The contribution of brown dwarfs to the local mass budget of the Galaxy

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Abstract. Based on the recent discoveries of free floating brown dwarfs we derive estimates of the local mass density of this population of objects. Mass density estimates from various surveys span the range 0.03 to 0.005 $M_\odot$ pc^{-3}. These estimates are compared with the local mass densities of the other constituents of the galactic disk and, in particular, with the dynamically determined total local mass density. We argue that brown dwarfs might indeed contribute significantly to the local mass budget, but that a local mass density as high as 0.03 $M_\odot$ pc^{-3} as suggested by Ruiz et al. (1997) is rather unlikely.

Key words: stars: low-mass, brown dwarfs – stars: kinematics – stars: statistics

1. Introduction

The recent discoveries of free floating brown dwarfs by the Calan-ESO proper motion survey (Ruiz et al. 1997), the DE-NIS mini survey (Delfosse et al. 1997, Tinney et al. 1997), the BRI survey (Irwin et al. 1991, Tinney 1998) and the UK Schmidt deep photographic survey (Hawkins et al. 1998) have now firmly established the long suspected existence of a population of single brown dwarfs in the disk of the Galaxy. Among the many interesting questions raised by these important discoveries is the local mass density of such objects. Although based at present on very low number statistics Ruiz et al. (1997) have pointed out that brown dwarfs may contribute significantly to the local mass budget. It is the aim of this note to assess the various density estimates and relate them to the total local mass density.

2. Estimates of the local mass density of brown dwarfs

2.1. Calan-ESO proper motion survey

The Calan-ESO proper motion survey has at present led to the discovery of one brown dwarf, Kelu-1 (Ruiz et al. 1997). The authors estimate that their effective search volume had a size of 23 pc^3, which implies a number density of 0.04 pc^{-3} or a mass density of 0.0028 $M_\odot$ pc^{-3}, if a typical mass of a brown dwarf

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of 0.065 $M_\odot$ is assumed. However, these numbers may underestimate the actual density. First, the survey detects only stars with proper motions exceeding 0.25 arcsec/yr, so that some stars with low space velocities might not be found. Furthermore, the plate limits imply that even among the very nearby brown dwarfs such as Kelu-1 only the bright brown dwarfs will be detected. Ruiz et al. (1997) and Tinney (1998) argue that these objects have ages less than one Gyr. In order to correct for both selection effects we assume that the distribution function of brown dwarfs in phase space is the same as that of the luminous stars. The velocity distribution is then described by Schwarzschild distributions, i.e. three-dimensional Gaussians with anisotropic axial ratios. As is well known from nearby stars (Wielen 1977), the velocity dispersions of the Schwarzschild distributions increase with the ages of the stars. We assume the same behaviour for the brown dwarfs, because the dynamical evolution of a population of brown dwarfs is expected to be the same as for luminous stars. The velocity distribution of young brown dwarfs with ages less than 1 Gyr is then modelled as

$$f(\mathbf{v}) = \nu_0 \int_0^{1\,\mathrm{Gyr}} d\tau \frac{r_{\mathrm{sfr}}(\tau)}{\sigma_U(\tau)\sigma_V(\tau)\sigma_W^2(\tau)} \tag{1}$$
$$\exp -\frac{1}{2}\left[\left(\frac{U - U_\odot}{\sigma_U(\tau)}\right)^2 + \left(\frac{V - V_\odot}{\sigma_V(\tau)}\right)^2 + \left(\frac{W - W_\odot}{\sigma_W(\tau)}\right)^2\right].$$

In Eq. (1) U, V, W denote the space velocity components of the brown dwarfs in the direction of the galactic center, the direction of galactic rotation and towards the galactic north pole, respectively. $\sigma_U, \sigma_V, \sigma_W$ are the corresponding velocity dispersions. They are assumed to increase with age as

$$\sigma_{U,V,W}^2(\tau) = \sigma_{U0,V0,W0}^2 + C_{U,V,W}\tau \,, \tag{2}$$

like the velocity dispersions of the luminous stars (Wielen 1977). The axial ratios of the velocity ellipsoid have been chosen according to the most recent discussion of the kinematics of nearby stars by Jahreiß & Wielen (1997) as $\sigma_U^2 : \sigma_V^2 : \sigma_W^2 = 2 : 1 : 0.57$. The diffusion coefficients $C_{U,V,W}$ follow the same ratios and have an absolute value of $C_U + C_U + C_W = 6 \cdot 10^{-7}$ (km/s)^2/yr. Initial velocity dispersions of $\sigma_{U0}^2 + \sigma_{V0}^2 + \sigma_{W0}^2 = 100$ (km/s)^2 have been assumed (Wielen 1977, Jahreiß & Wielen 1997). For the solar motion with respect to the local standard of rest standard values of $(U_\odot, V_\odot, W_\odot) = (9, 12, 7)$ km/s have

been adopted. The velocity distribution f is calculated by a superposition of Schwarzschild distributions for each generation of stars weighted by the star formation rate r_{sfr}, defined per surface density, which we have assumed to be constant with respect to time. Stars with higher vertical velocity dispersions settle with larger vertical scale heights in the galactic gravitational potential than stars with low vertical velocities , so that there will be a thinning-out of the density of such stars at the galactic midplane. This is modelled in Eq. (1) by an extra $\sigma_{\mathrm{W}}(\tau)^{-1}$ term. ν_0 takes care of all the normalization constants.

The expected number density of brown dwarfs in a cone towards the direction of Kelu-1 ($l{=}307.7°$, $b{=}36.8°$) is given by

$$\nu_{\mathrm{exp}} = \left(\frac{1}{3}\mathrm{d}_{\mathrm{max}}\right)^{-3} \int_0^{\mathrm{d}_{\mathrm{max}}} dr\, r^2 \int d^3v f(\mathbf{v}), \qquad (3)$$

where $\mathrm{d}_{\mathrm{max}}$ is the radial length of the probing volume investigated by Ruiz et al. (1997). The observed number density of brown dwarfs in the cone, ν_{obs}, can be expressed similarly to Eq. (3), if the proper motion limit of $\mu \geq 0.25$ arcsec/yr of the Calan-ESO poper motion survey is taken into account in the integration over the velocity components. To implement this proper motion limit one has to transform the cartesian velocity components U, V, and W in Eq. (3) to radial and tangential velocities and from that to proper motions. The integrand in Eq. (3) depends then explicitly on the radial distance r. We set the upper boundary of the r-integration at $\mathrm{d}_{\mathrm{max}} = 10$ pc. This is based on the observation that Kelu-1 is very similar to DENIS-P J1228.2-1547 (Tinney et al. 1997), implying an absolute magnitude of $\mathrm{M_R} = 19.5$ mag, which is about the plate limit of the Calan-ESO survey (Ruiz et al. 1997). [1] Integrating Eq. (3) and its modification numerically we find a ratio of

$$\frac{\nu_{\mathrm{obs}}}{\nu_{\mathrm{exp}}} = 0.39\,, \qquad (4)$$

which changes to 0.28 or 0.44, if $\mathrm{d}_{\mathrm{max}}$ is increased or decreased by a factor of 1.6 according to an estimated uncertainty of the distance modulus of ± 1 mag, respectively. Up to now we have considered only bright and young brown dwarfs. Very likely there are also fainter and older brown dwarfs, which will contribute to the mass budget as well, although they have not yet been found in the surveys. Assuming again a constant star formation rate and an age of the galactic disk of 10 Gyrs we estimate from Eq. (1)

$$\frac{\nu(\tau \leq 10\mathrm{Gyr})}{\nu(\tau \leq 1\mathrm{Gyr})} = \frac{\sqrt{\sigma_{\mathrm{W0}}^2 + C_{\mathrm{W}} \cdot 10\mathrm{Gyr}} - \sigma_{\mathrm{W0}}}{\sqrt{\sigma_{\mathrm{W0}}^2 + C_{\mathrm{W}} \cdot 1\mathrm{Gyr}} - \sigma_{\mathrm{W0}}} = 4.1\,. \quad (5)$$

Combining this with the estimate (4) we conclude that the contribution of brown dwarfs to the local mass density is 10 times

[1] We note that this places Kelu-1 at a distance of 9 pc, which is less than the 'astrometric' distance derived by Ruiz et al. (1997). However, we do not follow the authors in assuming that Kelu-1 is exactly at rest at the local standard of rest, so that its proper motion solely reflects the solar motion. Indeed, LTT 5054 and LTT 5122, which lie in the same direction as Kelu-1 and have very similar proper motions, but for which parallaxes are known, can be shown to be typical disk stars with non-zero space velocities.

the density of brown dwarfs deduced straightforward from the Calan-ESO survey. The same correction factor is given by Ruiz et al. (1997), although the authors do not explain in detail how they arrive at that estimate.

2.2. DENIS mini survey

The DENIS mini survey with a field size of 230 deg^2 has led to the discovery of three brown dwarf candidates (Delfosse et al. 1977). High resolution spectroscopy by Tinney et al. (1997) has clearly confirmed the brown dwarf nature of DENIS-P J1228.2-1547 by detecting a Li absorption line. However, Tinney et al. (1997) conclude that the other two objects must be also very cool low-mass objects. If we adopt the absolute K magnitude of DENIS-P J1228.2-1547 and the plate limit in the K band given by Delfosse et al. (1997), we find that the search volume of the DENIS mini survey for brown dwarfs is 162 pc^3. This implies a local number density of brown dwarfs of 0.019 pc^{-3}. In order to account for the fainter and older brown dwarfs, which have not yet been detected by the DENIS survey, the correction factor given in Eq. (5) has to be applied.

2.3. BRI survey

High resolution spectroscopy of very late type stars of the BRI survey (Irwin et al. 1991) by Tinney (1998) has led to the identification of the brown dwarf LP 944-20 = BRI 0337-3535. Tinney (1996, 1998) has also measured the parallax, proper motion and radial velocity of this brown dwarf. Its age is estimated as about 500 Myrs (Tinney 1998). The low space velocity of 7 km/s is consistent with such a young age (Wielen 1977). The BRI survey covers 1000 deg^2 and its plate limit is at 19.0 mag in the R band. In the NLTT catalogue (Luyten 1979) the apparent R magnitude of LP 944-20 is given as R = 17.5 mag. This implies that the search volume of the BRI survey for brown dwarfs is 99 pc^3. The local number density of brown dwarfs is then according to this determination 0.01 pc^{-3}. Since LP 944-20 is younger than the brown dwarfs found in the other surveys (Tinney 1998), the correction factor for taking into account the fainter and older brown dwarfs is 6.8 (cf. Eq. (5)).

2.4. UK Schmidt survey

Spectroscopy of very red stars of the UK Schmidt survey of ESO/SERC field 287 (Hawkins et al. 1998) has led to the identification of three brown dwarf candidates at distances between 37 and 48 pc. The plate limit is at 23.1 mag in the R band, and the field area is 25 deg^2, although crowding reduces the effective area of the survey by as much as a factor of 4. Using the apparent R magnitudes and the parallaxes given by Hawkins et al. (1998) we estimate that the survey is complete up to a distance of 50 pc. This implies an effective search volume of 80 pc^3 and the local number density of brown dwarfs is then 0.038 pc^{-3}. Hawkins et al. (1998) assume that the ages of the brown dwarfs, which they have found, are about one Gyr. Thus

the correction factor for the older brown dwarfs given in Eq. (5) has to be applied.

3. Discussion and conclusions

The four surveys have led to number density estimates of brown dwarfs of 0.46 pc^{-3}, 0.076 pc^{-3}, 0.069 pc^{-3}, and 0.15 pc^{-3} respectively. Assuming again a typical mass of a brown dwarf of 0.065 $M_\odot$ this corresponds to mass densities of 0.03 $M_\odot$ pc^{-3}, 0.0049 $M_\odot$ pc^{-3}, 0.0045 $M_\odot$ pc^{-3} and 0.01 $M_\odot$ pc^{-3}, respectively. We note, however, that despite the large differences the estimates are still statistically consistent within two standard deviations. This can be shown by integrating the Poisson probability function with respect to the mean value at a given number of N realizations. The range of mean values (x_l, x_u) of Poisson distributions from which the N realizations have been drawn with a probability of 95%, for instance, is then given by

$$\int_{0, x_u}^{x_l, \infty} \frac{x^N}{N!} e^{-x} dx = 0.025 \,. \tag{6}$$

If N=1, (x_l, x_u) = (0.24, 5.6) and in the case of N=3 (x_l, x_u) = (1.1, 8.8). This shows immediately that the statistical uncertainties of the density estimates of brown dwarfs overlap at two standard deviations.

The high estimate of the space density of Kelu-1 type objects, leads us to ask if they would be detectable in deep star count data taken with the Space Telescope (HST). We first consider star counts in the Hubble Deep Field (HDF) (Flynn et al. 1996). No very red stars, i.e. stars which appeared only in the I-band images and not in the V-band images, were detected in the HDF to a limiting magnitude of I=26.3. The number density implied by Kelu-1 itself is 0.1 pc^{-3}, while figuring in the older brown dwarfs associated with Kelu-1 raises the estimated number density to 0.4 pc^{-3}. Taking the absolute magnitude of Kelu-1 like other brown dwarfs as $M_I = 16.6$ and their local density to be 0.4 pc^{-3} and assuming an exponential scale height of 300 pc, we estimate that 6 Kelu-1 type objects would have appeared in the 4.4 square arcminute HDF, which is marginally inconsistent with none being observed, while only 0.5 would be expected if they have an exponential scale height of 100 pc, which is consistent with none observed. Stronger limits can be obtained using faint HST star counts in the Groth Strip (Gould et al. 1997), which covers 114.0 square arcminutes to a limiting I-band magnitude of $I = 23.8$. In this field we would expect 5 Kelu-1 type objects for a scale height of 100 pc and 15 for a scale height of 300 pc, whereas only 1 very red object (V-I>5.0) was detected. However, this assumes that all of the 0.4 pc^{-3} local space density of Kelu-type brown dwarfs would be as bright as Kelu-1 itself, whereas most will be older and fainter. For example, in a two-component toy model, containing a young component with a space density of 0.1 pc^{-3}, scale height 100 pc and $M_I = 16.6$ and an old component with a space density of 0.3 pc^{-3}, scale height 300 pc and $M_I = 18.7$ we would expect circa 1 star from each component in the Groth strip, consistent with 1 observed red star. We conclude that faint star counts in

HDF and the Groth strip are unable to rule out the high space density of Kelu-1 type objects measured by Ruiz et al. (1997).

These density estimates can be compared with measurements of the densities of the other constituents of the galactic disk. Jahreiß & Wielen (1997) derive from a discussion of the most recent data of nearby stars that the mass density of luminous stars in the solar neighbourhood is 0.039 $M_\odot$ pc^{-3}. Thus, if the mass density estimate of brown dwarfs based on the Calan-ESO survey is correct, brown dwarfs contribute almost as much to the local mass budget as the luminous stars. The mass density estimates of brown dwarfs can be also compared with dynamically determined local mass densities. Such measurements include all gravitating matter. Fuchs & Wielen (1993) and Flynn & Fuchs (1994) have used samples of K dwarfs and K giants, respectively, to measure the local slope of the K_z force law. Both measurements have led to a total local mass densities of 0.1 $M_\odot$ pc^{-3} with an estimated uncertainty of 20%. A repetition of the measurement using improved data of K giants indicates a total local mass density at the lower end of this range (Flynn & Fuchs, in preparation). Crézé et al. (1997) have used recently Hipparcos observations of A stars and determine a value of the total local mass density of 0.076 $\pm$ 0.015 $M_\odot$ pc^{-3}. The local surface density of interstellar gas in the form of cold HI and H$_2$ is 6 $M_\odot$ pc^{-2} (Dame 1993). If corrected for the presence of heavier elements and folded with a vertical scale height of 100 pc, this implies a local mass density of interstellar gas of 0.037 $M_\odot$ pc^{-3}. The mass density of warm HI and ionized interstellar gas is more difficult to assess, but is probably only 0.003 $M_\odot$ pc^{-3} (Kuijken & Gilmore 1984). We conclude from this discussion that there is evidence for a local mass density of brown dwarfs of the order of 0.01 $M_\odot$ pc^{-3}, which would seem to fill the gap between dynamical mass determinations and the mass density of so far identified stellar and interstellar matter, whereas the mass density estimate by Ruiz et al. (1997) (1997) seems to be on the high side. Hopefully, further discoveries of brown dwarfs, such as announced by the 2MASS survey (Kirkpatrick et al. 1998), will clarify this issue.

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