Unexpected stellar velocity distribution in the warped Galactic disk.

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It is now over forty years since the gaseous disc of our Galaxy was discovered to be warped from radio observations of neutral hydrogen [1]. Subsequently the warp has been detected in the distribution of galactic dust [2], molecular clouds [3], and luminous stars [4, 5]. Roughly half of all spiral galaxies have similarly warped discs, which suggests that warps are common and long-lived phenomenon. However, there is still no consensus as to what induces galactic discs to become warped: intergalactic winds, tidal interactions with satellites, magnetic pressure and massive dark halos have all been proposed as causative agents. Here we use data from the Hipparcos satellite [6] to probe the Milky Way's warp. These data are unique in their ability to detect the small motions on the plane of the sky (proper motions) that should accompany the warp, but which are undetectable in the gas. We find that while the spatial structure is in line with studies of hydrogen, the velocity signature has the *opposite* sign to that expected. Finding a plausible explanation of this result may be the key to solving the long-standing puzzle posed by galactic warps.

A previous attempt to detect warp-induced proper motions [5] was compromised by the difficulty of accurately detecting a small drift across the sky of a large field of stars. Two special features of the Hipparcos results make it possible to detect accurately such motions in this case: (i) its reference frame was set by distant radio galaxies rather than by a dynamical model of the Solar System; (ii) the measurements over the entire celestial sphere were made by a single instrument. Hipparcos proper motions have random errors $\lesssim 1\,\mathrm{mas\,yr^{-1}}$ [7], accuracies of $\sim 0.1\,\mathrm{mas\,yr^{-1}}$ [8], and are inertial to better than $0.25\,\mathrm{mas\,yr^{-1}}$ about any axis [7].

To study the kinematics of the warp we received from the Hipparcos Consortium a sample of 2422 OB stars positive parallaxes less than 2 mas, and having a Galactic longitude l in the range $(70^\circ - 290^\circ)$. This yielded a sample of 2422 stars. OB stars were chosen because they can be seen to large distances, and are young, so presumably trace the warp in the gaseous disc. By selecting stars with small parallaxes we focus on distant stars and avoid local, small-scale, structure in the OB stellar distribution, such as Gould's Belt. Unfortunately, the fractional error in the Hipparcos parallactic distances for such distant stars is $\gtrsim 50\%$. Thus Hipparcos indicates only that these are distant stars, and we had to employ spectroscopic distances with errors $\sim 20\%$ [9].

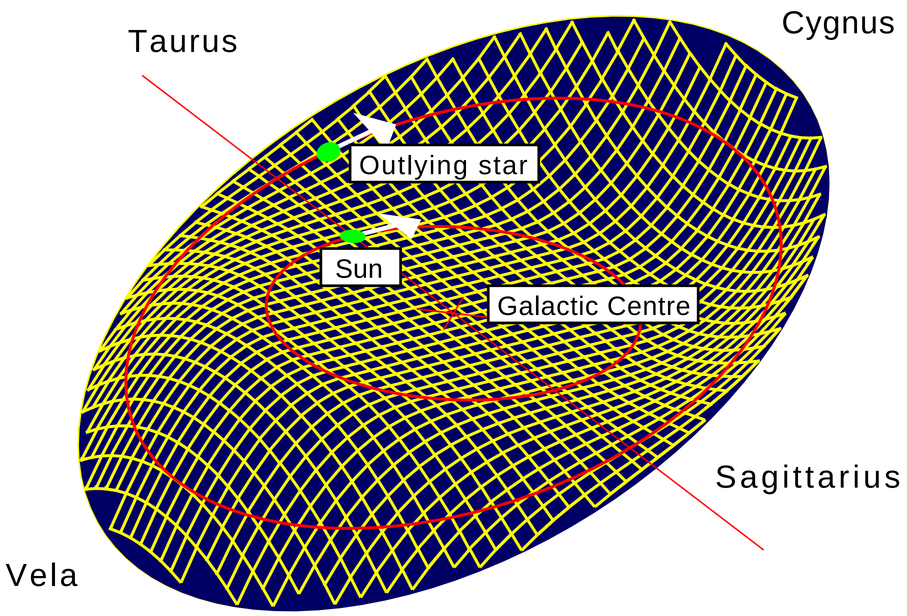

Figure 1: The disc of the Galaxy based on HI observations. The vertical axis is exaggerated by a factor of 10. The arrows show the motion of the Sun and an outlying star on their orbits in the Galaxy. Note the outlying star has an upward motion as seen from the Sun. Directions in the sky, as seen from the Earth, are indicated by the constellation names. The red line indicates the locus of zero vertical displacement for the warped disc.

To understand what trends one would expect to find in these data, consider Figure 1. The Galactic disc is flat to approximately the orbit of the Sun, and then turns up towards the north (Cygnus at $l \sim 90°$), while turning to the south on the opposite side of the Galaxy (Vela at $l \sim 270°$). Hence when we look out from the Sun in the anticenter direction ($l = 180°$), the band of the Milky Way should slope upwards from large l towards smaller l. More generally the warp appears as a sinusoidal variation in the distribution of stars on the sky (Figure 2). In addition, the Galaxy rotates clockwise, so we expect to find stars moving upwards in our sample as they pass through $l = 180°$.

Since the real observational situation involves several complexities that are ignored in the simple picture just described, we have compared the data with synthetic data sets (catalogues) derived from a statistical model of the OB star distribution in phase space. The details of this model are reported in Drimmel et al. [10]. We mention here that it places the young stars in a warped spiral distribution, models observational errors, and produces catalogues that are defined by the same selection criteria as the actual data set.

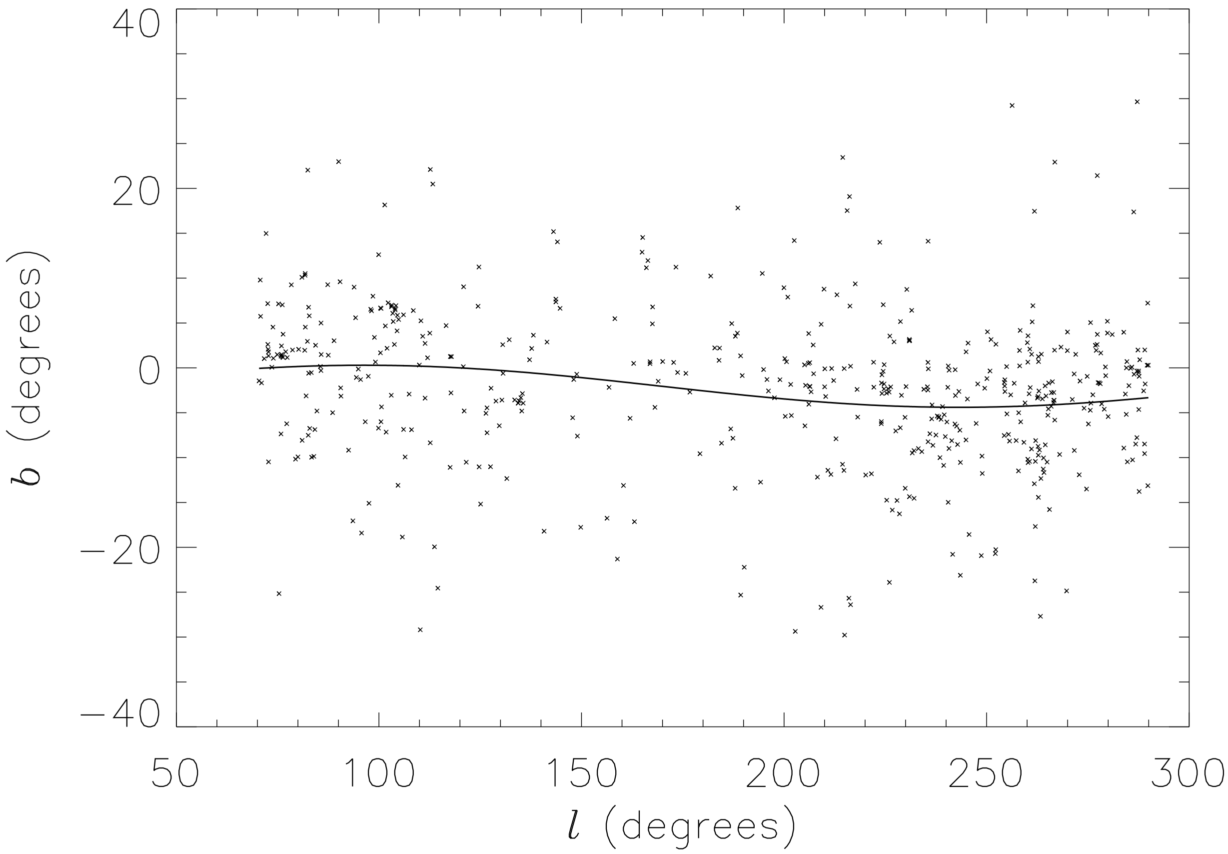

Figure 2: The distribution of OB stars in galactic coordinates to the completeness limit, $m_V < 7.5$. The curved line is a sine fit to the data. This shape results from stars in the first and fourth quadrant being on average closer to the Galactic center, and therefore lower in the warp structure.

The warp is best described in the system of cylindrical coordinates (r, ϕ, z) in which the z-axis runs perpendicular to the plane of the inner Galaxy, r measures galactocentric distance, and the Sun lies at $r_\odot = 8\,\mathrm{kpc}$ on the line $\phi = z = 0$. The azimuth ϕ increases in the direction of galactic rotation. The average height z of the model disc varies sinusoidally with ϕ:

$$z = h(r)\sin(\phi + \omega_p t)\ . \tag{1}$$

The model warp rotates with angular frequency ω_p, in the opposite direction to that of galactic rotation for $\omega_p > 0$. We assume that the Sun currently lies precisely on the line of nodes by setting $t = 0$, since the observational signature of the warp is not sensitive to the warp's phase [11]. As our data extend only a few kpc from the Sun, covering a small range in ϕ, the stars form a sloped distribution, as seen from the Galactic center, in (z, ϕ) at any given r. Consistent with the assumption of a warped disc, the observed slopes (Table 1) are in the correct sense, increase with r, and indicate that the warp begins *within* the orbit of the Sun, in agreement with recent infrared observations [13]. From these data, and consistent with the neutral hydrogen maps of Diplas and Savage [12], we find the height function $h(r)$ of equation (1) to be

$$h(r) = 0.067(r - 6.5)^2 \text{ kpc}, \tag{2}$$

for $r > 6.5\,\text{kpc}$. Note that h does not depend on t, and ω_p does not depend on r, reflecting our assumption that the warp is long-lived, i.e. lasting longer than a few galactic rotation times.

Table 1: Slopes of z versus ϕ for synthetic and observed catalogues.

Bin kpc	No warp	Warp	Data
r <8.5	-.716 ± 1.31	2.60 ± 1.40	2.74
8.0< r <9.0	-.192 ± 1.34	4.10 ± 1.33	5.06
8.5< r <9.5	.611 ± 1.06	6.84 ± 2.65	6.74

Table 2: *

Slopes are given in units of pc per degree. The slopes are for stars with $m_V \leq 7.5$, the completeness limit of this Hipparcos sample. For the warped and non-warped cases (columns 2 and 3) the slopes are means and standard deviations of 30 catalogues generated from a statistical model of the OB stellar distribution. The model for the warped case uses equations 1 and 2.

We now turn to the proper motions. At time t the azimuth of any star is given by $\phi = \phi_0 + \Omega(r)t$, where ϕ_0 is a constant and $\Omega(r)$ is the circular frequency. Differentiating equation (1) we find the predicted vertical velocity is given by

$$V_z(r) \equiv \frac{\mathrm{d}z}{\mathrm{d}t} = [\Omega(r) + \omega_p] h(r) \cos(\phi) \ . \tag{3}$$

This describes the *mean* systematic vertical velocity that must be associated with any long-lived warp of the form of equation (1).

From the Hipparcos proper motions we calculate an observed vertical velocity for each star, corrected for galactic rotation and solar motion (found to be $(U, V, W)_\odot = (9, 5, 7)\,\text{km}\,\text{s}^{-1}$ [10]). In doing so we have assumed circular rotation and a linear rotation curve, adopting a circular velocity of $v_c = 220\,\text{km}\,\text{s}^{-1}$ at the Sun and a slope $\mathrm{d}v_c/\mathrm{d}r = -3\,\text{km}\,\text{s}^{-1}\,\text{kpc}^{-1}$. The points in Figure 3a show median values of this observed velocity binned in galactocentric distance, r. If equation (3) were valid, the medians would scatter about the curve defined by the difference between the values it predicts for $V_z(r)$ and $V_z(r_\odot)$. Figure 3a shows two such curves for $\omega_p = 0$ and $-20\,\mathrm{km\,s^{-1}\,kpc^{-1}}$. It is evident that $\omega_p > -20\,\mathrm{km\,s^{-1}\,kpc^{-1}}$ does not predict the sign of the observations correctly, and even for large negative values of ω_p the model is a poor fit to the data. This result is startling since all current theories of warping predict that $\omega_p > 0$ [14]. Figure 3b shows the individual velocities; the scatter within 9.5kpc is dominated by the stellar peculiar velocities while outside 9.5kpc the errors begin to contribute significantly. Despite the large effects of errors and peculiar velocities it can still be seen that the data distribution has a systematic downward trend as indicated by the medians in figure 3a. All of the simulated kinematic warps using equations (1) and (3) show an upward trend contrary to the observations.

Are the observations flawed? There are three ways in which the data could be misleading: either (i) there are systematic errors of order $2\,\mathrm{mas\,yr^{-1}}$ in the measured proper motions, (ii) the sample is somehow biased towards negative values of latitude proper motions, or (iii) we are seeing something other than the warp. We believe that (i) is excluded by the demonstration that internal systematic errors are smaller than $0.1\,\mathrm{mas\,yr^{-1}}$. A comparison of the complete sample ($m_V < 8$) with the selected sample ($8 < m_V < 13$) shows no evidence for biasing. There is a chance that many of the stars form a moving group; however, from an analysis of the data at $8.5 < r/\mathrm{kpc} < 9.5$, such a group would have to be larger than 2 kpc in extent. Possibility (iii) is suggested spatially by neutral hydrogen observations [15]: $\sim 50\,\mathrm{pc}$ deviations from the plane are seen within the orbit of the Sun. These deviations are certainly affecting our determination of the warp parameters, but the change in z in the last distance bin is $\sim 200\,\mathrm{pc}$, twice the maximum variation within the Sun's orbit.

Though it depends on little more than the assumption that the warp's shape lasts longer than a Galactic rotation period, could equation (3) be invalid? Equations analogous to this are found to be compatible with observations of hydrogen in other warped galaxies, which the Milky Way presumably resembles. We also cannot exclude the possibility that, although the disc has recently been bent into the shape of a warp, it will soon look very different. A possible disturbing agent is the Sagittarius dwarf galaxy [16], but numerical simulations of this interaction are required before this suggestion can be considered plausible. If, rather, the Galactic warp is long-lived then large systematic motions must be present within the Galactic disc to account for the observations. However, given that no corresponding spatial structures have been identified, such systematic motions presently lack an explantion. We are therefore obliged to conclude that there is currently *no* convincing interpretation of the implications of Hipparcos data for the dynamics of the Warp in the Galactic disc.

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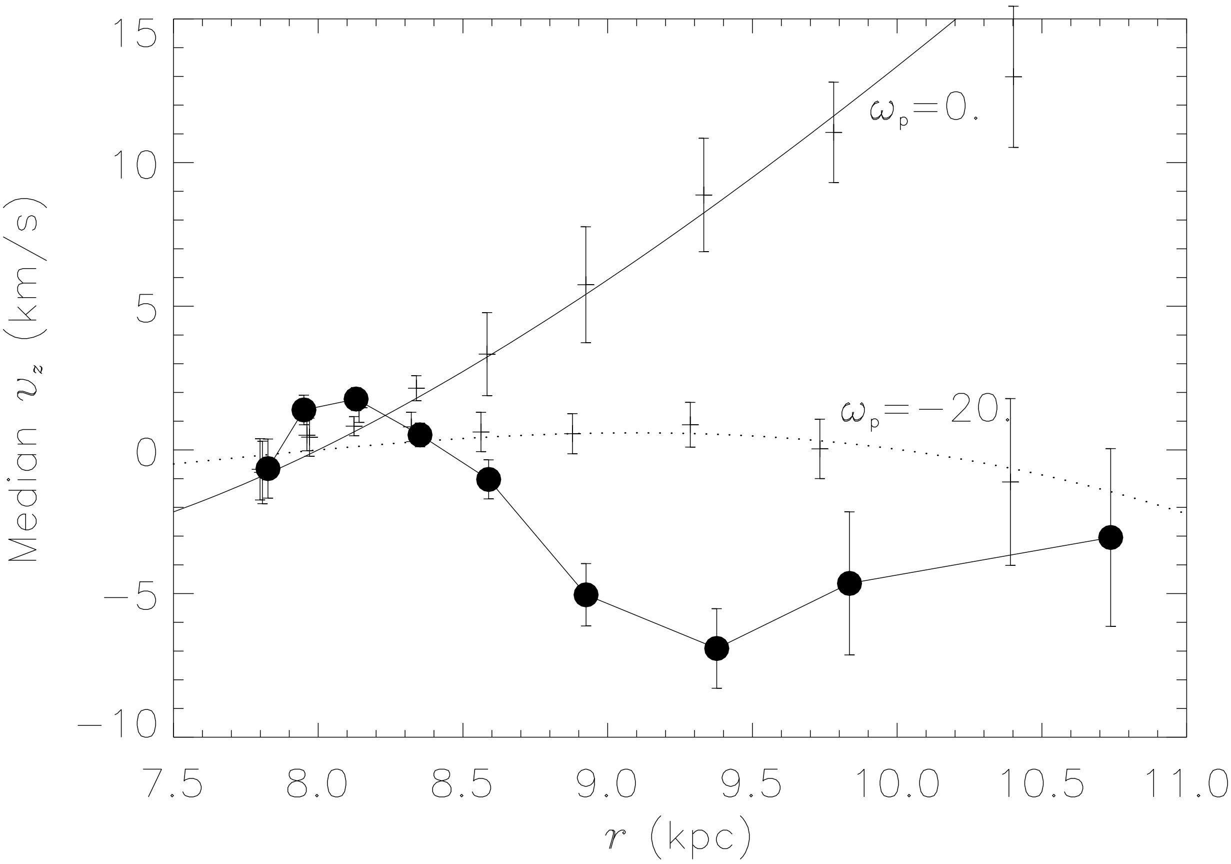

Figure 3: The systematic veritcal velocities as a function of Galactocentric distance r. In a The filled circles show, as a function of galactocentric distance r, medians of the observed vertical velocity, the error bars indicating their uncertainty. The curves show predicted $V_z(r) - V_z(r_\odot)$ using equation 3, for $\omega_p = 0$ (full line) and $\omega_p = -20\,\mathrm{km\,s^{-1}\,kpc^{-1}}$ (dashed line). Their error bars represent one standard deviation of medians from 30 simulated catalogues for each set of warp parameters. In b we plot the derived individual velocities which shows the large scatter due to the effects of peculiar velocities, especially within 9.5kpc where they dominate.

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