	P (days)	l	b	$F_\nu(2.2)$ (Jy)	$F_\nu(12)$ (Jy)	Δm (mag)	m_K (mag)	D (pc)
U Her	+20298	406	35°35	40°35	820	500v	7.0	−0.31v	310
Y Cap	...	412	38.67	−42.35		1.4	5.0	...	5400
SY Scl	−30002	411	39.92	−80.04	45	39	≥4.2	2.85	1400
RU Her	+30283	485	41.98	45.61	430	170	7.5	0.40v	490
V393 Her	...	426	49.66	30.75		33	6.5	...	1100
RS Peg	+10514	415	75.19	−33.18	240		6.5	1.04v	590
AI Her	+50257	407	75.43	39.12	54	17	≥3.5	2.66	1200
WZ Dra	+50261	402	79.67	37.98	45	9	5.5	2.86	1300
Z UMi	...	475	118.49	32.92		2.1	≥3.0	...	4800
S Psc	+10014	405	133.79	−53.39	44	30	7.1	2.87v	1400
WZ Eri	...	400	206.05	−43.66		25	≥3.5	...	1200
S Pic	...	428	254.84	−36.29	410	200	7.5	0.76	460
R Hor	...	408	265.46	−57.38	1700	730v	9.6	−1.10v	220
RT Phe	...	416	278.34	−65.05		0.30	≥2.1	...	12000
U Men	...	407	295.61	−32.22	580	340v	2.9	0.08	380
T Crv	−20242	401	298.08	45.21	74	35	≥5.0	2.31v	1000
T Com	...	406	325.61	85.69		34	4.1	...	1100
RR Phe	...	427	341.28	−73.52			≥4.6	...	
S Gru	...	402	345.90	−54.77	380	130v	9.0	0.54	460
R Tel	...	462	352.69	−33.31		42v	7.2	...	1100

NOTE.—We use "v" to denote variability either in the TMSS or at the ≥90% level in the *IRAS* Point Source Survey.

intermediate-period oxygen-rich Miras. In contrast, it appears that at ~1 kpc from the Galactic center, there are ~0.7 times as many long-period oxygen-rich Miras as there are intermediate-period oxygen-rich Miras (Lloyd Evans 1976).

There is a clear asymmetry with Galactic longitude in the distributions of stars listed in Table 1 in the sense that there are considerably more stars in the hemisphere facing the Galactic center (34) than in the hemisphere facing the Galactic anticenter (16). While the sample of stars is not very large, the data are consistent with a value for the scale length in the Galactic plane of $R_0 = 3.5$ kpc, similar to that of the intermediate-period Miras (Jura & Kleinmann 1992a).

4. MASS-LOSS RATES

Jura & Kleinmann (1992a) noted for the intermediate-period Miras that there is good agreement between the mass-loss rates derived from the strength of the CO emission and that derived from the strength of the 60 μm emission. Because there are relatively few measurements of the CO for the stars in Tables 1 and 2, we derive mass-loss rates from the infrared emission measured by *IRAS*. In particular, following Jura & Kleinmann (1992a), we write that

$$dM/dt = 1.1 \times 10^{-8} v_{\rm dust} D_{\rm kpc}^2 L_4^{-1/2} F_\nu(60) \lambda_{10}^{1/2} . \quad (8)$$

In this equation, $v_{\rm dust}$ is the outflow speed of the dust (km s^{-1}), L_4 denotes the luminosity of the star (10^4 $L_\odot$), $D_{\rm kpc}$ is the distance (kpc), $F_\nu(60)$ is the flux measured by *IRAS* at 60 μm (Jy), and λ is the mean wavelength of the emergent radiation (10 μm).

Measured values for the CO outflow velocity for the long-period Miras in Tables 1 and 2 are typically near 8 km s^{-1}. We adopt from the analysis of Dyck, Lockwood, & Capps (1974) and Robertson & Feast (1981) that at 2.2 μm,

$$L = 1.8 \nu L_\nu \quad (9)$$

Therefore, from equation (9), the typical luminosity for Miras with periods of 400 and 450 days are 6000 and 7000 $L_\odot$, respectively. We take the distances from Tables 1 and 2, the fluxes from the *IRAS* Point Source Catalog and we adopt $\lambda_{10} = 0.15$ (Jura & Kleinmann 1992a). With these results, the average value of the mass-loss rate for the stars in Table 1 is 4×10^{-7} $M_\odot$ yr^{-1}. This is significantly larger than the typical mass-loss rate of between 1 and 2×10^{-7} $M_\odot$ yr^{-1} exhibited by intermediate period oxygen-rich Miras (Jura & Kleinmann 1992a).

5. ROLE IN STELLAR EVOLUTION

Because the scale length and scale height of the long-period Miras are apparently the same for both the intermediate and long-period Miras, it seems reasonable to argue that they derive from the same main-sequence progenitor population of stars of typically ~1.1 $M_\odot$.

Jura & Kleinmann (1992a) estimated that the duration of the short-period Mira phase is 2×10^5 yr. Because the space density of long-period Miras is ~$\frac{1}{6}$ of that of the intermediate-period Miras, we estimate that the duration of the star in the long-period Mira phase is ~30,000 yr. With a mass-loss rate of ~4×10^{-7} $M_\odot$, yr^{-1} for the long-period Miras, we therefore derive a total amount of mass lost during this phase of stellar evolution of ~0.01 $M_\odot$. Jura & Kleinmann (1989) found that "very dusty" stars had a local surface density and lifetime projected onto the Galactic plane of 25 kpc^{-2} and ~30,000 yr, respectively, values close to those we have found for the optical long-period Miras. However, the "very dusty" stars have typically mass-loss rates near 10^{-5} $M_\odot$ yr^{-1} and are therefore much more important in the return of matter to the interstellar medium from AGB stars. About half of the "very dusty" stars within 1 kpc of the Sun are carbon rich.

As pointed out, for example, by Wood (1989), a star's average luminosity on the AGB increases with time; therefore, we expect its period as a Mira to lengthen from equations (2) and (9). In particular, from Wood & Cahn (1977), the change in luminosity for an AGB star of 5000 $L_\odot$, corresponding to

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$P = 349$ days from equations (2) and (9), is

$$dL/dt = +0.004\ L_\odot\ \mathrm{yr}^{-1} \tag{10}$$

Therefore, in 2×10^5 yr, the star increases in luminosity from 5000 $L_\odot$ to 5800 $L_\odot$. According to equations (2) and (9), this luminosity corresponds to a period of 388 days. Jura & Kleinmann (1992b) have argued from their relative numbers in the solar neighborhood that AGB stars probably spend about as much time as Semiregualrs in overtone pulsations as they do as Miras in the fundamental mode. We suggest that a Mira of initial period of ~300 days would evolve into a Mira of ~400 days in $\sim 5 \times 10^5$ yr. About half of this evolving time could be spent as a Mira and about half as a Semiregular. Vassilliadis & Wood (1992) have computed that the lifetime of a thermally pulsing AGB star initially of 1 $M_\odot$ of solar metallicity is 5×10^5 yr, in agreement with this interpretation of the statistics of long-period variables.

Wood (1989) and Vassiliadis & Wood (1992) have proposed that the relative numbers of Miras in different period ranges can be explained by presuming that the mass-loss rate from the star increases exponentially with the star's period. (Similar calculations have been presented by Bowen & Willson 1991). In particular, they propose that

$$\log dM/dt = -11.4 + 0.0125P \tag{11}$$

Qualitatively, this picture is very attractive. It seems likely that the longer period Miras lose mass more rapidly than do the intermediate-period Miras.

There are at least two problems with using equation (11) to model stellar evolution on the AGB. (1.) The mass-loss rate from a star is not simply a function of its period. It has been shown that Miras with more asymmetric light curves lose mass more rapidly than those with symmetric light curves (Bowers 1975; Onaka, de Jong & Willems 1989a, b; Vardya 1989; Jura & Kleinmann 1992b). (2.) Equation (11) does not clearly reproduce the available data. We consider the intermediate-period Miras listed in Table 1 of Jura & Kleinmann (1992a) and the long-period Miras listed in Table 1 of this paper. We use equation (8) to infer mass-loss rates with the assumptions that all stars have the luminosities given by equations (2) and (9), and an intrinsic color ($\lambda_{10} = 0.15$). We adopt dust outflow velocities from the argument (Jura & Kleinmann 1992a) that

$$v_{\mathrm{dust}} = 2v_\infty\ , \tag{12}$$

and we adopt (see Wood 1989; Vassiliadis & Wood 1992) that

$$v_\infty = -13.5 + 0.056P\ . \tag{13}$$

We take the 60 μm fluxes from the stars in the *IRAS* Point Source Catalog and the results are displayed in Figure 1. While, there is a tendency for the mass-loss rate to increase with period, our analysis of the data does not agree in detail with the predictions of Vassiliadis & Wood (1992). It is not yet clear why there are relatively few optical Miras with $P \geq 400$ days compared to the number of Miras with $400 > P \geq 300$ days.

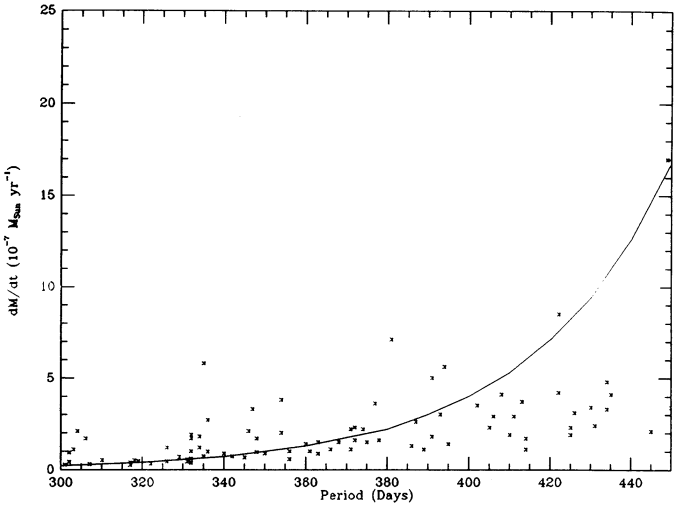

FIG. 1.—Plot of mass-loss rate vs. period for Miras listed in Table 1 of this paper and Table 1 of Jura & Kleinmann (1992a). The solid line displays the prediction by Wood (1989).

6. COMPARISON WITH THE MIRAS AT ~1 KILOPARSEC FROM THE GALACTIC CENTER

It is well established from colors and spectroscopy that there are a number of differences in the nature of the late-type giants between those in the solar neighborhood and those at ~1 kpc from the Galactic center (Frogel 1988; Frogel et al. 1990; Terndrup, Frogel, & Whitford 1990). Our results here, together with those of Lloyd Evans (1976), show that there is another observational difference between the local red giants and those at ~1 kpc from the Galactic center. In particular, the ratio of long-period ($P \geq 400$ days) oxygen-rich Miras to intermediate-period ($400 > P \geq 300$ days) oxygen-rich Miras in the observed regions near the Galactic center is ~0.7 much greater than the value of 0.2 for this ratio that we find in the solar neighborhood.

Optical surveys indicate that nearly all of the red giants at ~1 kpc from the Galactic center are oxygen-rich although a very few are carbon rich (see Blanco & Terndrup 1989; Westerlund et al. 1991). This result does not simply appear to be a selection effect owing to these surveys being based on optical fluxes. Stars near the Galactic center found in infrared surveys also are oxygen rich. For example, Whitelock et al. (1991) used *IRAS* fluxes to identify mass-losing red giants at ~1 kpc from the Galactic center. By comparing the near-infrared colors of the stars in their sample with the near-infrared colors of carbon stars in the solar neighborhood also selected in *IRAS* data base (see, for example, Epchtein, Le Bertre & Lépine 1990), it seems that the stars near the Galactic center in the sample of Whitelock et al. (1991) are likely to be oxygen rich. The low fraction of carbon stars near the Galactic center is another marked contrast with the local population of red giants. The usual explanation for the marked increase in the outer Milky Way in the fraction of red giants that are carbon rich (see Jura 1992) is that main-sequence stars with lower metallicities are much likely to become carbon-rich AGB stars because it is much easier to invert the carbon to oxygen ratio in a star with an initially low metallicity (Iben & Renzini 1983).

The local space density of high-luminosity carbon stars is ~100 kpc^{-3} (Claussen et al. (1987); ~0.5 the space density of intermediate-period oxygen-rich Miras of ~210 kpc^{-3} (Jura & Kleinmann 1992a). The typical mass of the main-sequence progenitors of these local high-luminosity carbon stars appears to be near 1.2 to 1.6 $M_\odot$, but there a few higher mass progenitors as well (see Barnbaum, Kastner, & Zuckerman 1991). The main-sequence masses of the progenitors of the red giants at ~1 kpc from the Galactic center are not well known; they could be as large as 1.5 $M_\odot$ (Frogel 1988). Presumably because

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they have higher metallicities than stars in the solar neighborhood, here, we propose that main-sequence stars with masses greater than 1 $M_{\odot}$ at ~ 1 kpc from the Galactic center never become carbon-rich AGB stars; instead they become oxygen-rich long-period variables. If this is the case, and because there are so many carbon stars in the solar neighborhood, it is plausible that in the region near the Galactic center, the number of long-period oxygen-rich Miras could be comparable to the number of intermediate-period Miras as observed by Lloyd Evans (1976).

Whitelock et al. (1991) have argued that in the stellar population near the Galactic center, the intermediate-period oxygen-rich Miras do not evolve into the bulk of the long-period oxygen-rich Miras. This argument is, in fact, consistent with our hypothesis that in the solar neighborhood, intermediate-period stars do evolve into long-period Miras because, near the Galactic center, there are a large number of high-metallicity main-sequence stars which do not have equivalents in the solar neighborhood. The progenitors and evolutionary histories of the long-period oxygen-rich Miras may be different between the solar neighborhood and near the Galactic center.

7. CONCLUSIONS

We have taken a systematic census of the nearby optical oxygen-rich Miras with $P \geq 400$ days.

1. We find that the exponential scale height of these stars is near 240 pc, that there are ~ 18 kpc^{-2} projected onto the Galactic plane and in the neighborhood of the Sun, the space density is ~ 38 kpc^{-3}.

2. The likely main-sequence progenitors of the long-period Miras are stars with masses near 1.1 $M_{\odot}$.

3. The duration of the optical, oxygen-rich Mira phase for stars with $P \geq 400$ days is probably near 30,000 yr, much shorter than our estimate of 2×10^5 yr for Miras with $400 > P \geq 300$ days.

4. The typical mass-loss rate for optical, oxygen-rich Miras with $P \geq 400$ days is near 4×10^{-7} $M_{\odot}$ yr^{-1}. The stars characteristically lose 0.01 $M_{\odot}$ during this phase.

5. The data appear to be consistent with the hypothesis that intermediate-period Miras ($400 > P \geq 300$ days) Miras evolve into long-period Miras ($P \geq 400$ days) in the course of 5×10^5 yr. The long-period Mira phase is relatively short lived; it is likely that these optical Miras rapidly become "very dusty" objects with very high mass-loss rates. Most of the mass lost from AGB stars occurs during a relatively short lived "very dusty" phase ($\sim$30,000 yr) with a high ($\sim 10^{-5}$ $M_{\odot}$ yr^{-1}) mass-loss rate.

6. The ratio of intermediate-period ($400 > P \geq 300$ days) oxygen-rich Miras to long-period ($P \geq 400$ days) oxygen-rich Miras is much lower at ~ 1 kpc from the Galactic center than in the solar neighborhood. One possible explanation for this difference is that main-sequence stars with masses greater than 1 $M_{\odot}$ near the Galactic center have metallicities substantially greater than that of the Sun; therefore, instead of becoming carbon-rich AGB stars, they evolve into long-period oxygen-rich Miras.

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