

MASS-LOSING M SUPERGIANTS IN THE SOLAR NEIGHBORHOOD

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ABSTRACT

We compile a list of the 21 mass-losing red supergiants (20 M type, one G type, $L > 10^5 L_\odot$) within 2.5 kpc of the Sun. These supergiants are highly evolved descendants of main-sequence stars with initial masses larger than $20 M_\odot$. The surface density is between about 1 and 2 kpc^{-2} . As found by previous authors, these stars are much less concentrated toward the Galactic center than W-R stars which are also highly evolved massive stars.

Although with considerable uncertainty, we estimate that the mass return by the M supergiants is somewhere between 1×10^{-5} and $3 \times 10^{-5} M_\odot \text{ kpc}^{-2} \text{ yr}^{-1}$. In the hemisphere facing the Galactic center there is much less mass loss from M supergiants than from W-R stars, but in the anticenter direction the M supergiants return more mass than do the W-R stars.

The duration of the M supergiant phase appears to be between 2×10^5 and 4×10^5 yr. During this phase a star of initially at least $20 M_\odot$ returns perhaps 3–10 M_\odot into the interstellar medium.

Subject headings: interstellar: matter — stars: mass loss — stars: stellar statistics — stars: supergiants

I. INTRODUCTION

Massive ($M > 20 M_\odot$) stars are important for the synthesis of heavy elements and thus the chemical evolution of galaxies. In addition to their return of mass into the interstellar medium, the evolution of these stars is dependent upon the amount of mass that they lose, and this process is not completely understood (Chiosi and Maeder 1986). After their main-sequence evolution, massive stars spend time as both red and blue supergiants; the duration in each phase is in large part controlled by the amount of mass loss. Previously, there have been studies of the number ratios of red and blue supergiants in the solar neighborhood (Brunish, Gallagher, and Truran 1986; Humphreys, Nichols, and Massey 1985; Lamb, Iben, and Howard 1976; Maeder, Lequeux, and Azopardi 1980). Here, beyond counting the numbers of stars, we are also interested in estimating the mass-loss rates from the red supergiants.

There are recent systematic studies of the massive objects when they are hot (Abbot *et al.* 1986; van der Hucht *et al.* 1988), and there has been considerable progress in the study of the mass loss from individual red giant and supergiant stars. However, these data have not been recently synthesized into a more comprehensive discussion, and the goal of this paper is to use infrared survey data to characterize the mass loss from a well-defined sample of red supergiant stars. Previously, for example, the *IRAS* data have been used most extensively to understand the mass loss from asymptotic giant branch (AGB) stars (see Claussen *et al.* 1987; Habing 1988; Jura 1986; Kleinmann, Jura, and Joyce 1989) which have main-sequence progenitor masses between 1 and $\sim 5 M_\odot$.

A major problem with studying the M supergiant stars that have massive ($M > 10 M_\odot$) progenitors is separating

them from mass-losing AGB stars which are descended from intermediate-mass stars ($1 M_\odot < M < 5\text{--}8 M_\odot$). The maximum luminosity of AGB stars is $6 \times 10^4 L_\odot$ (Iben and Renzini 1983). If a giant has a luminosity in excess of this value, it is probably an evolved massive star (see Chiosi and Maeder 1986). In order to avoid as much ambiguity as possible, we restrict our analysis to supergiants with $L > 10^5 L_\odot$; this means that we are considering stars with $M > 20 M_\odot$ (see Fig. 3 of Chiosi and Maeder 1986).

For single stars in the mass range between 25 and $60 M_\odot$, Chiosi and Maeder (1986, p. 346) propose the following evolutionary scheme: O star \rightarrow blue supergiant \rightarrow yellow/red supergiant \rightarrow W-R(N) \rightarrow W-R(C) \rightarrow supernova. W-R(N) and W-R(C) refer to Wolf-Rayet stars of types N and C, respectively (see Abbott and Conti 1987). If the mass-loss rate is "low," the W-R phase never occurs and the star becomes a supernova directly after the red supergiant phase. This scheme ignores mass transfer in binaries, which can also lead to the formation of a W-R star (Maeder 1981; Massey 1981; Schulte-Ludbeck 1989). In any case, by comparing the relative numbers of red supergiants and W-R stars, we can constrain this theoretical picture. The history of mass loss may also control the type of supernova that ultimately results (Chevalier 1986; Begelman and Sarazin 1986; Filippenko and Sargent 1986) because the optical light curve of a supernova is sensitive to the radius of the presupernova.

One advantage in studying luminous stars is that they are conspicuous. We are interested in sampling a sufficiently large volume to average over local fluctuations in the surface density of stars, yet a small enough volume to be reasonably complete. By analogy with studies of W-R stars (Abbott *et al.* 1986), we chose to study supergiants within 2.5 kpc of the Sun (see Humphreys and McElroy 1984).

In order to determine the luminosity of a star, it is necessary to measure its flux corrected for interstellar extinction and distance. There are now sufficiently complete data from infrared surveys (see Gezari, Schmidt, and Mead 1987), such as the data available from *IRAS* and the Two Micron Sky Survey (TMSS; Neugebauer and Leighton 1969), that we can estimate bolometric fluxes from cool stars reasonably accurately. Furthermore, the *IRAS* data extend to sufficiently long wavelengths that we are detecting emission from the circumstellar dust and we can therefore estimate the mass-loss rate. A major difficulty is that the distances are often uncertain.

In § II we list the red supergiants within 2.5 kpc of the Sun, and in § III we estimate their mass-loss rates. In § IV we discuss the implications of our results.

II. THE SUPERGIANT SAMPLE

We want to consider those stars with well-determined distances, such as membership in a cluster. Except for NML Cyg, all the stars were found from the catalogs of Humphreys (1978), Elias, Frogel, and Humphreys (1985), and White and Wing (1978). The distance and luminosity of NML Cyg are taken from Morris and Jura (1983). In Table 1 we list for each star the distance, the estimated interstellar reddening, and the inferred luminosity of the star. For the most part, the distances are taken from the compilation of data for

clusters of Humphreys (1978). When available, the reddening is taken from Humphreys (1978); otherwise we assumed that $A_K = 0.15 \text{ mag kpc}^{-1}$ (Jura, Joyce, and Kleinmann 1989). We adopt the interstellar reddening curve given by Savage and Mathis (1979). For some of the earlier M stars, a significant amount of the flux is emitted shortward of $1 \mu\text{m}$. For these objects we use when available the optical photometry from Lee (1970), the Bright Star Catalogue (Hoffleit and Jaschek 1982) and other sources of optical photometry as listed in Table 4. The derived luminosities are somewhat sensitive to the assumed amount of reddening, but the largest source of uncertainty in the luminosity is the distances to the stars. For example, Baud and Habing (1983) report a distance to VX Sgr of 0.5 kpc, a factor of 3 smaller than the value adopted here. Also, White (1980) has argued that α Ori is about 100 pc from the Sun rather than the more usually adopted value of 200 pc.

We include two stars in Table 1 whose distances are not well established but which have sufficiently long periods that they may be massive stars: KW Sgr ($P = 670$ days) and UY Sct ($P = 740$ days). Neither of these stars is a Mira, and spectroscopically they are classified as supergiants. We assume nominal distances to these stars of 2 kpc, but this is uncertain.

Except for ρ Cas (see Jura and Kleinmann 1990), all the stars in Table 1 that are losing substantial amounts of mass

TABLE 1
RED SUPERGIANTS WITHIN 2.5 KILOPARSECS OF THE SUN

Star	IRC	Spectral Type	d (kpc)	z (pc)	A_K (mag)	L ($10^5 L_\odot$)	References
KW Sgr	-30326	M0 Ia	2?	-25	0.30 ^a	1	
VX Sgr	-20431	M4 Ia	1.5	-26	0.26 ^a	1-2	1, 2
UY Sct	-10422	M4 Iab	2?	-16	0.30 ^a	1	
BD + 24°3902	+20438	M1 Ia	1.5	-18	0.60	1	3
BI Cyg	+40408	M4 Ia	1.8	3.5	0.55	2	4
BC Cyg	+40409	M3.5 Ia	1.8	13	0.65	4	4
KY Cyg	+40415	M3.5 Ia	1.8	5.7	0.83	4	4
NML Cyg	+40448	M	2.0	-67	0.30 ^a	5	5
μ Cep	+60325	M2 Ia	0.83	63	0.29	4	4, 6
ρ Cas	+60429	F8 Ia	2.5	-197	0.26	5	7
PZ Cas	+60417	M2 Ia	2.5	-2.2	0.36	2	4
TZ Cas	+60428	M2 Iab	2.5	-47	0.35	1	4
S Per	+60088	M3 Ia	2.3	-88	0.38	2	8
SU Per	+60086	M3 Iab	2.3	164	0.18	1	9
α Ori	+10100	M1	0.2?	-31	0.03 ^a	1	10
VY CMa	-30087	M5 I	1.5	-132	0.23 ^a	4	10
EV Car .....	...	M4 Ia	2.5	-93	0.19	2	7
CK Car .....	...	M3.5 Iab	2.5	-124	0.21	1	7
IX Car .....	...	M2 Iab	2.5	-26	0.23	1	7
V396 Cen .....	...	M4 Ia	2.5	49	0.16	2	7
AH Sco	-30282	M4	2?	149	0.30 ^a	3	11

^aDerived with the assumption that there is $0.15K \text{ mag kpc}^{-1}$ of extinction, rather than from Humphreys 1978.

REFERENCES.—(1) Chapman and Cohen 1986; (2) Lockwood and Wing 1982; (3) Elias, Frogel, and Humphreys 1985; (4) Lee 1970; (5) Morris and Jura 1983; (6) Le Borgne and Mauron 1989; (7) Jura and Kleinmann 1989; (8) Gezari, Schmidt, and Mead 1987; (9) Elias, Frogel, and Humphreys 1985; (10) Sopka *et al.* 1985; (11) Humphreys and Ney 1974.

TABLE 2
TMSS STARS CLASSIFIED AS A–M SUPERGIANTS

TMSS	OTHER NAME	<i>l</i> (degrees)	<i>b</i> (degrees)	FLUX DENSITY (Jy)					VARIABLE TYPE	PERIOD (days)	SPECTRAL CLASS
				0.9 μ m	2.2 μ m	12 μ m	25 μ m	60 μ m			
A. A Type											
+60120	HR 1040	142.2	2.1	85.3	45.6	4.6	2.7	6.1:	...	...	A0 Ia
+40109	ϵ Aur	162.8	1.2	343.0	152.0	9.3	2.8	0.5	EA/GS	9892	A8e Ia
-30099	3 Pup	244.4	-2.5	110.0	67.2	258.0	147.0	25.7	...	...	A3ep II
-20311	o Sco	352.3	18.0	176.0	148.0	11.1	2.7	< 5.6:	...	...	A5 II
+50337	α Cyg	84.3	2.0	> 950	291.0	...	...	...	ACYG	...	A2 Ia
+60326	ν Cep	102.3	5.9	102.0	48.7	3.7	1.1	< 0.5	...	...	A2 Ia
B. F Type											
+60046	ϕ Cas	126.7	-4.4	76.1	50.0	3.2	0.8	< 0.4	...	...	F0 Ia
+50095	α Per	146.6	-5.9	> 950	383.0	27.4	6.7	1.2:	...	...	F5 Ib
+40068	ν Per	153.8	-9.6	126.0	56.9	4.0	1.0	0.6	...	...	F5 II
-20073	α Lep	220.9	-25.1	344.0	112.0	8.1	1.9	0.4	...	...	F0 Ib
+20169	ζ Gem	195.7	11.9	175.0	89.4	6.3	1.5	< 0.4	DCEP	10.2	F7.5 Ib–G1.5 Ib
-30076	δ CMa	238.4	-8.3	> 950	444.0	35.1	8.5	1.5:	...	...	F8 Ia
-20150	11 Pup	240.6	3.1	112.0	58.0	4.1	1.2	< 0.4	...	...	F8 II
-20157	ρ Pup	243.1	4.4	280.0	108.0	7.2	1.8	0.4	DSCT	0.1	F5 IIP
+10210	o Leo	224.6	42.1	158.0	69.1	4.6	1.1	< 0.4	...	...	F6 II + A2
00431	ν Aql	37.3	-7.6	76.6	42.8	2.9	0.7	< 0.5	...	...	F2 Ib
+10420	...	47.1	-2.5	5.7	50.0	1350.0	2310.0	717.0:	...	...	F8 Ia:
00457	η Aql	40.9	-13.1	181.0	102.0	7.2	1.7	< 0.4:	DCEP	7.2	F7 Ib–G2 Ib
+40411	γ Cyg	78.2	1.9	> 950	331.0	22.1	< 2.2	< 31.4:	...	...	F8 Ib
+30434	41 Cyg	70.9	-5.0	97.0	40.9	3.0	0.7	< 0.5:	...	...	F5 II
+60356	δ Cep	105.2	0.5	144.0	71.7	5.2	1.5	< 2.9	DCEP	5.4	F5 Ib–G1 Ib
+60429	ρ Cas	115.3	-4.5	139.0	89.4	20.2	5.8	0.9:	SRD	320	Fvep Ia
C. G Type											
+60059	HR 461	129.1	-4.3	64.4	63.6	4.6	1.1	< 0.5	...	...	G5 II
+10028	ξ^1 Cet	154.6	-49.0	116.0	73.0	5.9	1.2	< 0.4	...	...	G8 IIP
+60108	BD +57°672	139.4	-1.0	43.1	67.8	6.9	1.8	< 0.6	...	...	G0 Ia
+50091	HR 969	144.9	-5.7	78.6	61.9	5.5	1.2	< 0.4	...	...	G5 II
+50110	μ Per	153.9	-1.8	159.0	107.0	8.2	1.9	< 0.5	...	...	G0 Ib
+40079	52 Per	159.4	-7.5	97.4	73.0	5.4	1.3	< 0.4:	...	...	G5 II + A,B
+40093	58 Per	161.8	-4.0	213.0	187.0	15.1	3.3	0.6	...	...	G8 II + A,B
+60151	β Cam	149.6	11.4	164.0	98.0	7.0	1.7	< 0.4:	...	...	G0 Ib
+10099	HR 2048	196.9	-7.6	45.4	47.4	3.8	0.9	< 0.4:	...	...	G9 II
+30164	ϵ Gem	189.5	9.6	> 950	554.0	40.5	9.2	1.7	...	...	G8 Ib
+20165	ω Gem	192.2	13.1	56.6	40.1	2.6	0.7	< 0.4	...	...	G5 Ib–IIa
-30084	HR 2786	239.7	-6.3	52.7	40.9	2.4	0.5	< 0.4:	...	...	G1 Iab–Ib
-30094	HR 2881	244.8	-6.0	85.9	51.0	3.9	1.0	< 0.4	...	...	G0 Ib
-20145	ξ Pup	241.5	0.6	380.0	263.0	21.1	5.3	0.8	...	...	G3 Ib
00171	ζ Mon	224.7	15.7	129.0	76.4	5.5	1.4	< 0.4	...	...	G2 Ib
-20160	20 Pup	236.6	10.1	71.2	51.9	3.9	0.9	< 0.4	...	...	G5 II
-10204	HR 3459	233.3	21.0	86.7	54.4	3.5	0.8	< 0.4	...	...	G1 Ib
+40202	HR 3612	184.3	42.1	101.0	63.0	5.7	1.5	< 0.4	...	...	G7 Ib–II
+20215	ϵ Leo	206.8	48.2	414.0	220.0	16.9	3.7	0.6	...	...	G1 IIab
+30223	37 LMi	195.3	60.8	79.1	46.1	3.2	0.8	0.3	...	...	G3 II
+40225	56 UMa	164.7	65.8	71.1	49.1	3.4	0.8	< 0.4	...	...	G8 IIb
+20301	HR 6152	37.8	39.8	91.3	89.4	6.9	1.6	< 0.4	...	...	G8 IIP
-20325	HR 6196	0.8	18.4	92.0	72.3	5.7	1.4	< 0.4	...	...	G8 II
+50266	β Dra	79.6	33.3	> 950	328.0	25.1	5.5	1.0	...	...	G2 Ib
-30324	X Sgr	1.2	0.2	105.0	61.9	4.0	< 9.6	< 59.0:	DCEP	7.0	cG2v
-20384	HR 6617	5.8	2.9	52.0	56.4	4.6	1.0	< 0.7	...	...	G3 Iab–Ib
-10382	Y Oph	20.6	10.1	47.6	51.0	4.1	1.0	< 0.4:	DCEPS	17	cG2v
-30351	W Sgr	1.6	-4.0	64.7	41.2	...	...	...	DCEP	7.6	cG2v
-20434	AX Sgr	11.6	0.7	35.8	47.8	37.3	51.0	33.1	SRD	350	G8 Ia
-10457	ϵ Sct	24.7	-2.0	111.0	93.6	4.7	< 3.1	< 7.3	...	...	G8 II
00376	β Sct	28.2	-1.2	178.0	135.0	13.1	3.5	< 13.1	...	...	G4 IIa
-20550	43 Sgr	18.7	-14.1	92.6	83.0	7.1	4.2	< 0.5	...	...	G8 II
+20426	α Sge	54.5	-2.1	106.0	56.4	4.0	0.8	< 0.6:	...	...	G1 IIab
+20461	22 Vul	63.5	-6.4	57.7	41.2	3.1	0.8	< 0.4	...	...	G3p Ib–II
-10534	α^1 Cap	31.1	-24.7	140.0	94.5	9.0	2.0	< 0.5	...	...	G3 Ib
-10565	β Aqr	48.0	-37.9	> 950	225.0	16.0	3.7	0.8	...	...	G0 Ib

TABLE 2—Continued

TMSS	OTHER NAME	<i>l</i> (degrees)	<i>b</i> (degrees)	FLUX DENSITY (Jy)					VARIABLE TYPE	PERIOD (days)	SPECTRAL CLASS
				0.9 μ m	2.2 μ m	12 μ m	25 μ m	60 μ m			
C. G Type											
+20518	9 Peg	72.0	-26.5	154.0	110.0	8.3	2.0	< 0.4	...	...	G5 Ib
+60332	HR 8374	103.5	5.5	43.6	47.4	4.1	1.0	< 0.5	...	...	G8 Ib
00513	α Aqr	59.9	-42.1	> 950	265.0	19.3	4.4	0.8	...	...	G2 Ib
+30499	η Peg	92.5	-25.0	> 950	296.0	20.0	4.6	0.8	...	...	G8 II: + F?
+60379	HR 8752	108.2	-2.7	149.0	137.0	13.0	4.0	0.5:	...	...	G5-0-Ia
-20640	104 Aqr	59.4	-71.4	71.1	40.5	2.8	0.7	< 0.4	...	...	G0 Ib-IIa
+50477	ψ And	111.3	-15.0	82.6	67.2	4.5	1.1	0.3	...	...	G5 Ib
D. K Type											
-10001	3 Cet	87.1	-70.0	146.0	157.0	12.7	3.4	0.6	...	...	K3 Ib
+70010	BD + 67°56	121.4	5.1	49.3	79.3	6.3	1.6	< 0.4	...	...	K2 Ib-II
+60014	BD + 59°91	121.3	-2.5	33.5	48.2	3.3	0.9	< 0.5:	...	...	K3 Ib-II
+20013	ζ And	121.7	-38.6	224.0	167.0	12.9	2.9	0.4	FBGSRs	...	K1 II
+60022	HR 237	122.9	-1.1	93.9	158.0	12.3	3.0	0.8:	...	...	K2 Ib-IIp
+70028	BD + 65°164	126.6	3.5	33.6	50.0	4.1	1.0	0.5	...	...	K2 Ib-IIp
+60055	HR 439	128.4	-4.1	85.6	112.0	8.9	2.1	< 0.4	...	...	K3 Ib: + B
+50039	BD + 54°315	129.0	-7.4	36.6	54.4	4.6	1.2	< 0.4	...	...	K3 Ib
+60066	BD + 64°243	129.2	2.7	78.3	144.0	11.1	2.8	0.6	...	...	K4 + Ib-IIa
+40034	γ^1 And	137.0	-18.6	> 950	1470.0	98.5	24.0	3.6	...	...	K3 - IIb
00029	HR 611	162.9	-61.2	113.0	138.0	9.5	2.5	0.5	...	...	cK5
+60076	BD + 62°369	132.3	1.9	33.4	51.9	3.9	0.8	< 1.0	...	...	K3 Ib
+70034	BD + 66°198	131.0	5.8	34.3	52.4	3.9	1.0	0.3	...	...	K4 II
+60099	η Per	139.1	-3.2	> 950	569.0	45.4	10.5	1.8	...	...	K3 - Ib-IIa
+60103	BD + 59°568	137.8	1.0	16.7	47.8	4.3	1.5	< 3.0	...	...	K5-M0 II
+60104	HR 861	136.0	4.7	94.5	163.0	11.8	3.0	0.5:	...	...	K3 Ib
+30058	HR 991	154.6	-19.4	151.0	151.0	10.7	2.6	< 0.4	...	...	K2 II
+60126	HR 1112	142.9	3.9	101.0	139.0	10.6	2.7	0.3:	...	...	K4 Ib
+60134	HR 1205	143.5	5.9	147.0	167.0	13.1	3.4	1.1	...	...	K3 II
+40099	HR1533	166.3	-4.6	149.0	164.0	12.5	3.0	0.8:	...	...	K4 II
+40104	BD + 43°1123	162.3	0.0	29.3	51.4	4.1	0.9	< 0.4	...	...	K5 II
+30100	ι Aur	170.6	-6.2	> 950	1250.0	87.3	20.6	3.6	...	...	K3 II
00065	π^6 Ori	197.6	-24.0	187.0	172.0	12.8	3.1	0.6	...	...	K2 II
+40107	6 Aur	165.9	-1.6	30.4	66.6	5.1	1.3	0.4	...	...	K4 I
+40110	ζ Aur	165.0	-0.4	> 950	564.0	41.9	9.9	1.9	EA/GS	972	K5 II + B
+40117	HR 1669	168.9	-1.5	50.9	76.4	6.5	1.8	< 1.3	...	...	cK3::
+60155	HR 1720	148.9	14.3	104.0	134.0	10.7	2.6	< 0.5	...	...	cK4
+10093	HR 1908	194.3	-11.0	72.2	80.0	7.1	1.7	< 0.4	...	...	K4 II
00089	56 Ori	204.4	-12.2	142.0	128.0	10.7	2.5	0.8:	...	...	K1.5 IIb
+50164	ψ^1 Aur	165.4	16.2	270.0	366.0	44.1	19.3	4.1	LC	...	K5-M0 Ia-Iab
00111	HR 2334	209.9	-5.2	69.3	51.9	3.9	1.0	< 0.4	...	...	K1 II
-20112	σ^1 CMa	235.0	-10.2	434.0	409.0	39.1	15.2	3.5:	...	...	K2 + Iab
+20163	41 Gem	199.5	9.2	78.0	97.1	8.1	2.0	< 0.5	...	...	K3 Ib
-30072	σ CMa	239.2	-10.3	> 950	998.0	77.0	21.6	3.0	...	...	K7 Ib
00145	BD - 4°1797	218.5	0.7	27.7	54.4	4.8	1.3	0.5	...	...	K5 Ib
00151	HR 2729	212.8	6.5	60.4	53.9	3.7	0.9	< 0.4	...	...	K2 II
-20125	HR 2764	236.5	-5.2	252.0	285.0	21.7	5.7	0.7	...	...	K3 Ib
-20139	HR 2959	232.1	3.6	140.0	160.0	13.0	3.1	0.4	...	...	K3 II
-30098	1 Pup	243.9	-2.3	283.0	325.0	23.9	6.0	1.1	...	...	K3 Ib
-20153	12 Pup	241.3	3.3	73.3	52.4	3.9	0.8	< 0.4:	...	...	cK2
-30123	HR 3282	252.1	2.1	141.0	130.0	10.1	2.5	0.4:	...	...	K3 - II
+40281	HR 6050	67.0	46.8	59.0	67.2	4.7	1.1	< 0.4	...	...	K4 II
+40295	π Her	60.7	34.3	> 950	642.0	48.2	11.4	1.7	...	...	K3 II
00304	σ Oph	26.8	20.8	252.0	251.0	18.7	4.7	0.6	...	...	K2 II
-30313	BM Sco	356.7	-0.9	6.0	83.8	96.3	47.3	9.8:	SRD	815	K2.5 Ib
+40306	θ Her	63.3	26.4	293.0	237.0	18.4	4.2	0.6	...	...	K1 IIap
-30374	HR 6842	5.2	-5.3	242.0	285.0	22.5	5.5	1.7	...	...	K3 II
+20360	105 Her	51.9	17.6	110.0	120.0	8.9	2.0	0.5	...	...	K4 II
-20478	21 Sgr	11.7	-3.7	172.0	194.0	14.2	3.3	< 1.4:	...	...	K2 II
-10433	HR 6959	17.6	-2.7	168.0	246.0	20.2	5.6	< 9.4	...	...	K5 Ib
-20495	24 Sgr	9.5	-7.1	142.0	188.0	14.1	< 11.5	< 10.0:	...	...	cK4
-10461	R Sct	27.4	-1.7	79.5	95.3	20.8	9.3	8.2	RVA	147	K0 Iab-Ibp
-20525	33 Sgr	14.0	-10.1	53.0	47.8	3.6	1.0	< 0.4	...	...	K1 Ib
-20526	ν^1 Sgr	12.7	-10.7	135.0	122.0	9.0	2.2	< 0.4	...	...	cK2
+30350	λ Lyr	62.9	12.4	128.0	133.0	9.9	2.3	< 0.4	...	...	K3 II
-30405	HR 7277	11.6	-16.0	52.3	59.6	4.4	0.9	< 0.4	...	...	cK0
+40341	θ Lyr	69.9	11.9	180.0	148.0	10.9	2.6	0.7:	...	...	K0 + II
+20409	BD + 14°3937	50.7	-1.3	25.4	51.9	4.0	0.9	< 5.8:	...	...	K5 II
+30370	β Cyg	62.1	4.6	> 950	569.0	39.8	10.0	1.3	...	...	K3 II: + B:
+20424	HR 7475	53.1	-2.7	90.6	148.0	11.6	3.4	0.7	...	...	K4 Ib
+30386	BD + 26°3654	62.8	1.6	41.1	53.4	3.9	0.9	< 0.8:	...	...	K3 II

TABLE 2—Continued

TMSS	OTHER NAME	<i>l</i> (degrees)	<i>b</i> (degrees)	FLUX DENSITY (Jy)					VARIABLE TYPE	PERIOD (days)	SPECTRAL CLASS
				0.9 μ m	2.2 μ m	12 μ m	25 μ m	60 μ m			
D. K Type											
+10439	γ Aql	48.7	-7.1	> 950	1140.0	76.5	20.0	2.9:	...	...	K3 II
+20434	BD + 22°3812	59.5	-1.4	40.1	72.3	5.6	1.5	< 4.1:	...	...	K3 Iab-Ib
+50320	V695 Cyg	82.7	6.8	27.2	41.6	28.8	8.0	< 2.0	EA/GS/D	3784	K2 II + B3 - V
+50322	32 Cyg	83.7	7.0	> 950	534.0	42.5	10.3	< 1.2:	...	...	K3 Ib-II + B
+40401	HR 7759	77.7	2.8	130.0	166.0	11.4	2.7	< 13.1:	...	...	K3.5 II
+40402	HR 7762	79.7	4.0	47.5	64.2	4.4	1.1	< 22.5:	...	...	K4 II:
-20587	σ Cap	24.5	-27.7	95.7	94.5	6.4	1.6	< 0.5	...	...	K3 II
+40404	BD + 38°4003	76.8	1.7	66.9	119.0	8.6	2.1	< 13.9	...	...	K5 Ib
+40433	47 Cyg	75.4	-2.9	275.0	325.0	27.0	7.4	< 1.5:	...	...	K4 Ib + B
+10474	θ Del	57.9	-16.6	63.0	70.4	5.1	1.2	< 0.4	...	...	K3 Ib
+50355	BD + 47°3266	88.7	1.0	29.8	46.9	3.8	1.0	< 0.4	...	...	K7 II
+40468	ξ Cyg	85.9	-2.1	> 950	684.0	...	...	...	...	...	K4.5 Ib-II
+50359	63 Cyg	88.9	0.2	235.0	253.0	17.9	4.5	< 1.7:	...	...	K4 Ib-IIa
+50384	HR 8248	90.8	-4.3	61.2	83.8	6.8	1.7	< 0.4	...	...	K1 Ib
+10503	ϵ Peg	65.6	-31.5	> 950	1420.0	104.0	25.0	4.0	...	...	K3 Ib
+50397	BD + 51°3135	96.5	-0.8	65.7	108.0	8.2	2.0	< 0.4:	...	...	K5 Ib
+20519	12 Peg	76.6	-22.8	83.0	80.8	...	...	...	...	...	K0 Ib
+50404	BD + 47°3584	94.9	-4.4	29.8	42.4	2.8	0.7	< 0.5:	...	...	K5 Ib
+60344	HR 8465	103.1	1.7	> 950	591.0	38.4	10.8	2.0:	...	...	K1.5 Ib
+30489	BD + 26°4399	85.4	-24.5	36.1	52.4	4.1	1.0	< 0.4	...	...	K5 II
+60353	RW Cep	103.2	-1.1	66.0	107.0	97.4	91.5	27.4:	SRD	346	K0 - 0-Ia
+60362	W Cep	106.0	0.1	35.3	59.6	121.0	87.0	12.1	SRC	...	K0ep Ia
+60370	...	108.4	0.9	10.1	44.0	142.0	175.0	39.8	...	...	K0: Ia
+50452	HR 8726	104.6	-9.0	225.0	313.0	24.5	5.9	0.9	...	...	K5 Ib
+60380	HR 8761	108.4	-2.6	41.7	46.9	3.7	0.9	< 0.4	...	...	K2 II
+30506	56 Peg	95.1	-31.7	141.0	129.0	9.2	2.3	< 0.4:	...	...	K0 Ibp
-20629	88Aqr	41.8	-66.0	338.0	267.0	...	...	...	...	...	K2 II
+60397	BD + 61°2423	112.6	1.7	108.0	270.0	28.3	8.4	2.4:	...	...	K4.5 Ib
+70198	HR 8952	116.9	9.7	82.6	104.0	8.8	1.9	0.5:	...	...	K0 Ib
+60422	HR 9010	114.3	-4.3	96.4	110.0	8.6	2.3	< 0.7:	...	...	K3 - II
00533	22 Psc	95.1	-56.7	527.0	1270.0	7.3	1.8	< 0.4	...	...	K4 II
E. M Type											
+60007	BD + 61°43	119.3	-0.8	62.3	124.0	9.4	2.7	< 2.7	...	...	M2 II:
+60008	MZ Cas	119.2	-2.7	13.6	54.9	24.5	10.1	9.4:	LC	...	M2 Iab
+60039	HS Cas	124.8	0.8	20.6	64.8	23.5	16.4	3.5	LC	...	M4 Ia
+30024	HR 363	128.9	-34.1	88.8	142.0	11.5	3.0	0.6	...	...	M3 IibS
+60061	BD + 55°388	130.0	-5.6	17.8	40.1	4.7	1.9	0.5:	...	...	M2 Ib
+50043	BD + 47°485	131.7	-13.5	59.9	107.0	12.1	6.3	1.5	...	...	M2 Ib
+60063	BD + 60°335	129.5	-1.2	15.2	56.9	12.7	8.7	3.6:	...	...	M3 Iab-Ib
+60064	BD + 59°319	129.8	-1.8	21.1	54.4	6.3	3.0	0.9	...	...	M3 Iab-Ib
+60070	BD + 58°342	131.4	-2.5	24.8	67.2	8.9	4.0	0.8:	...	...	M2 Iab
+50052	XX Per	133.1	-6.2	50.4	119.0	70.8	28.4	4.2:	SRC	415	M4 Ib + B
+60074	KK Per	133.7	-4.7	36.0	91.1	19.4	10.9	2.2	LC	...	M2 Iab
+60078	BU Per	134.5	-3.5	23.3	77.2	45.0	31.3	5.2:	SRC	367	M4 Ib
+60079	T Per	134.1	-2.0	22.2	53.9	10.4	7.2	2.1:	SRC	2430	M2 Iab
+60081	BD + 58°445	134.0	-1.3	19.5	60.2	12.0	8.8	2.2	...	...	M2 Iab
+60082	AD Per	134.9	-3.8	33.0	87.0	21.3	13.9	2.9	SRC	363	M3 Iab
+60083	FZ Per	134.9	-3.6	22.7	60.7	11.2	4.7	1.1:	SRC	184	M1 Iab
+60085	PR Per	134.7	-2.9	31.8	74.4	12.8	9.4	2.4	LC	...	M1 - Iab-Ib
+60086	SU Per	135.2	-4.1	63.6	158.0	48.7	30.7	6.9:	SRC	533	M3-4 Iab
+60087	RS Per	135.1	-3.6	31.2	129.0	74.4	47.8	9.9:	SRC	245	M4 Iab
+60088	S Per	134.6	-2.2	39.4	188.0	339.0	233.0	40.6:	SRC	822	M4 Ia
+60089	BD + 56°595	135.1	-3.5	27.2	66.0	9.1	2.8	0.8:	...	...	M0 Iab
+60090	BD + 56°609	135.3	-3.2	36.9	104.0	18.5	13.2	3.5:	...	...	M2 Iab
+60091	...	134.4	0.0	11.9	110.0	89.5	58.7	9.6:	...	...	M2 Iab
+60093	YZ Per	137.1	-2.8	36.6	85.4	38.9	26.1	5.3	SRB	378	M2 Iab
+60094	GP Cas	136.3	-0.4	23.7	103.0	25.7	18.5	4.5	LC	...	M2 Iab
+30047	W Tri	147.4	-23.1	88.7	235.0	42.7	21.3	3.1	SRC	108	M4 II
+60097	W Per	138.7	-2.2	21.5	88.6	90.6	78.9	14.9	SRC	485	M3 Ia
+60100	...	138.3	-1.4	23.0	90.2	39.0	26.4	6.5	...	...	M2 Iab
+60106	...	139.1	-1.3	14.7	69.7	11.8	3.8	0.7	...	...	M1 Iab:
+60110	IO Per	141.2	-2.3	20.8	169.0	240.0	185.0	35.1:	LC	...	M3 Iab:
+60111	...	139.0	1.9	25.3	95.3	18.0	12.2	3.5:	...	...	M1 Iab
+50089	...	142.7	-2.4	26.9	112.0	35.6	26.1	5.9	...	...	M3 Iab
+60117	HR 1009	138.5	6.4	287.0	465.0	39.5	11.1	2.1	...	...	M0 II
+50104	...	147.6	-1.2	8.6	42.8	3.9	1.0	< 0.5	...	...	M3 I + ?
+70046	HR 1155	140.0	8.7	> 950	1210.0	94.9	25.8	13.9:	...	...	M2 + II
-20049	V Eri	208.8	-44.0	206.0	1130.0	326.0	184.0	23.6	SRC	97	M6 II

TABLE 2—Continued

TMSS	OTHER NAME	<i>l</i> (degrees)	<i>b</i> (degrees)	FLUX DENSITY (Jy)					VARIABLE TYPE	PERIOD (days)	SPECTRAL CLASS
				0.9 μ m	2.2 μ m	12 μ m	25 μ m	60 μ m			
E. M Type											
+10062 ...	BD +4°696	190.0	-28.2	79.8	151.0	12.4	3.2	0.5	...	...	M3 II
+40105 ...	BD +43°1131	162.4	0.1	42.1	77.9	7.0	1.8	< 0.4	...	...	M2 Ib
+50138 ...	UX Aur	159.6	6.5	61.5	182.0	16.9	4.7	1.1	SRC	90	M4 II
+30115 ...	BD +29°897	177.0	-2.9	54.9	127.0	13.2	4.6	1.0:	...	...	M1 Ib
+20112 ...	CE Tau	187.2	-8.1	> 950	1630.0	145.0	46.4	7.0:	SRC	165	M2 Iab-Ib
+40133 ...	BD +41°1222	168.4	4.5	57.4	106.0	9.3	2.2	0.5	...	...	M2 II
+30124 ...	HR 1939	176.9	0.7	142.0	285.0	43.5	22.9	5.1	...	...	M2 Iab
+30129 ...	HR 2018	177.9	2.7	123.0	210.0	15.8	4.0	0.8	...	...	M4-IIab
+30131 ...	HR 2028	176.5	3.8	88.9	118.0	11.3	3.0	0.6	...	...	M2 II
+10100 ...	α Ori	199.8	-9.0	> 950	29300.0	4680.0	1740.0	299.0	SRC	2335	M2: Ia-Iab
+50156 ...	π Aur	166.6	10.9	> 950	1440.0	108.0	27.6	4.7	...	...	M3 II
+30137 ...	HR 2146	181.8	4.2	122.0	196.0	15.8	4.0	0.7:	...	...	M3 II
+20134 ...	TV Gem	189.1	1.6	121.0	253.0	96.1	41.2	6.1:	SRC	...	M0-1 Iab
+20135 ...	WY Gem	187.9	2.3	55.8	118.0	11.2	3.0	0.7	LC+E:	...	M2ep Iab+B
+20136 ...	BU Gem	188.2	2.2	131.0	258.0	78.2	47.6	10.5	LC	...	M1-2 Ia-Iab
+10116 ...	BD +5°1198	204.3	-4.2	34.7	76.4	6.8	1.9	0.4	...	...	M3 Ib-II
-10139 ...	HR 2508	220.5	-4.9	255.0	343.0	28.7	8.2	1.5:	...	...	M2 IIabS
00143 ...	BD -3°1694	217.5	0.7	55.8	87.8	6.8	1.8	0.5:	...	...	M1 Ib+A,B
-20118 ...	BD -20°1706	233.0	-6.5	37.5	53.9	4.6	1.1	< 0.4	...	...	M0 II
-30087 ...	VY CMa	239.4	-5.1	111.0	1190.0	9920.0	6650.0	1450.0	...	...	M5e Ia
-10169 ...	KQ PUP	230.7	2.5	367.0	618.0	52.1	13.8	2.3	LC	...	M2ep Iab+B
+10173 ...	HR 2967	205.6	17.5	213.0	337.0	25.2	6.5	1.1	...	...	M3+ IIbS
-20152 ...	BD -20°2302	238.7	4.5	43.1	93.6	76.9	50.7	7.9:	...	...	M2.5 Iab
-30115 ...	HR 3170	249.8	-0.7	314.0	478.0	45.1	14.2	2.3:	...	...	cM1
-10199 ...	RV Hya	234.8	18.9	151.0	383.0	76.8	40.3	5.8	SRC	116	M5 II
-10301 ...	BD -13°3845	331.3	44.5	87.9	155.0	14.7	4.3	0.6	...	...	M5 II
-30265 ...	α Sco	351.9	15.1	> 950	23300.0	3200.0	690.0	115.0	LC	...	M1.5 Iab
-30282 ...	AH Sco	353.1	4.3	129.0	469.0	630.0	350.0	73.3	SRC	714	M5 Ia-Iab
+10321 ...	BD +5°3352	26.8	24.4	19.7	44.4	2.3	0.5	< 0.4	...	...	M3 II
+10324 ...	α Her	35.5	27.8	> 950	15500.0	1510.0	428.0	83.8	SRC	...	M5 Ib-II
-30303 ...	...	356.2	0.2	2.7	49.1	24.1	15.5	< 17.4:	...	...	M2 Iab
-30304 ...	...	356.2	-0.2	9.1	54.9	25.4	16.5	< 39.9:	...	...	M3 Ia
-30305 ...	...	356.4	-0.3	4.5	62.4	50.0	36.6	< 24.6:	...	...	M3.3 Ib
-30312 ...	...	356.9	-0.7	72.7	104.0	102.0	69.3	15.7	...	...	M2.6 Ia-
-30320 ...	BD -28°13534	0.6	0.5	5.4	41.2	...	...	...	...	...	M2-4 I
-30322 ...	BD -28°13555	0.3	0.1	6.7	40.9	5.7	< 10.5	< 527.0	...	...	M1-3 I
-30326 ...	KW Sgr	1.5	-0.7	48.1	188.0	250.0	148.0	18.4:	SRC	670	M3 Ia
00328 ...	...	23.3	11.2	11.7	40.1	4.3	1.2	0.4	...	...	M4 I
-20405 ...	BD -23°13678	5.6	0.3	88.7	170.0	14.6	4.9	< 29.7:	...	...	M1 Ib
-30341 ...	HR 6693	0.4	-3.2	242.0	337.0	25.8	< 8.6	< 6.4	...	...	M2 Ib-II
-20409 ...	...	6.3	0.0	25.9	119.0	26.4	11.9	8.5	...	...	cM3:
-20429 ...	...	10.8	0.5	11.7	45.2	6.0	2.4	< 23.4:	...	...	M2 Iab-Ib
-20431 ...	VX Sgr	8.3	-1.0	144.0	886.0	2740.0	1380.0	263.0	SRC	732	M4e Ia
-20438 ...	BD +15° 4840	14.6	2.0	42.8	93.6	13.1	5.7	< 3.8	...	...	M1 Iab
-20449 ...	...	11.6	-0.7	15.7	47.4	7.7	8.3	< 14.7	...	...	M2.5 Ib
-10415 ...	FR Sct	18.5	0.3	11.4	87.0	10.1	2.9	< 25.2	ZAND	...	M3ep Ia:+O?
-10419 ...	...	17.8	-0.6	9.0	58.5	17.9	11.0	6.6	...	...	M2 Iab:
-10422 ...	UY Sct	19.1	-0.5	49.1	260.0	259.0	194.0	36.5	SRC	740	M4 Ia
-10435 ...	BD -14°5105	18.3	-2.5	50.5	129.0	34.9	18.3	5.3	...	...	M3 Iab
+40323 ...	XY Lyr	68.4	19.3	384.0	870.0	76.1	20.5	3.3	LC	...	M4-5 II
00371 ...	...	29.8	0.4	15.4	46.1	4.0	1.8	< 16.0	...	...	M3 I
+10384 ...	V913 Aql	42.8	4.2	117.0	299.0	23.7	6.5	1.3	SRA	50	M5 II
+40331 ...	δ^2 Lyr	66.9	15.3	> 950	1920.0	156.0	44.4	8.1	SRC	...	M4 II
00398 ...	UW Aql	34.0	-1.2	28.0	98.9	30.2	15.0	3.0	LC	...	M2 Ia-Iab
+10391 ...	V492 Aql	38.6	0.7	18.0	103.0	12.4	5.9	11.6:	LC	...	M2 Ia
00425 ...	BD -4°4781	32.2	-8.6	60.6	133.0	10.4	2.8	0.6	...	...	M0 II
+20399 ...	T Sge	52.0	1.5	145.0	779.0	140.0	65.7	11.8	SRB	166	cM3-4
-20565 ...	...	19.4	-17.0	28.7	52.4	14.1	7.9	1.4	...	...	M2 Ib
+20433 ...	δ Sge	55.8	-3.4	> 950	1460.0	102.0	25.7	4.5:	...	...	M2 II: +B:
+20438 ...	NR Vul	61.6	-0.7	27.8	130.0	106.0	58.8	12.3	...	...	M1 Ia
+40365 ...	HR 7568	72.8	5.7	179.0	353.0	30.4	8.9	1.2	...	...	M4 IIb
+30412 ...	BD +25°4097	64.0	-3.4	50.3	138.0	13.0	4.9	1.3:	...	...	M3-Ib
+40406 ...	...	74.2	-0.6	24.8	143.0	41.7	27.6	< 7.1	...	...	M3 Iab:
+40408 ...	BI Cyg	75.3	0.1	55.0	356.0	335.0	245.0	51.2:	LC	...	M4 Iab
+40409 ...	BC Cyg	75.8	0.4	75.1	539.0	< 424.0	< 1220.0	< 7420.0:	SRC	700	M4 Ia
+40415 ...	KY Cyg	77.0	0.2	40.8	487.0	511.0	330.0	50.7	LC	...	M3 Ia
+40424 ...	RW Cyg	78.7	0.7	83.8	380.0	298.0	190.0	60.7:	SRC	550	M3-4 Ia-Iab
+40427 ...	...	79.5	0.7	5.0	66.6	13.1	6.5	6.4	...	...	M0-2 I
+30438 ...	FG Vul	69.9	-7.2	24.7	73.7	6.9	2.0	0.7:	SRC	86	M5 II:
+40439 ...	...	79.3	-1.5	4.6	132.0	45.5	30.9	5.2:	...	...	M2-4 I
+20481 ...	U Del	63.0	-15.2	393.0	878.0	142.0	78.1	10.8	SRB	110	M5-6 II

TABLE 2—Continued

TMSS	OTHER NAME	<i>l</i> (degrees)	<i>b</i> (degrees)	FLUX DENSITY (Jy)					VARIABLE TYPE	PERIOD (days)	SPECTRAL CLASS
				0.9 μm	2.2 μm	12 μm	25 μm	60 μm			
E. M Type											
+40448 ...	NML Cyg	80.8	-1.9	5.5	356.0	...	...	...	...	...	M6 III
+50351 ...	AZ Cyg	87.0	0.5	62.0	214.0	...	...	...	SRC	459	M2-4 Iab
+60305 ...	BD +59°2342	98.7	8.0	200.0	554.0	54.2	28.8	6.9:	...	...	M2- Ib
+60313 ...	BD +58°2249	98.2	6.4	182.0	322.0	24.5	6.8	< 0.7:	...	...	M1ep Ib+B
+50374 ...	BD +48°3348	91.7	-0.3	77.6	237.0	20.5	6.7	2.2:	...	...	M5 II
+60317 ...	SW Cep	101.6	8.6	37.5	128.0	77.7	58.2	10.6:	SRC	70	M3.5 Ia-Iab
+60325 ...	μ Cep	100.6	4.3	> 950	3620.0	1300.0	608.0	127.0:	SRC	730	M2 Ia
+60333 ...	VV Cep	104.9	7.0	431.0	757.0	70.3	21.5	3.7:	EAGSSRC	7430	M2+ Ia-Iab
+60343 ...	AZ Cep	103.6	2.9	17.8	63.0	16.4	11.3	2.4	LC	...	M2 Ia
+50433 ...	5 Lac	99.7	-8.7	> 950	575.0	47.1	12.1	2.0	...	...	M0 Iab+B
+60357 ...	ST Cep	104.6	-0.8	42.9	120.0	55.0	36.0	7.4	LC	...	M2 Iab
+60361 ...	...	105.9	0.7	11.8	98.9	77.7	46.6	8.0	...	...	M1 Ia:
+50446 ...	U Lac	105.8	-3.6	37.4	134.0	124.0	61.5	9.0:	SRC	...	M4 Iab+B
+60367 ...	...	107.9	0.1	7.8	55.9	19.0	14.5	3.3	...	...	M2 Ib:
+60388 ...	GU Cep	111.1	0.7	11.9	49.1	7.8	4.0	2.2:	LC	...	M2 Iab
+50459 ...	SS And	108.0	-7.1	73.9	258.0	45.0	19.6	3.3:	SRC	153	M6 II
+60410 ...	V358 Cas	112.3	-3.2	23.0	91.1	83.7	69.3	12.5:	LC	...	M3 Ia-Iab
+60417 ...	PZ Cas	115.1	0.0	61.8	255.0	373.0	398.0	96.5	SRC	925	M2 Ib:
+60428 ...	TZ Cas	115.9	-1.1	34.2	134.0	75.1	51.8	9.5:	LC	...	M2 Iab
00535 ...	HR 9047	94.1	-59.5	300.0	524.0	44.7	11.4	1.9	...	...	M5 Iib

are of type M. Our criterion that a star lose mass is generally that

$$F_{\nu}(12 \mu\text{m}) > 0.10F_{\nu}(2 \mu\text{m}). \quad (1)$$

This criterion for the presence of circumstellar dust is discussed by Kleinmann, Jura, and Joyce (1989). While there may be stars that are losing mass without forming dust, in almost all cases that we know about, substantial mass loss is accompanied by dust formation. Additional evidence in support of this view is that all the supergiants listed in Table 4 (except ρ Cas) have values of $F_{\nu}(25)/F_{\nu}(12)$ which are much larger than those which we might expect from the Rayleigh-Jeans portion of the Planck curve and instead indicate the presence of circumstellar dust.

To investigate the completeness of our sample in the northern hemisphere ($81^{\circ} > \delta > -33^{\circ}$), in Table 2 we list all the stars of type A and later in the TMSS that have been classified optically (Bidelman 1980) as “supergiants.” We convert the *I'* photometry to the standard *I* band as described by Claussen *et al.* (1987), and we assume that $K = 0.0$ mag and $I = 0.0$ mag correspond to 620 and 2430 Jy, respectively (Beckwith *et al.* 1976; Johnson 1965). This table is most useful for developing a more comprehensive understanding of stars that are bright in the infrared. For example, it is possible to use this star and identify both the “normal” and “abnormal” objects such as ρ Cas (Jura and Kleinmann 1990).

In Table 3 we list that subset of stars in Table 2 that are candidate mass-losing red supergiants which we do not include in Table 1. Our criteria for including a star in Table 3 are the following: (1) The star was classified as a “supergiant” (Bidelman 1980); that is, it appears in Table 2. (2) Equation (1) is satisfied. (In fact, most of the red giant stars in the TMSS that obey this criterion are not listed in Tables 1–3. Instead, they are AGB stars, and many of them are listed in

Kleinmann, Jura, and Joyce 1989 for oxygen-rich types, in Claussen *et al.* 1987 for carbon-rich stars, and in Jura 1988 for S stars.) (3) We require $m_K < 2.0$, as expected for supergiants at distances within 2.5 kpc of the Sun.

The 35 stars in Table 3 are a mixed group. Some, like α Sco and α Her, are probably 10–20 M_{\odot} stars and have luminosities lower than $10^5 L_{\odot}$. Others may actually be AGB stars, since their periods are so short ($P < 150$ days; e.g., W Tri, V Eri, UX Ari, V913 Aql, U Del, and Sw Cep) that they are not likely to be extremely luminous (probably $L < 10^4 L_{\odot}$; Fox and Wood 1982). Unless the period is greater than 400 days, we assume that the star cannot have $L > 10^5 L_{\odot}$ even if it is classified optically as a supergiant. A few stars, such as RW Cep, are thought to have high luminosities but to be at distances greater than 2.5 kpc (Humphreys 1978). Also, if a star is of luminosity class II or III in the Bright Star Catalogue (Hoffleit and Jaschek 1982), we assume that $L < 10^5 L_{\odot}$. Finally, there are 15 stars for which we have insufficient information to determine whether they in fact have $L > 10^5 L_{\odot}$.

The data in Tables 1 and 3 provide bounds on the spatial distribution of M-type supergiants. From the 21 known supergiants within 2.5 kpc of the Sun that are listed in Table 1, we deduce a surface density of these stars of 1 kpc^{-2} . If we include all 15 potential supergiants listed in Table 3, the surface density of these stars could be as high as 2 kpc^{-2} .

Figure 1 shows a projection onto the Galactic plane of the mass-losing red supergiant stars in Table 1. Of the 21 stars in Table 1, somewhat more than half (13 out of 21; 62%) are in the hemisphere facing the Galactic center. The mean absolute distance from the Galactic plane of these stars is 64 pc, consistent with the view that they are extreme Population I objects. In contrast, Conti *et al.* (1983) and van der Hucht *et al.* (1988) both report 44 W-R stars within 2.5 kpc of the Sun, although they do not always agree on the distances of the stars, and in fact they have only 30 stars in common

TABLE 3
REJECTED TMSS RED STARS ($m_K < 2.0$ mag)

TMSS	Other Name	$(dM/dt)_{\text{IR}} (10^{-5} M_{\odot} \text{ yr}^{-1})$	z (pc)	Reason for Rejection
+50164.....	HR 2289	0.07	560	Insufficient information
+60353.....	RW Cep	...	...	Too far (3.5 kpc); Humphreys 1978
+60397.....	BD +61°2423	0.05	60	Insufficient information
+50052.....	XX Per	...	...	Period too short
+60087.....	RS Per	...	...	Period too short
+60090.....	BD +56°609	0.07	-110	Insufficient information
+60091.....	...	0.2	-2.3	Insufficient information
+60094.....	GP Cas	...	...	Luminosity too low
+30047.....	W Tri	...	...	Period too short
+60110.....	IO Per	...	...	Luminosity too low
+50089.....	...	0.1	-83	Insufficient information
-20049.....	V Eri	...	...	Period too short
+30115.....	BD +29°897	0.02	-100	Insufficient information
+30124.....	HR 1939	...	...	Luminosity class III
+20134.....	TV Gem	...	...	Luminosity too low
+20136.....	BU Gem	...	...	Luminosity too low
-10139.....	HR 2508	...	...	Luminosity class II
-10199.....	RV Hya	...	...	Period too short
-30265.....	α Sco	...	...	Luminosity too low
+10324.....	α Her	...	...	Mass too low (binary)
-20409.....	...	0.2	-0.2	Insufficient information
-10435.....	BD -14°5105	0.1	-86	Insufficient information
+40323.....	XY Lyr	...	...	Luminosity class II
+10384.....	V913 Aql	...	...	Period too short
+40332.....	HR 7139	...	...	Luminosity class II
+10391.....	V492 Aql	0.2	24	Insufficient information
+20438.....	...	0.2	-25	Insufficient information
+40406.....	...	0.1	-22	Insufficient information
+40424.....	RW Cyg	1.0	24	Insufficient information
+40439.....	...	0.1	-51	Insufficient information
+20481.....	U Del	...	...	Period too short
+60317.....	SW Cep	...	...	Period too short
+60357.....	ST Cep	0.1	-26	Insufficient information
+50446.....	U Lac	0.2	-123	Insufficient information
+50459.....	SS And	...	...	Period too short

between the two lists. In any case, in both papers, 38 stars are in the hemisphere facing the Galactic center (86%), while only six are in the anticenter hemisphere. Therefore, unless we have missed most of the M supergiants in the hemisphere facing the Galactic center, there is a substantial difference between the spatial distribution of the W-R stars and that of the M supergiants (see also Maeder, Lequeux, and Azzopardi 1980).

Of the 15 stars which are listed in Table 3 with "insufficient information" and which are therefore most likely to belong in the massive supergiant category, seven are in the hemisphere facing the Galactic center, while eight are in the opposite hemisphere. These numbers do not represent the true distribution of M supergiants because the TMSS samples about a factor of 2 more of the Galactic plane in the anticenter hemisphere compared with the hemisphere facing the Galactic center. Given the longitude coverage of the TMSS, it seems that again about 60% of the M supergiants that might belong in Table 1 are in the hemisphere facing the Galactic center. It does not seem likely that uncoun-

stars will lead to a great change in the apparent galactocentric gradient of M supergiants.

If we arbitrarily assume that all the stars listed in Table 3 are 2 kpc from the Sun, they might be mass-losing supergiants because their mean absolute distance from the Galactic plane is 86 pc. If we exclude the star farthest from the plane, +50164, the corresponding mean absolute distance is 57 pc.

III. MASS-LOSS RATES

We now estimate the mass-loss rates from these stars. We assume a constant outflow velocity and constant mass-loss rate in a spherically symmetric distribution. There are certainly stars, such as ρ Cas (Jura and Kleinmann 1990), where the mass loss is time-dependent. Also, the assumption of a single outflow velocity is not appropriate in all cases (Chapman and Cohen 1986). Finally, the assumption of spherical symmetry is inaccurate for at least some circumstellar shells, such as that around VY CMa (Herbig 1972).

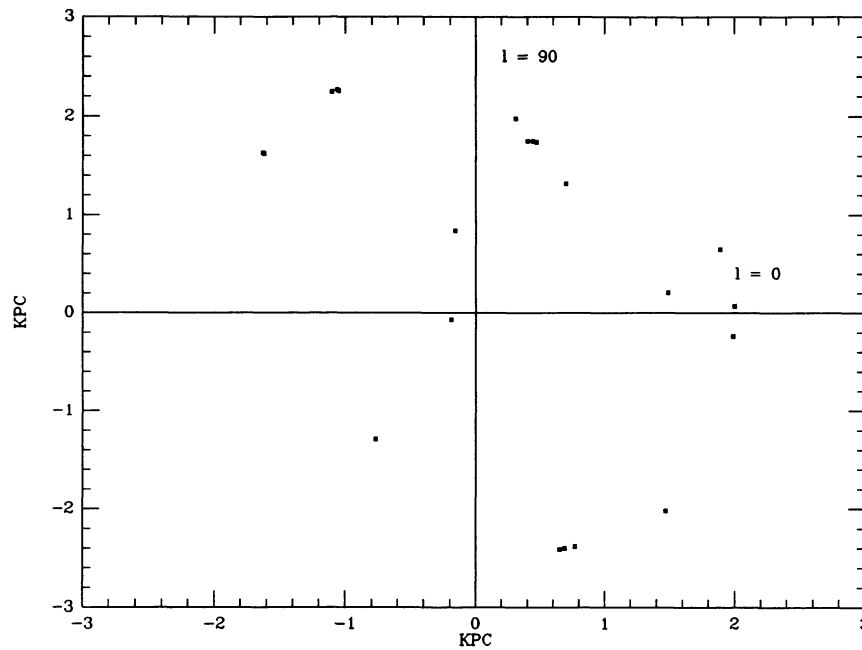


FIG. 1.—Plot of the spatial distribution of red supergiants from Table 1 projected onto the plane of the Milky Way. The Sun is located at the center of the plot.

As a first approximation, for most stars we assume that dust is associated with the mass loss and that the dust-to-gas ratio is the same in the red supergiants as it is for the AGB stars. Because the physical conditions in the red supergiants are different from those in AGB stars, this assumption may not be valid. Nevertheless, with this model, we can write (Jura, Joyce, and Kleinmann 1989)

$$dM/dt = 1.7 \times 10^{-7} v_{15} D_{\text{kpc}}^2 F_{\nu,60} (\lambda_{10}/L_4)^{1/2}, \quad (2)$$

where dM/dt ($M_{\odot} \text{ yr}^{-1}$) is the mass-loss rate, v_{15} is the outflow velocity (15 km s^{-1}), D_{kpc} is the distance (kpc), $F_{\nu,60}$ is the flux from the circumstellar dust envelope (Jy), λ_{10} is the average wavelength of the emitted light from the star and circumstellar shell (μm), and L_4 is the luminosity of the star ($10^4 L_{\odot}$). In the absence of other information, because these stars have high luminosities, we assume that $v_{15} = 2$ (Jura 1983), and using the *IRAS* fluxes, and the distances and luminosities given in Table 1, we derive mass-loss rates. We assume that all of the $60 \mu\text{m}$ flux is derived from the circumstellar dust.

The $60 \mu\text{m}$ fluxes for the sources in Table 1 were obtained by co-adding all of the available *IRAS* survey scans using the ADDSCAN program provided by the Infrared Processing and Analysis Center (IPAC). This method provided a means of checking whether any of the sources was significantly extended or confused with other objects; it also provided measurements for NML Cyg, which was not included in the *IRAS* Point Source Catalog (1985) because it was in a region scanned too few times by *IRAS* to have been included in the catalog. The ADDSCAN data indicate that both of the nearest stars in Table 1, α Ori and μ Cep, are significantly extended at $60 \mu\text{m}$ compared with the *IRAS* 1.5×4.7 beam

(Neugebauer *et al.* 1984). The ADDSCAN profiles for a few other stars in Table 1 differ from that expected for a point source, in the sense that other low-level, more diffuse emission is present. Since these stars are all more distant than α Ori and μ Cep, we have assumed that this diffuse emission is due to other nearby objects rather than to extended emission physically associated with each of these stars. The star BC Cyg is clearly confused with another source at 25 and $60 \mu\text{m}$, so its flux could not be estimated.

In Table 4 we also list values for the mass-loss rates that are derived by other arguments besides that given by equation (2). These other procedures for determining the mass-loss rate vary from star to star; they include using free-free radio emission, emission from molecules such as CO, and even other infrared techniques and are all normalized to the adopted distance. It can be seen that there is usually agreement between two different methods of determining the mass-loss rate to within a factor of 3 or 4. Two stars are markedly discrepant, α Ori and ρ Cas. As discussed by Jura and Kleinmann (1990), the dust-to-gas ratio in the circumstellar envelope around ρ Cas is probably much lower than in most M stars. For α Ori the dust-to-gas ratio may be unusually low, as suggested by the relatively low value of the gas outflow velocity (see Jura and Morris 1981; Glassgold and Huggins 1986).

We also make estimates for the mass-loss rates for the stars in Table 3 which are potential M-type supergiants. We apply equation (2) and use the $60 \mu\text{m}$ flux measured by *IRAS* and assume that all these stars are 2 kpc from the Sun, and that $v_{15} = 2$, $\lambda_{10} = 0.2$, and $L_4 = 10$. The inferred mass-loss rates are included in Table 3. Except possibly for RW Cep, none of the stars in Table 3 is apparently losing a large amount of mass.

TABLE 4
INFERRED MASS-LOSS RATES

Star	$F_{\nu}(12)/F_{\nu}(25)$	$F_{\nu}(60)$ (Jy)	v (km s ⁻¹)	$(dM/dt)_{\text{IR}}$ (10 ⁻⁵ M_{\odot} yr ⁻¹)	$(dM/dt)_{\text{other}}$ (10 ⁻⁵ M_{\odot} yr ⁻¹)	References
KW Sgr	0.59	18	...	0.4	...	
VX Sgr	0.50	263	30	4.0	1.0	1
UY Sct	0.75	37	...	0.7	...	
BD +24°3902	0.55	12	...	0.1	...	
BI Cyg	0.73	51	...	0.6	0.7	2
BC Cyg	?	?	...	?	0.7	2
KY Cyg	0.65	51	...	0.4	...	
NML Cyg	0.76	970	23	10	6-16	3, 4
μ Cep	0.47	166 ^a	10	0.09	0.085-0.64	5
ρ Cas	0.29	0.5	30	0.003 ^b	10	6
PZ Cas	1.07	96	27	1.0	1.1	7, 8
TZ Cas	0.69	9.5	...	0.3	...	
S Per	0.69	41	15	0.7	2.7	8, 9
SU Per	0.63	7	...	0.6	...	
α Ori	0.37	368 ^a	10	0.02	0.4	10
VY CMa.....	0.67	1450	39	10	23	3
EV Car	0.62	26	...	0.6	...	
CK Car	0.62	14	...	0.2	...	
IX Car	0.72	29	...	0.9	...	
V396 Cen	0.75	5.0	...	0.1	...	
AH Sco.....	0.56	73	...	0.8	...	

^aAs described in the text, these fluxes are from the ADDSCAN analysis, not the *IRAS* Point Source Catalog. The ADDSCAN fluxes for NML Cyg at 12, 25, and 100 μm are 5340, 4050, and 305 Jy, respectively.

^bSee Jura and Kleinmann 1990.

REFERENCES.—(1) Knapp *et al.* 1989; (2) Gehrz and Woolf 1971; (3) Bowers, Johnstone, and Spencer 1983; (4) Morris and Jura 1983; (5) Le Borgne and Mauron 1989; (6) Jura and Kleinmann 1989; (7) Netzer and Knapp 1987 (distance, however, unspecified); (8) te Lintel Hekkert *et al.* 1989; (9) Lane *et al.* 1987; (10) Glassgold and Huggins 1986.

The total mass-loss rate inferred from the infrared from all the stars in Table 4 is $3 \times 10^{-4} M_{\odot} \text{ yr}^{-1}$, which corresponds to a projected mass-loss rate of about $1.5 \times 10^{-5} M_{\odot} \text{ kpc}^{-2} \text{ yr}^{-1}$. This number is uncertain mostly because of the difficulties of establishing accurate mass-loss rates. (The net mass-loss rate from all the stars in Table 3 is only $3 \times 10^{-5} M_{\odot} \text{ yr}^{-1}$, a factor of 10 less than the sum from the stars that have been identified above as losing large amounts of mass.) If we use the higher mass-loss rates for all the stars listed in Table 4, the total mass-loss rate is $6 \times 10^{-4} M_{\odot} \text{ yr}^{-1}$. Therefore, we expect the total mass-loss rate from the stars in Table 4 is probably somewhere between 2×10^{-4} and $6 \times 10^{-4} M_{\odot} \text{ yr}^{-1}$; this implies that the mass-loss rate projected onto the Galactic plane is somewhere between 1×10^{-5} and $3 \times 10^{-5} M_{\odot} \text{ kpc}^{-2} \text{ yr}^{-1}$.

In contrast, the W-R stars return a total of about $6 \times 10^{-5} M_{\odot} \text{ kpc}^{-2} \text{ yr}^{-1}$. (There are about 2 W-R stars kpc^{-2} in the solar neighborhood, each of which returns about $3 \times 10^{-5} M_{\odot} \text{ yr}^{-1}$ of mass into the interstellar medium; Abbott 1982.) The W-R stars dominate the mass return from hot stars within the interstellar medium (Abbott 1982), and thus the total mass lost from W-R stars and M supergiants is somewhere near $8 \times 10^{-5} M_{\odot} \text{ kpc}^{-2} \text{ yr}^{-1}$. In the anticenter direction, M supergiants appear to dominate the return of mass to the interstellar medium, while in the center direction

the return is dominated by W-R stars. In the context of the discussion of Chioussi and Maeder (1986) described in § I, this could be the consequence of less mass loss from the anticenter stars. Since mass loss in early-type stars can be driven by radiation pressure on metal atoms, the anticenter stars, with a lower metallicity, may lose less mass and therefore are less likely to become W-R stars than are the supergiants that are closer to the Galactic center. Finally, the known mass-losing AGB stars in the solar neighborhood are returning between 3×10^{-4} and $6 \times 10^{-4} M_{\odot} \text{ kpc}^{-2} \text{ yr}^{-1}$ (Jura and Kleinmann 1989).

Unlike the W-R stars, there is a wide range (greater than a factor of 100) in the mass loss from the M supergiants, as is shown in Figure 2. We do not yet have any good theoretical explanation for this wide range in mass-loss rates.

It can be argued that mass loss from AGB stars is in part driven by radiation pressure on the grains that form in the circumstellar envelope (Jura 1986). The data for the M supergiants are also consistent with this hypothesis. For all the stars in Tables 1 and 2, we find that if v is the outflow velocity,

$$v dM/dt < L/c. \quad (3)$$

In the above equation L/c is the momentum available to drive the mass loss from the star.

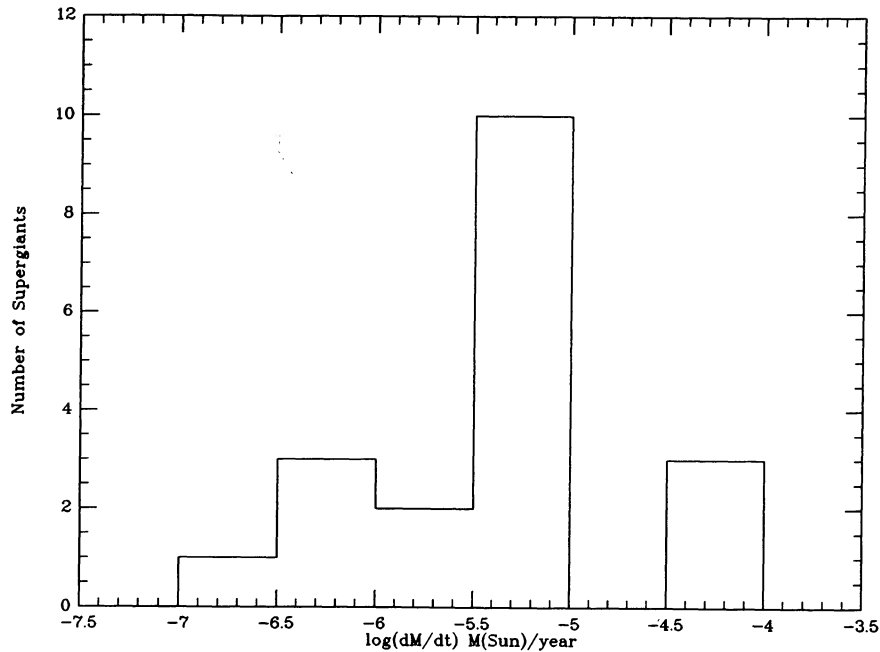


FIG. 2.—Histogram of the mass-loss rates derived from the infrared data (using eq. [2]) of red supergiants listed in Table 4, except for ρ Cas, which is of much earlier spectral type than the other stars and apparently has a much lower dust-to-gas ratio in its outflow.

IV. EVOLUTIONARY IMPLICATIONS

The rate of massive star formation given by Miller and Scalo (1979) requires that about $15 \times 10^{-5} M_{\odot} \text{ kpc}^{-2} \text{ yr}^{-1}$ is incorporated into new stars with $M > 20 M_{\odot}$. We expect that almost all of this material ultimately is returned to the interstellar medium. The W-R stars and M supergiants are returning $6 \times 10^{-5} M_{\odot} \text{ kpc}^{-2} \text{ yr}^{-1}$ and $2 \times 10^{-5} M_{\odot} \text{ kpc}^{-2} \text{ yr}^{-1}$, respectively, for a total of $8 \times 10^{-5} M_{\odot} \text{ kpc}^{-2} \text{ yr}^{-1}$ into the interstellar medium. Although uncertain, it seems that a significant fraction ($\sim 50\%$) of the mass incorporated into massive stars is returned to the interstellar medium by stellar winds.

Also, from Miller and Scalo (1979), it seems that the birthrate of stars with $M > 20 M_{\odot}$ in the solar neighborhood is about $5 \times 10^{-6} \text{ kpc}^{-2} \text{ yr}^{-1}$. Since we find a surface density of the M supergiant phase of these stars of between 1 and 2 kpc^{-2} , this implies that the M supergiants spend between about 2×10^5 and $4 \times 10^5 \text{ yr}$ in this phase. According to Table 2 of Chiosi and Maeder (1986), stars with initial solar masses of 25 and $40 M_{\odot}$ are predicted to have lifetimes in the He-burning phase with effective temperatures less than 6300 K of 4.6×10^5 and $1.2 \times 10^5 \text{ yr}$, respectively. Within the uncertainties, there is good agreement between the theoretical and the derived lifetimes.

With an average mass-loss rate of between 1×10^{-5} and $3 \times 10^{-5} M_{\odot} \text{ yr}^{-1}$, and a lifetime of perhaps $3 \times 10^5 \text{ yr}$, we

suggest that each star of initially at least $20 M_{\odot}$ loses perhaps $3\text{--}10 M_{\odot}$ in the M supergiant phase.

V. SUMMARY

Our results can be summarized as follows:

1. As found by previous authors, the surface density of luminous ($> 10^5 L_{\odot}$) M supergiants in the solar neighborhood is between 1 and 2 kpc^{-2} . The galactocentric gradient in the density of M supergiants is appreciably smaller than the similar gradient for W-R stars.

2. The total mass return rate from M supergiants is in the range $(1\text{--}3) \times 10^{-5} M_{\odot} \text{ kpc}^{-2} \text{ yr}^{-1}$. There is a wide range (more than a factor of 100) in the mass lost from individual M supergiants. In the solar neighborhood the W-R stars return more mass to the interstellar medium, but in the anticenter direction the mass loss from the M supergiants is greater than the mass loss from the W-R stars.

3. The duration of the M supergiant phase appears to be between 2×10^5 and $4 \times 10^5 \text{ yr}$. A star that is initially at least $20 M_{\odot}$ may lose between 3 and $10 M_{\odot}$ as an M supergiant.

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