Distribution of Giant M Stars in the Galactic Disk

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The space distribution of giant M stars is determined in the Groningen–Palomar variable star Fields 1, 2, and 4. Infrared spectroscopic techniques were used to detect and classify these stars to a distance of 8 kpc. Space densities are derived, and from these empirical formulas describing the galactic distribution of the giant M stars are established.

I. INTRODUCTION

THE distribution of giant M stars along the Milky Way shows that, in general, these stars are concentrated toward the galactic plane and that they are most frequently found close to the galactic center (Nassau and Blanco 1954; Wehlau 1954; Blanco and Münch 1955; Smith and Smith 1956; Sanduleak 1957; and Neckel 1958). These distribution features are particularly pronounced for the giant stars later than type M5. In clear regions the smooth variation in the number of these stars per unit area along the Milky Way suggests that they form part of the galactic disk population. The early giant M stars show concentrations at certain longitudes which suggest that these stars may form a part of a galactic spiral pattern.

In selected low-latitude regions, space densities for the giant M stars have been determined by Westerlund (1959a,b), by Albers (1962), and by McCuskey and Mehlhorn (1963). These studies support the findings based on surface distributions. In the present study, space densities of giant M stars are determined in three intermediate latitude regions each covering an area of five square degrees. The regions are located within the Groningen–Palomar variable star Fields 1, 2, and 4 (Plaut 1959). These fields have unusual interstellar transparency and are centered respectively at $l^{II}=0°$, $b^{II}=+29°$; $l^{II}=4°$, $b^{II}=+12°$; $l^{II}=82\overset{\circ}{.}0$, $b^{II}=+11\overset{\circ}{.}0$. Together with the similar regions previously investigated in detail at lower latitudes, these three fields form a useful network for a quantitative study of the salient features of the over-all galactic distribution of the giant M stars.

In order to determine space densities, one must secure photometric and interstellar absorption data, in addition to spectral classes. For the regions studied here, these data are discussed in Secs. II–V. The space density analysis is discussed in Sec. VI, and the results in Sec. VII.

II. OBSERVATIONAL MATERIAL

The Burrell–Schmidt-type telescope of the Warner and Swasey Observatory was used for this study. Spectra were obtained with a 4° objective prism attached to the telescope. Kodak IN plates exposed through a Schott RG 8 filter were used for the near-infrared spectral region from 6800 to 8800 Å. The dispersion at the atmospheric A band is 1700 Å/mm. Most of the infrared-sensitive spectral plates were hypersensitized in ammonia solutions prior to exposure. It was possible to segregate and classify M stars brighter than $I=13\overset{m}{.}0$. The I magnitudes used here are in the system of Kron, Gascoigne, and White (1957).

For determining spectral types to be used in evaluating space reddening Kodak IIaO plates were taken with the Schmidt telescope and the 4° objective prism. The dispersion obtained at Hγ is 280 Å/mm. These plates permitted the classification of photometric sequence stars to $B=12\overset{m}{.}0$.

For photometry, Kodak 103a-O plates were exposed through a Schott GG 13 filter, and 103a-D plates through a Schott GG-14 filter for the measurement of B and V magnitudes, respectively. I magnitudes were measured on nonhypersensitized Kodak 1N plates exposed through a Schott RG 8 filter. At least three plates were measured for determining each final magnitude. Field errors were minimized by securing the plates, as far as possible, in pairs with the telescope E and W of the piers, and by using photometric sequences located close to the measured stars.

III. SPECTRAL CLASSIFICATIONS

The Case system for spectral classification of M stars in the near-infrared spectral region has been described by Nassau and Velghe (1964). Systematic differences between this system and the Mt. Wilson classifications by Adams, Joy, and Humason (1926) have been evaluated by Blanco (1964). In the present study spectral types were assigned to the M stars after direct comparisons of their infrared spectra with similar spectra of selected stars classified by Adams, Joy, and Humason. The Mt. Wilson classifications do not extend beyond type M7. For such stars the criteria established by Nassau and Velghe were used.

M-type spectral images in all the fields were identified in three independent surveys. The numbers of M stars detected in each survey were used to estimate the degree of completeness of the surveys with methods described by van Gent (1933) and by Plaut (1965). It

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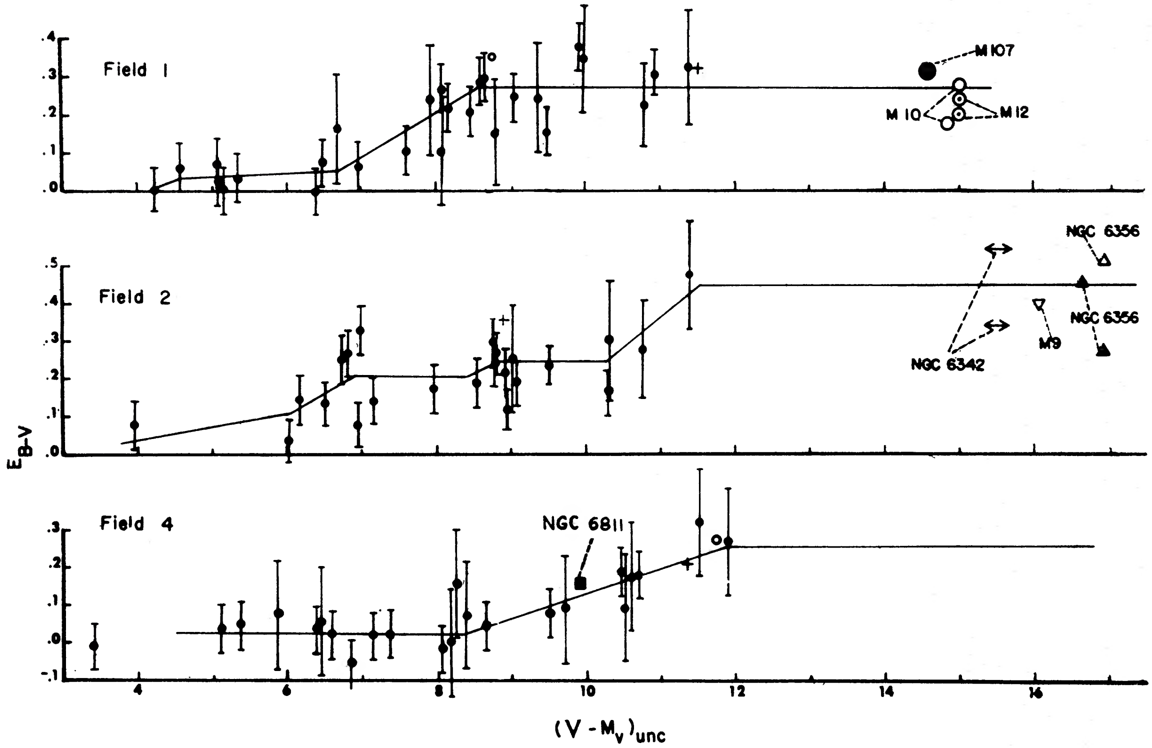

FIG. 1. Color excess E_{B-V} as a function of uncorrected distance modulus in Plaut Fields 1, 2, 4. Error bars indicate the estimated uncertainties in the plotted points. See text for further description.

was found that the surveys are essentially complete to $V=16^m0$ for stars of types M7 to M10, and to $V=15^m0$ for the earlier type stars.

In the low-dispersion spectra used in the present study, it is not possible to differentiate luminosity classes. However, the expectation of finding dwarfs, subgiants, and supergiants to the limiting magnitude of the present study is negligible (Blanco 1963). The dispersion also makes it difficult to recognize stars of classes M0 and M1. The surveys were therefore limited to class M2 or later.

For the determination of interstellar absorption, spectral types for the brighter stars in the photometric sequences were derived from the blue-sensitive plates by comparison with MK standard spectra.

IV. PHOTOMETRY

For the present study, Dr. Lukas Plaut kindly made available for all three fields unpublished photometric sequences established by photographic transfers, and photoelectric data for about 10 stars in each sequence obtained by Dr. J. Borgmann at the Lowell Observatory. Additional photoelectric data for stars in Dr. Plaut's sequences were made available by Dr. P. Wehinger and Dr. D. J. MacConnell. These data were obtained with the 16- and 36-in. telescopes at the Kitt Peak National Observatory. Photoelectric observations of additional stars in Field 4 were made with the 36-in. Cassegrain telescope at the Warner and Swasey Observatory. From these data, reliable photometric sequences in the UBV system extending to the 16th mag were established in all three fields. These sequences will be published elsewhere. From the B and V magnitudes I sequences were computed with the aid of the relationship between $B-V$ and $V-I$ colors determined by The (1960) and by Blanco (1964).

Photographic photometry was carried out with a modified Eichner astrophotometer. The probable errors achieved for the field stars for V, $B-V$, and $V-I$ are, respectively, $\pm 0^m07$, $\pm 0^m06$, and $\pm 0^m08$.

V. INTERSTELLAR ABSORPTION

A relationship between E_{B-V} and apparent distance modulus was established for each field by using the stars in the photoelectric sequences. The luminosity calibrations published by Blaauw (1963) were used here. The results are plotted in Fig. 1 with filled circles and probable error bars for the E_{B-V} estimates. These errors were computed by taking into account observational errors of $\pm 0^m02$ in V and $B-V$, and estimated intrinsic color errors of $\pm 0^m06$ for stars of types A, F, and G and $\pm 0^m15$ for later type stars. The latter are principally caused by spectral classification errors.

For a few sequence stars, color excesses were estimated from photometric data alone. The results for

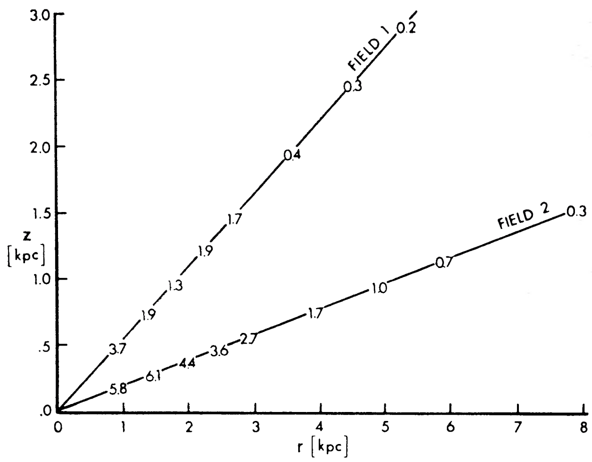

FIG. 2. Variations in space density of giant M2–M4 stars in Plaut Fields 1 and 2 with distance from the sun and with distance from the galactic plane. The numbers give the density, stars per 10^6 pc^3.

such stars are indicated in Fig. 1 by crosses. Color excesses and distance moduli for the stars HD 147117 and HD 188209 as published respectively by Roman (1955) and Bouigue, Boulon, and Pedoussaut (1961) are plotted with open circles in Fig. 1. These stars are close to Fields 1 and 4, respectively. The open cluster NGC 6811 is in the vicinity of Field 4. The color excess and distance modulus of this cluster as determined by Becker (1961) are also plotted in Fig. 1.

The photometric data described so far cannot be used to obtain color excesses for distance moduli greater than 12.0. In Field 1, the leveling off of interstellar absorption with increasing distance modulus observed at $(V-M_V)_{\rm unc}=9.0$ suggests that the line of sight has effectively penetrated beyond the galactic layer of absorption. This is supported by the color excesses and distance moduli of the neighboring globular clusters M107 (Sandage and Katem 1964), M10, and M12 (Kron and Mayall 1960) as shown in Fig. 1. For M10 and M12 the two sets of E_{B-V} and $V-M_V$ values discussed by Kron and Mayall are plotted separately. In the vicinity of Field 2 are found the globular clusters M9, NGC 6342, and NGC 6356 for which photometric data have also been published by Kron and Mayall, and a distance in the case of NGC 6342 by de Kort (1941). The data for these clusters are also plotted in Fig. 1, and they show that the total absorption levels off at modulus 12.0.

From the data plotted in Fig. 1, linear least-squares solutions were made of the E_{B-V}, $V-M_V$ relationship for various segments of the plots. The results are indicated in Fig. 1. The mean relationships thus obtained were then used to determine total absorption A_V as a function of true distance. The results are

TABLE I. Adopted absorption A_V in the direction of Fields 1, 2, and 4 (in magnitudes).

r (pc)	Field 1	2	4
0	.00	.00	.00
50	.00	.00	.08
100	.14	.25	.08
150	.17	.45	.08
200	.19	.63	.09
250	.47	.65	.09
300	.77	.65	.09
350	.83	.69	.13
400	.87	.74	.18
500	.92	.80	.28
750	.96	.83	.44
1000	.96	.95	.59
1500	.96	1.03	.79
8000	.96	1.05	.80

TABLE II. Number of M stars per 5 sq deg within $V\pm0^{m}.25$.

V	Field 1 M2–M4	Field 1 M5–M10	Field 2 M2–M4	Field 2 M5–M10	Field 4 M2–M4	Field 4 M5–M10
7.5	...	...	...	...	...	...
8.0	...	...	...	...	...	...
8.5	...	...	...	...	...	...
9.0	0.9	...	...	...	...	...
9.5	1.2	...	0.6	...	1.1	...
10.0	1.5	...	1.8	...	2.0	...
10.5	2.0	...	4.0	...	3.8	1.0
11.0	3.0	...	7.0	...	7.0	2.0
11.5	4.4	...	9.3	1.1	13.6	2.6
12.0	6.1	1.0	12.7	1.4	21.0	3.6
12.5	8.0	1.0	16.5	3.2	24.6	5.0
13.0	6.5	...	26.1	7.4	21.0	7.7
13.5	2.9	...	42.5	5.6	17.0	10.2
14.0	...	...	20.0	10.8	11.0	14.5
14.5	...	...	24.0	14.3	5.0	2.5
15.0	...	...	7.0	19.8	...	2.5
15.5	...	...	...	29.1	...	2.0

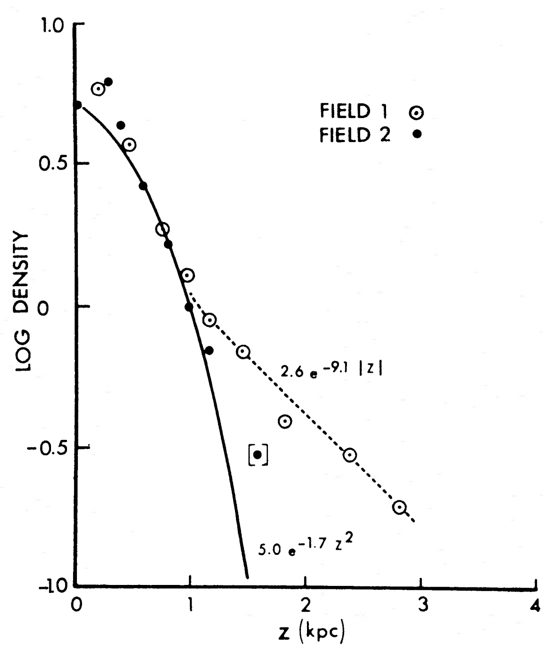

FIG. 3. Density gradient of giant M2–M4 stars perpendicular to the galactic plane, determined from data for Plaut Fields 1 and 2.

presented in Table I. The ratio A_V/E_{B-V} was assumed to be 3.2 in these computations.

VI. SPACE DENSITIES

Smoothed star counts according to V magnitude are presented in Table II. In view of the degree of completeness in the surveys, the scarcity of M giants in Field 1 where $b^{II}=+29.0°$ is striking. Comparison of the star counts in this field with those in Field 2, where $b^{II}=+12.0°$ indicates that the M giants show a moderate degree of galactic concentration.

For the computation of space densities, the absolute magnitudes adopted by Blanco (1965) were used after they were reduced to mean magnitudes per unit volume according to Malmquist's formula (1927).

Space densities were computed according to Schwarzschild's method as described by Bok (1937). The derived densities were corrected for effects of interstellar absorption. As a check on the computed densities, Malmquist's (1927) method of numerical density analysis was also applied. The two computations show very good agreement. The results obtained by Schwarzschild's method are presented in Table III.

VII. DISCUSSION OF RESULTS

A. Early-type M stars. Since Fields 1 and 2 are approximately in the longitude of the galactic center, it is instructive to plot the space densities found in these fields as a function of z, the distance from the galactic plane, and r, the distance from the sun toward the galactic center. For stars of type M2–M4 this plot is presented in Fig. 2. If the natural uncertainty in the density estimates nearest and farthest from the sun is taken into account, Fig. 2 suggests a plane-parallel distribution of stars extending approximately to a distance of 5 kpc from the sun.

Figure 3 presents for the M2–M4 group the logarithm of the space density as a function of z. For $z<1.0$ kpc the densities D, in both Fields 1 and 2 are fairly well represented by

$$D=5.0e^{-1.7z^2} \quad (z<1.0 \text{ kpc}), \tag{1}$$

where D is the number of stars per 10^6 pc^3. At $z=0$ this formula predicts 5/3 as many stars per unit volume as previously estimated by Blanco (1965) for the solar vicinity from the space distribution of the M giants listed by Adams, Joy, and Humason (1926). It is possible that Eq. (1) is not valid for relatively small z values. Another possibility is that in the solar vicinity there is a scarcity of giant M stars. A contributing factor to the discrepancy may be a systematic error in the classification of the earlier M stars in the present study. These stars are difficult to classify with precision and it is possible that a number of earlier stars were included in the group classified here as M2 to M4.

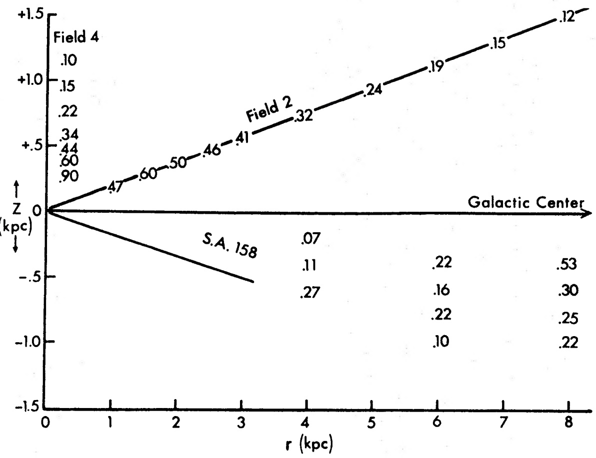

FIG. 4. Variations in space density of giant M5–M10 stars in Plaut Fields 2 and 4. Space densities for a field at $l^{II}=3.9°$, $b^{II}=-9°$ (McCuskey and Mehlhorn 1963) are also shown. The numbers give the density, stars per 10^6 pc^3.

Equation (1) also represents fairly well the variation of density with z in Field 4. This suggests that the plane-parallel distribution found for $z<1.0$ kpc in the galactic center direction holds also at $l^{II}=82°$.

Beyond $z=1.0$ kpc, Eq. (1) fails to represent the observed densities in Field 1. In this case, a better representation is obtained with

$$D=2.6e^{-0.91|z|} \quad (z>1 \text{ kpc}). \tag{2}$$

The over-all observed density distribution suggests that a polytropic relationship may hold between the observed densities and z. However, an attempt to fit the observations for all z values with an Emden function of index 5 showed that in order to fit the observed data excessively high densities had to be assumed at the galactic plane.

B. The late M stars. Figure 4 summarizes the space densities for the stars of type M5 or later, at various z and r values. No data for Field 1 are presented because of the scarcity of such stars in that region. Presented in Fig. 4 are density values obtained for a similar group of stars by McCuskey and Mehlhorn (1963) in the region of SA 158, which is south of the galactic equator ($l^{II}=3.9°$; $b^{II}=-9.0°$). The densities derived

TABLE III. Space densities of giant M stars (stars per 10^6 pc^3). Parentheses indicate uncertain values.

Distance (pc)	Field 1 M2–M4	Field 2 M2–M4	Field 2 M5–M10	Field 4 M2–M4	Field 4 M5–M10
750	...	...	...	...	...
1000	(3.7)	(5.8)	...	(1.3)	...
1500	1.9	6.1	...	3.1	.9
2000	1.3	4.4	.5	3.0	.6
2500	.9	3.6	.4	2.7	.4
3000	.7	2.7	.4	2.3	.3
4000	.4	1.7	.3	1.5	.2
5000	.3	1.0	.2	.9	.2
6000	.2	.7	.2	.5	.1
8000	...	(.3)	(.1)	...	...

here when compared with those obtained by McCuskey and Mehlhorn indicate that the late giant M stars are symmetrically distributed about the galactic plane. The results obtained at $r=8$ kpc by McCuskey and Mehlhorn suggest that at that distance, the density can be represented by relationships

$$D=1.9e^{-5.1z^2} \quad (z<0.5 \text{ kpc}) \tag{3}$$

and

$$D=0.6e^{-1.2|z|} \quad (z>0.5 \text{ kpc}). \tag{4}$$

The densities found here for the late M giants in Field 4, are satisfied for $z<1.0$ kpc by

$$D=1.0e^{-3.8z^2}. \tag{5}$$

Assuming that Eqs. (3) and (5) are valid, the space densities of the late giant M stars for $z=0$ are 1.0 near the sun, and 1.9 at 8 kpc in the galactic center direction. For the density distribution in the galactic disk at $z=0$, Allen (1954) has suggested a law of the form

$$D(R)=A/(R^2+B), \tag{6}$$

where R is the distance from the galactic center. From the data already presented, we find $A=202$ stars per 10^6 pc^3, $B=102$ kpc^2 if R is in kpc, and if we assume that R(sun)$=10$ kpc.

Equations (3) and (6) suggest that near the galactic nucleus the density of the late M giants may be represented for $z<0.5$ kpc by

$$D(R,z)=[202/(R^2+102)]e^{-5.1z^2}. \tag{7}$$

Arp (1965) has determined the surface distribution of field stars according to color and magnitude in the vicinity of the globular cluster NGC 6522 ($l^{II}=+1\overset{\circ}{.}0$, $b^{II}=-3\overset{\circ}{.}9$). Twenty-three stars with $(B-V)>2.10$ were found brighter than $V=16.5$ in an annular area whose inner and outer diameters are 52″ and 238″, respectively. From the total interstellar absorption determined by Arp all 23 stars are expected to be giant M stars of type M0 or later and to be located within 10 kpc from the sun. As a rough check on the space densities found in the present study, we assumed Eq. (7) to be valid throughout the line of sight within the area studied by Arp. Further, we assumed that the ratio between the space density of the M0 to M4 giants and that of the giants of type M5 and later is 29 as found by Blanco (1965), for the solar vicinity. A numerical integration based on Eq. (7) yields an expectation of 18 giant M stars, a figure that compares favorably with the observed number from Arp's study.

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