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LOCAL MASS DENSITY OF HALO STARS*

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ABSTRACT

From the kinematically unbiased sample of halo stars, the local mass density of halo dwarfs is estimated as $6.0 \sim 6.3 \times 10^{-4}$ $m_{\odot}/pc^3$ by adopting a color-magnitude relation and a mass-luminosity relation. The derived halo mass density is not much different from the results of previous studies, which were derived from the kinematically biased sample of halo stars. Therefore it is confirmed that the local mass density of halo stars is far less than that required by Ostriker-Peebles to stabilize the galactic disk against barlike instabilities.

I. INTRODUCTION

Subdwarfs are believed to be the local representatives of the oldest stellar objects, remnants of the earliest phase of the Galaxy formation. They provide the significant clues to the problems of galactic structure and dynamics as well as galactic evolution. Despite of these significance, the fraction of the mass of the Galaxy contributed by these halo stars is still very uncertain. The halo mass is of more than usual interest, since Ostriker and Peebles (1973) have suggested that a massive halo may be required to stabilize the galactic disk. So far the local mass density of halo stars has been estimated (Schmidt 1975; Weistrop 1975; Eggen 1979b, 1983) from the halo stars identified only on the basis of kinematic criteria, overlooking low-velocity metal poor stars. Therefore in this study, the local mass density of halo stars is attempted to derive from a sample of subdwarfs free of a kinematic bias.

A list of metal poor stars is published by Bidelman and MacConnell (1973) among their examples of the spectroscopically unusual stars in the southern hemisphere. Recent studies on the Bidelman-MacConnell "weak-metal" stars by Norris et al. (1985) as well as by Carney (1978, 1980) made it possible to sample out the halo dwarfs among them, adopting

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Eggen's criteria (1979a) for halo population stars. Therefore the local mass density from the sample of halo dwarf stars is estimated by adopting a color-magnitude relation and a mass-luminosity relation for halo stars.

II. LOCAL MASS DENSITY OF HALO STARS

a) Selection of Halo Stars

Bidelman and MacConnell (1973, hereafter BM) have published the early results of a "quick-look" through the southern hemisphere objective prism plates, identifying numerous examples of spectroscopically unusual stars. They are kinematically unbiased samples for many classes of stars, including metal-poor stars. Their survey covers approximately 81% of the southern hemisphere and is completed to 10 visual magnitude. However among the sample of metal-poor stars of BM stars, horizontal branch stars, red giants, subgiants, subdwarfs, a few blue stragglers, and even RV Tauri variables are included. Fortunately, Carney's (1978, 1980) UBV photometry and Norris et al.'s (1985) BVRI and DDO photometry for most of BM stars make it possible to seperate giants, subgiants, and dwarfs. Also the estimated metal abundance [Fe/H] and the derivation of $\delta_{0.6}(U-B)$ can segregate the halo stars from disk stars by adopting Eggen's criteria $[Fe/H] \leq -0.6$ for halo stars. In his discussion of a complete sample of high-velocity stars, Eggen (1979a) classified all objects with $[Fe/H] \leq -0.6$ as halo population objects, where $[Fe/H] = \log(Fe/H)_{*} - \log(Fe/H)_{\odot}$. This metallicty criterion corresponds to the normalized ultraviolet exess $\delta_{0.6} > 0.14$ at $(B-V) = 0.6$ according to the relation between stellar ultraviolet excesses and metal abundances derived by Carney (1979a).

On the basis of BVRI and DDO photometry for 309 of the 326 BM stars of Norris et al. (1985), their photometric taxonomy and metal abundance classify 52 stars as halo dwarfs. However, among them, BD $-12°$ 2669 is more likely to be a blue straggler because of its color $B-V=0.295$ and $U-B=-1.555$ as well as its spectral type of sdA5. And HD 219221 seems more likely to be disk star in spite of its metal abundance $[Fe/H] = -0.67$ estimated by Norris et al. (1985) because its ultraviolat excess $\delta_{0.6}=0.11$ and also another abundance $[Fe/H]=-0.56$, which has been derived from ubvy photometry by Eggen (1984). Accordingly the above two stars are excluded in our sample of halo dwarfs and the following three stars are added. HD 61902 and HD 105004 are not included in Norris et al.'s program, but their ultraviolet exesses $\delta_{0.6}$ are larger than 0.14. HD 208061 has $[Fe/H]=-1.16$ (Eggen, 1984) rather than $[Fe/H]=-0.43$ of Norris et al. (1985). However considering its spectral type of F3V and class of metal weakness "EXT" by BM, we take Eggen's (1984) value for metal abundance. Also V, $B-V$ data of Norris et al. (1985) are taken for this star in Table 1.

All 53 halo subdwarfs selected for the analysis of halo mass deensity are listed in Table 1 with their 1950's coordinates and V, $B-V$, and $U-B$ photometry data taken from

Carney (1978, 1980) except 5 stars from Norris et al. (1985). The ultraviolet excesses $\delta_{0.6}$ are derived and the metal abundances are taken from Norris et al. (1985) and the absolute magnitudes are estimated by the color-magnitude relation which is derived in next section.

b) The Color-Magnitude Relation

In order to get the distances of subdwarfs, a color-magnitude relation for halo dwarf stars has been derived from the subdwarfs with good trigonometric parallaxes and the main sequence stars of the globular clusters with known distances. The data for the trigonometric parallax of subdwarfs are adopted from the Table 1 of Carney (1979b) except HD 140283. The improved parallax data (Ianna and McAlister, 1974) of HD 140283 yield $M_v=5.11$ instead of $M_v=5.52$ of Carney (1979b). The data for four globular clusters (M3, M13, M15, and M92) are adopted from Sandage (1970) except the distance meduli and metal abundances of M3 and M92, which are from recent data of Sandage (1982). Eight subdwarfs with good parallax data and the main sequence points of M3 (open circles, $m_v-M_v=14.85$, $[Fe/H]=-1.69$), M13 (crosses, $m_v-M_v=14.42$, $[Fe/H]=-1.4$), M15 (triangles, $m_v-M_v=14.93$, $[Fe/H]=-2.1$), and M92 (squares, $m_v-M_v=14.36$, $[Fe/H]=-2.19$) are plotted and a fiducial line for halo stars are drawn by eye in the (M_v, $B-V$)-plane of Figure 1. Although the interstellar reddeing is corrected for globular clusters, the color $B-V$ of subdwarf is the observed one since most subdwarfs including sample stars are located within 150*pc* from the sun.

The average abundance [Fe/H] of eight subdwarfs and four globular clusters is -1.72 ± 0.41 and the average abundance of the subdwarfs listed in Table 1 is -1.23 ± 0.44. Therefore, the adopted fiducial line represents the color-magnitude relation for subdwarfs

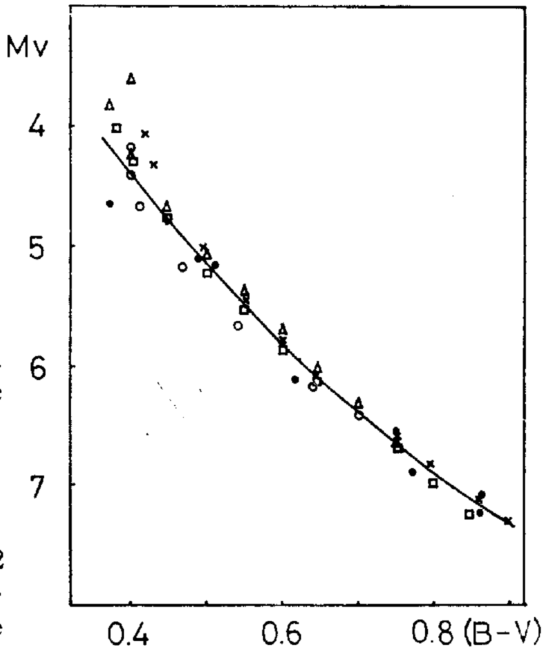

FIG. 1—The Color-Magnitude Relation. The filled circles represent subdwarfs with trigonometric parallaxes, the open circles, stars in M3($m_v-M_v=14.85$, $[Fe/H]=-1.69$), the crosses, stars in M13($m_v-M_v=14.42$, $[Fe/H]=-1.4$), the triangles, stars in M15 ($m_v-M_v=14.93$, $[Fe/H]=-2.1$), the squares, stars in M92 ($m_v-M_v=14.36$, $[Fe/H]=-2.19$). The continuous line is the adopted color-magnitude relation.

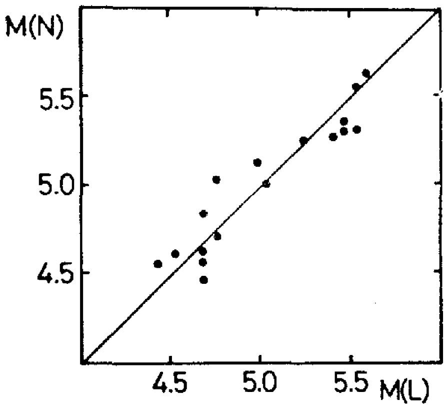

FIG. 2-The comparison between absolute magnitudes derived in the present work, $M_v(L)$, and that of Norris et al. (1985) $M_v(N)$.

with lower metal abundance than the sample of subdwarfs. The real line representing the sample of subdwarfs may be a little bit above the adopted fiducial line as long as a constant helium abundance is assumed for halo stars. Although Lee (1983) showed that the average difference in magnitude between Hyades main-sequence and a sequence of the high-velocity stars in the region between $B-V=0.4$ and 1.4 is $\sim 1^m.25 \pm 0.30$, the suitable correction is not available. The magnitudes estimated from this color-magnitude relation are compared with those of Norris et al. (1985) in Figure 2. The magnitudes by Norris et al. (1985) which are compared in Figure 2 are selected only for the case whose magnitude has been estimated by all three of their methods for a given star. The agreements are pretty good and the mean difference in magnitude is $\sim 0^m.11$. And also there seems to be no systematic trend at all which could be caused by using a systematically lower fiducial line in the $(M_v,\ B-V)$ plane. Therefore the fiducial line shown in Figure 1

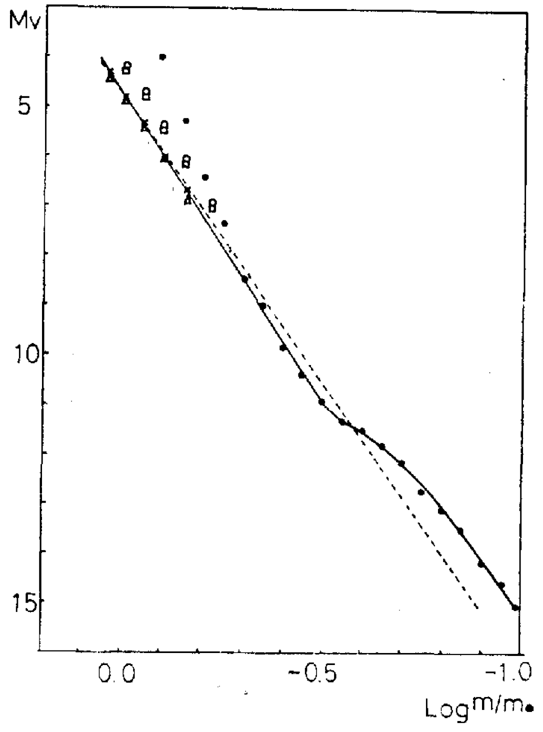

FIG. 3-The Mass-Luminosity Relation. The filled circles represent a mass-luminosity relation for $Y=0.25$ and $Z=0.001$ from Gunn and Griffin (1979). The crosses ($Y=0.2$, $Z=0.0001$), the open circles ($Y=0.3$, $Z=0.0001$), the triangles ($Y=0.2$, $Z=0.001$), and the squares ($Y=0.3$, $Z=0.001$) are from VandenBerg (1983). The dashed line represents disk stars and the solid line is an adopted one.

is used for the derivation of the absolute magnitudes in Table 1.

c) The Mass-Luminosity Relation

To calculate the mass density, a mass-luminosity relation for halo stars should be applied. However all known mass-luminosity relations for hlao stars are model-based and somewhat differ from each other, as shown in Figure 3. The filled circles are representing a mass-luminosity relation for $Y=0.25$ and $Z=0.001$, adopted from the table III of Gunn and Griffin (1979) and the crossess ($Y=0.2$, $Z=0.0001$), the open circles ($Y=0.3$, $Z=0.0001$), the triangles ($Y=0.2$, $Z=0.001$), and the squares ($Y=0.3$, $Z=0.001$) are from VandenBerg (1983). The dashed line which represents a mass-luminosity law for disk stars is given by the relation $M_v=4.8-11.4\log m/m_\odot$. (Schmidt 1975), and this coincides well with the stars of $m\sim 1m_\odot$ and $Y=0.2$ of VandenBerg (1983).

Considering that helium abundance of subdwarfs has been estimated as $Y=0.19\pm 0.04$ by Carney (1979b) and the brightness of a dwarf depends strongly on the helium abundance for low metal stars of a given mass shown in Figure 3, we adopt a solid-line in Figure 3 as a mass-luminosity relation for halo stars. However it's fainter portion ($M_v\geq 11$) is just that of Gunn and Griffin's (1979), although their case is for $Y=0.25$ and $Z=0.001$.

d) The Mass Density of Halo Stars

Adopting the color-magnitude relation shown in Figure 1, we have estimated the stellar absolute magnitudes and distances of the sample stars of Table 1. Since the survey of BM stars is completed up to 10 visual magnitude, the stars in the absolute magnitude bin of $M_v=4$, 5 and 6 are completely surveyed up to the distance of 125, 79 and 50 parsec respectively. Table 2 lists the number of observed stars within the distance limit for each absolute magnitude bin, N_{obs} (d_{lim}) and the estimated luminosity function for the sample of halo stars, corrected for the missing survey area of the sky. Since this observed luminosity function covers only stars of $M_v=4\sim 6$, the fainter portion ($M_v\geq 7$) of the luminosity function should be adopted. However Eggen (1983) has derived a halo luminosity function from the kinematically selected sample of high-proper-motion stars. Nontheless his halo luminosity function agrees fairly well with the results of present study around $M_v=5$ and 6. Therefore we adopted his halo luminosity function by normalizing at $M_v=5$ for the fainter portion of the luminosity function.

Adopting the mass-luminosity relation of previous section, the mass density of the halo stars fainter than $M_v=+4$ is estimated as $4.8\times 10^{-4}\ m_\odot/\mathrm{pc}^3$. However the photometric data does not cover the all BM stars, a correction, $\sim 5\%$, should be added. And also for the binary frequency among the halo stars, Carney (1983a, b) found as high as $20\%\sim 25\%$. Being corrected for unobserved stars ($\sim 5\%$) and for binary stars ($20\%\sim 25\%$), the local halo mass density of $6.0\sim 6.3\times 10^{-4}\ m_\odot/\mathrm{pc}^3$ is estimated.

TABLE 1. Sample of Subdwarfs

HD	α (1950)		δ		V	$B\text{-}V$	$U\text{-}B$	$\delta_{0.6}$	[Fe/H]	M_v
3567	00	36.5	−08	50	9.25	0.46	−0.15	0.18	−0.82	4.83
7983	01	14.1	−09	27	8.90	0.59	−0.02	0.14	−0.78	5.73
BD-10°388	01	45.6	−09	52	10.37	0.41	−0.19	0.24	−2.05	4.45
11569	01	48.4	−72	27	9.02	0.37	−0.15	0.21	−1.10	4.16
BD-14°363	01	51.7	−14	40	9.69	0.62	0.15	0.00	−0.72	5.92
13889	02	10.1	−42	11	9.57^a	0.55^a	—	—	−1.12	5.46
15395	02	23.5	−54	59	9.44^a	0.56^a	—	—	−1.42	5.54
BD-17°484	02	26.7	−17	26	10.48	0.43	−0.20	0.24	−1.28	4.60
16031	02	29.4	−12	49	9.78	0.44	−0.22	0.26	−1.79	4.68
22879	03	35.3	−03	32	6.70	0.54	−0.08	0.16	−1.00	5.40
31128	04	48.1	−27	13	9.12	0.49	−0.19	0.24	−1.71	5.04
34328	05	11.5	−59	46	9.43	0.48	−0.20	0.25	−1.69	4.98
CD-48°1741	05	15.7	−48	58	10.65	0.52	−0.19	0.26	−1.36	5.26
38510	05	41.2	−27	02	8.25	0.50	−0.09	0.13	−0.92	5.12
CD-33°3337	06	51.2	−33	37	9.07	0.48	−0.15	0.19	−1.12	4.98
59392	07	24.6	−37	47	9.72	0.45	−0.205	0.24	−0.97	4.75
61902	07	36.3	−50	50	8.24	0.47	−0.11	0.15	—	4.90
74000	08	36.2	−15	58	9.66	0.405	−0.24	0.30	−2.03	4.41
78747	09	04.7	−50	04	7.73	0.56	−0.06	0.16	−0.92	5.54
91345	10	27.6	−71	03	9.05	0.555	−0.10	0.18	−1.30	5.50
97320	11	06.9	−64	52	8.19	0.45	−0.18	0.21	−1.01	4.75
99383	11	21.0	−38	19	9.11	0.44	−0.225	0.26	−1.70	4.68
102200	11	40.6	−45	30	8.77	0.44	−0.21	0.25	−1.22	4.68
105004	12	00.3	−26	01	10.40	0.54	−0.10	0.17	—	5.40
106411	12	09.3	−43	32	9.30	0.55	−0.06	0.15	−0.64	5.46
108405	12	22.1	−47	34	9.30	0.57	−0.06	0.16	−1.06	5.60
110621	12	38.3	−44	07	9.93	0.47	−0.16	0.20	−1.38	4.90
111971	12	47.9	−57	07	8.05	0.50	−0.10	0.14	−0.81	5.12
111980	12	48.0	−17	57	8.38	0.53	−0.11	0.18	−0.83	5.32
113083	12	56.1	−26	50	8.05^a	0.54^a	—	—	−0.83	5.40
116064	13	16.1	−38	47	8.83	0.44	−0.22	0.26	−1.78	4.68
122196	13	55.2	−37	33	8.76	0.45	−0.18	0.21	−1.17	4.75
132475	14	54.2	−21	36	8.55	0.55	−0.12	0.20	−1.00	5.46
CD-33°10593	15	28.0	−33	36	9.56	0.50	−0.08	0.12	−0.85	4.70
140283	15	37.7	−10	36	7.21	0.49	−0.20	0.24	−2.21	5.04
152924	16	51.2	−64	24	8.05	0.45	−0.10	0.12	−0.64	4.75
160617	17	35.8	−40	15	8.74	0.44	−0.19	0.22	−1.66	4.68
166913	18	07.6	−59	26	8.23	0.44	−0.16	0.19	−1.46	4.68

HD	α (1950)		δ		V	B-V	U-B	$\delta_{0.6}$	[Fe/H]	M_v
175606	18	51.0	−51	35	9.78	0.47	−0.23	0.27	−1.86	4.90
181743	19	16.5	−45	14	9.69	0.45	−0.24	0.28	−1.96	4.75
188031	19	46.8	−43	36	10.12	0.42	−0.26	0.31	−1.56	4.53
192718	20	11.2	−07	44	8.40	0.57	0.00	0.10	−0.87	5.60
BD-22°5393	20	14.1	−22	26	10.23	0.61	0.03	0.11	−0.74	5.86
196892	20	35.1	−19	08	8.25	0.50	−0.15	0.20	−0.93	5.12
CD-30°18140	20	38.0	−30	21	9.97	0.42	−0.23	0.28	−1.73	4.53
CD-48°13714	20	47.1	−48	36	10.71	0.49	−0.13	0.16	−0.81	5.04
205156	21	28.3	−50	13	8.14	0.62	−0.01	0.16	−0.98	5.92
208061	21	48.5	−48	15	9.68^a	0.68^a	—	—	−1.16^b	4.56
213657	22	27.9	−42	33	9.65	0.41	−0.23	0.28	−1.71	4.45
215801	22	42.6	−46	35	10.05	0.44	−0.20	0.24	−1.97	4.68
217515	22	56.1	−18	51	9.43	0.35	−0.09	0.14	−0.82	4.00
218810	23	05.8	−30	32	8.42	0.39	−0.12	0.16	−0.65	4.32
222766	23	38.9	−62	28	10.15^a	0.69^a	—	—	−0.90	6.29

a. Photometric data from Norris et al. (1985)
b. abundance data from Eggen (1984)

TABLE 2. Luminosity Function and Mass Density for Halo Stars

M_V	$N_{obs}(d_{limit}$ pc)	log $\phi_{M_v}+10$	$m_\odot/10^6$ pc^3
4	5 (125 pc)	4.18	1.2
5	24 (79 pc)	5.46	28.0
6	4 (50 pc)	5.28	15.4
7	—	5.74	36.8
8	—	5.75	30.9
9	—	6.07	54.1
10	—	6.19	58.9
11	—	6.35	71.6
12	—	6.41	54.0
13	—	6.41	41.1
14	—	6.54	45.1
15	—	6.64	41.7

III. DISCUSSION

In a study of proper motion stars, Eggen (1983) estimated the mass density of halo stars fainter than $M_v=4$, which is $7.5\times10^{-4} m_\odot/\mathrm{pc}^3$ including $2.4\times10^{-4}\ m_\odot/\mathrm{pc}^3$ contributed by white dwarfs. To get the stellar luminosity function he adapted the method formulated by

Schmidt (1968) for quasar statistics and later adapted to the stellar luminosity function (Schmidt 1975). However Eggen's halo luminosity function at $M_v=5.5$, which is log $\phi_{M_v=5.5}+10=5.58$, agrees fairly well with the result of present study, which is log $\phi_{M_v=5}+10=5.46$. But Eggen adopted the model-based mass-luminosity relation of Gunn and Griffin (1979), which is fairly different from the results of VandenBerg (1983) for stars brighter than $M_v=8$, as seen in Figure 3. Therefore more proper mass-luminosity relation has been adopted in this study. But our result of halo mass density was utilized for the fainter portion of Eggen's halo luminosity function by normalizing at $M_v=5$. Therefore the halo mass density derived from kinematically unbiased sample of this study slightly depends on the halo luminosity function of Eggen (1983) which is based on the high-proper-motion stars. Although the present study is based on the kinematically unbiased sample of halo stars, it is difficult to conclude that the result of the halo mass density is completely kinematically unbiased. However our result for local halo mass density would be the one, least affected by the kinematical selection effects, so far.

Schmidt (1975) has derived the local mass density of halo stars $\sim 1.7\times10^{-4} m_\odot/\mathrm{pc}^3$ from a study of high velocity stars, which is less than 1/3 of the present result. The fundamental difference from the present study is the criterion used for halo stars. He selected halo stars on the basis of the tangential velocity larger than 250km/s, which is the median value for RR Lyrae stars with ΔS larger than 5. This is effectively selecting stars with $[\mathrm{Fe/H}]\leq-1$, whereas our adopted criterion is $[\mathrm{Fe/H}]\leq-0.6$. For the criterion, $[\mathrm{Fe/H}]\leq-1$ (or $\delta_{0.6}\geq0.20$), the mass density of halo stars is estimated as $3.6\sim3.8\times10^{-4} m_\odot/\mathrm{pc}^3$, after applying corrections for missing photometry stars and binary stars among halo stars. This result is still more than two times of the result of Schmidt (1975). And the distribution of the metal abundances of globular closters prefers the dividing criterion of $[\mathrm{Fe/H}]\leq-0.6$ between halo and disk stars.

Therefore we conclude that from this study, the local mass density of halo stars is estimated as $6.0\sim6.3\times10^{-4} m_\odot/\mathrm{pc}^3$, which is the result least affected by any kinematic bias, at present. However this result is far less than the densities required by Ostriker-Peebles for the stable disk of Galaxy.

REFERENCES

Bidelman, W.P., and MacConnell, D.J. 1973, A.J., **78**, 687.
Carney, B.W. 1978, A.J., **83**, 1087.
Carney, B.W. 1979a, Ap. J., **233**, 211.
Garney, B.W. 1979b, Ap. J., **233**, 877.
Carney, B.W. 1980, A.J., **85**, 38.
Carney, B.W. 1983a, A.J., **88**, 610.
Carney, B.W. 1983b, A.J., **88**, 623.
Eggen, O.J. 1979a, Ap. J., **229**, 158.

Eggen, O.J. 1979b, Ap. J., **230**, 786.
Eggen, O.J. 1983, Ap. J. Suppl., **51**, 183.
Eggen, O.J. 1984, A.J., **89**, 1878.
Gunn, J.E., and Griffin, R.F. 1979, A.J., **84**, 752.
Ianna, P.A., and McAlister, H.A. 1974, A.J., **79**, 1314.
Lee, S-G. 1983, J. Korean Astron. Soc., **16**, 23.
Norris, J., Bessell, M.S., and Pickles, A.J. 1985, Ap. J. Suppl., 58, 463.
Ostriker, J.P., and Peebles, P.J.E. 1973, Ap.J., **186**, 467.
Sandage, A. 1970, Ap. J., **162**, 841.
Sandage, A. 1982, Ap. J., **252**, 553.
Schmidt, M. 1968, Ap. J., **151**, 393.
Schmidt, M. 1975, Ap. J., **202**, 22.
VandenBerg, D. 1983, Ap. J. Suppl., 51, 29.
Weistrop, D. 1975, A.J., **80**, 303.