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The Vertical Structure of the Halo Rotation ⋆

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Abstract. New GSC-II proper motions and radial velocities of RR Lyrae and Blue Horizontal Branch 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. Streaming motions cannot be excluded.

Key words. Galaxy: structure

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 the local circular velocity of -220 kms^{-1} (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 kms^{-1} 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 or a slightly prograde rotation. The present work attempts to resolve this discrepancy; it stems 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, radial velocities and proper motions. The recent availability of absolute proper motions (Spagna et al. 1996) based on the GSC-II catalogue

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(Lasker et al. 1995; McLean et al. 2000), as well as our new spectroscopic observations for radial velocities, afford a new opportunity to evaluate the rotation of the halo outside the Plane. This paper gives preliminary results from a limited sample of halo stars within 10 deg of the North Galactic Pole (NGP).

2. The Data

1. Selection of halo stars – We used blue horizontal branch (BHB) and RR Lyrae stars as tracers. The former were selected from the surveys of Sanduleak (1988), Pesch & Sanduleak (1989) and 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 et al. 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.

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 = 0.23[Fe/H] + 0.92 (cf. Chaboyer 1999 and Cacciari 2002). These M_V values are consistent with an LMC modulus of 18.50. [Fe/H], however, has still to be determined for most of our RR Lyrae sample, so we used the relation based on the period (P) and Fourier coefficients (A1 and A3) given by Kovács & Walker (2001): $M_V = -1.876 \log P - 1.158A1 + 0.821A3 + 0.43$. The constant was derived by Kinman (2002b) and 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.

3. Proper Motions – We used proper motions 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 extragalactic sources to have null tangential motion. Since our results depend critically on the success of this transformation, we have tested the GSC-II proper motions of a sample of 51 QSO brighter than 18th magnitude falling in our area. After rejecting 5 objects with suprisingly large (≥10 mas/yr) total proper motions (cf. Kinman et al. 2003) that were identified spectroscopically as stars (A. Dey and B. Jannuzi, priv. comm.), we obtained the following mean GSC-II proper motion: $\mu_\alpha = -0.646 \pm 0.357$ mas/yr, and $\mu_\delta = -0.300 \pm 0.507$ 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, and suggest that the systematic error in the mean rotation (V) is probably no more than 25 kms^{-1} (1σ error) or at most 36 kms^{-1} (2σ error) for our program objects with a mean distance of about 5 to 6 kpc.

3. Results

Our complete sample consists of 87 confirmed BHB stars and 73 RR Lyrae stars. 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 & Soderblom 1987), we put the radial velocity equal to zero (with an error of ± 150 kms^{-1}) 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 in Table 3 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

Table 1. The Halo rotation from nearby stars (Z ≤ 2 kpc)

Halo tracer (Stellar type)	No. of stars in sample	Mean Rotation <V> (kms^{-1})	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

Table 2. The Halo rotation from stars out of the Galactic Plane (Z > 4 kpc)

Halo tracer (Stellar type)	No. of stars in sample	Mean Rotation <V> (kms^{-1})	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 the North Galactic Pole
[b] Stars with [Fe/H]≤−1.5 ; eccentricity ≤0.85 & Z_{max} ≥ 4 kpc
[c] Same as for Carney et al. (1996) with Z_{max} ≥ 4 kpc and with kinematic bias correction
[d] Stars with [Fe/H]≤−1.5 & Z_{max} ≥ 4 kpc

Table 3. UVW velocities for our NGP sample compared with those of Martin & Morrison (1998)

U kms^{-1}	V kms^{-1}	W kms^{-1}	σ_u kms^{-1}	σ_v kms^{-1}	σ_w kms^{-1}	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±21	−219±10	−5±10	193	91	96	84	(3)

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

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 kms^{-1} 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 kms^{-1} 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 NGP 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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