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The Dark Side of the Milky Way

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Abstract. The familiar picture of our Galaxy is that of a myriad of bright stars assembled in a flat disk which we call the Milky Way. But what, if, like a shadow, another massive disk population of formerly bright stars inhabited the Galaxy from the beginning, though characterized by somewhat larger scales, but then managed to fade out? Here we present very recent results of such a scenario from the local census of long-lived stars and from the detailed scrutiny of the involved time scales, that has now become possible on the base of the *Hipparcos* astrometry.

1. Prolog

Field stars of spectral type F and G are intrinsically bright and also long-lived in that they evolve on time scales of billions of years to white dwarfs. Perhaps most F stars may not become as old as the Galaxy, but this should be true for the majority of the G-type stars. This is at least our common wisdom, and has invoked numerous Galactic formation and evolution studies with G stars as tracers, and, among others, G-dwarf problems as their outcome.

The realization that stars arise from various populations and do not exhibit the same metallicity, not even intrinsically, is nowadays by no means challenging, but it was so in the 1940s and 1950s with the landmark papers of Baade (1944) and Chamberlain & Aller (1951). Our generation is instead plagued to internalize that star formation never offers a simple one-to-one metal enrichment, nothing like a well-behaved age-metallicity relation. In fact, while it seems true that the local halo population is almost negligible, the 1980s brought to light that our Galaxy accomodates at a locally small but noticeable level what has since been termed the *thick-disk* population (Gilmore & Reid 1983). Its members have a mean metallicity of [Fe/H]~ -0.6, but with considerable overlap to the locally dominant (then) *thin disk* with respect to e.g. the α-elements. The thick disk is also evidently a very old population (e.g. Wyse 1996), and it is only within the last few years that a star formation gap between thick disk and thin disk was realized as a possible scenario for the Milky Way evolution (cf. Gratton et al. 1996). This is particularly important, since it potentially provides the ultimate legitimacy for the existence of two *discrete* disk populations, which has been a matter of debate for many years.

Indeed, as we will show in what follows, the early hiatus in star formation must have lasted for no less than three billion years and this again raises the question: *What is a long-lived star if there are two disk populations involved?* Certainly, if we intend to compare the properties of the thin disk to that of the thick disk, we have to resort to only those stars that do not evolve to white dwarfs within 13 or 14 Gyr. But if, as we will see, it happens that, rather unexpected, the *majority* of the ubiquitous thin-disk G-type stars do not withstand this criterion, then what? Most obviously this raises the importance of the thick-disk population considerably, its inconspicuous appearance becomes rather superficial, and we have a vague presentiment that the light of the much younger, bright, and pestering thin-disk stars is much of a shabby "trick".

In the end we may find that the Galactic thick disk is as massive as the familiar thin-disk population, but with a principal "carrier" that consists of stellar remnants, such as that in Fig. 1, instead of ordinary stars. If so, we may have to approve the existence of a lot of *baryonic* dark matter to the Milky Way Galaxy, one which may actually cause the Sun to rotate at its $\sim$220 km s^{-1} around the Galactic center, and without invoking any non-baryonic components to this.

Figure 1. Map towards Taurus including the very faint (V=19), but local, white dwarf WD 0346+246, a putative thick-disk object that was serendipitously discovered in 1997 by Hambly, Smartt, & Hodgkin at a distance of 28 pc. Guess where it lurks! *(The interested reader will find the answer, as well as the object's change in position with time, in the Astrophysical Journal, issue #489, on p. L159)*

2. The ages and time scales of the local disk populations

We will focus our discussion on bright and long-lived FGK stars and on particularly those objects that one can find within 25 pc of the Sun. This is of course only 10% of the scale height of the thin disk and even less than 1% of its scale length. In fact a tiny volume compared to the structure of the Milky Way! But, it is currently the largest sample where our knowledge of the stellar inventory down to the early K stars is thought to be *complete* in terms of accurate astrometric data from the *Hipparcos* satellite. There is also no *a priori* reason to believe that the solar neighborhood is somehow special compared to other mid-plane regions at this distance to the Galactic center. At the same time, our sample is not too large for an *individual* spectroscopic study at high S/N ($\sim$150-400) and high resolution ($\lambda/\Delta\lambda \sim 60000$). All spectra are obtained with the fiber optics Cassegrain échelle spectrograph FOCES (Pfeiffer et al. 1998) on top of the Calar Alto mountain and are thus as well restricted to stars north of $\delta = -15^{\rm o}$. Up to now some 160 stars have been analyzed, which is more than half of the final sample. For details of the applied methods and individual stellar parameters we must refer here to Fuhrmann (1998, 2001), but we will present at least a few explicit results for some of the real *key stars* in what follows.

What is the age of the solar neighborhood? Binney, Dehnen, & Bertelli (2000) have recently tried to answer this question. But, as we think, it is meaningless to ask like this without, first, clarifying the origin of the nearby stars. Instead what one should rather put forward is: *What are the stellar populations that one can eventually identify in the solar neighborhood?* And, if so: *What are the ages of these populations?* As it turns out, and as expected, the Galactic halo and bulge populations are negligible for the nearby stars. But there is a significant thick-disk population that we can separate from that of the thin disk. Fig. 2 summarizes these findings for the stars' chemistry with respect to iron and the α-element magnesium. Herein additional stars beyond 25 pc of the thick disk and halo are included as well to better represent the various regimes in somewhat larger numbers. As we can see, there is some degeneracy in the chemical abundances of the disk populations, and the same holds true for the kinematics of the stars (see Fig. 8, below). However, what makes the thick disk a discrete entity is its age. Thus, while the thin disk has a mean age that is approximately solar and does not exceed $\sim$8 Gyr, the thick disk is instead very old, most likely beyond $\sim$12 Gyr, representing eventually the oldest stars in our Galaxy.

To see this, we have searched for nearby subgiants, where detailed evolutionary tracks can nowadays pose meaningful constraints to their ages. This is because, first, the *Hipparcos* data provide accurate absolute visual magnitudes (typically a factor five better than heretofore possible), and, second, the uncertainty in the effective temperature determination is rather insignificant in the subgiant stage of evolution.

But, while we have several thin-disk subgiants within 25 pc at our disposal, the fact that we can identify only a dozen (northern) thick-disk stars within this volume entails that there exists actually no subgiant of this population. Fortunately, the *Hipparcos* data are also fairly accurate out to 50 pc, and in a systematic search we found indeed three *bona fide* thick-disk subgiants, all observable from Calar Alto, and we took FOCES spectra of these in January

2000. We were also lucky to find a subgiant, HR 7569, among the few objects with intermediate chemistry (designated as "transition stars" in Fig. 2) that, as it turns out, provides an upper limit to the *onset* of the thin-disk formation.

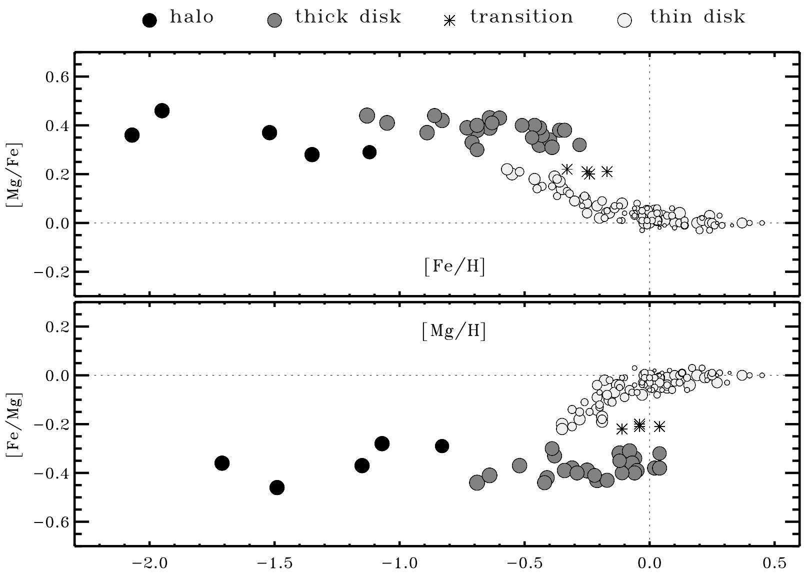

Figure 2. Top: abundance ratio [Mg/Fe] versus [Fe/H] for the sample stars. Bottom: the same data, but with magnesium as reference element. Except for the few "transition stars" (the asterisks), depicted circles are in proportion to the stellar ages. Different *stellar populations* are given with various grayscale symbols as indicated in the legend on top, and are based on abundance, kinematics, and age informations.

Fig. 3 presents a detailed evolutionary track for 70 Vir, the oldest thin-disk subgiant that we could identify so far. For this star we get internal errors of $\Delta\tau(M_{bol})$=0.5 Gyr, $\Delta\tau$([Fe/H])=0.3 Gyr, and $\Delta\tau(T_{eff})$=0.1 Gyr. In Fig. 4 we present the results for HR 7569, for which we obtain τ=9.1$\pm$1.0 Gyr. HD 10519, one of the three thick-disk subgiants, is shown in Fig. 5. All relevant data are also summarized in Table 1. Two results are very striking: first, all three thick-disk subgiants (HR 173, HD 10519, HD 222794) are significantly older than the corresponding thin-disk objects, and, second, all are of similar age, as also expected from their common Fe/Mg abundance ratios in Fig. 2 (cf. also Mashonkina & Gehren 2000, 2001, for recent intriguing results on Ba and Eu).

Thus there is clear evidence for a significant, if not huge, star formation gap of 3 to 5 Gyr for the two disk populations, and hence *we have every reason to accept their discreteness*. We note here in passing that our stellar interior calculations are done with state-of-the-art input physics and include helium diffusion. We adopt Y=0.2723 for the unknown helium fraction but verified that e.g. Y=0.25 would reduce the nominal ages of our thick-disk subgiants by $\sim$0.7 Gyr. Likewise metal diffusion resulted in $\sim$1 Gyr younger stars at maximum – except for HR 173, where this mechanism becomes inefficient due to the star's evolved stage near the bottom of the giant branch.

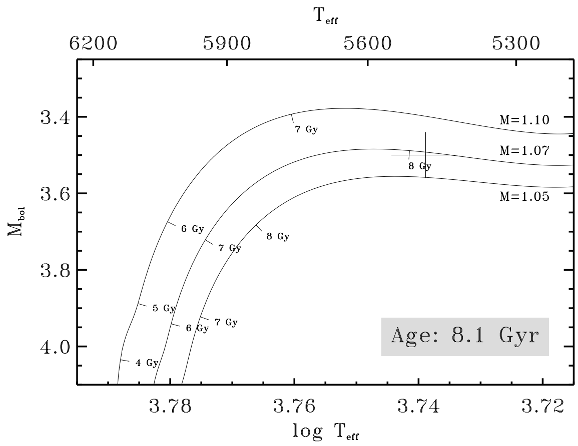

Figure 3. Evolutionary tracks with $M_\star = 1.05$, 1.07, and 1.10 $M_\odot$, at [Fe/H]$= -0.11$, and [Fe/Mg]$= -0.08$, as derived for the old thin-disk subgiant 70 Vir. Tick marks are given in steps of 1 Gyr.

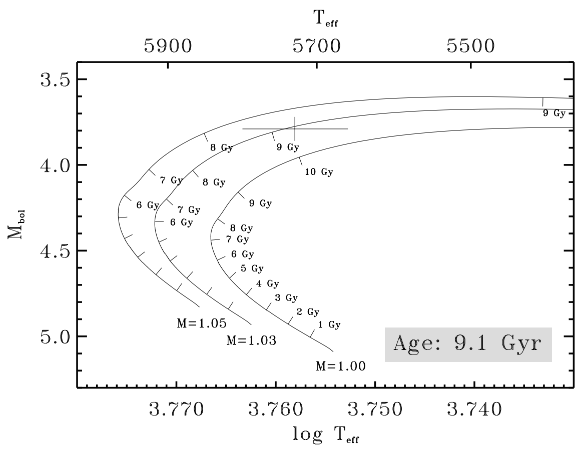

Figure 4. Same as Fig. 3, but for the disk "transition star" HR 7569.

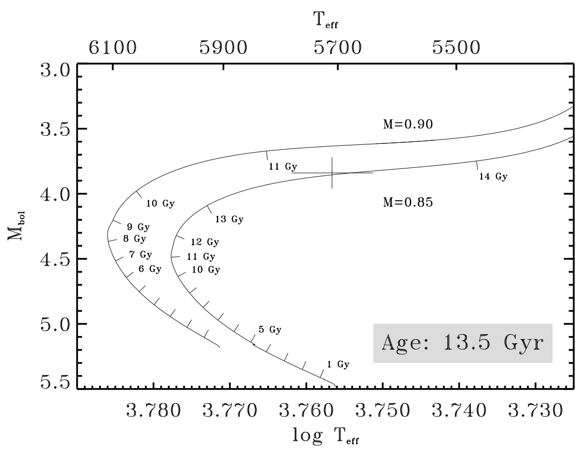

Figure 5. Same as Fig. 3, but for the thick-disk subgiant HD 10519.

Table 1. Basic stellar parameters of the seven nearby subgiants.

Object	T_{eff} [K]	$\log g$ [cgs]	[Fe/H]	[Fe/Mg]	M_{bol} [mag]	Mass [$M_\odot$]	Age [Gyr]
109 Psc	5614±80	3.96±0.1	+0.10±0.06	+0.00±0.05	3.54±0.08	1.16±0.03	6.8±0.6
70 Vir	5481±70	3.83±0.1	–0.11±0.07	–0.08±0.05	3.50±0.06	1.07±0.03	8.1±0.6
μ Her	5592±70	3.94±0.1	+0.24±0.07	+0.00±0.05	3.64±0.05	1.17±0.05	7.0±0.7
HR 7569	5729±70	4.01±0.1	–0.17±0.08	–0.21±0.05	3.79±0.07	1.03±0.03	9.1±1.0
HR 173	5373±70	3.82±0.1	–0.64±0.07	–0.39±0.05	3.63±0.07	0.84±0.03	13.8±1.3
HD 10519	5710±70	4.00±0.1	–0.64±0.07	–0.43±0.05	3.84±0.12	0.85±0.04	13.5±1.3
HD 222794	5623±70	3.94±0.1	–0.69±0.07	–0.40±0.05	3.66±0.08	0.86±0.03	12.5±1.1

3. Long-lived or not long-lived

To understand how the Galaxy was formed and then evolved we must now try to better assess the relative contributions of thick-disk and thin-disk stars. This not only requires to identify the local thick-disk stars – in fact only a handful of objects – but also to find the long-lived thin-disk stars. As mentioned above, it was found something of a surprise that the detailed analyses reveal most G stars to become degenerates *within* 14 Gyr (cf. Fig. 6). Indeed even some K stars, such as 83 Leo A, can be short-lived! This all has to do with the notorious shortcomings of spectral classification, which we can note here only in passing. Its net effect however is, that the temporally unbiased local normalization of the thick disk is as high as 14...18%. Thus, if one adopts h_r=3.0 kpc for the scale length of the thin disk, and a disk scale-height ratio ∼4.7 according to Phleps et al. (2000), the mass of the thick disk is *comparable* to that of the thin disk!

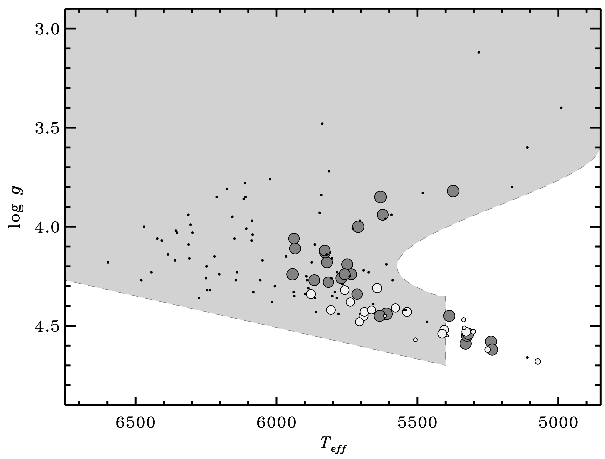

Figure 6. *Kiel diagram* of the long-lived *disk* stars. Grayscaling and symbol sizes have the same meaning as in Fig. 2, except for the small black dots, which depict the position of either halo or short-lived disk stars. Shading indicates the selected region of the volume-limited sample, with T_{eff} = 5400 K taken as the lower limit on the main sequence.

As illustrated in Fig. 7 this result is also somewhat dependent on the rather unknown scale length of the thick disk, and, of course, it assumes an invariant initial mass function. The latter assumption, is, as discussed in more detail in Fuhrmann (2001), however presumably not fulfilled. Instead, there is good evidence from the work of Favata, Micela, & Sciortino (1997) for a thick disk with a low-mass cut at $M \sim 0.7\ M_\odot$ and hence for a top-heavy initial mass function. The resulting high star formation rate at the very early epoch of the Galaxy implies, in turn, a strong Galactic wind and gives thus rise to the hot, massive, and considerably metal-enriched intragroup or intracluster deposits. In this scenario the thick disk is nowadays a massive remnant-dominated population, very much alike as envisaged in Larson (1986). It may thus not only account for a good deal of the massive compact halo objects (cf. also Gates & Gyuk 2001) – which might then mutate to massive compact thick-disk objects[1] – but particularly implies that most of the recently detected *blue* white dwarfs (Hansen 1998) on various deep fields (e.g. Knox, Hawkins, & Hambly 1999, Ibata et al. 1999, 2000, Méndez & Minniti 2000, Scholz et al. 2000, Harris et al. 2001) have their origin in this ancient population.

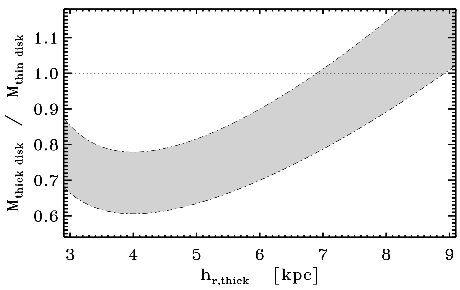

Figure 7. Disk mass ratio as a function of the scale length of the thick disk. Shading indicates the mass range that results from a local density of 14-18% of thick-disk vs thin-disk stars.

At the end, we come back to WD 0346+246, the nearby white dwarf of Hambly, Smartt, & Hodgkin (1997) in Fig. 1 (see also Fontaine, Brassard, & Bergeron, this volume), as well as another very cool degenerate LHS 3250, that was recently discussed in Harris et al. (1999). We show simulations for both in Fig. 8, the Toomre diagram of our sample stars. With Galactic coordinates ($l = 166^o$, $b = -23^o$) the unknown radial velocity of WD 0346+246 is mostly projected into the U component of the space velocity. The radial velocity of LHS 3250, in turn, varies along its V component. Although, of course, by adopting extremely large radial velocities one can always arrive at halo kinematics, the fact that both white dwarfs are very nearby make the assumption of a thick-disk membership at least a factor ten more likely than that of halo objects. We have thus simulated in Fig. 8 the velocity ranges $-100 < U < +100$ km s^{-1} and $-160 < V < -30$ km s^{-1} that encompass our current sample (N$\sim$30) of identified thick-disk stars. From inspection of Fig. 8 it is clear that both white dwarfs are indeed *bona fide* thick-disk members, thereby strongly supporting the notion that our "home" is embedded in a huge coffin of dead stars.

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[1]for those who like acronyms, we are then consequently looking for "MACTDOs"

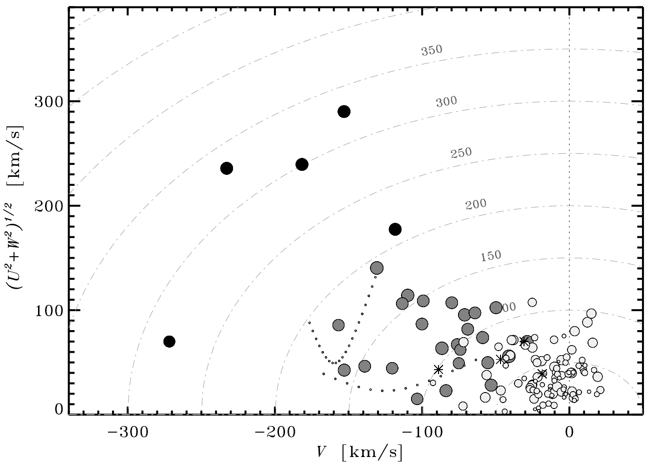

Figure 8. Toomre diagram for the stars of Fig. 2. Circles delineate constant peculiar space velocities $v_{pec} = (U^2 + V^2 + W^2)^{1/2}$ in steps of $\Delta v_{pec} = 50$ km s^{-1}. Likely positions of the *bona fide* thick-disk white dwarfs WD 0346+246 (v-shaped) and LHS 3250 (lower, flat curve) are given by the two dotted traces in steps of $\Delta RV = 10$ km s^{-1}.

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