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THE VERTICAL STRUCTURE OF THE HALO ROTATION

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Abstract. New GSC-II proper motions of RR Lyrae and Blue Horizontal Branch (BHB) stars near the North Galactic Pole are used to show that the Galactic Halo 5 kpc above the Plane has a significantly retrograde galactic rotation.

1 Introduction

Recent determinations of the mean rotation (<V>) of the field component of the Galactic halo are summarized in Table 1 for stars within 2 kpc of the Sun and in Table 2 for stars at distances (Z) more than 4 kpc above the Plane. Metal-poor subdwarfs are mostly discovered by their high proper motions and so a substantial correction for kinematic bias is required if they are to be used as tracers. No such kinematic bias correction is needed for RR Lyrae stars or halo K giants (discovered from objective prism surveys) but (as also for the subdwarfs) a correction is needed for a thick disk component. The first four estimates in Table 1 use somewhat different approaches to this disk correction and all give values of <V> for the halo in the solar neighbourhood that are close to that of the local circular velocity of -220 km/s (Kerr & Lynden-Bell 1986); so there is some consensus that the local halo does not rotate.

The situation is different for estimates of <V> for halo stars out of the Plane (Table 2). The only estimate for an *in situ* out-of-plane sample is that of Majewski (1992) and Majewski *et al.* (1996) who found <V> to be 55 km/s retrograde. The estimates of Carney (1999) and Chiba & Beers (2000) come from stars whose calculated orbits take them more than 4 kpc from the plane; they find no rotation

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Table 1. The Halo rotation from nearby stars (Z $\leq$ 2 kpc)

Halo tracer (Stellar type)	No. of stars in sample	Mean Rotation <V> (km/s)	Reference
RR Lyrae	84	-219 ± 10	Martin & Morrison(1998)
RR Lyrae	162	-210 ± 12	Layden *et al.* (1996)
RR Lyrae & K giant[a]	124	-217 ± 21	Chiba & Yoshi (1998)
RR Lyrae	101	-214 ± 10	Dambis & Rastorguev (2001)
Subdwarf[b]	97	-208 ± 6	Carney *et al.* (1996)
Subdwarf[c]	97	-144 ± 9	Carney (1999)
Subdwarf[d]	230	-161 ± 7	Chiba & Beers (2000)

[a] Stars with [Fe/H]≤-1.6
[b] Stars with [Fe/H]≤-1.5 & eccentricity ≤0.85
[c] Same as for Carney *et al.* (1996) but with kinematic bias correction
[d] Stars with [Fe/H]≤-1.5

or a slightly prograde rotation for these stars. 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.

The determination of the rotation vector V for stars in the North Galactic Cap depends critically on selecting appropriate tracer halo stars and having accurate distances and proper motions. The recent availability of absolute proper motions (Spagna *et al.*, 1996) based on the GSC-II catalogue (Lasker *et al.*, 1995; McLean *et al.*, 2000) affords a new opportunity to evaluate the rotation of the halo outside the Plane. This paper gives preliminary results from a limited sample.

2 The Data

2.1 Selection of halo stars

We used blue horizontal branch (BHB) stars and RR Lyrae stars as tracers. The former were selected from the surveys of Sanduleak (1988) and Pesch & Sanduleak (1989) and from the surveys of Beers *et al.* (1996). These candidate stars were confirmed by uBV-photometry (Kinman *et al.* 1994) and spectroscopy. Most of the confirming spectra of the BHB stars were taken at the Kitt Peak 4-m Mayall telescope (Kinman *et al.* 1996). RR Lyrae stars were selected from the GCVS (Kholopov 1985) and subsequent Name-Lists and also from Kinman (2002a). Intensity-weighted mean magnitudes of the RR Lyrae stars are derived from our recently observed light curves as these become available. A program to obtain spectra of the RR Lyrae stars at the 3.5-m TNG telescope is in process. Only 6 of these RR Lyrae stars and none of the BHB stars in our current sample

Table 2. The Halo rotation from stars out of the Galactic Plane

Halo tracer (Stellar type)	No. of stars in sample	Mean Halo Rotation <V> (km/s)	Reference
Subdwarf[a]	21	−275±16	Majewski (1992); Majewski *et al.* (1996)
Subdwarf[b]	30	−265±22	Carney *et al.* (1996)
Subdwarf[c]	30	−196±13	Carney (1999)
Subdwarf[d]	212	−220±8	Chiba & Beers (2000)

[a] *In situ* sample at North Galactic Pole
[b] Stars with [Fe/H]≤−1.5 ; eccentricity ≤0.85 & $Z_{max} \geq 4$ kpc
[c] Same as for Carney *et al.* (1996) with $Z_{max} \geq 4$ kpc and with kinematic bias correction
[d] Stars with [Fe/H]≤−1.5 & $Z_{max} \geq 4$ kpc

are included in the recent list of halo stars by Beers *et al.* (2000).

2.2 Absoute Magnitudes, Reddenings and Distances

The absolute magnitudes of RR Lyrae stars can be determined from their metallicity [Fe/H] by a linear empirical relation of the form: $M_V = A\ [Fe/H] + B$. Chaboyer (1999) gives 0.23 and 0.93 while Cacciari (2002) gives 0.23 and 0.92 respectively for A & B. These values are consistent with an LMC modulus of 18.50 and give M_V which are in the middle of the range of recent M_V determinations (Popowski & Gould 1999). [Fe/H], however, has still to be determined for most of our RR Lyrae sample, and so we used the relation based on the period (P) and Fourier coefficients (A1 and A3) given by Kovács & Walker (2001):

$$M_V = -1.876 \log P - 1.158 A1 + 0.821 A3 + \text{const.}$$

The constant was taken as 0.448 (Kinman 2002b) which gives M_V close to the same scale as those derived from [Fe/H]. In the case of the BHB stars, we used the M_V *vs.* $B-V$ relation given by Preston *et al.* (1991) adjusted so that $M_V = +0.60$ at $(B-V) = +0.20$. The reddening given by Schlegel *et al.* (1998) was adopted.

2.3 Proper Motions

We used proper motions that are based on the plate material used for the construction of the GSC-II catalogue (Spagna *et al.*, 1996). The relative proper motions are transformed to an absolute reference frame by forcing the extended extragalactic sources to have null tangential motion. Since our results depend critically on the success of this transformation, it seemed desirable to test the GSC-II proper motions of a sample of QSO which have an image structure and colour similar to

Table 3. Objects described as QSO that have large GSC-II proper motions

Identification	Catalogue Source	Redshift Source	Total proper motion (mas/yr)	Present Classification
CSO 832	HB	V	24.3±2.7	Star
CSO 823	HB	V	19.7±3.5	Star
KUG 12491+2932	VV	D	18.5±2.5	Star
CSO 835	HB,VV	V	16.8±3.9	Star
1306+293; BG 57 34	HB,VV	V	13.5±3.1	Star
1306+274	HB,VV	W	10.2±5.4	QSO

Redshift references: V = Vaucher (1982); D = Darling *et al.* (1994); W = Wills & Wills (1976)

the program stars. The area studied contains 51 objects that have GSC-II proper motions and that are listed as QSO brighter than 18th magnitude by Hewitt & Burbidge (1993, HB) and Véron-Cetty & Véron (2001, VV) in their catalogues. Six of these objects have suprisingly large (≥10 mas/yr) total proper motions and are listed in Table 3. Spectra of these objects were taken by Arjun Dey and Buell Jannuzi using the Kitt Peak 4.0-m telescope; their new classifications (private communication) are given in the final column of the Table. We note that VV rejected CSO 832 and CSO 823 from their catalogue citing Sanduleak & Pesch (1990) and Edwards *et al.* (1988) respectively. We therefore rejected the first five objects in Table 3 and assumed that the remaining 46 objects are all QSO which should have no proper motion. These 46 objects have the following mean GSC-II proper motion:

$$\mu_\alpha = -\ 0.646 \pm 0.357 \text{ mas/yr}$$
$$\mu_\delta = -\ 0.300 \pm 0.507 \text{ mas/yr}$$

These mean proper motions are an indication of the systematic errors that could be present in the GSC-II proper motions over a sky area and magnitude range similar to that of our program objects. In terms of the U and V velocity vectors at the North Galactic Pole, they correspond to:

$$\text{U} = -1.8\pm1.9 \text{ km/s and V} = -2.9\pm2.2 \text{ km/s at 1 kpc}$$
$$\text{U} = -9.0\pm9.6 \text{ km/s and V} = -14.3\pm11.0 \text{ km/s at 5 kpc}$$
$$\text{U} = -18.0\pm19.2 \text{ km/s and V} = -28.6\pm22.0 \text{ km/s at 10 kpc}$$

This suggests that the systematic error in the mean rotation (V) is probably no more than 25 km/s (1σ error) or at most 36 km/s (2σ error) for our program objects with a mean distance of about 5 to 6 kpc.

Table 4. UVW velocities for our NGP sample compared with those of Martin & Morrison (1998)

U km/s	V km/s	W km/s	σ_u km/s	σ_v km/s	σ_w km/s	No. of stars	Source
−7±22	−285±17	−26±15	155	125	92	53 (39)	(1)
−1±19	−285±14	−25±13	127	92	76	47 (35)	(2)
−1±26	−219±24	−5±10	193	91	96	84	(3)

Sources : (1) Present paper; (2) Present sample (10 % outlyers trimmed); (3) Martin & Morrison (1998)

2.4 Results

Our complete sample consists of 87 confirmed BHB stars that have b $\geq 75°$ (72 of which have b $\geq 80°$). There are also 73 RR Lyrae stars in this area for which we are in the process of getting light curves and spectra. Our present results refer to a subset of 35 BHB stars (30 having radial velocities) and 18 RR Lyrae stars (of which 9 have radial velocities). In calculating the UVW vectors (Johnson 1987), we put the radial velocity equal to zero (with an error of ±150 km/s) if no radial velocity was available. In such cases, the U and V vectors should be very close to the correct values but the W velocity must be discarded. These heliocentric UVW are compared with those found by Martin & Morrison (1998) for their HALO2 sample of local RR Lyrae stars. They excluded disk RR Lyrae stars and trimmed 10% of the "outlyers" from their sample. We have not attempted to remove disk stars from our sample (Z > 1.6 kpc) but found that trimming hardly changes the mean values of U, V and W although it does reduce the velocity dispersions σ_u, σ_v and σ_w. Martin & Morrison used a M_V that is less than 0.1 mag fainter than ours, but this should not account for the 60 km/s difference in V velocities (but very comparable σ_v). The 42 stars in our sample with Z < 10 kpc have almost the same <V> (−286±19 km/s at <Z> = 5.3 kpc) as for the whole sample.

Gilmore *et al.* (2002) have recently reported retrograde halo rotation out of the Plane from their radial velocity determinations of stars at galactic longitude 270°. We shall determine UVW from our total sample at the North Galactic Pole in the near future, and hope 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 retrograde rotation is caused by local streaming or is part of a more widespread effect.

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