DISENTANGLING THE HERCULES STREAM

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ABSTRACT

Using high-resolution spectra of nearby F and G dwarf stars, we have investigated the detailed abundance and age structure of the Hercules stream. We find that the stars in the stream have a wide range of stellar ages, metallicities, and element abundances. By comparing to existing samples of stars in the solar neighborhood with kinematics typical of the Galactic thin and thick disks, we find that the properties of the Hercules stream distinctly separate into the abundance and age trends of the two disks. Hence, we find it unlikely that the Hercules stream is a unique Galactic stellar population but rather is a mixture of thin and thick disk stars. This points toward a dynamical origin for the Hercules stream, probably caused by the Galactic bar.

Subject headings: Galaxy: disk — Galaxy: evolution — Galaxy: formation — solar neighborhood — stars: abundances — stars: kinematics

1. INTRODUCTION

The stellar velocity distribution in the solar neighborhood is manifoldly structured (see, e.g., Dehnen 1998; Skuljan et al. 1999; Famaey et al. 2005; Helmi et al. 2006; Arifyanto & Fuchs 2006). Prominent features are the Pleiades-Hyades supercluster, the Sirius cluster, and the Hercules stream (also known as the u-anomaly). From a large sample of nearby G and K giants, Famaey et al. (2005) found that the Hercules stream makes up approximately 6% of the stars in the solar neighborhood and that they have a net drift of \( \sim 40 \) km s\(^{-1}\) directed radially away from the Galactic center. Just as for the Galactic thick disk, their orbital velocities around the Galaxy lag behind the local standard of rest (LSR) by \( \sim 50 \) km s\(^{-1}\) (see also Ecuvillon et al. [2007], who found similar properties for the Hercules stream using nearby F and G dwarf stars).

Numerical simulations have shown that the excess of stars at \((U_{\text{LSR}}, V_{\text{LSR}}) = (-40, -50)\) km s\(^{-1}\) can be explained as a signature of the Galactic bar (e.g., Raboud et al. 1998; Dehnen 1999, 2000; Fux 2001). If it is a chaotic process, where stars get gravitationally scattered from the inner Galactic regions by the bar, or if they are coupled to the outer Lindblad resonance of the bar, is, however, uncertain (Fux 2001). Either way, this points to an origin for the Hercules stream that is related to the inner disk regions. So, is the Hercules stream a distinct stellar population with a unique origin and evolutionary history, or is it a mixture of different populations?

Using available data in the literature, Soubiran & Girard (2005) found that most Hercules stars tend to follow the thin disk abundance trends. They, however, concluded that the existing knowledge about the chemical properties of the Hercules stream did not admit safe conclusions about the origin of the stream. We note that the distinct and well-separated chemical signatures that the two disks exhibit (Fuhrmann 2004; Bensby et al. 2003, 2004a, 2005; Mishenina et al. 2004; Feltzing et al. 2007) are less separated in the abundance plots in Soubiran & Girard (2005; compare, e.g., the abundance trends for oxygen in their Fig. 10 with Fig. 10 in Bensby et al. 2004a). This is likely an effect of merging different data sets, each containing different systematic errors.

To further study the origin of the Hercules stream, we have observed a sample of 60 F and G dwarf stars, all kinematically selected to be members of the stream. By performing a strictly differential detailed abundance analysis of the Hercules stream stars relative to stars of the two disk populations previously studied by us (Bensby et al. 2003, 2005), we minimize uncertainties due to systematic errors in the analysis.

In this Letter, we focus on two elements that show distinct abundance trends for the thin and thick disks: Mg (e.g., Fuhrmann 2004; Feltzing et al. 2003; Bensby et al. 2003, 2005) and Ba (e.g., Mashonkina et al. 2003; Bensby et al. 2005). Other \( \alpha \)-elements, iron peak elements, and \( r \)- and \( s \)-process elements will be presented in an upcoming paper (T. Bensby et al. 2007, in preparation), where we will also describe the observations, data reductions, abundance analysis, etc. (see, however, Bensby et al. [2007], where the results for a few other elements are briefly presented).

2. IDENTIFICATION OF HERCULES STREAM STARS

We used the kinematical method from Bensby et al. (2003, 2005) to define a sample of Hercules stream stars. This method assumes that a stellar population has a Gaussian velocity distribution and constitutes a certain fraction of the stars in the solar neighborhood. Assuming that the solar neighborhood is a sole mixture of the thin disk, the thick disk, the Hercules stream, and the halo, it is then possible to calculate the probabilities for individual stars (with known space velocities) to belong to either of the populations. We selected Hercules stream stars as those stars that have probabilities of belonging to the Hercules stream that are at least as large as twice the probabilities of belonging to any of the other populations.

The Nordström et al. (2004) catalog contains kinematic information for 13,240 F and G dwarf stars in the solar neighborhood. Considering the full catalog, we are able to kinematically tag 12,040 stars as likely thin disk members, 438 as likely thick disk members, and 112 as likely Hercules stream members. Figure 1 shows a contour plot of the distribution for all stars in the catalog (thin solid lines) and density contours for the thick disk (thick solid lines).

The 60 Hercules stream stars in this study are shown in a Toomre diagram in Figure 2 together with the 102 thin and thick disk stars from Bensby et al. (2003, 2005). Our Hercules
stream sample is well confined and forms a distinct kinematical group. None of the thin and thick disk stars in Bensby et al. (2003, 2005) can be classified as Hercules stream stars.

3. BRIEF SUMMARY OF OBSERVATIONS, ABUNDANCE ANALYSIS, AND AGE DETERMINATIONS

High-resolution \((R \approx 65,000)\), high-quality \((S/N \approx 250)\) echelle spectra were obtained for 60 F and G dwarfs by T. B. in 2006 January, April, and August with the MIKE spectrograph (Bernstein et al. 2003) on the Magellan Clay 6.5 m telescope at the Las Campanas Observatory in Chile. Solar spectra were obtained during the runs by observing the asteroid Vesta (in January), the Jovian moon Ganymede (in April), and the asteroid Ceres (in August).

For the abundance analysis, we used the Uppsala MARCS stellar model atmospheres (Gustafsson et al. 1975; Edvardsson et al. 1993; Asplund et al. 1997). The chemical compositions of the models were scaled with metallicity relative to the standard solar abundances as given in Asplund et al. (2005) but of the models were scaled with metallicity relative to the standard solar abundances as given in Asplund et al. (1997). Final abundances were normalized on a line-by-line basis with our solar values as reference and then averaged for each element.

Stellar ages were determined from the Yonsei-Yale \((Y)\) \(\alpha\)-enhanced isochrones (Kim et al. 2002; Demarque et al. 2004) in the \(T_{\text{eff}}-M_{\star}\) plane. Upper and lower limits on the ages were estimated from the error bars due to an uncertainty of \(\pm 70\) K in \(T_{\text{eff}}\) and the uncertainty in \(M_{\star}\) due to the error in the parallax (see Bensby et al. 2003).

4. RESULTS AND DISCUSSION

Our abundance results are shown in Figures 3a–3d. While the [Mg/Fe] versus [Fe/H] trends for the thin and thick disks are clearly separated, they do merge as [Fe/H] \(\approx 0\) is reached. The [Ba/Fe] versus [Fe/H] trend, on the other hand, keeps the two disks well separated until [Fe/H] \(\approx 0.1\). The separation between the thin and thick disks is larger when Mg is used as the reference element.

The observed thick disk [Mg/Fe] versus [Fe/H] trend is due to the different production sites of Mg and Fe in Types II and Ia supernovae, respectively, operating at different timescales (see, e.g., McWilliam 1997).

The solar system abundance of Ba has been built up by two different production mechanisms that work on different timescales: the \(r\)-process, which dominated at low metallicities \([\text{[Fe/H]} \leq -1.5]\) and contributed \(\sim 20\%\), and the \(s\)-process, which dominated at higher metallicities and contributed \(\sim 80\%\) (Travaglio et al. 1999). The increase (or the “bump”) that can be seen in the [Ba/Fe]-[Fe/H] trend for the thin disk is likely to be a signature of when the \(s\)-process enrichment from asymptotic giant branch stars became significant (Travaglio et al. 1999). For other environments, the mixture may be different; compare, e.g., the Ba and Eu trends in Mashonkina et al. (2003). For the thick disk, the flat [Ba/Fe] trend could indicate that the \(s\)-process did not play a significant role in the Ba enrichment of the gas from which the thick disk formed (and hence the lack of the bump).

4.1. Abundance Bimodality?

A first impression is that most Hercules stream stars follow the trends as outlined by the thick disk. In the [Ba/Fe] versus [Fe/H] plot, this is especially evident, even up to metallicities as high as [Fe/H] \(\approx +0.1\). In the [Mg/Fe] versus [Fe/H] plot, the Hercules stars follow the thick disk trend up to [Fe/H] \(\approx -0.2\) and may then show signs of mixing between the two disks for higher metallicities. The [Fe/Mg] and [Ba/Mg] trends with [Mg/H] give similar results.

Apart from one star, HIP 44927, we do not find any Hercules stream stars that deviate from the thin and thick disk abundance trends. Recent observations have shown that bulge stars have large \(\alpha\)-enrichments at solar and supersolar metallicities (Fulbright et al. 2006; Zoccali et al. 2006). This compares very well with what we see for HIP 44927, indicating that we might have picked up a bulge star in our Hercules sample. Its age, 3.8+0.4−0.4 Gyr, is, however, inconsistent with the bulge being an old population. But there are indications that the bulge could contain stars as young as a few hundred million years (Gilmore 2003).
4.2. Age Bimodality?

In Figure 4, we plot stellar ages versus [Fe/H]. At metallicities below [Fe/H] = 0, it appears that the Hercules stream divides into two (or maybe three) branches: one that follows the thick disk age trend (the downward age-metallicity relation we see for the thick disk trend was seen in Bensby et al. [2004b] and then verified by Haywood [2006] and Schuster et al. [2006]); one that follows the thin disk age trend; and a few stars (four or five) that tend to have high ages of ~15 Gyr in the interval −0.4 ≤ [Fe/H] ≤ 0. Once again, we see that the stars of the Hercules stream follow the trends outlined by the stars with kinematics typical of the thin and thick disks. As the uncertainties in the age determinations are notoriously difficult to estimate (see, e.g., Jørgensen & Lindegren 2005), and generally come out too small when using standard methods, one should be careful to make far-fetched interpretations about the few outliers.

4.3. Origin of the Hercules Stream

Some Galactic streams may have origins due to minor mergers (e.g., Navarro et al. 2004). Could this be the case for the Hercules stream? Such a merging system must then have had chemical properties similar to the present Galactic disks. Thus, such a merging galaxy must have had chemical properties that depart considerably from those of local dwarf galaxies (see, e.g., Venn et al. 2004) and would presumably be more similar to a major spiral galaxy. There is no observational evidence that such a substantial merger occurred in the Milky Way during the last 10 Gyr (Gilmore et al. 2002). Instead, our results strongly suggest that the Hercules stream has a dynamical origin, presumably due to the dynamical effects of the Galactic bar, and it may consist of stars from the inner Galactic disks.

Are we then tracing the inner thin disk or the inner thick disk? As no detailed abundance data for the inner disks have been obtained yet, only indirect evidence is available. The thick disk velocity dispersion is about twice that of the thin disk, but its rotational velocity is just ~80% of that of the thin disk. According to the Toomre stability criterion \( Q \propto V_{\text{rot}}(\sigma/R)_{1964} \), the thick disk should be slightly more stable than the thin disk \( Q_{\text{thick disk}} \approx 1.6Q_{\text{thin disk}} \) and less disturbed by gravitational influences from the Galactic bar. Since the inner thin disk is thought to have more evolved stellar populations, as judged from its abundance and age gradients, the higher ages and [α/Fe] ratios of the Hercules stream seem consistent with an inner thin disk origin. On the other hand, the abundance patterns are better matched to the thick disk in general, and it is plausible that the thick disk also has a metallicity gradient,
which would then match the relative number of high-metallicity stars in the stream.

As the stars of the Hercules stream display the distinct abundance and age trends of both the thin and thick disk stars, it is likely that it actually is a mixture of the two disks. This is also suggested by the Toomre stability criterion being similar for the two disk components. A preliminary investigation of the relationship between the ages and abundance ratios for our stars in the Hercules stream shows that they are correlated in a way expected for a Hercules stream composed of Galactic disk stars (for more details, see T. Bensby et al. 2007, in preparation).

5. CONCLUSION

The Hercules stream is unique in the sense that it forms a well-defined enhancement in the velocity distribution of nearby stars. However, large ranges in stellar ages and elemental abundances indicate that it is not a distinct stellar population. Instead, as the age and abundance trends in the Hercules stream are similar to the trends in the thin and thick disks, we conclude that the Hercules stream is a mixture of thin and thick disk stars. This result is in accordance with models that suggest that the kinematical properties of the Hercules stream are coupled to dynamical interactions with the Galactic bar. Whether the Hercules stream stars have a real inner disk origin or whether they are nearby stars whose kinematics are an effect of the outer Lindblad resonance of the bar, which may be situated near the solar neighborhood (Dehnen 2000), is unclear. Further insights into this problem could be gained by making comparisons to detailed abundance data from the in situ inner Galactic thin and thick disks. As such data currently are unavailable, we have initiated a study to obtain them.

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