STRUCTURE OF THE GALACTIC HALO TOWARDS THE NORTH GALACTIC POLE

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arXiv:astro-ph/0410736 v1 29 Oct 2004

ABSTRACT

We have used RR Lyrae and Blue HB stars as tracers of the old Galactic halo, in order to study the halo structure and the galactic rotation as a function of height above the plane. Our sample includes 40 RR Lyrae and 80 BHB stars that are about 2 to 15 kpc above the plane, in a roughly 250 deg^2 area around the North Galactic Pole (NGP). We use proper motions (derived from the GSC-II database) and radial velocities to determine the rotation of the halo. From the whole sample the motion appears to be significantly more retrograde than the samples in the solar neighborhood, confirming Majewski (1992) results and our own preliminary results based on 1/3 the present sample (Kinman et al. 2003; Spagna et al. 2003). However, the better statistics has now revealed the likely existence of two components, whose characteristics need an accurate analysis of systematic errors on the proper motions in order to be assessed in detail.

Key words: Kinematics, Galactic structure, RR Lyrae, Blue HB stars.

1. INTRODUCTION

The kinematics of halo stars in the solar neighborhood ($Z \leq 2$ kpc) is well established: mean heliocentric rotation velocity $\langle V \rangle \sim -220 \pm 10$ km s^{-1} (from RR Lyrae and K giant stars, cf. Martin & Morrison 1998; Layden et al. 1996; Chiba & Yoshii 1998; Dambis & Rastorguev 2001).
From halo stars observed at larger distances ($Z \geq 5$ kpc), the kinematics of the high halo is less clear: the mean rotation was found retrograde ($\langle V \rangle = -275 \pm 16$ km s^{-1}) by Majewski (1992) and Majewski, Munn & Hawley (1996) in SA 57 near the NGP, and confirmed by Gilmore, Wyse & Norris (2002) in other directions.
However, other estimates calculated from orbital parameters (Carney 1999; Chiba & Beers 2000), as well as Sirko et al. (2004) recent analysis of very distant BHB stars from the SDSS, do not support any significant halo rotation. The present work attempts to resolve this discrepancy; it grew from earlier studies of halo stars in the North Galactic Cap (Kinman et al. 1996) which confirmed the streaming motion (in the W vector) that Majewski found for his subdwarf sample in SA 57.
So the questions are: *i) Is the high halo in retrograde rotation? ii) Is there any halo substructure that may mimic retrograde rotation in some directions?*

*NOAO is operated by AURA Inc. under contract with the National Science Foundation.

2. OUR DATA

Our sample of halo tracers consists of 80 blue HB (BHB) and 40 RR Lyrae (RRL) stars spread over an area of approximately $22^\circ \times 12^\circ$ around the NGP, at a distance $Z \simeq 1.5$ to ~ 16 kpc above the galactic plane. This area is the combination of 6 POSS fields where proper motions from the GSC-II database were measured (see later), and is shown in Fig. 1. We refer the reader to Kinman et al. (2003) for details on the target selection.
For these stars we have:

- Absolute Magnitudes ($\pm$0.2 mag) $\Longrightarrow$ distances. In particular, $E(B-V)$ values are from Schlegel, Finkbeiner & Davies (1998); for the BHB stars, M_V have been estimated from the M_V vs. $(B-V)$ relation given by Preston, Shectman & Beers (1991) adjusted so that $M_V = 0.6$ at $(B-V) = 0.2$; for the RRab stars, we used $M_V = 0.22\,[Fe/H] + 0.93$ if $[Fe/H]$ was available, or $M_V = -1.619 \log P + 0.20$ (Kinman 2002) if only the period was available, or else $M_V = 0.6$. For the RRc stars it is assumed that $M_V = 0.6$.

- Proper Motions (formal r.m.s. errors ≤ 3 mas yr^{-1}). These are based on the plate material used for the construction of the GSC-II catalogue using the method described in Spagna et al. (1996).

- Radial velocities ($\pm 10 - 50$ km s^{-1}), obtained at the 4m-RC (KPNO) and 3.5m-LRS (TNG).

From the above data we have derived heliocentric space velocity components U, V, and W using the program by Johnson & Soderblom (1987, updated version for the J2000 reference frame), with a further update of the transformation matrix derived from the Volume 1 of the Hipparcos data catalogue. Finally, the heliocentric UVW velocities have been corrected adopting the solar motion $(\mathrm{U,V,W})_\odot = (10.0, 5.25, 7.17)$ km s^{-1} with respect to

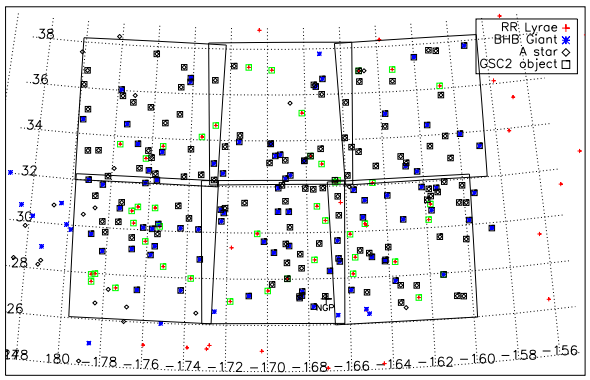

Figure 1. The POSS fields at the NGP where we have performed the present analysis. Right ascension, along the X axis, is expressed in arc degrees.

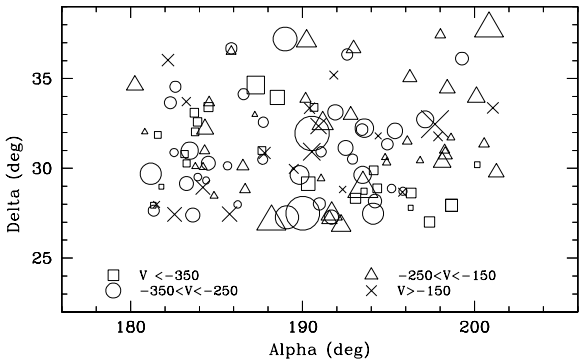

Figure 2. Rotational velocity V after correction for pm systematic errors in each field, as a function of position and distance. Different symbols represent different V intervals, and the size of the symbol is proportional to the parallax.

the LSR, from Dehnen & Binney (1998).

3. ERRORS

An error in M_V will not have a large effect on the derived U and V velocities (a total uncertainty of as much as ± 0.2 mag would correspond to $\pm 10\%$ in the distance and hence V). The U and V velocities are nearly independent of the radial velocity in the direction of the NGP.
In this case, the greatest uncertainty in V will come from errors in the proper motions.
Therefore it is important to test the systematic errors in the proper motion (pm) data using the QSOs and galaxies present in the observed fields. Proper motions have been derived for 65 QSOs and 50 galaxies, omitting a few objects whose pm or errors exceed 10 mas yr^{-1} (Kinman et al. 2003). These 115 objects, which should have zero proper motion, have the following average GSC-II pm:

$$\begin{cases} \mu_\alpha &= -0.109 \pm 0.122 \text{ mas yr}^{-1} \\ \mu_\delta &= -0.422 \pm 0.162 \text{ mas yr}^{-1} \end{cases} \quad (1)$$

Presumably these systematic errors (< 1 mas yr^{-1}, comparable to those of the pm measured by Hipparcos for much brighter stars) apply to our program stars over the same sky area and a similar magnitude range.
A preliminary check shows systematic errors of similar size in our individual fields. Although these individual field errors are necessarily more poorly determined, we have used them to correct our BHB and RRL motions in this preliminary analysis. The distribution of V shows little systematic trend with either position or distance (see Fig. 2), so these corrections introduce little or no bias.
Currently, the accuracy of the GSC-II proper motions represents the best available for the large-field surveys that are needed for studies of Galactic structure; higher precision is necessary but must await dedicated space missions such as GAIA.

4. RESULTS

In calculating the UVW vectors we put the radial velocity equal to zero (with an error of ± 150 km s^{-1}) if no radial velocity was available. In such cases (7 RRL stars at $Z > 4$ kpc), the U and V vectors should be scarcely affected but the W vector is discarded. For a better characterization of our stars, we have also trimmed 10% of the most deviating stars from our sample when estimating mean values or distributions. We have found that trimming has little effect on the mean values of U, V and W, although it does reduce the velocity dispersions $\sigma_{\rm U}$, $\sigma_{\rm V}$ and $\sigma_{\rm W}$. In Table 1 we compare the mean heliocentric UVW values of our entire sample and of the subsample at $Z > 4$ kpc with those found by Martin & Morrison (1998) for their HALO2 sample of local RRL stars (in all cases 10% of outliers were trimmed). We also show the W–U, W–V and U–V plots in Fig. 3.
A KMM test (cf. Ashman, Bird & Zepf 1994) on the entire trimmed sample gives *about 90% probability that the sample is formed by two groups, one containing* $\sim 56\%$ *of the stars with estimated* $\langle V \rangle = -316 \pm 8$ *km s*$^{-1}$, *and the other containing* $\sim 44\%$ *of the stars with estimated* $\langle V \rangle = -177 \pm 9$ *km s*$^{-1}$, *same dispersion* $\sigma = 61$ *km s*$^{-1}$.
We show in Fig. 4 the distributions of V as a function of the distance Z above the Galactic plane, where the bimodal shape is evident at all distance intervals as well as for the entire sample.

5. CONCLUSIONS

Our present results, based on a 3 times larger sample than our previous preliminary analysis (Kinman et al. 2003; Spagna et al. 2003), seem to lead to the following conclusions:

- For $Z < 4$ kpc, the mean rotation V is close to that found for the halo in the solar neighborhood (see corresponding panel in Fig. 4).

- For $Z > 4$ kpc, the *mean rotation is significantly more retrograde* - in agreement with Majewski's earlier finding. This seems to be due to a *group of very retrograde stars*, whose relative importance increases with Z with respect to the dissipative halo component, and is particularly significant in the range $Z = 4 - 10$ kpc (see Fig. 4). Therefore, this is likely to be a *local substructure, maybe associated with an accretion event*,

Table 1. Space motion vectors for the present halo stellar sample, and for a local halo sample for comparison.

U	V	W	$\sigma_{\rm u}$	$\sigma_{\rm v}$	$\sigma_{\rm w}$	No. of stars	Source
-12 ± 15	-256 ± 9	-10 ± 9	153	92	91	108 (101 for W)	Present sample
$+4\pm15$	-264 ± 9	-20 ± 9	158	91	95	82 (75 for W)	Present sample at Z $>$ 4 kpc
-1 ± 26	-219 ± 24	-5 ± 10	193	91	96	84	Martin & Morrison (1998) local sample

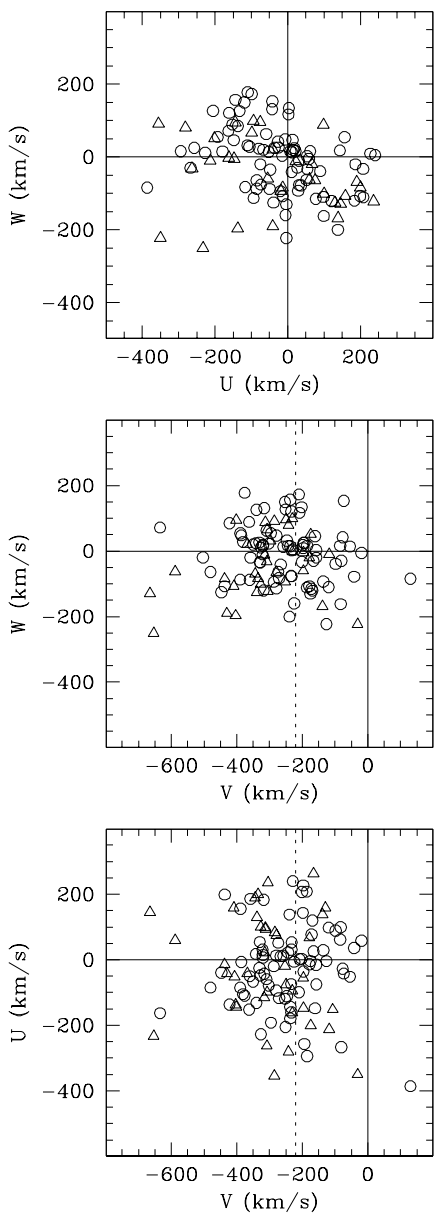

Figure 3. Plots W–U, W–V and U–V of the entire stellar sample, including the "outliers" that were trimmed out in the previous considerations. Triangles and circles represent RR Lyrae and BHB stars, respectively. The mean heliocentric rotation velocity $\langle V \rangle \sim -220 \pm 10$ km s^{-1} is reported in the V plots (shaded line). Note that in the different velocity planes the contamination from disk stars is always quite small.

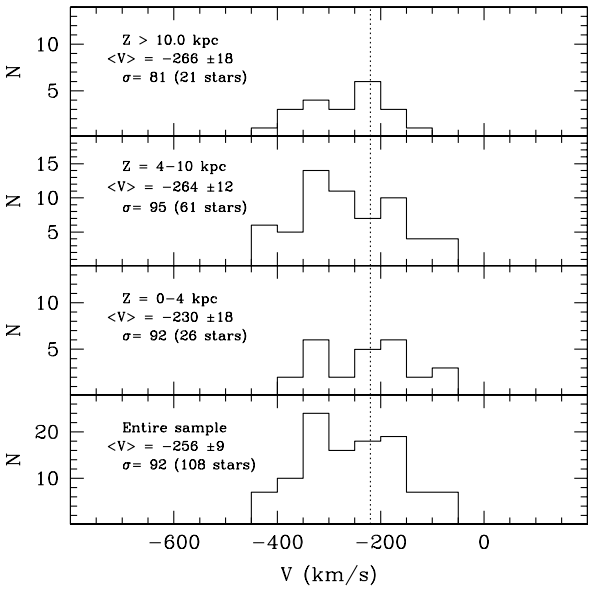

Figure 4. Histograms of rotational velocity V as a function of distance Z above the Galactic plane: all distributions suggest a bimodal structure.

since Sirko et al. (2004) analysis of a large number of distant BHB stars spread over the sky shows little deviation from the solar neighborhood (dissipative halo) value.

It will be interesting to extend the work to halo stars in Anticentre fields. Possibly this will allow us to detect gradients in the V motion and discover whether this is a local effect limited to the NGP or part of a larger systematic effect.

The errors in the GSC-II are small enough to make our results worth consideration. On the other hand, they are large enough to make it clear that *GAIA proper motions are essential for a detailed knowledge of the Galactic structure*.

ACKNOWLEDGMENTS

The GSC-II is a joint project of the Space Telescope Science Institute (STScI) and the INAF-Osservatorio Astronomico di Torino (INAF-OATo). We acknowledge the GSC-II team and in particular M.G. Lattanzi and R.L. Smart for their valuable support to this study.
The present work has been supported by the MIUR (Ministero dell'Istruzione, dell'Università e della Ricerca).

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