High-velocity white dwarfs: *thick disk*, not dark matter

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ABSTRACT

We present an alternative interpretation of the nature of the extremely cool, high-velocity white dwarfs identified by Oppenheimer *et al.* (2001) in a high-latitude astrometric survey. We argue that the velocity distribution of the majority of the sample is more consistent with the high-velocity tail of a rotating population, probably the thick disk, rather than a pressure-supported halo system. Indeed, the observed numbers are well matched by predictions based on the kinematics of a complete sample of nearby M dwarfs. Analysing only stars showing retrograde motion gives a local density close to that expected for white dwarfs in the stellar ($R^{-3.5}$) halo. Under our interpretation, none of the white dwarfs need be assigned to the dark-matter, heavy halo. However, luminosity functions derived from observations of these stars can set important constraints on the age of the oldest stars in the Galactic Disk.

Subject headings: stars: white dwarfs; Galaxy: stellar content, dark matter

1. Introduction

Tracking down the nature of dark matter could be described as the astronomical obsession of the twentieth century. The concept first emerged through Oort's comparison of the census of luminous material (stars, gas, dust) in the Solar Neighbourhood with dynamical estimates of the local mass density derived from the motions of K giants, high in the Galactic Disk (Oort, 1932). Like Zwicky's (1937) near-contemporary suggestion that cluster-galaxy kinematics required dark mass on much larger scales, the problem of the local 'missing mass' was not taken up immediately. However, the discrepancy in mass densities, a factor of ~ 3, prompted a flurry of survey activity in the 1960s and 70s, largely centred on what proved to be substantial overestimates of the number density of M dwarfs (see Reid & Hawley, 2000, ch. 7). Debate continues over the significance of the Oort limit discrepancy (Bahcall *et al.*, 1992; Crézé *et al.*, 1998).

In a cosmological context, dark matter came to prominence with the realisation that rotation curves of many galaxies were not Keplerian at radii beyond the visible extent of the disk (e.g. Rubin, Ford & Thonnard, 1978). Some were flat, implying that the enclosed mass increases linearly with radius (Ostriker, Peebles & Yahil, 1974). Extrapolating to the Holmberg radius, the enclosed mass approached $\sim 10^{12} M_\odot$, with mass-to-light ratios more than an order of magnitude higher than expected for an old stellar population. Ostriker *et al.* suggested that the additional material could be distributed in a near-spherical structure (a 'heavy halo', thereby dynamically stabilising the disk in spiral galaxies (Ostriker & Peebles, 1973). The implied radial density law is $\rho_{HH}(R) \propto R^{-2}$, where R is the distance from the centre of the Galaxy. This is substantially flatter than the $\rho_S(R) \propto R^{-3.5}$ density distribution of the few times $10^9 M_\odot$ traditional stellar halo (Schmidt, 1975).

Subsequent developments have been reviewed by Trimble (1987), Fich & Tremaine (1991) and Ashman (1992). Recent estimates, based on satellite galaxy motions, place the mass of the Milky Way at $\sim 5 \times 10^{11} M_\odot$ for $R < 50$ kpc. (Wilkinson & Evans, 1999). Approximately 10% of the total can be accounted for by stars, gas and dust in the Galactic disk and the stellar halo (Alcock *et al.*, 2000). Candidates for remaining dark matter include exotic particles, cold molecular gas, and compact objects, ranging from $10^6 M_\odot$ black holes through brown dwarfs to space rocks. Of these categories, the last is potentially most accessible to direct astronomical observation through gravitational microlensing (Paczynski, 1986). A number of extended photometric monitoring campaigns have been conducted, directed towards the high star-density regions of the LMC, SMC and the Galactic Bulge, and a substantial number of lensing events detected.

The most recent results from the MACHO group indicate the detection of 13-17 events towards the LMC, from which they deduce a total mass density of $\sim 9 \times 10^{10} M_\odot$ (Alcock *et al.*, 2000), although there have been other interpretations (see, e.g., Sahu & Sahu, 1998). In any case, it is clear that MACHOs are at most a minor constituent of the dark halo. Moreover, the best estimate of the mass of the foreground lensing objects, based on the distribution of event timescales and the assumed halo kinematics, proves to be surprisingly high, $\langle M \rangle = 0.5 \pm 0.3\ M_\odot$.

The set of compact astronomical objects with $M \sim 0.5 M_\odot$, and luminosities sufficiently low to escape detection, is small; white dwarfs are the obvious candidate, particularly since recent theoretical work (Hansen, 1999) suggests that old, cool, hydrogen-atmosphere white dwarfs have flux distributions which show significant departure from blackbody curves. Several examples have been found in the field (e.g. LHS 3250, Harris *et al.*, 1999). Contemporaneously, analysis by Ibata *et al.* (1999) of second-epoch images of the Hubble Deep Field, taken two years after the first-epoch data, led to the tentative identification of two to five very faint, blue, point-like sources which appeared to exhibit significant proper motion. If one accepts Ibata *et al.*'s conjecture that those sources are heavy-halo white dwarfs, the mass density is sufficient to account for all of the dark matter in the Galactic halo. However, the proper motions have recently been withdrawn based on third epoch HST observations, taken three years after the second-epoch observations (Richer, 2001).

The local mass density of the dark halo is $\sim 10^{-2} M_\odot$ pc^{-3} (for an R^{-2} mass dependence). If $0.5 M_\odot$ objects contribute 20% of the dark halo, this corresponds to a density of 0.004 MACHOs pc^{-3} in the Solar Neighbourhood. Ibata *et al.* (2000) identify two nearby cool white dwarfs, but Flynn *et al.* (2001) failed to identify any likely counterparts amongst published proper motion surveys, while Monet *et al.* (2000) were similarly unsuccessful with a proper motion survey combining accepted and rejected POSS II plate material in 35 fields ($\sim$ 1380 square degrees).

Recently, however, Oppenheimer *et al.* (2001) have completed a deep proper motion survey towards the South Galactic Cap and have identified 38 cool white dwarfs. Based on the kinematics, they assign the majority to a halo-like population, and argue that the high inferred number density implies that most of the white dwarfs must be members of the heavy halo. We present an alternative scenario. In the following section we discuss the Oppenheimer *et al.* observations in the broader context of stellar population kinematics; the final section summarises our conclusions.

2. Galactic populations and local kinematics

2.1. Heavy-halo white dwarfs?

Oppenheimer *et al.*'s sample is drawn from 196 Schmidt fields, covering 4165 square degrees towards the South Galactic Cap. They derive BRI magnitudes and proper motions for their sample by combining measurements of IIIaJ, IIIaF and IVN plate material from the UK/AAO Schmidt. The (B-R) colours are used to estimate photometric parallaxes from a linear colour-magnitude relation, with uncertainties of $\sim$ 20%. Radial velocities have not been measured for any of the white dwarfs; indeed, most have featureless DC-type spectra. However, towards the Galactic Poles the transverse motion is dependent most strongly on the U and V velocity components, motion towards the Galactic Centre and and in the direction of Galactic rotation respectively. Thus, while the available data do not permit a reliable estimate of W, the velocity perpendicular to the Galactic Plane, the planar (U, V) velocities can be estimated from the astrometric data.

Oppenheimer *et al.* derive U and V velocities for each target, allowing for Solar Motion, and setting W=0 kms^{-1} for each star. Systems with

$$\sqrt{U^2 + V^2} \; > \; 94 \text{ kms}^{-1}$$

fall outwith the limits of a velocity ellipsoid defined by the 2σ motions of stars in the Galactic disk (from Chiba & Beers, 2000), and are identified as having halo-like kinematics. The local density of these white dwarfs is substantially higher than expected for degenerates in the stellar halo, and Oppenheimer *et al.* argue that they are most likely local representatives of the dark matter which constitutes the Milky Way's heavy halo.

We have computed motions for Oppenheimer *et al.*'s dataset using a slightly different assumption; we adopt their distance estimate (and associated uncertainty) and proper motion measurements, but set V$_{rad}$ = 0 kms^{-1} rather than setting W=0 kms^{-1}. Since we have no information on either W or V_{rad}, both assumptions are equally valid. We note that the mean W velocity for the sample under our assumption is 0.6 ± 54 kms^{-1}, giving no indication of our having introduced a significant bias. We also allow for the Solar Motion, adopting $U_\odot$=10.0 kms^{-1}, $V_\odot$=5.3 kms^{-1} and $W_\odot$=7.2 kms^{-1}, from Dehnen & Binney's (1998) analysis of Hipparcos data.

Figure 1 plots the resulting (U, V) distribution, where we include errorbars reflecting the 20% uncertainty in the distance estimates. Our approach moves several dwarfs within the 2σ disk velocity contour; it is possible that these might be replaced by lower velocity white dwarfs, plotted but not tabulated by Oppenheimer *et al.* However, the most striking attribute of both Figure 1 and Oppenheimer *et al.*'s Figure 3 is the uneven distribution of velocities: the halo 1σ and 2σ ellipsoids are plotted for zero rotation and a dispersion of 120 kms^{-1}; a non-rotating population with those kinematics would be expected to be concentrated largely within the 1σ contours. In fact, only 9 of the 38 white dwarfs fall within the halo 1σ contours. Moreover, there is an obvious concentration of stars around the boundaries of the disk 2σ velocity ellipsoid. This is exactly the behaviour that one expects for the high-velocity tail of a rotating population, not a non-rotating, pressure-supported halo.

Oppenheimer *et al.* argue that the observed distribution is skewed by difficulties in detecting very high-motion objects; however, this effect cannot be significant, since with an average distance of 73 parsecs, their upper limit of 3 arcsec yr^{-1} corresponds to a transverse motion of 1040 kms^{-1} - over a factor of two higher than the highest velocity dwarf plotted in Figure 1. Stars with such high motions would be expected to exceed the local escape velocity. This selection effect does not account for the scarcity of white dwarfs with retrograde motion: 34 of the 38 white dwarfs plotted in Figure 1 have $V > -220$ kms^{-1}.

2.2. The velocity distribution of nearby M dwarfs

Is there another potential source of these dwarfs? Figure 2 plots (U, V) data for a volume-complete sample of M dwarfs within the Solar Neighbourhood (from Reid, Hawley & Gizis, 1995). All of the stars have both proper motion and radial velocity measurements, and the space motions are accurate to 10-20 kms^{-1} in each co-ordinate. Twenty of the 514 systems (4%) lie outwith the disk 2σ velocity ellipsoid and would be classed as candidate halo stars by Oppenheimer *et al.* Since these are M dwarfs rather than white dwarfs, we can test whether they are members of the halo by measuring their metallicity. Halo stars have low metal abundance [Fe/H]<-1; heavy halo members might be significantly more metal poor. Metal-poor M subdwarfs have weaker TiO absorption than solar-abundance disk dwarfs with the same CaH absorption (Gizis, 1997). None of the outliers in Figure 2 have halo-like CaH/TiO bandstrength ratios (Figure 3).

This result is far from unexpected; the local density of M subdwarfs is $\sim 0.2\%$ the local density of M dwarfs, and a 2σ selection limit only eliminates 95% of a sample, consistent with the 3.5% of high velocity stars in Figure 2. More significantly, there are striking similarities between the overall

M-dwarf velocity distribution and the location of high-velocity white dwarfs in Figure 1. Specifically, the M dwarfs exhibit a clear extension towards (U=-100, V=-60), the major concentration of white dwarfs, while a smaller number of M dwarfs lie close to the sparser (U=+100, V=-80) white dwarf concentration. These disk main-sequence stars can be expected to have evolved degenerate counterparts.

3. White dwarfs, dark matter and the thick disk

The morphological similarities between Figures 1 and 2 suggest strongly that a significant fraction of the Oppenheimer *et al.* sample are members of the Galactic disk. Moreover, since velocity dispersion increases with age, these high-velocity white dwarfs are likely to be associated with the oldest sub-population within the Galactic disk - the thick disk (Gilmore & Reid, 1983). Current estimates, based either on kinematics (Reid *et al.*, 1995) or starcount analysis (Siegel *et al.*, in prep.) indicate that approximately 10% of the local stars can be classed as thick disk. While the origin of this sub-population is not yet established beyond doubt, starcounts at large distances above the Plane show that the main-sequence turnoff lies at $M_V > 4.5$, indicating an age $\tau > 5$ Gyrs (Gilmore & Reid, 1983). Recent detailed abundance analysis of individual thick disk stars suggests that these stars formed shortly after the stellar halo, and have ages of 10 Gyrs or more (Prochaska *et al.*, 2000). Thus, thick-disk white dwarfs can have effective temperatures which are similar to those expected for halo white dwarfs (either stellar or dark matter).

We can make a crude estimate of the likely number density of high-velocity disk white dwarfs from the statistics of stars within 8 parsecs of the Sun. Twelve white dwarfs are currently known: seven single stars, two wide companions of low-mass red dwarfs, two companions of massive stars (Sirius and Procyon) and one unresolved companion of an M-dwarf (Reid & Hawley, 2000). Excluding the binaries, the local number density is

$$\rho_{WD}(\text{disk}) \;=\; (3.26 \pm 1.23) \times 10^{-3} \text{ stars pc}^{-3}$$

Scaling by 4% gives a local density of $\sim 1.3 \times 10^{-4}$ stars pc^{-3} However, there are ten additional main-sequence stars (including Sirius and Procyon) which will have evolved to become white dwarfs in a 10-Gyr population, doubling the white dwarf number density. If the thick disk has a mass function similar to the old disk, and there are no indications to the contrary, then the relative number of high velocity white dwarfs (HV disk) and M dwarfs should be scaled accordingly. White dwarfs in the stellar halo contribute an additional 2×10^{-5} stars pc^{-3} (Gould *et al.*, 1998). Thus, we expect

$$\rho_{WD}(\text{HV disk}) \;\approx\; 2.8 \times 10^{-4} \text{ stars pc}^{-3}$$

In comparison, Oppenheimer *et al.* measure a local number density of

$$\rho_{WD}(\text{HH}) \;=\; 1.7 \times 10^{-4} \text{ stars pc}^{-3}$$

from their full sample. However, they argue that incompleteness affects their statistics at faint magnitudes. Limiting the sample to R59F$<$ 19.45, based on $\frac{V}{V_{max}}$ statistics, they derive

$$\rho_{WD}(\mathrm{HH}) \;=\; 3.9 \times 10^{-4} \text{ stars pc}^{-3}$$

within a factor of two of our estimate of the combined number density of high-velocity white dwarfs from the thick disk and the stellar halo.

Alternatively, we can use the number of retrograde-rotating white dwarfs in Figure 1 to estimate the local density of halo white dwarfs, since those high velocity stars are extremely unlikely to be members of the disk. The halo is non-rotating, so we expect equal numbers of prograde and retrograde rotators. We measure V< -220 kms^{-1} for four white dwarfs: F351-50 (M_R=15.53), LHS 147 (M_R=13.32, WD0135-039 (M_R=13.57) and WD0300-044 (M_R=14.61). All four are brighter than the R59F=19.45 completeness limit of the survey. Summing $\frac{1}{V_{max}}$, allowing for 10% sky coverage, gives a density of $\rho = 1.5 \times 10^{-5}$ stars pc^{-1}. Doubling that value to take prograde rotators into account gives

$$\rho_{WD} \;=\; 3.0 \times 10^{-5} \text{ stars pc}^{-3}$$

This is consistent with the expected contribution from the *stellar* halo (Gould *et al.*, 1998). Given these results, we do not believe it necessary to invoke a substantial contribution from hypothetical white dwarfs in the dark matter halo.

Despite these caveats, it is clear that the stars discovered in Oppenheimer *et al.*'s South Galactic Cap survey represent a significant addition to the catalogue of cool white dwarfs. Besides providing further insight to cooling processes during the final stages of evolution of degenerate dwarfs, statistical analysis of the sample can provide important information on the star formation history of the Galaxy. In particular, if we are correct in our conjecture that the bulk of these stars are members of the thick disk, then their luminosity function can be used to probe the age of that population, calibrating the first epoch of star formation within the Galactic disk.

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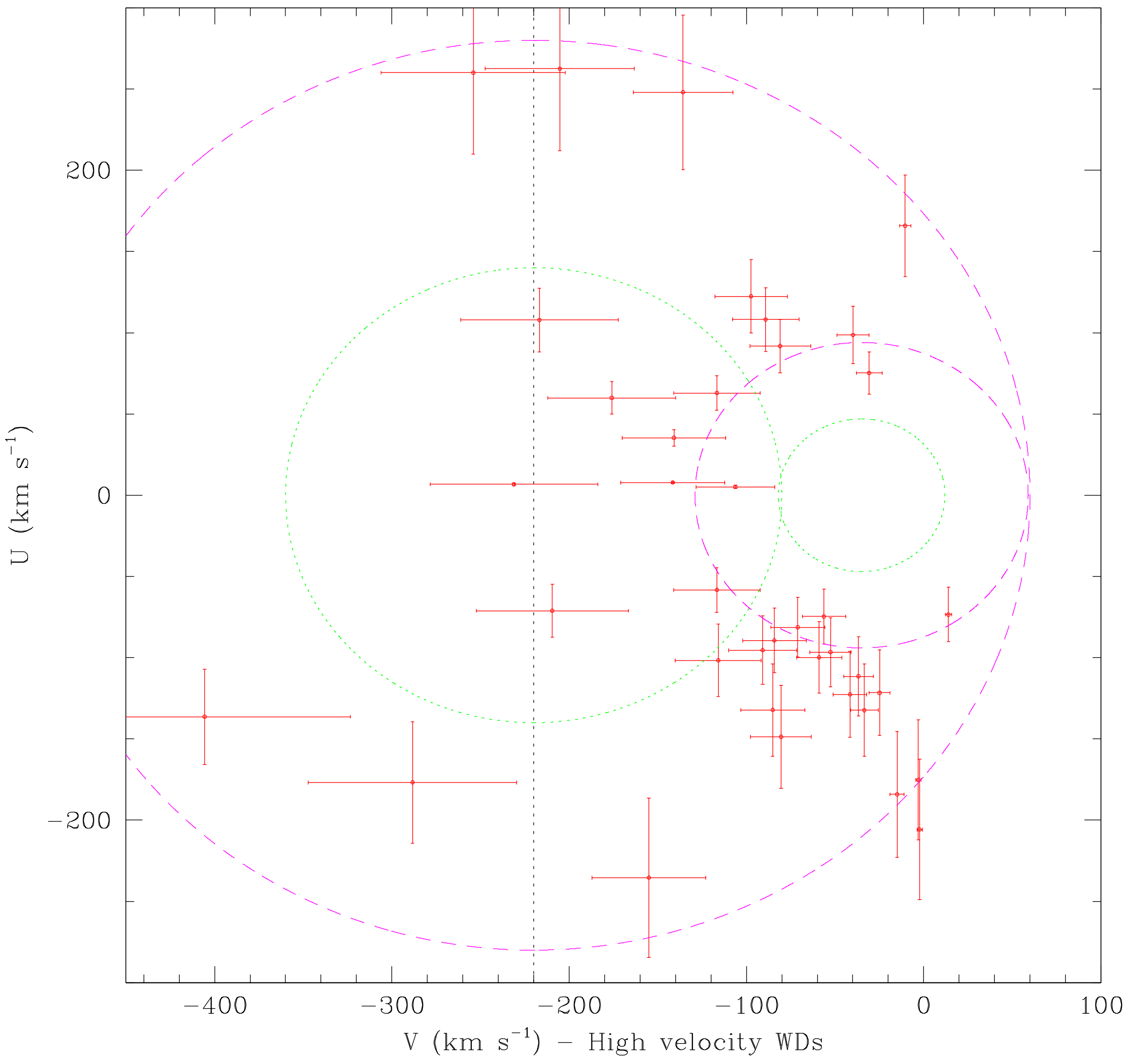

Fig. 1.— The (U, V) velocity distribution for the 38 candidate halo white dwarfs from Oppenheimer *et al.*. The velocity zeropoint in V is defined by the Local Standard of Rest; the vertical dotted line marks V=-220 kms^{-1}, corresponding to zero net rotation. The ellipsoids plot the 1σ (dotted) and 2σ (dashed) contours for the Galactic disk and stellar halo populations, based on kinematics from Chiba & Beers (2000). The errorbars reflect only the 20% distance uncertainties given by Oppenheimer *et al.* and do not take any other systematics into account.

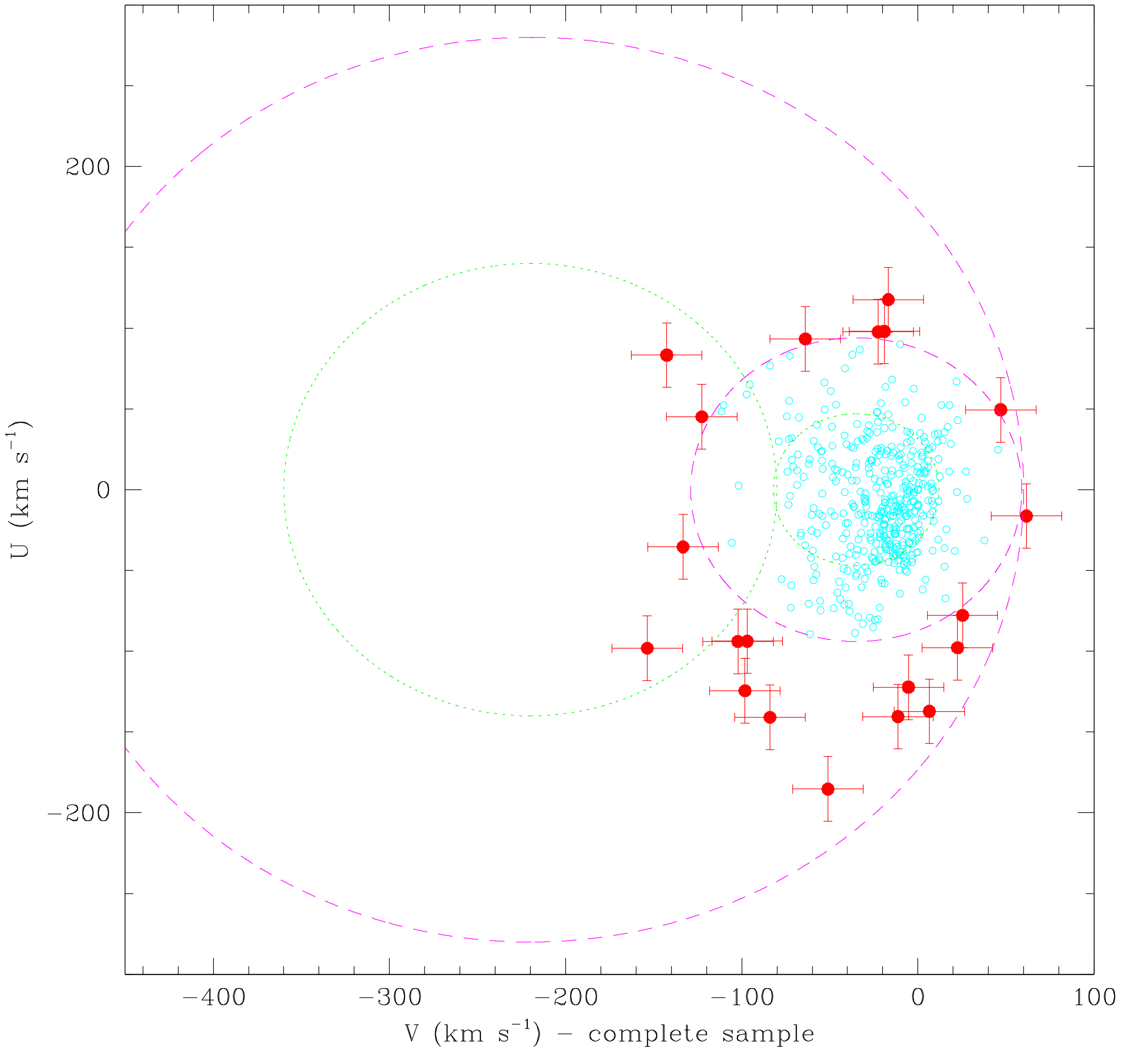

Fig. 2.— The (U, V) velocity distribution for a complete sample of 514 M-dwarf systems (from Reid, Hawley & Gizis, 1995). All of the stars are members of the Galactic disk; 20 stars, identified as solid points with ± 20 kms^{-1} errorbars, lie outside the 2σ disk velocity contours.

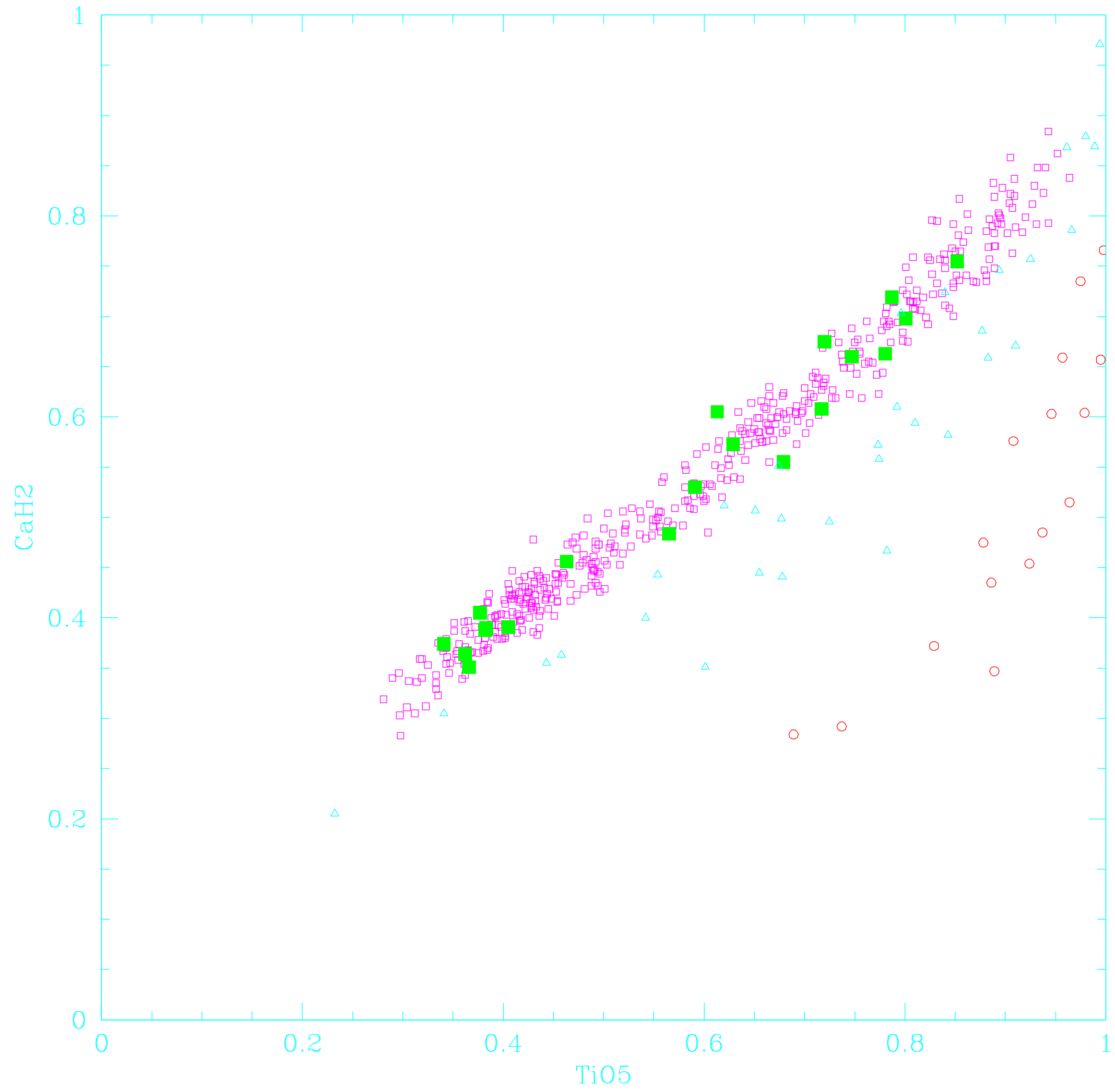

Fig. 3.— The (TiO5, CaH2) diagram for late-type dwarfs: both TiO5 and CaH2 decrease in value with decreasing temperature, and the sequence runs from ∼K7 to ∼M8. Data for the complete sample of nearby dwarfs are shown as open squares, with solid squares denoting the 20 high-velocity dwarfs. Metal-poor stars fall below the disk sequence: intermediate-abundance halo subdwarfs ([Fe/H]≈ -1) are plotted as open triangles, while extreme metal-poor subdwarfs ([Fe/H]≈ -2) are plotted as open circles (from Gizis, 1997). It is clear that the high-velocity dwarfs have near-solar abundance.