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ASTRONOMY AND ASTROPHYSICS
9.7.1997

Halo stars in the immediate solar neighbourhood*

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Received; accepted

Abstract. We have searched the Fourth Catalogue of Nearby Stars for halo stars and identified 15 subdwarfs and a high velocity white dwarf in the solar neighbourhood. This search was motivated mainly by the recent determinations of MACHO masses of about $0.5\mathcal{M}_\odot$, which are typical for halo dwarfs. The local mass density of these stars is $1.5{\cdot}10^{-4}$ $\mathcal{M}_\odot$ pc^{-3}, which is only 3% of the current estimate of the local mass density of the MACHO population. We compare the local density of subdwarfs with constraints set by HST observations of distant red dwarfs. Using models of the stellar halo with density laws that fall off like $r^{-\alpha}$, $\alpha = 3.5$ to 4, we find that the HST constraints can only be matched, if we assume that the stellar halo is flattened with an axial ratio of about 0.6. The non–detection of the analogues of MACHOs in the solar neighbourhood allows to set an upper limit to the luminosity of MACHOs of $M_{\rm B} > 21$ magnitudes.

Key words: Galaxy: halo – Galaxy: solar neighbourhood – Galaxy: structure – Cosmology: dark matter

1. Introduction

The stellar halo of the Galaxy has been studied with renewed interest since the MACHO (Alcock et al. 1996) and EROS (Ansari et al. 1996) collaborations have reported results of their campaigns of observing microlensing events towards the LMC. These indicate that MACHOS have masses typically of half a solar mass and contribute about one half to the mass budget of the halo of the Milky Way. Such masses are typical for red and white dwarfs, implying that MACHOs might possibly be members of the stellar halo instead of the dark halo of the Galaxy, as was previously thought. Bahcall and collaborators (Bahcall et al. 1994, Flynn, Gould & Bahcall 1996, Gould, Bahcall & Flynn 1997) have made by very deep star counts based on HST data *in situ* measurements of the space density of such stars in regions, where the microlenses are expected to be physically located. Their conclusion is that halo dwarfs contribute only a few percent to the mass of the halo and are thus unlikely MACHO candidates. Graff & Freese (1996) infer from the same data that the local mass density of halo dwarfs is even less than one percent of the combined local densities of the dark and stellar halos.

On the other hand, halo dwarfs are directly observed in the solar neighbourhood. Liebert (1995) discusses the results of the USNO parallax programme for red dwarfs and finds that the number of halo dwarfs in that sample is consistent with the HST data. We have followed a complementary approach. Recently the Third Catalogue of Nearby Stars (CNS3) has been completed at the Astronomisches Rechen-Institut (Jahreiß & Gliese 1997) and, after HIPPARCOS (ESA 1997) parallaxes and proper motions have become available, is presently updated to the Fourth Catalogue of Nearby Stars (CNS4; Jahreiß & Wielen 1997). This provides the now most complete inventory of the solar neighbourhood up to a distance of 25 pc from the Sun and allows a new determination of the local density of halo stars. Preliminary results based on the CNS3 have been reported by Fuchs & Jahreiß (1997).

2. Subdwarfs in the CNS4

We have searched the CNS4 for halo dwarfs. These reveal themselves by their position on the subdwarf sequence in the colour-magnitude diagram (CMD), their low metallicity, and their high space velocities. Unfortunately, there is in this metallicity range a broad overlap of the comparatively few halo stars and the much more abundant thick disk stars. We have therefore adopted a very conservative search strategy in order to isolate a true halo population, even if this will lead to an undersampling of the halo population. We have examined first the stars on the subdwarf sequence, which can be clearly seen in the CMD shown in Fig. 1. The reliability of the photometry and the parallaxes of each star has been checked carefully, which led to the omission of quite a number of stars with

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* Based in part on observations made with the ESA Hipparcos astrometry satellite

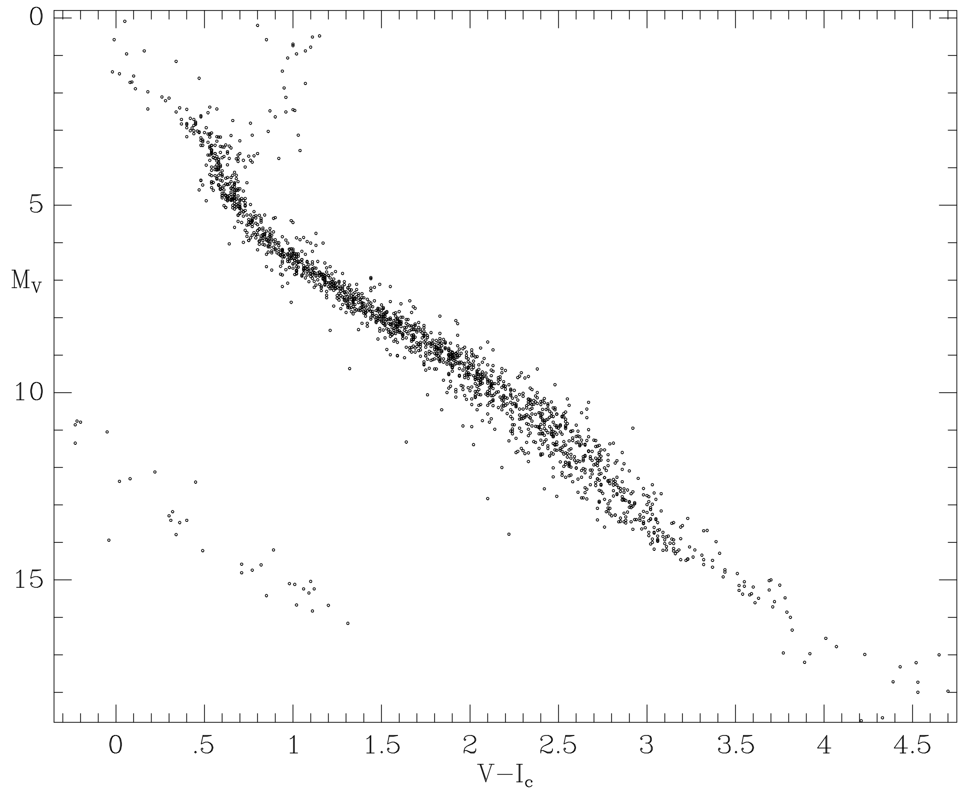

Fig. 1. Colour–Magnitude diagram of nearby stars with $\sigma_{M_V} \leq 0.3$ mag.

inaccurate parallaxes. In this way we identified LHS 2815, Gl 191, Gl 781, WO 9722 = LHS 64, GJ 1062, LHS 3409, and LHS 375 as likely halo stars. A number of stars in the CNS4 are classified as subdwarfs by their spectral type. This enables us to search for subdwarfs in that part of the CMD, $V - I < 1.5$, where the subdwarf sequence comes very close to the main sequence. We include GJ 1064A+B and Gl 53A+B into our list on the basis of this criterion. All stars, with the exception of LHS 2815, have decidedly large space velocities (cf. Table 1 and Fig. 2). In addition to these stars we found 5 stars, Gl 158, Gl 299, Gl 451A, WO 9371 = LHS 42 and the white dwarf Gl 699.1 (spectral type DA7), which do not lie very prominently on the subdwarf sequence, but have space velocities, which clearly identify them as halo stars.

All the stars in our list have very low metallicities. Leggett (1992) has determined the metallicities of a large number of nearby M dwarfs from their position in the $(J - H) - (H - K)$ infrared-colour diagram. According to that determination Gl 191, Gl 781, GJ 1062, and Gl 299 have metallicities [Fe/H] < -1 dex. LHS 375 has been classified as a cold subdwarf by Ruiz and Anguita (1993). The metallicities of Gl 53A, Gl 158, Gl 451, and GJ1064A, B have been taken from the compilation by Taylor (1994). Reid et al. (1995) have classified GJ 1062, Gl 781 [1], WO 9722, and LHS 3409 as likely subdwarfs on the basis of their spectra. Similarly, Gizis (1997) has classified WO 9371 as a subdwarf. Jones et al. (1996) confirm the low metallicity of Gl 299. The metallicity of LHS 2815 has been determined by Axer, Fuhrmann & Gehren (1994). There are many apparently low metallicity stars in the catalogue, which must be thick disk stars. For instance Leggett (1992) has assigned to 20 stars in the CNS4 a metallicity of [Fe/H] < -1 dex, of which only 4 have been finally included in our sample.

In Table 1 we give the list of stars selected out of the CNS4 as described above, of which we are now reasonably certain that they are genuine halo stars. The velocity components of the subdwarfs given in columns 6 to 8 in Table 1 are referred to the Sun. In order to reduce them to the LSR the solar motion $(U, V, W)_\odot = (+9, +12, +7)$ km/s has to be added. Note that U points towards the galactic center. The velocity distribution of our sample is shown as a Toomre diagram in Fig. 2. It is consistent with a distribution centered on V = –220 km/s. No clustering near V = –40 km/s, which would indicate a contamination by thick disk stars, is detected. The dispersion of $\sqrt{U^2 + W^2}$ is 155 $\pm$ 30 km/s, which is within statistical errors consistent with other determinations (Layden 1995)

[1] Gl 781 is a variable star and shows H_α emission. However, it is a spectroscopic binary, which, in our view, accounts for this phenomenon.

Table 1. Subdwarfs in the CNS4.

	d [pc]	M_V [mag]	$V-I_c$ [mag]	U	V [km/s]	W	[Fe/H] [dex]	$\mathcal{M}$ [$\mathcal{M}_\odot$]
Gl 191	3. 9^H	10.89	1.98	20	–288	–53	< -1	0. 2
Gl 299	6. 8	13.65	2.92	107	–126	–49	< -1	0. 1
Gl 53A	7. 6^H	5.78	0.79	–43	–158	–35	–0.6	0. 73
Gl 53B	7. 6^H	11.00						0. 2
Gl 451A	9. 2^H	6.64	0.85	280	–159	–14	< -1	0. 6
Gl 699.1	15. 6	13.34	0.50	–149	–294	–42		0. 6
GJ 1062	16. 0	12.00	2.21	74	–219	-5	< -1	0. 15
Gl 781	16. 5	10.91	2.03	106	–47	35	< -1	0. 2
Gl 158	18. 5^H	7.17	0.93	–41	–190	21	< -1	0. 6
LHS 3409	20. 3	13.59	2.76	–31	–101	43	low	0. 1
WO 9371	22. 6^H	10.43	1.87	135	–309	124	low	0. 26
WO 9722	23. 9	11.39	2.05	264	–215	–93	low	0. 17
LHS 375	24. 0	13.78	2.27	30	–183	153	< -1	0. 1
GJ 1064A	24. 5^H	6.22	0.86	–96	–115	–76	–1	0. 70
GJ 1064B	24. 5^H	6.82	1.02	–96	–115	–76	< -1	0. 63
LHS 2815	25. 0^H	5.99	0.72	–29	–47	–37	< -1	0. 72

^{H} HIPPARCOS parallax and proper motions

of the kinematical parameters of halo stars. The masses given in the last column of Table 1 have been assigned using the mass-to-luminosity relation calculated theoretically for a metallicity of [Fe/H] = –1.35 dex by Alexander et al. (1997).

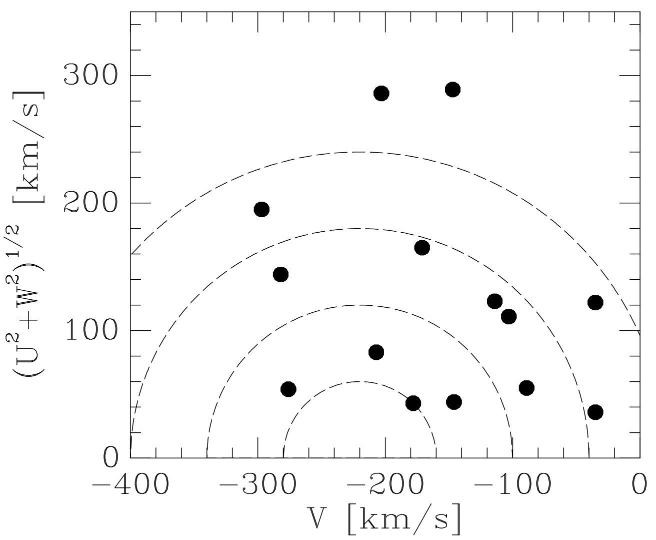

Fig. 2. Toomre diagram of the nearby halo dwarfs. The dashed lines indicate lines of constant kinetic energy of the halo stars.

The changes due to the introduction of HIPPARCOS parallaxes can be seen by comparing Table 1 and the corresponding Table 1 of Fuchs & Jahreiß (1997).

3. Results and discussion

3.1. Local density

The local mass density of halo stars can be estimated in various ways. In Fig. 3 we show density estimates, which have been calculated from the cumulative distribution of the stars in our sample, i.e. by adding up the masses of stars within given distances and dividing by the corresponding spherical volumes. The stars within 10 pc give rather high density estimates of the order of 10^{-3} $\mathcal{M}_\odot$ pc^{-3}. Wielen & Jahreiß (Wielen 1976) found similar values, when evaluating the second edition of the Gliese catalogue. A careful analysis of the spatial distibution of the stars shows, however, that the high density peaks are of purely statistical nature and certainly not realistic. We find a plateau in the density run, when we consider the stars within the 20 pc sphere (cf. Fig. 3). Beyond that the density drops off, probably because the catalogue becomes incomplete. The most likely value of the local mass density lies according to our determination in the range 1.5 to $1{\cdot}10^{-4}$ $\mathcal{M}_\odot$ pc^{-3}. We note that just outside the nominal boundary of the CNS4 there are two further subdwarfs, LHS 173 and GL 788.2, at distances 25.5 pc and 25.6 pc, respectively. If they are included, the mass density is $1{\cdot}10^{-4}\mathcal{M}_{\odot}$ pc^{-3}, which, in our view, is a firm lower limit to the local mass density of halo stars.. The local density of the dark halo (Bahcall, Schmidt & Soneira 1983, Gates et al. 1996) is about $9{\cdot}10^{-3}$ $\mathcal{M}_{\odot}$ pc^{-3}, so that the local density of halo stars is about 1.7% of the halo density or 3% of the local MACHO density as determined by the MACHO collaboration. We have broken down our sample

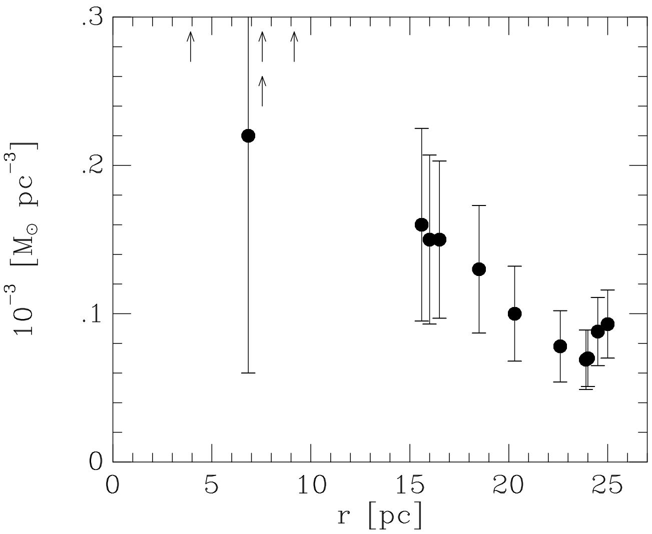

Fig. 3. Mass density of nearby halo dwarfs as function of the distance from the Sun. Within 10 pc for some of the stars only the positions are indicated. The errorbars indicate the statistical uncerntainties.

of subdwarfs with respect to absolute magnitudes. The resulting 'luminosity function' is compared with the subdwarf luminosity function obtained by Dahn et al. (1995) for stars with $M_{\rm V} > 10$ mag in Table 2. Both agree well within statistical uncertainties.

Table 2. Luminosity function of red subdwarfs.

$M_{\rm V}$ [mag]	$N_{\rm CNS4}$	$\nu_{\rm CNS4}$ [10^{-5} mag^{-1} pc^{-3}]	$\nu_{\rm Dahn}$
10	0	0	6
11	3	16	10
12	1	5	6
13	0	0	4
14	1	5	1
14.5	0	0	0.6

3.2. Matching the constraints by HST data.

It is interesting to confront the density of halo stars derived here with density estimates based on the HST data. Graff & Freese (1996) find in a detailed analysis of earlier HST data (Bahcall et al. 1994) a value about five times less than our estimate, which is partly due to their restriction to red dwarfs redder than $V-I \approx 2$ mag. Whereas these authors tried to infer the local density of halo stars from the star counts, we reverse the approach and make predictions of the expected number of stars in the star count field. Recently Flynn et al. (1996) have reported an analysis of the Hubble Deep Field (HDF). The HDF has a size of 4.4 square arcminutes and is located at $l = 126°$, $b = 55°$. Flynn et al. (1996) were able to identify stars down to a limiting magnitude of 26.3 mag in the I–band.

In the following we assume for the population of halo stars a density law of the form

$$\nu_{\rm h} = \nu_{\rm h_\odot}\left(\frac{r_{\rm c}^2 + r_\odot^2}{r_{\rm c}^2 + r^2}\right)^{\alpha} \tag{1}$$

with an arbitrarily chosen core radius of $r_{\rm c} = 1$ kpc. Such density laws are typical for other tracers of the halo population, such as RR Lyrae stars (Wetterer & McGraw 1983), horizontal branch stars (Preston et al. 1983), in the Milky Way or external galaxies (Pritchet & van den Bergh 1994). The exponent α lies typically in the range 3.5 to 4. Note that the dark halo is usually described by a density law of the form as in equation (1) with $\alpha = 2$. If the subdwarfs are observed locally at a density $\nu_{\rm h_\odot}$, one predicts by integrating along the line of sight

$$N = \nu_{\rm h_\odot} \cdot\Omega \int_{\rm d_{min}}^{\rm d_{max}} s^2 \left(\frac{r_{\rm c}^2 + r_\odot^2}{r_{\rm c}^2 + r_\odot^2 + s^2 - 2sr_\odot \cos l \cos b}\right)^{\alpha} ds \tag{2}$$

stars in the star count field. Ω is the angular area of the field and the minimum and maximum distances are determined by the limiting magnitudes.

We concentrate first on the colour range $V-I = 1.8$ to 3.5 mag. We have 4 stars in that range within 16.5 pc, where we believe our sample to be reasonably complete. If we project these into the cone towards the HDF, we obtain the star numbers summarized in Table 3. The limiting distances have been calculated for each star individually,

$$d_{\rm min,max} = 10^{0.2(I_{\rm min,max} + (V-I) - M_{\rm V} + 5)}, \tag{3}$$

where, in order to avoid confusion with disk stars in the HDF, we adopt a lower limit of $I_{\rm min} = 24.6$ mag. As can be seen from Table 3 we predict 7 to 11 stars in the HDF, whereas Flynn et al. (1996) have actually detected no star. Despite the low number of stars involved, this discrepancy seems to be statistically significant. Several explanations might account for this discrepancy. First, the stellar halo might be much more irregular and lumpy than previously

Table 3. Predicted Number of Stars in the HDF and the GS.

	$V-I>1.8$		$V-I<1.8$	
α	c/a	n_{HDF}	n_{HDF}	n_{GS}
3.5	1	11	17	258
4	1	7	7	140
3.5	0.6	4	5	67
4	0.6	2	2	31

thought. Second, the stellar halo is almost certainly flattened (Wetterer & McGraw 1983, Preston, Shectman & Beers 1983, Pritchet & van den Bergh 1994) with an axial ratio around c/a $\approx$ 0.6. If we take such a flattening into account in the halo model,

$$\nu_{\rm h} = \nu_{\rm h\odot} \left(\frac{r_{\rm c}^2 + R_\odot^2}{r_{\rm c}^2 + R^2 + z^2/(c/a)^2} \right)^\alpha \quad , \tag{4}$$

where R, z denote cylindric coordinates, we predict 2 to 4 stars in the HDF, i. e. star numbers which are statistically consistent with no star seen by Flynn et al. (1996).

The star counts in the HDF in the colour range $V-I<1.8$ mag can be interpreted in a similar way. Disk stars in this colour range are so bright that they would have to lie several kpc above the midplane to appear fainter than $I=22$ mag. Thus in order to avoid confusion with disk stars in the HDF, we consider only stars fainter than $I=22$ mag. In our sample there are 4 stars within 20 pc in this colour range. Their $V-I$ colours cluster around 0.9 and the white dwarf has $V-I=0.5$. Thus we define a colour range $0.5<V-I<1.8$, in which we compare the predictions with actually observed numbers of stars. If the stars of our sample are projected into the cone towards the HDF using spherical halo models, we predict 7 to 17 stars depending on the model, whereas Flynn at al. (1996) have observed 4 stars. If we assume again a flattening of c/a = 0.6, the number of expected stars is consistent with the observed number.

Gould et al. (1997) have very recently investigated another field observed by HST. This is the so-called Groth strip (GS), which has an angular size of 114 square arcminutes and is located at $l=96°$ and $b=60°$. Its limiting magnitude is $I=23.9$ mag. Gould et al. (1997) have very kindly made their data available to us, so that we were able to make star counts in this field. Due to the limiting magnitude of $I=23.9$ mag even the faintest stars in the GS with colours redder than $V-I=1.8$ could be disk stars. Thus we focus on the colour range $V-I<1.8$ and adopt the same halo zone as in the HDF. The GS has 66 stars in this zone. There is a slight chance that this zone might be contaminated by faint white dwarfs in the galactic disk. It can be shown, however, that, if the local density of disk white dwarfs as determined by Jahreiß (1987, 1997) and conventional estimates of the vertical scale height of the galactic disk are adopted, one would expect about one white dwarf in this zone of the GS. If we project the local subdwarfs into the cone towards the GS, we obtain the numbers of predicted stars summarized in the last column of Table 3. Again a flattened halo model is a better fit to the data.

3.3. Constraints on the absolute magnitude of MACHOs.

Like previous authors we have *not* detected the analogues to MACHOs in the solar neighbourhood. This raises the question why. All subdwarfs in our sample appear in the LHS high-proper motion star catalogue. Being halo objects, MACHOs in the solar neighbourhood must have similar proper motions. The fact that they have not been found in high-proper motion surveys allows to set an upper limit to their luminosity (Fuchs & Jahreiß 1997). The LHS catalogue (Luyten & La Bonte 1973, Dawson 1986) is claimed to be about 90 % complete for stars down to apparent magnitude $B=21$ mag and with proper motions $2.''5/\mathrm{a} > \mu > 0.''5/\mathrm{a}$. For stars brighter than $B=10$ mag it is claimed that all stars with proper motions $\mu > 0.''3/\mathrm{a}$ are contained in Luyten's NLTT catalogue. We assume that the MACHOs are homogeneously distributed around the Sun and have a gaussian velocity distribution,

$$dN = \frac{\nu_{\rm M\odot}}{(2\pi)^{3/2}\sigma_{\rm M}^3} exp - \frac{1}{2\sigma_{\rm M}^2}(U^2+(V-\overline{V})^2+W^2) d^3v d^3r \ , \tag{5}$$

centered on $\overline{V}$ = –220 km/s and with a velocity dispersion typical for halo objects, $\sigma_{\rm M} = \overline{V}/\sqrt{2}$. Integrating now over all radial velocities and the proper motions according to the specifications of the LHS we can determine the radius r_2 of the sphere out of which one would expect say 2 MACHOs in the LHS,

$$\begin{aligned} 2 \ = \ & 4.74^2 \frac{\nu_{\rm M\odot}}{\sigma_{\rm M}} \int_0^{r_2} dr r^4 \int_{\mu_l}^{\mu_h} d\mu\mu \int_0^{2\pi} dl \int_{-\pi}^{+\pi} db \cos b \\ & \cdot I_0 \left(\frac{\overline{V}}{\sigma_{\rm M}^2} 4.74 \mu r \sqrt{1-\sin^2 l \cos^2 b} \right) \\ & \cdot exp - \frac{1}{2\sigma_{\rm M}^2} \left(\overline{V}^2 (1-\sin^2 l \cos^2 b) + (4.74\mu r)^2 \right) \ , \end{aligned} \tag{6}$$

where I_0 denotes the Bessel function. According to Poisson statistics two expected MACHOs would be still consistent with no MACHO actually seen in the LHS survey. In Table 4, we give results of numerical integrations of equation (6) assuming a local density of MACHOs of $\nu_{\rm M\odot} = 0.5 \cdot 0.01\ \mathcal{M}_\odot\ {\rm pc}^{-3}\ /\ 0.5\ \mathcal{M}_\odot$ as determined by the MACHO collaboration. A lower limit of the absolute magnitude of the MACHOs is then given by $M_{\rm B} = 21 - 5\log r_2 + 5$, because MACHOs more distant than r_2 will not show up in the LHS, since they are fainter than the apparent magnitude limit of the LHS, $B=21$ mag. From Table 4 we

Table 4. Estimated absolute magnitudes of MACHOs.

r_N [pc]	N	M_B [mag]
6	0.31	22.1
9	2.3	21.2
12	9.4	20.6
15	27.3	20.1
18	64.0	19.7

conclude that MACHOs are fainter than $M_B = 21.2$ mag. The southern hemisphere ($\delta < -30°$) and the galactic belt are not sampled by the LHS survey. Thus one could argue that only the region $b \geq 30°$ is properly sampled. This would reduce the numbers in the second column of Table 4 by a factor of 0.25 and shift the lower limit of the absolute magnitude of the MACHOs to $M_B = 20.6$ mag. If the distribution of MACHOs is irregular and lumpy, the micro-lensing results could mimic a too high mean density of MACHOs. If we assume a local MACHO density of only 10% of the value determined by the MACHO collaboration, the lower limit of the absolute magnitude of MACHOs would be $M_B = 20.1$ mag.

If the MACHOs were identified with faint red dwarfs, their masses would have to be less than 0.1 $\mathcal{M}_\odot$ in contradiction to the estimate by the MACHO collaboration. As an alternative very faint white dwarfs have been discussed in the literature as MACHO candidates (Charlot & Silk 1995). Graff et al. 1997 discuss various aspects of this scenario and point in particular to the problem that such faint white dwarfs must have been born due to the long cooling times very early in the evolution of the universe.

What would be the requirements to detect such faint objects in future proper motion surveys? Assuming, for instance, a limiting magnitude of $B = 22.5$ mag as for UKST plates, an object with an absolute magnitude of $M_B = 21$ mag could be detected up to a distance of 20 pc from the Sun. Its typical proper motion would be $3\overset{''}{.}5$/a. Assuming again a volume density of $10^{-2}\mathrm{pc}^{-3}$, one would expect 333 objects distributed evenly over the sky.

Acknowledgements. We are indebted to C. Flynn, K. Freese, N.W. Evans, and R. Wielen for many valuable hints and comments. We are grateful to J. Bahcall, C. Flynn, and A. Gould for making available to us the their data on the Groth strip prior to publication. This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France.

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