FGK Stars of the Solar Neighborhood

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Among the various fields in the physical sciences, astronomy is presumably the one most liable to selection effects. It is well known, for instance, that the existence of dark objects around the bright, nearby stars Sirius and Procyon was already suspected in the midst of the 19th century. But when they were ultimately discovered astronomers called them ironically "white" dwarfs. The existence of even dimmer objects – so-called "brown" dwarfs – was only realized a century from then. Nowadays it appears however that these low-mass objects may even outnumber the ordinary stars. Since the late 1990s astrophysics is now confronted with another class of objects, white dwarfs by nature, but extremely dim, tiny, mostly crystallized, and massive, and it appears that these degenerate "black" dwarfs play actually a key role in the formation of the Milky Way Galaxy.

Since white dwarfs, brown dwarfs, and black dwarfs came only into play with the more sophisticated methods of observations, the consensus is that stellar tracers can only provide a meaningful guide for an understanding of the Milky Way's history if all potential biases can be excluded from the outset. This in mind, there can be no doubt that the solar neighborhood must be the most suited astrophysical laboratory in this context, the *sine qua non*, so to speak, that enforces one to work on the bright stellar objects.

But it is just another selection effect that – at variance with some expectations – the bulk of these tracers are not to be found in the famous *Bright Star Catalogue*, the latter being essentially a source for massive and/or evolved stars spread over large distances.

Volume-complete samples of nearby stars focus instead on fairly inconspicuous objects, most of them at best equipped with ordinary HD numbers. If we go out to 25 pc – the limit of the Gliese & Jahreiß *Catalogue of Nearby Stars* – and down to early K-type dwarfs of, say, $M_V \leq 6.0$, most of them will not be visible without any instrumentation. It is also worth mentioning that the so-defined sample is only known since 1997 – the year of the release of the Hipparcos data – as no less than one half of the objects originates from distances between 20 and 25 pc, which in turn requires accurate parallax measurements.

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Now, on closer inspection we notice that more than 95 per cent of these stars assemble in a fairly flat or “thin” disk. We witness this stellar disk in the sky and we are used to call it the Milky Way band. Only a minority, a small fraction of about five per cent of the local FGK stars, does not stick to this familiar picture. We could ignore these few “mavericks”, but this might be a bad advice since – and the attentive reader may already guess the reason why – what we observe, even in the nearby sky, is actually another selection effect.

But who is playing tricks on us? Why is the stars’ light – even in a volume-limited sample designed just to avoid these selection effects – again a bad guide? Why is then ”light traces mass” nothing but a misleading phrase? The answer is simple and straight: it is *time*, it is the billions of years of Galactic evolution that gradually blurs the set if we don’t care for it. And the above mentioned stellar “mavericks”? They are the ambassadors of the early Milky Way epoch, the survivors of an ancient phase of vigorous star formation, such that our present epoch appears at best as the boring aftermath of a truly bright past.

At this point the reader may wonder: what is the observational evidence for a picture like this? What is the unequivocal fossil record from the nearby stars? To answer these and related questions it is important to understand that if we intend to trace the Milky Way’s history it is not only to have a well-defined sample such as the one above at one’s disposal. It is also of key importance to work on high-resolution, high signal-to-noise spectroscopy, it is important to aim at redundancy with all kind of observations, and it is particularly important to refer to a calibrating star with accurately known properties for analyses that are throughout differential. This particular star most favourably evolves on times scales of giga years, it is then most favourably an F- or G-type object, in other words: it is our Sun.

Since about a decade FOCES is the high resolution échelle spectrograph on Calar Alto. And as the Hipparcos astrometry became available soon after FOCES went into operation, there was the immediate challenge to work on high-resolution spectroscopy of a statistically meaningful, volume-limited, and *complete* sample of nearby FGK stars. Now in 2004 about two-thirds of the more than 400 stars and star systems of the relevant sample have been analyzed and most of the observations are secured.

Yet it was as early as 1998, after some fifty nearby FGK stars had been analyzed, that there was strong evidence for the local inventory of stars to be manufactured of essentially two distinct populations. Thus – and much as originally envisioned by Jan Oort in the 1920s – there is, first, the above mentioned and apparently dominating “thin disk”, with the Sun as a typical thin-disk member; and second, there is another disk-like population, relatively metal-rich, fairly co-rotating with the thin disk, but much less confined to the

Galactic plane, and evidently consisting of very old objects. And these "thick disk" stars, as Gilmore & Reid first dubbed them in 1983, turned out to be the real tell-taling objects for the formation picture of the Milky Way.

The evidence that the stars of the thick disk may be extremely old received much support as we began a dedicated search for nearby subgiants of that population. Three *bona fide* candidates were soon identified and a few weeks later, in January 2000, observed with FOCES. The basic stellar parameters then in hand, stellar interior calculations by Jan Bernkopf revealed all these subgiants to be older than 12 billion years. Any counterparts of the thin disk in turn proved to be younger than about eight billion years. No doubt, this was compelling evidence for a hiatus in star formation in our solar neighborhood for no less than three billion years!

So, the question was: what could be the reason for this huge star formation gap? And a convincing answer was offered upon discriminating between so-called *long-lived* and *short-lived* thin-disk stars. A distinction like this is necessary as the stars of the thick disk are almost 10 billion years older compared to an average thin-disk star. Hence for a meaningful comparison of the number of stars that were ever formed in the thick disk, we must count all stars that are still alive as well as all objects that have since become stellar remnants. As any astrophysicist who is a bit familiar with the characteristics of white dwarfs may know, this is a hopeless undertaking. What one can do instead is however to follow the evolution of the existing thin-disk FGK stars up to the thick-disk age, i.e. up to about 12 or 13 billion years and then ask: how many of them will still be there after that time span? In doing so the Sun, for instance, is a short-lived object. But, much to our surprise, it turned out that a clear majority of our whole FGK star sample must be considered short-lived as well.

In the end it became clear that taking the short-lived/long-lived selection effect into account, no less than 20 per cent of the nearby stars may originate from the thick disk. Now, keeping in mind the eponymous characteristic of that population, meaning that it has a larger scale height, this caused the provocative finding that the thick disk must be a very massive component of the Milky Way Galaxy. For the reader's convenience we illustrate this result in Fig. 1 with a light blue color for the thin-disk stars and with dark blue for the thick-disk component. Inspection of this figure clearly demonstrates: the thick disk provides a much different mass to light ratio, in other words, it represents the dark side of the Milky Way.

If, however, the thick disk has formed a comparative number of stars as the thin disk but on a significantly shorter time scale, the inevitable consequence is that the star formation rate in the early Milky Way epoch must have been much higher. There is indeed good evidence that, even more, the thick-disk's

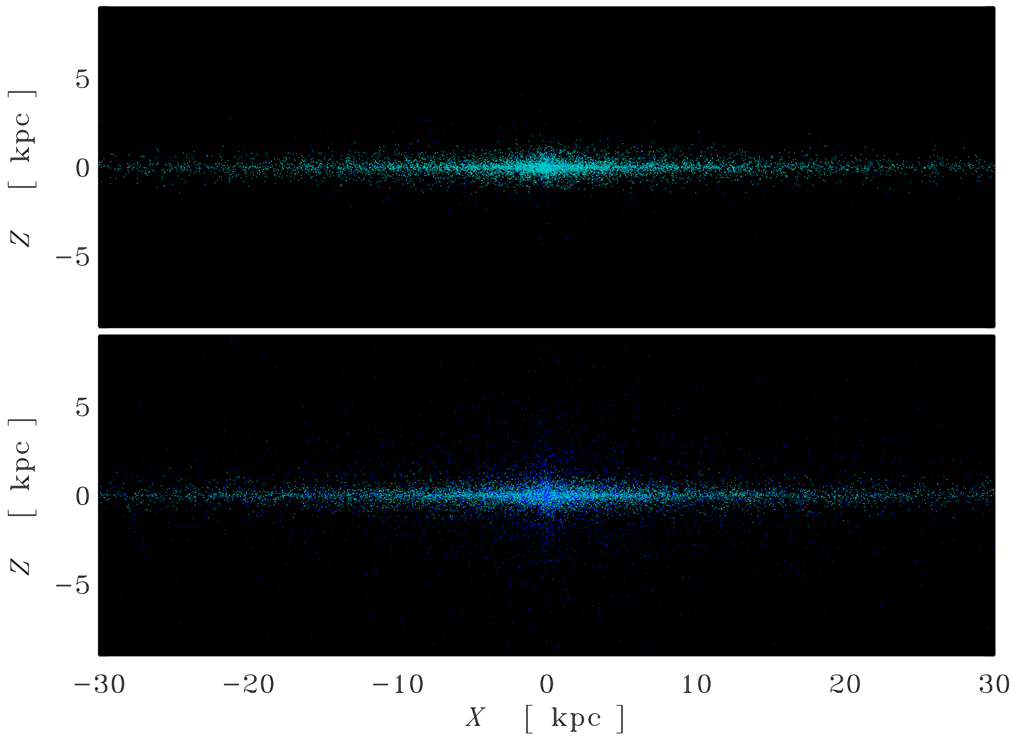

Fig. 1. Visualization of a double-exponential Milky Way with a 2% local normalization (top) of thick-disk stars (depicted in dark blue) as suggested in the original work by Gilmore & Reid (1983, MNRAS, 202, 1025), and a 20% local normalization (bottom) as implied from high-resolution, high signal-to-noise spectroscopy of the nearby FGK stars. Adopted scale lengths and heights are $h_{r,thin} = 3$ kpc, $h_{r,thick} = 4$ kpc, $h_{z,thin} = 300$ pc, $h_{z,thick} = 1200$ pc. Note that this map refers only to the *positions* of the stars; an illustration in which each point includes as well the star's *luminosity* would render the thick-disk population fairly invisible – in particular so in the likely case of a top-heavy initial mass function. *(from Fuhrmann 2004, AN 325, 3)*

initial mass function was also biased to more massive stars. A bright time, then, for the young Milky Way Galaxy, but likewise a straight explanation why this phase of vigorous star formation came soon to an end for billions of years. At the same time, the massive thick disk offers a natural explanation for the Sun's ~ 220 km s^{-1} orbital rotation around the Galactic center, i.e. one without any reference to non-baryonic dark matter. And although it appears that the *stellar* thick-disk component cannot account for a flat Milky Way rotation curve, it is also known that there is considerably more non-stellar matter in the intragroup or intracluster medium; and interestingly, the metal enrichment of this component is quite comparable with that of the stellar thick disk.

Now the reader will ask: if the thick disk has actually formed that many stellar objects, what are the prospects to observe those that turned to dead stars, as the bulk of the thick-disk white dwarfs must still be around? This question leads us back to the "black" dwarfs that we have mentioned at the beginning. There are indeed nearby white dwarfs that have cooled down to effective temperatures of 4000 K and below, we have just started to discern them. The first object of this class, WD 0346+246, was actually a serendipitous discovery in 1997, but many others have been detected since then. Unfortunately, these objects are not only the coolest white dwarfs, but also – by virtue of Chandrasekhar's mass-radius relation – the smallest degenerates of its class. It is therefore a tremendous task to search for these diamonds in the sky, but as illustrated in Fig. 2, this search is no doubt much rewarding.

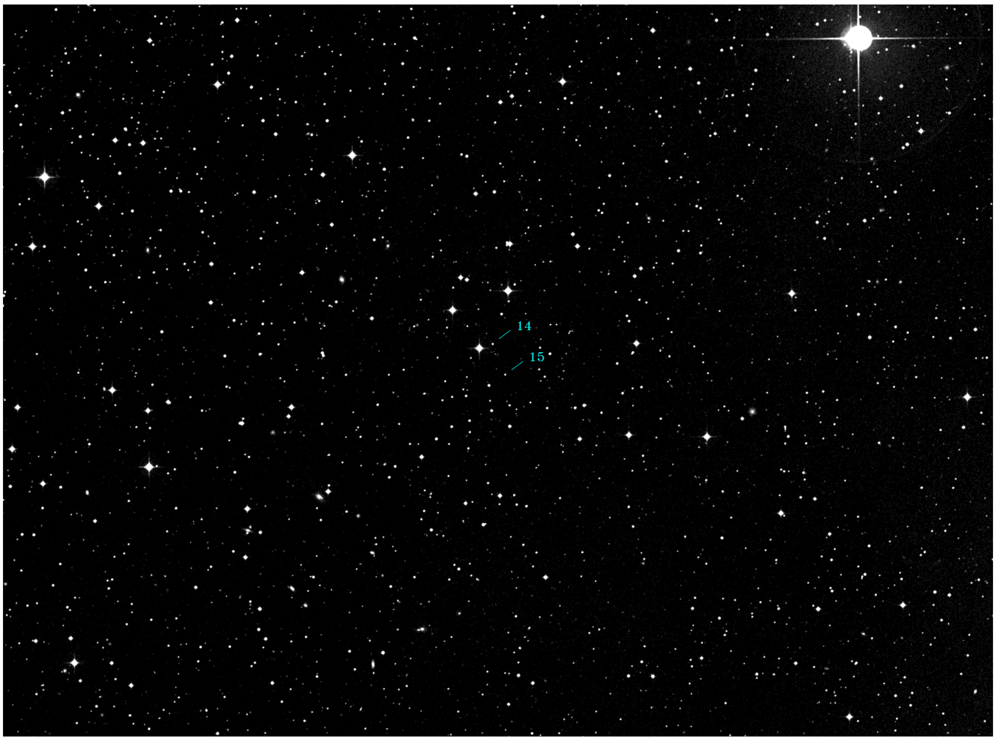

Fig. 2. Field around the very nearby ($9 < d < 15$ pc) cool white dwarf pair SSSPM J2231–7514 and SSSPM J2231–7515 at $V = 16.60$ and $V = 16.87$ that was recently detected by Scholz et al. (2002, ApJ 565, 539). The high space velocity and low effective temperatures ($T_{eff} < 4000$ K) of this common-proper-motion pair ($\rho \sim 93''$) both provide striking evidence for a thick-disk membership.