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LETTER

Letter to the Editor

Evidence for a signature of the galactic bar in the solar neighbourhood*

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Abstract. Using available kinematical data for a subsample of NLTT stars from the HIPPARCOS mission we confirm the existence of a previously reported local anomaly in the (u, v) plane: the mean motion $\overline{u}$ for old disc stars, with $v < -30\,\mathrm{km\,s^{-1}}$, is largely positive ($+19 \pm 9\,\mathrm{km\,s^{-1}}$ w.r.t. the Galactic Center).

With the use of the newest global self-consistent numerical models of our Galaxy (Fux 1997), we show that a bar could be responsible for this observed velocity anomaly. A fraction of our stars have bar perturbed "hot" orbits, allowing them to erratically wander from inside the bar to regions outside the corotation, in particular through the solar neighbourhood.

Key words: Galaxy: structure, kinematics and dynamics

1. Introduction

The kinematical properties of disc stars in the solar neighbourhood have been extensively studied in the past. Velocity dispersion increase with age and vertex deviation have been well known facts for a long time and have been recently reconfirmed (Dehnen & Binney 1997).

A feature of local stellar motions which practically passed unnoticed is a global asymmetry of the star distribution in the (u, v) plane of velocities relative to the Sun [1], in addition to the vertex deviation which essentially concerns stars of small epicyclic energies: the mean *u*-velocity ($\overline{u}$) of the old disc stars, as inferred from various samples, appears significantly different from zero even if we correct it for the solar motion, contrarily to the expectation for a stationary axisymmetric galaxy. This anomaly was already apparent with the Gliese & Jahreiss (1991) and the Woolley (1970) space-velocities of nearby stars and could be inferred from the positions of Eggen's old disc stellar groups in the (u, v) plane (Eggen 1987 and references therein). Mayor (1972) emphasized a significant excess $\overline{u}(h) > 0$ (h = angular momentum) for stars having a mean asymmetrical drift $\langle S \rangle \approx 20$–$30\,\mathrm{km\,s^{-1}}$. Nevertheless, a quantitative interpretation of the origin of this phenomenon has never been given until now.

Two new facts allow us to go more deeply into this question. At first, after the de Vaucouleurs (1964) presumption, series of recent more or less direct observational evidences indicate that our Galaxy is definitely barred (see e.g. Kuijken 1996 for a review). Fux (1997) realised global self-consistent numerical simulations of our Galaxy which all develop a long-lasting bar.

Secondly, Grenon observed a large sample of 5443 NLTT (New Luyten's Two Tenths, i.e. $\mu > 0.18 \pm 0.02$ arcsec yr^{-1}) stars for which space velocities and partly chemical compositions are available. The sample will be described in details in Sect. 2. Its size allows us to deal with outstanding questions of galactic structure and evolution.

In the present letter, taking benefit of these progresses, we aim to examine whether the bar could be responsible for the kinematical anomaly mentioned above.

2. Observational data

The nearby star samples are notoriously poor in halo and very old disc stars. In order to test the effect of a bar in the inner Galaxy, we must consider stars moving on eccentric orbits bringing them in the bar proximity. The sample used here is an extension of the Gliese's and Woolley's catalogues towards larger volume and space velocities at the expense of the completeness in low space-velocity stars. It is a subset of a vast programme prepared for the HIPPARCOS mission. The initial set of 10047 stars was formed of all stars from Luyten's NLTT Catalogue with $m_R < 11.5$ if of color class from a to k-m, or $m_R < 12.5$ if the class was m or m+. According to internal priorities favouring the selection of parallaxe stars, namely those within 100 pc, and to satellite observing possibilities, 7824 stars have been included in the HIPPARCOS programme.

Since the sample is absolute magnitude limited with $M_\mathrm{V} < 6.5$ at 100 pc, i.e. well below the turn-off luminosity, it shows no bias against metal-rich and super metal-rich (SMR) stars (Grenon 1987). It is also proper-motion limited and hence tangential velocity limited, i.e. $V_t > 0.85 \cdot d\,\mathrm{km\,s^{-1}}$ with distance d in [pc].

Our sky coverage $\delta < +10°$ includes in particular a complete south galactic cap defined by $b < -53°$. For the HIP-

* Based on data from the ESA HIPPARCOS satellite, on photometric data collected at the Swiss telescope at La Silla and on data collected with CORAVELs at the Haute Provence Observatory (France) and at ESO, La Silla Chile

[1] u positive in the anti-center direction, v in the rotation direction

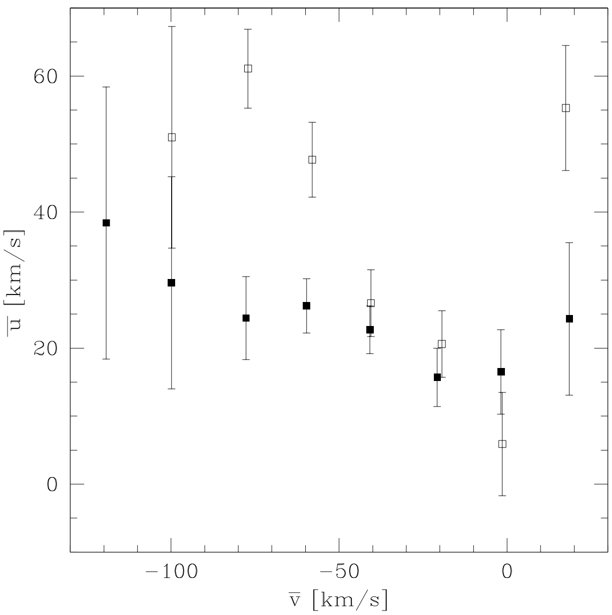

Fig. 1. Observed $\overline{u}$ as a function of the $\overline{v}$ (w.r.t. the Sun) velocities for disc stars with $\pi < 40$ mas, at South Galactic Pole (filled squares, 673 stars) and towards the anti-rotation (open squares, 462 stars with l between 240° and 300° and $|b| < 40°$).

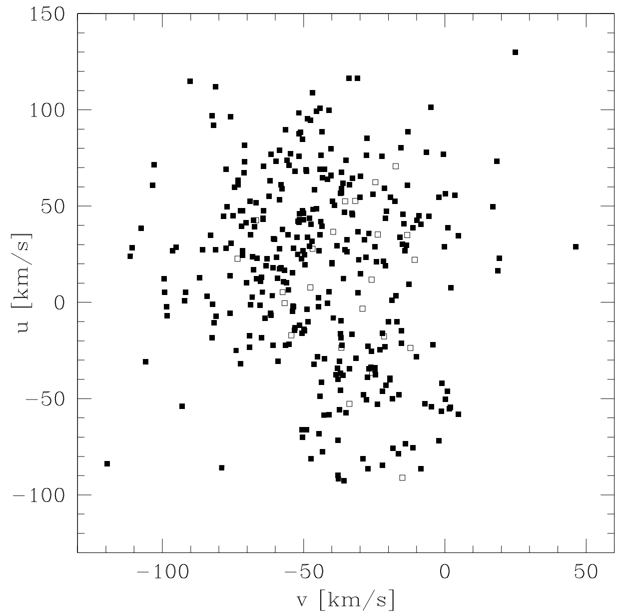

Fig. 2. Observed (u, v) plane (w.r.t. the Sun) for metal-rich stars with $[M/H]$ between 0.25 and 0.65, without Hyades group members. Filled squares stand for single stars and open squares for multiple ones.

PARCOS mission preparation and for the obtention of physical parameters from photometry, all programme stars south of $\delta = +10°$ were observed at the Swiss telescope at La Silla, from 1981 on. A total of 39435 measurements were accumulated for 5443 different stars. Calibrations of the Geneva photometric system and susbsequent revisions by Grenon (1977) were used to derive $T_{\rm eff}$, M_v and $[M/H]$, with precisions varying with the temperature and gravity ranges. For late G dwarfs, the internal errors are of 20–40 K on $T_{\rm eff}$, 0.03–0.05 dex on $[M/H]$ and 0.15 on M_v, for single stars. Stars later than K3V have no $[M/H]$ estimate.

Radial velocities were obtained for all programme stars by Grenon with CORAVEL at Haute-Provence Observatory in the declination zone $\delta = -20°$ to +10° and as part of a dedicated ESO Key Programme (Mayor et al. 1998) south of $\delta = -20°$. A few velocities were taken from literature, in particular from the Carney et al. (1994) and from the Barbier-Brossat et al. (1994) catalogues. Binaries were identified either from the radial velocity changes or the comparison between trigonometric and photometric parallaxes, or detected by HIPPARCOS

For the present study, stars were kept if their HIPPARCOS and photometric parallaxes were larger than 10 mas. Moreover, uncertain parallaxes with standard errors > 5 mas were rejected. In our final sample, space velocities are available for 4143 stars and overall metallicities for 2619 of them.

3. Kinematical properties of the sample

The old disc stars of our sample show largely positive mean $\overline{u}$ motions, confirming the trend already apparent in the earlier results recalled in the Introduction.

At given $v < -30\,{\rm km\,s^{-1}}$, there is no bias in favour of inward or outward motions when stars are observed in the south galactic cap or towards the anti-rotation where $V_t = \sqrt{u^2 + w^2}$. With increasing distances the fraction of small $|u|$ decreases in favour of large $u+$, $u-$ velocities. When old disc stars are selected in the π range from 10 to 40 mas, the unbalance between $u+$ and $u-$ becomes stricking, see Fig. 1, and reaches up to $+50\,{\rm km\,s^{-1}}$ towards the anti-rotation. When subsamples are complete according to v components (e.g. all stars with $v < -50\,{\rm km\,s^{-1}}$ are retained), the u anomaly is correctly estimated with values within the range $+29 \pm 2\,{\rm km\,s^{-1}}$ w.r.t. the Sun, i.e. $+19 \pm 9\,{\rm km\,s^{-1}}$ w.r.t. the Galactic Center (GC) after correction for local motions inferred from Kuijken & Tremaine (1991).

Stars with metallicities atypical for the young local disc, i.e. with $[M/H] > 0.25$ or < -0.30, form the best test sample to investigate large scale perturbations of stellar orbits. The metal poor group should contain stars born inside and outside the solar orbit, whereas the metal-rich group should consist of stars born uniquely within the solar orbit. It is therefore well suited to test the orbital anomalies in the inner disc. Its (u, v) plane is displayed in Fig. 2.

If we consider the (u, v) plane for all stars with known $[M/H]$, the area $u > 10\,{\rm km\,s^{-1}}$ and $-130 < v < -30\,{\rm km\,s^{-1}}$ contains not only metal-rich stars but a sample of old disc stars with metallicities covering the whole range of $[M/H]$ observed in the old disc population from ~ -0.6 dex to $+0.6$ dex and showing a peak at solar metallicity (Fig. 3). The $[M/H]$ distribution is essentially the same as that observed in situ in the bulge by McWilliam & Rich (1995), an indication of a common origin for both populations. The ages are also heterogeneous with a range between 6 to 10 Gyr (Fig. 4).

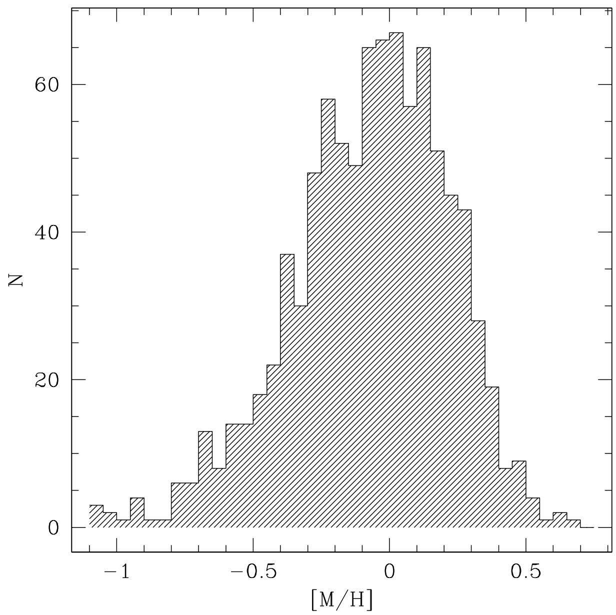

Fig. 3. Metallicity distribution for NLTT stars with $u > 10$ km s^{-1} and $-130 < v < -30\,\mathrm{km\,s^{-1}}$. This distribution is similar to the one observed for stars of the galactic bulge (see Fig. 17 of McWilliam & Rich (1995)).

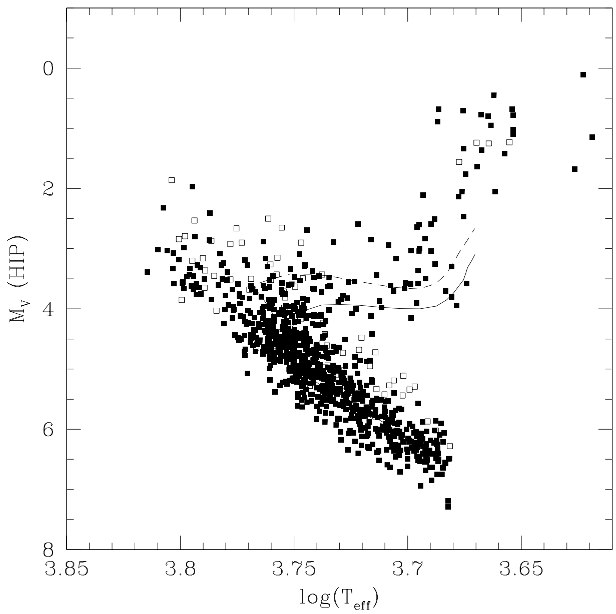

Fig. 4. HR diagram for stars with $[M/H] > -0.55$. The solid and dashed lines correspond to isochrones of log t = 10.0 and 9.8 respectively. The filled squares stand for single stars and the open squares for multiple ones.

The $\overline{u}$ anomaly has hence to be interpreted as a common response of old stars to secular gravitational sollicitations rather than as a memory of initial conditions.

4. Stellar response to a bar

In this section we compare the observational features mentioned above with the local kinematics of old disc particles inferred from simulation with global self-consistent 3-D numerical models of our Galaxy developed by Fux (1997). These models have a bar axis ratio $b/a = 0.5 \pm 0.1$ and a bar pattern speed $\Omega_p = 50{\pm}10\,\mathrm{km\,s^{-1}}$ corresponding to a corotation radius of 4.3 ± 0.5 kpc. The Fux model m08 at t=3.2 Gyr presents the best agreement with the different local and global observational constraints considered by Fux.

In this m08 simulation we follow the mean radial motion $\overline{u}$ of particles w.r.t. the GC as a function of time, across a toroidal region of 1 kpc diameter at a distance $R = R_0 = 8$ Kpc from the GC. In the considered models, built with particules which essentially represent the old disc, the global deviation with respect to axisymmetry is practically negligible before 2 Gyr (Fig. 5). The bar, if it exists, could be at most confined to a very small region around the center. Some transitory spiral density waves are observed, but $\overline{u}$ is never very different from zero during this early period. However, as soon as the bar is stabilized (for $t > 2.9$ Gyr), $\overline{u}$ differs significantly from 0 and depends on ϕ, the angle between the bar and the line Sun-galactic center.

The bar produces a sine-like behaviour in ϕ for the mean velocity $\overline{u}$ (note that the streaming motion $\overline{u}$ is zero when integrated over ϕ for several bar rotational periods, even for stochastic orbits). The mean amplitude of $\overline{u}(\phi)$ is ~ 17 km s^{-1}, but $|\overline{u}|$ values as high as 28 km s^{-1} are temporarily obtained. For example, around $t = 4.53$ Gyr and $\phi = 30°$ (which is the angle corresponding to the best statistical agreement of the models with the COBE/DIRBE data), $\overline{u}$ of the order of 20 km s^{-1} are obtained, in agreement with the observational results reported in Sect. 3. Fig. 6 is a slice cutting of Fig. 5 for $\phi = 30°$. The values of $\overline{u}$ have been averaged within bins of 200 Myr width. One obtains a significantly positive value of $\overline{u}$ when the bar is stabilized.

The presence of a bar in our Galaxy implies characteristic orbital behaviours of stars. Detailed discussions on the kind of trajectories followed by stars in self-consistent barred potentials have been presented by Sparke & Sellwood (1987), Pfenniger & Friedli (1991) and Kaufmann & Contopoulos (1996). Let us distinguish here two categories of orbits: 1) elongated orbits confined to the bar, trapped about the long-axis x_1 family of periodic orbits (bar particles), 2) "hot" orbits which essentially display a typical chaotic behaviour, erratically wandering between regions inside the bar and outside corotation. Whereas orbits of kind 1) have an Hamiltonian $H < H(L_{1,2})$, the "hot" orbits have $H > H(L_{1,2})$, $H(L_{1,2})$ being the Hamiltonian at the Lagrange point L_1 and L_2 for a zero velocity in the rotating frame. Examples of these kinds of orbits can be seen for ex. in Fig. 15 of Sparke & Sellwood (1987).

In the solar neighbourhood, we are not able to observe the first category of orbits as the Sun is outside corotation. But at the present time we observe near the Sun some number of hot orbit stars which are able to visit our neighbourhood after spending more or less time in the inner region of the bar. In particular metal-rich old disc stars, which are typical contributors to the kinematical anomaly according to Fig. 2, follow such

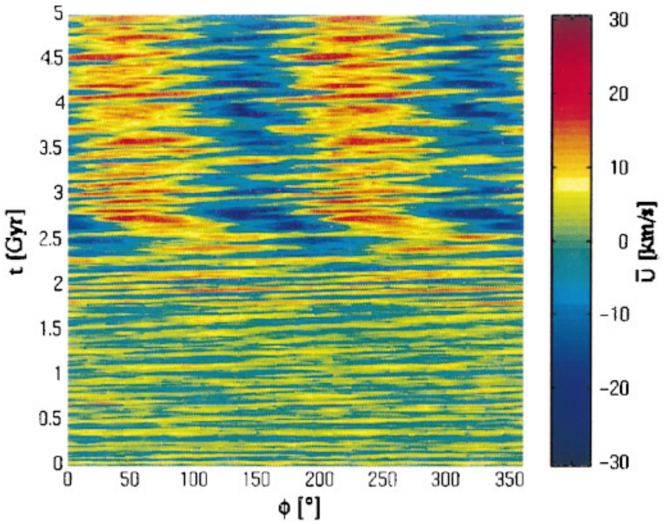

Fig. 5. Time behaviour of $\overline{u}(\phi)$ over 5 Gyr, for stars observed within a torus between $\tilde{R}$ = 7.5 and 8.5 (in the initial units of the simulation m08, Fux 1997).

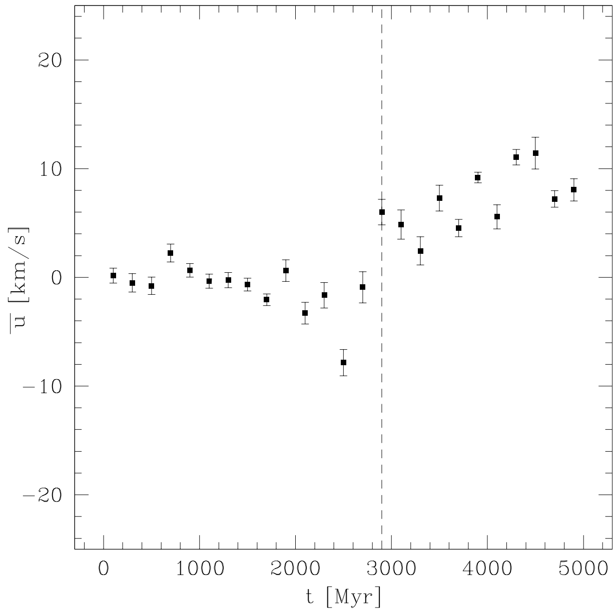

Fig. 6. Time behaviour of $\overline{u}(\phi = 30°)$ over 5 Gyr, averaged in bins of 200 Myr, for stars located within a torus between $\tilde{R}$ = 7.5 and 8.5 (in the initial units of the simulation m08, Fux 1997). In this simulation the bar is completely settled at the right of the vertical dashed line. This graphic is merely a smoothed cut through Fig. 5, for $\phi = 30°$.

kind of orbits. Those with $u > 0$ indeed have an Hamiltonian $H > H(L_{1,2})$. As for the well known, but not considered in this letter, two peak (Hyades, Sirius) distribution for stars with small epicyclic energy, the respective influence of local spiral density waves (Mayor 1972) and of a bar (Kalnajs 1991) is not well established. It depends on the relative strength of these perturbations.

5. Conclusion

The present letter suggests an explanation for the kinematical anomaly observed in the solar neighbourhood, characterized by a significant positive mean value of the center-anticenter motions of stars with trailing azimuthal velocities with respect to the circular motion.

Our conclusions are the following:

1) Recent samples of old disc stars with $v < -30$ km s^{-1} confirm a mean positive motion $\overline{u}$ of 19 ± 9 km s^{-1} (w.r.t. the GC), signature of an anomaly in the local kinematics with respect to a stationary axisymmetric case.

2) Our numerical simulation shows that the bar in our Galaxy such as constrained by various observational data (Fux 1997) produces a sine-like behaviour in ϕ for the mean radial velocity $\overline{u}$ w.r.t. the GC for old disc particles. For the value of ϕ corresponding to the presently Sun-galactic center angle, $\overline{u}$ is positive in agreement with observations. These calculations suggest that the local kinematic anomaly for the old disc could be a signature of the bar.

3) The bar is able to perturb orbits of stars either born or passing through its region and wandering through the solar neighbourhood. For example, we calculate that in a time interval of 5 Gyr a star with $(u, v, w) = (50, -50, 0)$ km s^{-1} at the Sun can visit regions between ~ 3 kpc and ~ 10 kpc from the galactic center. This range would be limited to 3 kpc in an axisymmetric galaxy. "Hot" orbits ($H > H(L_{1,2})$) detected in the solar neighbourhood, populated by the metal-rich old stars mentioned above, are among these perturbed orbits.

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