The kinematic signature of the Galactic warp in Gaia DR1

I. The Hipparcos sub-sample

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ABSTRACT

Context. The mechanism responsible for the warp of our Galaxy continues to remain unknown, as well as its dynamical nature. With the advent of high precision astrometry, new horizons have been opened for detecting the kinematics associated with the warp and constraining possible warp formation scenarios for the Milky Way.

Aims. The aim is to establish whether the first Gaia data release (DR1) already shows significant evidence of the kinematic signature expected from a long-lived Galactic warp in the kinematics of distant OB stars. As the first paper in a series, we here present our approach for analyzing the proper motions and apply it to the sub-sample of Hipparcos stars.

Methods. We select a sample of distant spectroscopically-identified OB stars from the New Reduction of Hipparcos (van Leeuwen 2007), and a subset that are also in the first Gaia data release (DR1). We develop a model of the spatial distribution and kinematics of the OB stars from which we produce synthetic catalogues with the same error properties as our two samples, and compare the proper motion distributions produced including (or not) the systematic motions expected from a long-lived warp with the observed (pre-Gaia) Hipparcos proper motions of the OB stars and with the subset of Hipparcos OB stars in Gaia DR1.

Results. We find that neither the Gaia nor Hipparcos proper motions of the OB stars clearly support the presence of warp-induced vertical motions, notwithstanding the significant improvement in the precisions of the proper motions for the Hipparcos stars found in Gaia DR1. Indeed, the observed dispersion of proper motions is dominated by the intrinsic velocity dispersions in this sample, whose main limitation is its size.

Conclusions. A larger and deeper sample of stars with Gaia astrometry will be needed to unambiguously reveal and constrain the dynamical nature of the Galactic warp.

Key words. Galaxy: kinematics and dynamics – Galaxy: disk – Galaxy: structure – Proper motions

1. Introduction

It has been known since the early HI 21-cm radio surveys that the outer gaseous disk of the Milky Way is warped with respect to its flat inner disk (Burke 1957; Kerr 1957; Westerhout 1957; Oort et al. 1958), bending upward in the north (I and II galactic quadrants) and downward in the south (III and IV galactic quadrants). The Galactic warp has since been seen also in the dust and stars (Freudenreich et al. 1994; Drimmel & Spergel 2001; López-Corredoira et al. 2002; Robin et al. 2008), with the amplitude in the stellar, dust and HI components apparently increasing in this order (Robin et al. 2008). Our Galaxy is not peculiar with respect to other disk galaxies: about 50 percent or more of spiral galaxies are warped (Sanchez-Saavedra et al. 1990; Reshetnikov & Combes 1998). The high occurrence of warps, even in isolated galaxies, implies that either these features are easily and continuously generated, or that they are stable over long periods of time. In any case, the nature and origin of the galactic warps in general are still unclear (Sellwood 2013).

While many possible mechanisms for generating warps in disk galaxies have been proposed, which is actually at work for our own Galaxy remains a mystery. This is due to the fact that while the shape of the Galactic warp is known, its dynamical nature is not; vertical systematic motions associated with the warp are not evident in radio surveys that only reveal one component of the velocity of the observed gas, namely that along the line-of-sight. Being located within the disk of the Milky Way, systematic vertical motions will primarily manifest themselves to us in the direction perpendicular to our line-of-sight. Moreover, the fact that the warp in the stellar component has been observed to start inside or very close to the Solar circle (Drimmel & Spergel 2001; Derriere & Robin 2001; Robin et al. 2008) suggests that, if the warp is stable, the associated vertical motions should be evident in the component of the stellar proper motions perpendicular to the Galactic disk. Measuring the kinematic signature of the Galactic warp is needed to reveal whether the warp of our Galaxy is a transient or long-lived stable structure, and may even provide practical constraints on the possible mechanisms responsible for this feature of the Milky Way.

A first attempt to detect a kinematic signature of the warp in the proper motions of stars was first made using OB stars (Miyamoto et al. 1988), as they are intrinsically bright, thus can be seen to large distances, and are short-lived, so are expected to trace the motions of the gas from which they were born. More recently a study of the kinematic warp was carried out by López-Corredoira et al. (2014) using red clump stars from the PPMXL survey; they concluded that the data might be consistent with a long-lived warp, though they admit that smaller systematic errors in the proper motions are needed to confirm this tentative finding. Indeed, large-scale systematic errors in the ground-based proper motions compromise efforts to detect the Galactic warp. The first real hopes of overcoming such systematics came with
global space-based astrometry. However, using Hipparcos (ESA 1997) data for OB stars, Smart et al. (1998) and Drimmel et al. (2000) found that the kinematics were consistent neither with a warp nor with a flat unwarped disk.

Before the recent arrival of the first Gaia Data Release (Gaia Collaboration et al. 2016, DR1), the best global astrometric accuracy is to be found in the New Redution of the Hipparcos catalogue (van Leeuwen 2007, HIP2), which improved the quality of astrometric data by more than a factor of two with respect to the original Hipparcos catalogue. The primary aim of this work is to assess whether either the HIP2 or the new Gaia astrometry for the OB stars in the Hipparcos shows any evidence of the systematics expected from a long-lived warp in the kinematics of distant OB stars. Our approach is to compare the observations with the expectations derived from a model of the distribution and kinematics of this young population of stars, taking into full account the known properties of the astrometric errors, thereby avoiding the biases that can be introduced by using intrinsically uncertain distances to derive biased unobserved quantities.

In Section 2 we describe the data for our selected sample of OB stars from HIP2 and from Gaia DR1, including updated spectrophotometric distance calibrations to be used with the HIP2 proper motions. In Section 3 we present the model developed to create mock catalogues reproducing the observed distributions. In Section 4 we report the results of comparing the proper motion distributions of our two samples with the probability distribution of the proper motions derived from models with and without a warp. In the last sections we discuss our results and outline future steps.

2. The data

2.1. Selected samples

We select from the New Hipparcos Catalogue (hereafter HIP2) the young OB stars, due to their high intrinsic luminosity. Moreover, being short-lived, they are expected to trace the warped gaseous component. However, the spectral types in the HIP2 are simply those originally provided in the first Hipparcos release. In the hope that the many stars originally lacking luminosity class, in the Hipparcos catalogue would have by now received better and more complete spectral classifications, we surveyed the literature of spectral classifications available since the Hipparcos release. Most noteworthy for our purposes is the Galactic O-star Spectroscopic Survey (GOSSS) (Maíz Apellániz et al. 2011; Sota et al. 2011, 2014), an ongoing project whose aim is to derive accurate and self-consistent spectral types of all Galactic stars ever classified as O type with $B_J$ magnitude $< 12$. From the catalogue presented in Sota et al. (2014), which is complete to $B_J = 8$ but includes many dimmer stars, we imported the spectral classifications for the 212 stars that are present in the HIP2 catalogue. Thirteen of these HIP2 sources were matched to multiple GOSSS sources, from which we took the spectral classification of the principle component. Also worth noting is the Michigan Catalogue of HD stars (Houk & Cowley 1994; Houk 1993, 1994; Houk & Smith-Moore 1994; Houk & Swift 2000), which with its 5th and most recent release now covers the southern sky ($\delta < 5^\circ$), from which we found classifications for an additional 3585 OB stars. However, these two catalogues together do not cover the whole sky, especially for the B stars. We therefore had to resort to tertiary sources that are actually compilations of spectral classifications, namely the Catalogue of Stellar Spectral Classifications (4934 stars; Skiff (2014)), and the Extended Hipparcos Compilation (3216 stars; Anderson & Francis (2012)). In summary, we have spectral classifications for 11947 OB stars in Hipparcos.

We select from the HIP2 only those stars earlier than B3, effectively limiting our sample to stars younger than about 30 Myrs (Underhill et al. 1982). (In this way we also avoid a significant number of stars lacking luminosity class, though these are only needed for spectro-photometric distances.) We also limit our sample to stars with an apparent magnitude $V_J \leq 7.5$, the completeness limit of the HIP2, and with galactic latitude $|b| < 30^\circ$, resulting in 1167 OB stars. From this sample of HIP2 stars we define two subsamples: a HIP2 sample whose measured Hipparcos parallax is less than 2 mas, and a TGAS(HIP2) sample consisting of those HIP2 stars that appear in the Gaia DR1 whose measured TGAS parallax is less than 2 mas. The cut in parallax, together with the cut in galactic latitude, is done to remove local structures (such as the Gould Belt). Our HIP2 sample contains 559 stars (including 5 stars without luminosity class), while our TGAS(HIP2) sample contains only 331 stars. This lack of HIP2 stars is largely due to the completeness characteristics of DR1, discussed further in Section 3.5 below.

Notwithstanding the parallax cut we found that there were HIP2 stars in our sample that are members of nearby OB associations known to be associated with the Gould Belt. We therefore removed from the HIP2 sample members of the Orion OB1 association (11 stars, as identified by Brown et al. (1994)) and, as according to de Zeeuw et al. (1999), members of the associations Trumpler 10 (2 stars), Vela OB2 (6 stars), Lacerta OB1 (8 stars), all closer than 500 pc from the Sun. We also removed 19 stars from the Collinder 121 association as it is thought to also be associated with the Gould Belt. With these stars removed we are left with a final HIP2 sample of 508 stars. It is worth noting that the superior Gaia parallaxes already result in a cleaner sample of distant OB stars: only 13 members of the above OB associations needed to be removed from the TGAS(HIP2) sample after the parallax cut.

Figure 1 shows the position of the stars in our two samples in Galactic coordinates.

![Fig. 1. Our final sample of Hipparcos OB stars on the sky, plotted in galactic coordinates. The dashed line shows the orientation of the Gould belt according to Comeron et al. (1992). Colored points indicate the stars that are identified members of the OB associations Orion OB1 (red), Trumpler 10 (purple), Vela OB2 (blue), Collinder 121 (green) and Lacerta OB1 (cyan).](image-url)
A final comment on the observed OB distribution can be made considering Figure 2, where the data are plotted in the l-b space and two robust linear fits are performed for the stars toward and away from the Galactic Center. We found the slope for stars toward the anti-center, that generally lie beyond the Solar Circle, is significantly different from zero, consistent with a warped distribution of stars. However, given the possible effects of patchy extinction, it would be dangerous to make any detailed conclusions about the large scale geometry of the warp from this sample with distance limited to a few kiloparsecs.

2.2. Spectro-photometric distances

Due to the above mentioned parallax cut, our sample mostly contains stars more distant than 500 pc, for which the large relative errors on the trigonometric parallaxes do not allow us to obtain reliable distance estimates. Though our analysis will only marginally depend on the distances, we use spectro-photometric parallaxes when a distance is needed. Numerous spectral class - luminosity calibrations for OB stars are available in the literature. In order to select an appropriate calibration, we evaluated those listed in Table 1 using a set of OB stars located approximately at the same distance from the Sun, namely from the LMC. Since these stars can be assumed to be at nearly the same distance, there should be no trends in the distance modulus with respect to spectral class or intrinsic color. To test this for each calibration, we select 352 O-B0 stars (hereafter, the O sample) presented in Walborn et al. (2014), based on the VLT-FLAMES Tarantula Survey (VFITS, Evans et al. 2011) which performed a census of the hot luminous stars (Doran et al. 2013) in the 30 Doradus (the Tarantula nebula) star forming region, and 330 B0-B3 stars (hereafter, the B sample) in the two LMC clusters N11 and NGC 2004, selected from Hunter et al. (2008).

For each calibration the distance modulus \((m - M)_\text{cal} = m_V - M_{V,\text{cal}} - A_V,\text{cal}\) is computed for each star, where the extinction \(A_V\) is determined from the observed \((B - V)\) color excess, using a constant value of visual reddening \(R_V\), taken from the literature. For the O sample in the 30 Doradus nebula, we used \(R_V = 4.5 \pm 0.2\) estimated by De Marchi & Panagia (2014), while for the B sample in the clusters N11 and NGC 2004 we used the standard Galactic reddening \((R_V = 3.1)\) in line with Hunter et al. (2008). Where possible, both absolute magnitude and intrinsic color are taken from the same author, for consistency. Otherwise we import the intrinsic color from another calibration that the author used or mentioned in their work. Finally, the trends with respect to spectral type and intrinsic color were evaluated by performing linear fits with respect to these parameters, as shown in Figures 3 and 4.

Based on their minimum dependence on the spectral type and intrinsic color, we selected the calibration of Martins (2005) for the O stars and Humphreys (1984) for the B stars. Given that the extinction in these star forming regions of the LMC is a subject of study, we repeated the same analysis with different values for the reddening (\(R_V\)) for the 30 Doradus nebula, \(R_V = 3.5\) within the MEDUSA region and \(R_V = 4.2\) within the R136 region, as suggested by Doran et al. (2013). Although the distributions were shifted, the global trends were approximately preserved and the calibrations of Martins and Humphreys remained the preferred ones.

Since two calibrations are to be used for our Hipparcos OB sample, we checked their consistency using the stars in the LMC O sample, using the same value for the reddening (\(R_V = 4.5\)). (For the Humphreys calibration only those stars in the O7 to B0 range are used.) Figure 5 shows the distribution of \((m - M)_\text{cal} - (m - M)_0\), where \((m - M)_0 = 18.50 \pm 0.10\) is the ”canonical” value for distance modulus of the LMC (Freeman et al. 2001). We obtain a mean value of \(<(m - M)_\text{O,Hum}> = 18.55 \pm 0.04\) and standard deviation \(\sigma_{(m-M)_\text{O,Hum}} = 0.73 \pm 0.03\) using the Martins’ calibration, while from the Humphreys’ calibration we find \(<(m - M)_\text{O,Hum}> = 18.52 \pm 0.04\) and \(\sigma_{(m-M)_\text{O,Hum}} = 0.73 \pm 0.04\). According to the Kolmogorov-Smirnov test, the two distributions are from the same parent distribution at the 95% confidence level. The consistency of the results suggests that, even if the calibrations were produced by different authors and were obtained using different methods, they can be applied to a unique sample containing both O and B stars without introducing a discontinuity in the distance determinations. The \(\sigma_{(m-M)} = 0.73\) is comparable with the error model presented in Drimmel et al. (2000), which we adopted in this work.

3. The model

Here we describe the model used to produce synthetic catalogues and probability distribution functions of the observed quantities to compare with our two samples of Hipparcos OB-stars de-

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**Table 1. Absolute magnitude and intrinsic color calibrations.**

| Calibration       | Spectral range | References |
|-------------------|----------------|------------|
| Straizys (1981)   | O3-B9          | 1, 2       |
| Schmidt-Kaler (1982) | O3-B9          | 3          |
| Humphreys (1984) | O7-B3          | 4, 5       |
| Vacca (1996)     | O3-B0.5        | 6, 2       |
| Loktin (2001)    | O9-B8          | 7, 2       |
| Martins (2005)   | O3-O9.5        | 8, 9       |
| Wegner (2006)    | O5-B9.5        | 10, 11     |

**References.** (1) Straizys & Kuriliene (1981); (2) Stražižys (1992); (3) Schmidt-Kaler (1982); (4) Humphreys & McElroy (1984); (5) Flower (1977); (6) Vacca et al. (1996); (7) Loktin & Beshenov (2001); (8) Martins et al. (2005); (9) Martins & Plez (2006); (10) Wegner (2006); (11) Wegner (2014).
Fig. 3. Distance modulus in function of spectral type (top) and intrinsic color (bottom) for the O sample. From left to right: (A) Straizys & Kuriliene (1981), (B) Schmidt-Kaler (1982), (C) Vacca et al. (1996), (D) Martins et al. (2005), (E) Wegner (2006). The solid line shows the linear fit to the data, while the dotted line represents the value found in literature (Freedman et al. 2001, see text).

Fig. 4. Distance modulus in function of spectral type (top) and intrinsic color (bottom) for the B sample. From left to right: (A) Straizys & Kuriliene (1981), (B) Schmidt-Kaler (1982), (C) Humphreys & McElroy (1984), (D) Loktin & Beshenov (2001), (E) Wegner (2006). The solid line shows the linear fit to the data, while the dotted line represents the value found in literature (Freedman et al. 2001, see text).

scribed above, taking into account the error properties of the Hipparcos astrometry (for the HIP2 sample) and of the Hipparcos subsample in Gaia DR1 (for the TGAS(HIP2) sample), and applying the same selection criteria used to arrive at our two samples. To model the TGAS (HIP2) sample, a model of the incompleteness is used. The distribution on the sky and the magnitude distribution of the HIP2 sample, assumed to be complete, are first reproduced (Sections 3.1 and 3.2), using models of the color-magnitude and spatial distribution of the stars, and a 3D extinction model. Then a simple kinematic model for the OB stars is used to reproduce the observed distribution of proper motions (Section 3.3) of our two samples, including (or not) the ex-
Density stars are incremented by $-\frac{1}{10}$ are randomly labelled as giant. The absolute magnitude of these to an assumed giant fraction (see below), a fraction of the stars (Figure 6), which linearly increases as stars get fainter. According to (Section 3.4). A comparison of the observed samples with the expectations from the different warp/no-warp models is presented in Section 4.

The model that we present here is purely empirical. Many parameters are taken from the literature, while a limited number have been manually tuned when it was clear that better agreement with the observations could be reached. We therefore make no claim that our set of parameters are an optimal set, nor can we quote meaningful uncertainties. The reader should thus interpret our choice of parameters as an initial “first guess” for a true parameter adjustment, which we leave for the future when a larger dataset from Gaia is considered. In any case, after some exploration, we believe that our model captures the most relevant features of the OB stellar distribution and kinematics at scales between 0.5 – 3 kpc.

3.1. Luminosity function

There are different initial luminosity functions (ILF) in the literature for the upper main sequence (Bahcall & Soneira 1980; Humphreys & McElroy 1984; Scalo 1986; Bahcall et al. 1987; Reed 2001). Given the uncertainties in the ILF for intrinsically bright stars (absolute magnitude $M < -3$), we assume $N(M) \propto 10^{\alpha M}$, and use the value $\alpha = 0.72$ that we find reproduces well the apparent magnitude distribution (Figure 10) with the spatial distribution described in Section 3.2. We use a main sequence Color-Magnitude relation consistent with the adopted photometric calibrations (Section 2.2). Absolute magnitudes $M$ are randomly generated consistent with this ILF then, for a given absolute magnitude, stars are given an intrinsic color generated uniformly inside a specified width about the main sequence (Figure 6), which linearly increases as stars get fainter. According to an assumed giant fraction (see below), a fraction of the stars are randomly labelled as giant. The absolute magnitude of these stars are incremented by $-0.5$ mag, and their color is generated uniformly between the initial main sequence color and the reddest value predicted by our calibrations, $(B - V)_0 = -0.12$. The giant fraction $f_g$ is function of the absolute magnitude

$$f_g(M) = \begin{cases} 
1, & \text{if } M \leq -7 \\
-0.25M - 0.75, & \text{if } M \leq -4 \& M \geq -7 \\
0.25, & \text{if } M \geq -4
\end{cases}$$

in rough agreement with what we find in the observed catalogue. We caution that this procedure is not intended to mimic stellar evolution. Instead, we simply aim to mimic the intrinsic color-magnitude distribution (i.e. Hess diagram) of our sample.

3.2. Spatial distribution and extinction

Since we wish to model the distribution of OB stars on scales larger than several hundred parsecs, we use a mathematical description of this distribution that smooths over the inherent clumpy nature of star formation, which is evident if we consider the distribution of young stars within 500 pc of the Sun. On these larger scales it is nevertheless evident that the OB stars are far from being distributed as a smooth exponential disk, but rather trace out the spiral arms of the Galaxy, being still too young to have wondered far from their birth-places. In our model we adopt $R_0 = 8.2$ kpc as the Sun’s distance from the Galactic center, and a solar offset from the disk midplane of $z_0 = 25$ pc, for galactocentric cylindrical coordinates $(R, \phi, z)$, as recommended by Bland-Hawthorn & Gerhard (2016). For the spiral arm geometry we adopt the model of Georgelin & Georgelin (1976), as implemented by Taylor & Cordes (1993), rescaled to $R_0 = 8.2$ kpc, with the addition of a local arm described as a logarithmic spiral segment whose location is described by $R_{Loc} = R_{Loc,j} \exp(-|\tan \rho_p \phi|)$, $p$ being the arm’s pitch angle. The surface density profile across an arm is taken to be gaussian, namely: $\rho \propto \exp(-d_\rho^2/w_{\rho}^2)$, where $d_\rho$ is the distance to the nearest arm in the $R,\phi$ plane, and $w_{\rho} = c_{\rho} R$ is the arm half-width, with $c_{\rho} = 0.06$ (Drimmel & Spergel 2001). An “overview” of the modelled surface density distribution is shown in Figure 7. The stars are also given an exponential vertical scale height $\rho \propto \exp(-|z'|/h_z)$, where $h_z$ is the vertical scale height and...
\[ z' = z - z_w(z_{\text{Loc}}), \quad z_w(R, \phi) \text{ being the height of the warp as described in section 3.4, and } z_{\text{Loc}} \text{ is a vertical offset applied only to the local arm.} \]

**Fig. 7.** Modelled Surface density of the OB stars. Sun’s position is indicated by the star.

We generate the above spatial distribution in an interactive Monte-Carlo fashion. Ten thousand positions in \((x, y)\) coordinates are first generated with a uniform surface density to a limiting heliocentric distance of 11 kpc, and with an exponential vertical profile in \([z']\). The relative surface density \(\Sigma(x, y)\) is evaluated at each position according to our model described above, and positions are retained if \(u < \Sigma(x, y)/\max(\Sigma)\), where \(u\) is a uniform random deviate between 0 and 1. Each retained position is assigned to a \((M_V, (B - V)_0)\) pair, generated as described in the previous section. The extinction to each position is then calculated using the extinction map from Drimmel & Spergel (2001) and the apparent magnitude found. Stars are then retained if the apparent magnitude \(V \leq 7.5\). In the case of modelling the TGAS-like catalogue we also randomly retain stars according to the completeness fraction as a function of the observed apparent magnitude and color, as described below (section 3.5). This procedure is iterated until a simulated catalogue of stars is generated matching the number in our observed sample.

Good agreement with the HIP2 distribution in galactic latitude was found adopting a vertical scale height \(h_z = 70\) pc and assuming \(z_{\text{Loc}} = 25\) pc, as shown in Figure 8. Figure 9 compares the modelled and observed distributions in galactic longitude, which is dominated by the local arm. This observed distribution is reproduced by placing the local arm at a radius of \(R_{\text{Loc}} = 8.3\) kpc, with a pitch angle of 6.5° and a half-width of 500 pc. (The curves in Figures 8 and 9 are non-parametric fits to the distributions obtained through kernel density estimation with a gaussian kernel, as implemented by the generic function \(\text{density}\) in \(\mathbb{R}\).)

The smoothing bandwidth is fixed for all the curves in the same figure, with values of 2.5° and 15° for the latitude and the longitude distribution, respectively.)

Figure 10 shows the resulting apparent magnitude distribution, as compared to the HIP2 sample. Comparing the observed and the simulated longitude distributions in Figure 9, we note that our model fails to reproduce well the observed distribution in the longitude range \(l = 300 – 360\) degrees. This is probably revealing a deficit in the geometry adopted for the Sagittarius-Carina arm, which we have not attempted to modify as we are primarily interested in the kinematics toward the Galactic anticenter. It should also be noted that, for both the longitude and latitude distributions, the presence or absence of a warp (modelled as described in Section 3.4) has very little effect.

The careful reader will note that our approach assumes that the Hess diagram is independent of position in the Galaxy. We recognize this as a deficit in our model, as the spiral arms are in fact star formation fronts, in general moving with respect to galactic rotation. We thus expect offsets between younger and
older populations, meaning that the Hess diagram will be position dependent. However, if the Sun is close to co-rotation, as expected, such offsets are minimal.

Fig. 10. Apparent magnitude distribution for the data (histogram) and the simulations (black dots). The error bars show 2σ uncertainty, calculated with 30 simulated samples.

3.3. Kinematics

Now that the spatial distribution has been satisfactorily modelled, we can address the observed distribution of proper motions. The kinematics of the OB stars is described with a simple model for the velocity dispersions along the three main axes of the velocity ellipsoid: $\sigma_{(1,2,3)} = \sigma_{(1,2,3)}^0 \exp\left(\frac{R_\odot - R}{2h_R}\right)$, where $h_R = 2.3$ kpc is the radial scale length and $\sigma_{(1,2,3)}^0 = (14.35, 9.33, 5.45)\text{ km s}^{-1}$ are the three velocity dispersions in the solar neighborhood for the bluest stars (Dehnen & Binney 1998). A vertex deviation of $l_c = 30^\circ$ is implemented, as measured by Dehnen & Binney (1998) for the bluest stars, although we find that it has no significant impact on the proper motion trends.

As recommended by Bland-Hawthorn & Gerhard (2016), we adopted $\Theta_0 = 238$ km s$^{-1}$ for the circular rotation velocity at the Solar radius $R_0$. Given that current estimates of the local slope of the rotation curve varies from positive to negative values, and that our data is restricted to heliocentric distances of a few kpc, we assume a flat rotation curve. In any case, we have verified that assuming a modest slope of $\pm 5$ km/s/kpc does not significantly impact the expected trend in proper motions.

After local stellar velocities $(U, V, W)$ of the stars are generated, proper motions are calculated assuming a Solar velocity of $v_\odot = (U_\odot, V_\odot, W_\odot) = (11.1, 12.24, 7.25)\text{ km s}^{-1}$ (Schönrich et al. 2010). Observed proper motions in $(\alpha, \delta)$ are derived by adding random errors as per an astrometric error model, described in the Section 3.6. Finally, the proper motions in equatorial coordinates are converted to galactic coordinates, i.e. $(\mu_l^*, \mu_b)$, where $\mu_l^* = \mu_l \cos b$.

Figure 11 shows the derived proper motions in galactic longitude for both the data and simulations using the bivariate local-constant (i.e. Nadaraya-Watson) kernel regression implemented by the npregbw routine in the np R package with bandwidth $h = 45^\circ$. The solid black line shows the trend obtained for the simulation with the above listed standard parameters. Our simple model of Galactic rotation fails to reproduce the observations, even if we assume $\Theta_0 = 220$ or 260 km s$^{-1}$ (upper and lower dash-dotted black lines, respectively). We also tried modifying the $(U_\odot, V_\odot, W_\odot)$ components of the solar motion (equivalent to adding a systematic motion to the LSR), but without satisfactory results. We finally obtained a satisfactory fit by assigning to the stars associated with the Local Arm an additional systematic velocity of $\Delta V_C = 6$ km s$^{-1}$ in the direction of Galactic rotation and $\Delta V_R = 1$ km s$^{-1}$ in the radial direction. Such a systematic velocity could be inherited from the gas from which they were born, which will deviate from pure rotation about the galactic center thanks to post-shock induced motions associated with the Local Arm feature. Similar, but different, systematics may be at play for the other major spiral arms, which we have not tried to model given the limited volume that is sampled by this Hipparcos derived dataset. In any case, the addition (or not) of these systematic motions parallel to the Galactic plane does not significantly influence the the proper motions in galactic latitude, as discussed in Section 4.

As is well known, the International Celestial Reference Frame (ICRF) is the practical materialization of the International Celestial Reference System (ICRS) and it is realized in the radio frequency bands, with axes intended to be fixed with respect to an extragalactic intertial reference frame. The optical realization of the ICRS is based on Hipparcos catalogue and is called Hipparcos Celestial Reference Frame (HCRF). van Leeuwen (2007) found that the reference frame of the new reduction of Hipparcos catalogue was identical to the 1997 one, aligned with the ICRF within 0.6 mas in the orientation vector (all 3 components) and within 0.25 mas/yr in the spin vector $\omega$ (all 3 components) at the epoch 1991.25. It is evident that a non-zero residual spin of the HCRF with respect to the ICRF introduces a systematic error in the Hipparcos proper motions. Depending on the orientation and on the magnitude of the spin vector, the associated system-
atic proper motions can interfere or amplify a warp signature and must therefore be investigated and taken into account. In the following section, when modelling the HIP2 sample, we consider the effects of such a possible spin, adding the resulting systematic proper motions to the simulated catalogues following Equation 18 of Lindegren & Kovalevsky (1995), and using the residual proper motions to the simulated catalogues following Equation 3 of Lindegren et al. (2016).

### 3.4. Warp

In this Section, we warp the spatial distribution and introduce the associated kinematics. In Section 3.2, we constructed a flat disk distribution with vertical exponential profile. We shift the z-coordinates by \( z_w \), where:

\[
z_w(R, \phi) = h(R) \sin(\phi + \phi_w)
\]

Following Burton (1988), we assume that the Sun \((\phi = 0)\) lies approximately on the line of nodes of the warp \((\phi_w \approx 0)\). The increase of the warp amplitude with Galactocentric radius is described by the height function

\[
h(R) = h_0 (R - R_0)^2
\]

where \( h_0 \) and \( R_0 \) are the warp amplitude and the radius at which the Galactic warp starts, respectively. Assuming that the Galaxy can be modeled as a collisionless system, the \( 0^\text{th} \) moment of the collisionless Boltzmann equation in cylindrical coordinates gives us the mean vertical velocity \( \bar{v}_z(R, \phi) \). If we use the warped disk as described above and suppose that \( \bar{v}_z \approx 0 \) (i.e. that the disc is not radially expanding or collapsing), we obtain:

\[
\bar{v}_z(R, \phi) = \frac{\bar{v}_b}{R} h(R) \cos \phi
\]

Equations 1, 2 and 3 assume a perfectly static. This is the model we will refer to as warp model. It is of course possible to construct a more general model by introducing time dependencies in Equation 2, which will result in additional terms in Equation 3, including precession or even a oscillating (i.e. "flapping") amplitude. For our purpose here, to predict the expected systematic vertical velocities associated with a warp, such time dependencies are not considered.

Our alternative model will be the no-warp model, where Equation 3 reduces to the trivial \( \bar{v}_z = 0 \).

Figure 12 (left) shows the prediction of our warp model for the mean proper motions \( \mu_b \) in the Galactic plane. For the no-warp model (here not shown), we expect to have negative \( \mu_b \) values symmetrically around the Sun as the reflex of the vertical component of Solar motion, progressively approaching 0 with increasing heliocentric distance. For the warp model, a variation of \( \mu_b \) with respect to galactic longitude is introduced, with a peak toward the anti-center direction \((l = 180^\circ)\). Note that Figure 12 shows the true proper motions derived from the above equations of our Galactic warp model. In Section 4 we show the expected observed proper motions for our two models, as compared to our HIP2 sample.

### 3.5. TGAS(HIP2) completeness

In our model of the HIP2 sample we have assumed that the selected sample of OB stars to \( V_f < 7.5 \) is complete. Our model of the TGAS(HIP2) sample is effectuated by modelling the (in)completeness of the Hipparcos subsample in DR1 with respect to the Hipparcos catalogue. We find that the TGAS-HIP completeness is strongly dependent on the observed magnitude and color of the stars: 50% completeness is reached at \( V_f = 6.5 \) mag and \( B - V = 0 \), with the brightest and bluest stars missing from DR1. This incompleteness of the brightest and bluest stars is a result of the quality criteria used for constructing DR1 and of the difficulty of calibrating these stars due to their relative paucity. Figure 13 shows a map of the TGAS(HIP2) completeness as a function of apparent magnitude and color.

![Figure 12](image1.png)

**Fig. 12.** The true \( \mu_b \) in the Galactic plane as a function of Galactic longitude (right) according to the warp model. The three curves show the expected \( \mu_b(l) \) trend for heliocentric distances of 0.5, 1 and 1.5 kpc (solid, dashed and dotted line respectively).

![Figure 13](image2.png)

**Fig. 13.** Fraction of HIP2 OB stars present in HIP-TGAS as a function of the observed color and the apparent magnitude.

The completeness reaches a maximum plateau of about 80%, however this is not uniform across the sky. Due to the scanning strategy of the Gaia satellite, and limited number of months of observations that have contributed to the DR1, some parts of the sky are better covered than others. This results in a patchy coverage, which we have not yet taken into account. However, this random sampling caused by the incomplete scanning of the sky.
by Gaia is completely independent of the stellar properties, so that our TGAS(HIP2) sample should trace the kinematics of the stars in an unbiased way.

3.6. Error model

Our approach to confronting models with observations is to perform this comparison in the space of the observations. Fundamental to this approach is having a proper description (i.e. model) of the uncertainties in the data. For this purpose we construct an empirical model of the astrometric uncertainties in our two samples from the two catalogues themselves. Below we first describe the astrometric error model for the HIP2 sample, based on the errors in the HIP2 catalogue, and then that of the TGAS(HIP2) sample based on the error properties of the Hipparcos subsample in Gaia DR1. We note that, while we are here principally interested in the proper motions, we must also model the uncertainties of the observed parallaxes $\varpi$ since we have applied the selection criteria $\varpi < 2$ mas to arrive at our OB samples, and this same selection criteria must therefore be applied to any synthetic catalogue to be compared to our sample.

3.6.1. Hipparcos error model

It is known that the Hipparcos astrometric uncertainties mainly depend on the apparent magnitude (i.e. the S/N of the individual observations) and on the ecliptic latitude as a result of the scanning law of the Hipparcos satellite, which determined the number of times a given star in a particular direction on the sky was observed. These dependencies are not quantified in van Leeuwen (2007), which only reports the formal astrometric uncertainties for each star. To find the mean error of a particular astrometric quantity as a function of apparent magnitude and ecliptic latitude we selected the stars with $(B-V) < 0.5$ from the HIP2 catalogue, consistent with the color range of our selected sample of OB stars. We then bin this sample with respect to apparent magnitude and ecliptic latitude and find the median errors for $\alpha, \delta, \varpi, \mu_\alpha$, and $\mu_\delta$ for each bin. The resulting tables are reported in the Appendix, which gives further details on their construction.

![Histogram showing observed parallax distribution](https://example.com/histogram.png)

**Fig. 14.** The histogram shows the observed parallax distribution. The dashed and the solid curves show, respectively, the synthetic distributions with $F=1$ and $1.5$ (see text for explanation).

However, before using these formal HIP2 uncertainties to generate random errors for our simulated stars, we first evaluate whether the formal errors adequately describe the actual accuracy of the astrometric quantities. For this purpose the distribution of observed parallaxes is most useful, and in particular the tail of the negative parallaxes, which is a consequence of the uncertainties since the true parallax is greater than zero. In fact, using the mean formal uncertainties in the parallax to generate random errors, we are unable to reproduce the observed parallax distribution in our sample (see Figure 14). Assuming that our model correctly describes the true underlying distance distribution, we find that the formal HIP2 uncertainties must be inflated by a factor of $F = 1.5$ to satisfactorily reproduce the observed distribution. This factor $F$ is then also applied to the mean formal uncertainties of the other astrometric quantities. We note that this correction factor is larger than that implied from an analysis of the differences between the Hipparcos and Gaia DR1 parallaxes.

(See Appendix B of Lindegren et al. (2016).)

To better fit the HIP2 proper motion distributions we also take into consideration stellar binarity. Indeed, approximately $f_b \approx 20\%$ of stars of our sample has been labelled as binary, either resolved or unresolved, in the HIP2 catalogue. For these stars, the uncertainties are greater than for single stars. Therefore, we inflate the proper motion errors for a random selection of $20\%$ of our simulated stars by a factor of $f_{bin} = 1.7$ to arrive at a distribution in the errors comparable to the observed one.

Finally, we also performed similar statistics on the correlations in the HIP2 astrometric quantities published by van Leeuwen (2007), using the four elements of the covariance matrix relative to the proper motions (see Appendix B of Michalik et al. (2014)). We find that the absolute median correlations are less than $0.1$, and therefore we do not take them into account.

3.6.2. TGAS(HIP2) error model

A detailed description of the astrometric error properties of the TGAS subset in Gaia DR1 is described in Lindegren et al. (2016). However, on further investigation we found that the error properties of the subset of 93635 Hipparcos stars in Gaia DR1 are significantly different with respect to the larger TGAS sample. In particular, we find that the zonal variations of the median uncertainties seen with respect to position on the sky are much less prominent for the Hipparcos stars in DR1, and are only weakly dependent on ecliptic latitude. The parallax errors with respect to ecliptic latitude are shown in Figure 15. Meanwhile the TGAS(HIP2) parallax errors show no apparent correlation with respect to magnitude or color. Figure 16 shows the distribution of parallax uncertainties for three ecliptic latitude bins, which we model with a gamma distribution having the parameters reported in Table 2.

| Ecliptic latitude [k] (deg) | $k$ | $\theta$ | offset |
|---------------------------|----|---------|--------|
| 0-40                      | 1.5| 0.113   | -0.658 |
| 40-60                     | 1.2| 0.115   | -0.658 |
| 60-90                     | 1.1| 0.08    | -0.67  |

The errors for the proper motions also show a weak dependence on ecliptic latitude, as well as additional dependence with respect to magnitude. Indeed, we find that the proper motion errors for the Hipparcos subset in Gaia DR1 are strongly cor-
Fig. 15. Logarithm of the parallax errors in function of ecliptic latitude for the Hipparcos subsample in TGAS. The point show the medians, while the error bars show the 10th and the 90th percentiles of the distribution.

Fig. 16. Distribution of the logarithm of the parallax uncertainties for the HIP-TGAS stars. Three subsets with different ecliptic latitude are shown.

Fig. 17. For each star of the Hipparcos subset in TGAS, the published error $\sigma_{\mu_r}(\text{TGAS})$ is compared to the prediction based on Hipparcos uncertainties $F \sigma^H(m, \beta)/\Delta t$ (see text). The dashed line represents the bisector. The solid line has null intercept and coefficient $C_\alpha = 1.42$, which is used to calibrate our error model (see text).

related the Hipparcos positional errors, as one would expect, given that the Hipparcos positions are used to constrain the Gaia DR1 astrometric solutions (Michalik et al. 2015). We use this correlation to model the proper motion errors of the Hipparcos subsample in DR1. Figure 17 shows the agreement which results when we take as our model $\sigma_{\mu_r} = C_\alpha [F \sigma^H(m, \beta)/\Delta t]$, where $F$ is the correction factor applied to the Hipparcos astrometric uncertainties, as described in Section 3.6.1. $\sigma^H(m, \beta)$ is the Hipparcos error in right ascension, interpolated from Table A.1 in the Appendix, and $\Delta t$ is the difference between the Gaia (2015) and Hipparcos (1991.25) epoch. The adopted coefficient $C_\alpha = 1.42$ is the median of $\sigma_{\mu_r}/[F \sigma^H(m, \beta)/\Delta t]$ for the stars of the TGAS(HIP2) sample. An analogous model is used for $\sigma_{\mu_\beta}$, with $C_\beta = 1.44$.

Finally, in contrast to the correlations in the HIP2 sample, we find that the correlations in DR1 between the astrometric quantities of the Hipparcos subsample vary strongly across the sky, but are significantly different from the complete TGAS sample, shown in Figure 7 of Lindegren et al. (2016). Figure 18 shows the variation across the sky of the correlations between the parallaxes and the proper motions.

4. Comparison between models and data

In this section we first attempt to derive the systematic vertical motions from the observed proper motions and compare these with those predicted from the model, to demonstrate the weaknesses of this approach. We then compare the observed proper motions of our two samples with the proper motion distributions derived from models with and without a warp.

4.1. Mean vertical velocity in function of Galactocentric radius

We first consider the mean vertical velocity $\bar{v}_z$ as a function of Galactocentric radius $R$ that one would derive from the measured proper motions and spectro-photometric distances, comparing the data with what we expect from the no-warp and warp models. In the no-warp case, the true mean vertical velocities are zero, while the warp model predicts that they increase with $R$ outside the radius $R_w$ at which the Galactic warp starts. (See equation 1.) Figure 19 shows the mean vertical velocities, after removing the solar motion, for the data and the no-warp and warp simulated catalogues. (The choice of the warp parameters is described in section 4.2.) The simulated catalogues include the modelled errors, as described in Section 3.6. Taking into account both distance and proper motion errors, the observed trend is biased toward negative velocities with increasing distance. This bias is particularly evident with the no-warp model, where the true $\bar{v}_z(R) = 0$ (dashed line in Figure 19), but similarly effects the warp model. One might be tempted to proceed to compare models to the data in this space of derived quantities, assuming the error models are correct, but this approach gives the most weight to the data at large distances, i.e. those with the highest errors and the most bias. Indeed, from Figure 19 one might
quickly conclude that the data was consistent with the no-warp model, based however on trends that are dominated by a bias in the derived quantities.

A better approach is to compare the data to the models in the space of the observations, i.e. the mean proper motions as a function position on the sky, thereby avoiding the biases introduced by the highly uncertain distances. That is, better to pose the question: which model best reproduces the observations?

4.2. Proper motion $\mu_b$ in function of Galactic longitude

As reported in Section 3.4, a long-lived warp causes the proper motions $\mu_b$ to increase toward the anticenter, as shown in Figure 12. Figure 20 shows the observed trends of $\mu_b$ with respect to the warp and no-warp models. As expected, the warp model catalogues exhibit a peak toward the anti-center, while the no-warp model primarily reflects the Solar motion. The data also exhibit a peak close to the anti-center, similarly to the warp model catalogues. It now seems that the data is more consistent with a warped model!

To add a third dimension, we divided our catalogue into nearby and distant objects. For the HIP2 sample, we use the spectro-photometric distances and choose the median heliocentric distance of the HIP2 sample $d_{med} = 1$ kpc as a break. (Since here the distances are only used for binning, distance errors are not expected to significantly bias the observed trends.) For the TGAS-HIP sample we instead take advantage of the superior Gaia parallaxes to dividing our sample using with parallaxes less/greater than 1 mas. Results are shown in Figure 21. For both samples we observe that for nearby stars the warp model reproduces reasonably well the observed trend, while at larger distances the data appear to be quite flat toward the anticenter direction with respect to the expectations from the warp model. Moreover, the data confidence bands (95%) are very broad, and for most longitudes overlap with both models. For our most distant stars neither model is strongly favored more than the other.

We note that the models shown for the HIP2 case in Figures 20 and 21 do not include the residual spin in the Hipparcos reference frame. However, we find only minor deviations in the resulting simulated $\mu_b$ vs $l$ trends with respect to those shown here.

For the warp model, we chose warp parameters that approximately reproduce the proper motion trends in Figure 21, resulting in at $R_w = 6.5$ kpc and $h_0 = 0.055$ kpc$^{-1}$. Of course, as discussed in section 3, we cannot assert that these are a unique set of optimal warp parameters. Our aim here is more modest: to determine whether either of our two samples favor either the warp or the no-warp model. To achieve this, we adopted the approach of calculating the likelihood associated with each model, as the
probability of the observed data set arising from the hypothetical model (as described in Peacock 1983).

Given an assumed model (i.e., parameter set), we generated 1000 synthetic catalogues and performed a two-dimensional kernel density estimation in the $l - \mu_b$ space. The obtained number density is the Probability Density Function (PDF), $f(l, \mu_b)$, which can be interpreted as the probability of observing a star in each point according to the model. We adopted the conditional PDF so that, for a fixed longitude $l$, $\int f(l, \mu_b) d\mu_b = 1$. The motivation for this normalization is that we want to assign the probability of observing a given value of $\mu_b$, independent of the longitude distribution, which is highly heterogeneous. That is, we wish to quantify which model best reproduces the observed proper motion trends. In any case, we also performed the normalization imposing $\int f(l, \mu_b) d\mu_b = 1$, obtaining results similar to the ones presented below. Figure 22 shows the PDFs for the warp/no-warp models for the TGAS(HIP2) sample. The PDFs for the HIP2 sample are very similar as the proper motion distribution is dominated by the intrinsic velocity dispersion rather than by the proper motion errors.

Once the PDFs for the two different models are constructed, we found the probability $f(\mu_b, l)$ associated with the $i$-th observed stars in the dataset according to the two models. The likelihood associated with the model is $L = \prod_{i=1}^{N} f(\mu_{b_i}, l_i)$, where $N$ is the total number of stars in our dataset; for computational reasons, we used instead the log-likelihood $\ell = ln(L) = \sum_{i=1}^{N} ln(f(\mu_{b_i}, l_i))$. Also for practical reasons we applied a cut in $\mu_b$, considering only the range $(-10 < \mu_b < 5)$ mas/yr when calculating $\ell$, reducing our HIP2 dataset to 493 stars, and our TGAS(HIP2) sample to 310 stars. Since we are only interested in a relative difference between the two log-likelihoods, we assume that this cut is not biasing the outcome.

Table 3 shows the results for the HIP2 sample, with and without taking into account the spin of the HCRF, while 4 is dedicated to TGAS(HIP2) results. The difference between the log-likelihoods of the two models (i.e., the ratio of the likelihoods, showing which model is more likely) slightly favours the warp case for the HIP2 sample corrected for the spin, consistently with TGAS(HIP2) results. We performed a bootstrap analysis of the log-likelihood to quantify how significant this difference is. Bootstrap catalogues were generated extracting randomly $N$ stars from the observed $N$ stars of the dataset (resampling with replacement). As suggested by Feigelson & Babu (2012), $N^B \approx N(lnN)^2$ bootstrap resamples were generated. The log-likelihood was computed for each bootstrap catalogue and mean and standard deviation were calculated. The mean values were consistent with the values presented in Tables 3 and 4. The obtained standard deviations were $\sigma \approx 25$ for the HIP2 and $\sigma \approx 18 - 19$ for the TGAS(HIP2) samples. Considering the obtained standard deviations, we can affirm that for both HIP2 and TGAS(HIP2) there is no strong evidence that one model is more likely with respect to the other. Qualitatively, this can also be seen in Figure 22, where the difference of the two log-likelihoods is shown: the gold/green regions show where it is more/less likely to observe stars according to the warp/no-warp model. The white regions are the areas in this $\mu_b, l$ space where the two PDF of the two models are equivalent, and where the stars will not help us to decide in favour of either of the two
5. Discussion

Our search for a kinematic signature of the Galactic warp presented above is a preliminary study that adopts an exploratory approach, aimed at determining whether there is clear evidence in the Gaia and/or the pre-Gaia Hipparcos astrometry for such a signal. This was done by selecting a sample of bona fide spectroscopically identified OB stars from the New Hipparcos Reduction, and analyzing both the pre-Gaia astrometry for a sample complete to $V_J$ magnitude 7.5 (HIP2), and a subset of these stars with Gaia DR1 astrometry (TGAS(HIP2)). We use a model of...
the HIP2 sample, with and without correcting the synthetic parallaxes for selecting our two samples. The two PDFs

Fig. 23. Distribution of the data in the $l$-$\mu_b$ plane (black dots), together with the surface obtained calculating: $\ln f(\mu_b | l)_{\text{NOWARP}} - \ln f(\mu_b | l)_{\text{WARP}}$. The two PDFs $f(\mu_b | l)$ are shown in Figure 22.

Table 3. Difference of the log-likelihoods of the warp and nowarp models for the HIP2 sample, with and without correcting the synthetic parallaxes for the spin of the HCRF. The results obtained removing the stars labelled as binaries in van Leeuwen (2007) are also presented.

| HIP2 subset          | Spin | $\ell_{\text{WARP}} - \ell_{\text{NOWARP}}$ | $N_{\text{stars}}$ |
|----------------------|------|---------------------------------------------|--------------------|
| All                  | No   | -0.11                                       | 493                |
| Excluding HIP2 binaries | No   | -0.73                                       | 399                |
| All                  | Yes  | 4.66                                        | 493                |
| Excluding HIP2 binaries | Yes  | 2.90                                        | 399                |

Table 4. Difference of the log-likelihoods of the warp and nowarp models for the TGAS(HIP2) sample. The results are also shown for sample obtained removing the $\Delta Q$ objects, where $\Delta Q$ is the difference between the TGAS and Hipparcos proper motion (Lindegren et al. 2016). $\Delta Q_{95\%} = 23$ and $\Delta Q_{99\%} = 11$ are the percentiles the $\Delta Q$ distribution for all the Hipparcos subset in TGAS. We also present the results excluding the stars labelled as binaries in van Leeuwen (2007).

| TGAS(HIP2) subset       | $\ell_{\text{WARP}} - \ell_{\text{NOWARP}}$ | $N_{\text{stars}}$ |
|-------------------------|---------------------------------------------|--------------------|
| All                     | 3.34                                        | 310                |
| $\Delta Q < \Delta Q_{95\%}$ | 1.57                                        | 303                |
| $\Delta Q < \Delta Q_{99\%}$ | 3.47                                        | 266                |
| Excluding HIP2 binaries | 3.39                                        | 270                |

A study of the pre-Gaia astrometry together with the Gaia astrometry proved useful and even necessary. Since our approach to analyzing the proper motions is significantly different from that used previously by Smart et al. (1998) and Drimmel et al. (2000) for the first Hipparcos release, and given that a new reduction of the Hipparcos data has since become available, a re-analysis is merited. It is also worth pointing out that the study of the Hipparcos error properties was necessary for understanding the astrometric error properties of the Hipparcos subsample in Gaia DR1 because of the intrinsic connection, by construction, between the astrometry of the New Hipparcos Reduction and Gaia DR1. The two samples, while related, are complementary, as the Hipparcos sample can be considered nearly complete and is substantially larger than the Hipparcos subsample of OB stars in Gaia DR1 with superior astrometry.

Considering both data sets, the proper motions perpendicular to the Galactic plane follow a trend with respect to galactic longitude similar to what would be expected from a warp, especially for the Gaia DR1 sample. Figure 22 shows that the PDFs of the observed proper motions of the two models, which take into account the astrometric errors, are clearly distinct. This clear distinction suggests that the quality of the data is sufficient to detect a Galactic warp signature. In addition, the PDFs for the Hipparcos HIP2 sample (not shown) and the Gaia DR1 TGAS(HIP2) sample are very similar. This also shows that the astrometric errors are not a limiting factor, and that the width of the proper motion distribution is mostly determined by the intrinsic velocity dispersion of our sample. However, both models yield similar likelihood values with the warp model only being slightly favored, suggesting that our two datasets do not significantly favor either of the two models. So, while on one hand we can affirm that we don’t need a warp signal to explain the proper motions, on the other we cannot exclude such a model. For this reason, the data for our two chosen samples can be considered inconclusive.

Our main limitation is that we have restricted ourselves to a rather small dataset. Albeit possessing excellent astrometry, the lack of distant stars in directions where the warp signature is most evident, especially toward Galactic anti-center, hinders our ability to unambiguously detect the kinematic signature of the warp. Indeed, as Figure 23 shows, most of the OB stars are distributed in parts of the $l$-$\mu_b$ space where the warp/no-warp PDFs do not significantly differ.

One may note that our choice of warp parameters for the OB stars leads to a significant vertical velocity at the Sun’s position of 4.6 km/s. Assuming that the LSR (defined with older stars) participates in the same warp, this would imply a total vertical velocity of the Sun inconsistent with the measured proper motion of Sag A* (Reid 2008). While our chosen parameters were an attempt to arrive at proper motion trends consistent with the HIP2 observations (Figure 21), they are not the result of an optimum fit. Nevertheless, an inspection of Figure 21 reveals a systematic difference toward the Galactic center in the proper motions $\mu_b$ of more than 0.5 mas/year between the observations and the no warp model for the more distant stars. This offset can only be accounted for with an additional systematic vertical velocity difference between these objects and the observer, which the warp model accounts for.

There may be additional unmodelled systematics in the proper motions that could mask the signature of a large-scale warp. We have accounted for the systematic proper motion er-
errors introduced by a residual spin in the Hipparcos frame, as measured by Gaia, and confirmed that it is not large enough to significantly alter the expected kinematic signature of a stable warp, though taking it into account does marginally improve the agreement between the warp model and the HIP2 data. There is also the possibility that, in addition to the large-scale warp, systematic velocities are being introduced by other phenomenon. Indeed, the incongruity of our implied vertical motion of the bar and spiral arms (Widrow et al. 2012, 2014; Williams et al. 2013; Gómez et al. 2013; Monari et al. 2015). If such effects are as present, then only sampling over a larger volume of the Galactic disk will allow the kinematic signature of the large-scale warp to be disentangled from these other effects.

### 6. Conclusion and future steps

The present work is dedicated to the search of the warp kinematic signal in the Hipparcos subset of the first Gaia data release (DR1). Our approach consists in comparing the astrometric observations with the expectations derived from a model of distribution and kinematics of the OB stars, together with a model of the astrometric errors. The systematic trends in the proper motions obtained performing nonparametric regressions suggest that the warp model is slightly favoured. However, the likelihood approach doesn’t reveal significant evidence in favor of the kinematic signal expected from a long-lived Galactic warp.

The Gaia DR1 astrometry will already allows us to sample a larger volume of the disk of the Milky Way. In future work we will expand our sample to a fainter magnitude limit, using selection criteria based on multi-waveband photometry from other catalogues. We will also compare the kinematics of this young population to an older population representative of the relaxed stellar disk.

Gaia was constructed to reveal the dynamics of the Milky Way on a large scale, and we can only look forward to the future Gaia data releases that will eventually contain astrometry for over a billion stars. We expect that Gaia will allow us to fully characterize the dynamical properties of the warp, as suggested by Abedi et al. (2014, 2015), and allow us to arrive at a clearer understanding of the nature and origin of the warp. At the same time, Gaia may possibly reveal other phenomenon causing systematic vertical velocities in the disk of the Milky Way.

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Appendix A: Hipparcos astrometric errors

The tables A.1, A.2, A.3, A.4 and A.5 show the median formal errors of the astrometric parameters $\alpha$, $\delta$, $\sigma_\alpha$, $\mu_\alpha$ and $\mu_\delta$ in function of apparent magnitude and ecliptic latitude for the HIP2 stars. They were obtained considering the entire HIP2 catalogue (as given by van Leeuwen 2007) excluding the stars redder than $(B-V) = 0.5$. We also excluded stars for which there was a claim of binarity in van Leeuwen (2007), taking account for binary systems after the single stars errors are generated, as described in the text. To construct the tables, we binned the resulting sample of 15197 HIP2 stars with respect to apparent magnitude and ecliptic latitude and found the median errors for each bin. Table A.6 shows the number of objects in each bin.

Table A.1. Median formal uncertainties for $\sigma_\alpha$.

| $m_V$ | Ecliptic latitude ($|\beta|$, (deg)) | 0-10 | 10-20 | 20-30 | 30-40 | 40-50 | 50-60 | 60-90 |
|-------|-------------------------------------|------|------|------|------|------|------|------|
| 3-4   |                                    | 0.22 | 0.19 | 0.40 | 0.23 | 0.12 | 0.11 | 0.20 |
| 4-5   |                                    | 0.24 | 0.25 | 0.25 | 0.20 | 0.15 | 0.16 | 0.15 |
| 5-6   |                                    | 0.34 | 0.32 | 0.31 | 0.27 | 0.21 | 0.19 | 0.20 |
| 6-7   |                                    | 0.49 | 0.46 | 0.44 | 0.37 | 0.29 | 0.29 | 0.29 |
| 7-8   |                                    | 0.66 | 0.64 | 0.60 | 0.51 | 0.40 | 0.39 | 0.40 |

Table A.2. Median formal uncertainties for $\sigma_\delta$.

| $m_V$ | Ecliptic latitude ($|\beta|$, (deg)) | 0-10 | 10-20 | 20-30 | 30-40 | 40-50 | 50-60 | 60-90 |
|-------|-------------------------------------|------|------|------|------|------|------|------|
| 3-4   |                                    | 0.16 | 0.12 | 0.31 | 0.19 | 0.12 | 0.13 | 0.26 |
| 4-5   |                                    | 0.16 | 0.18 | 0.18 | 0.17 | 0.17 | 0.17 | 0.16 |
| 5-6   |                                    | 0.23 | 0.22 | 0.23 | 0.24 | 0.23 | 0.21 | 0.21 |
| 6-7   |                                    | 0.32 | 0.32 | 0.33 | 0.32 | 0.32 | 0.31 | 0.29 |
| 7-8   |                                    | 0.44 | 0.44 | 0.44 | 0.44 | 0.45 | 0.42 | 0.40 |

Table A.3. Median formal uncertainties for $\sigma_\varpi$.

| $m_V$ | Ecliptic latitude ($|\beta|$, (deg)) | 0-10 | 10-20 | 20-30 | 30-40 | 40-50 | 50-60 | 60-90 |
|-------|-------------------------------------|------|------|------|------|------|------|------|
| 3-4   |                                    | 0.20 | 0.19 | 0.19 | 0.21 | 0.16 | 0.13 | 0.14 |
| 4-5   |                                    | 0.25 | 0.26 | 0.25 | 0.23 | 0.24 | 0.19 | 0.16 |
| 5-6   |                                    | 0.36 | 0.34 | 0.35 | 0.34 | 0.33 | 0.26 | 0.22 |
| 6-7   |                                    | 0.51 | 0.51 | 0.49 | 0.47 | 0.47 | 0.38 | 0.31 |
| 7-8   |                                    | 0.71 | 0.70 | 0.69 | 0.66 | 0.66 | 0.53 | 0.45 |

Table A.4. Median formal uncertainties for $\sigma_{\mu_\alpha}$.

| $m_V$ | Ecliptic latitude ($|\beta|$, (deg)) | 0-10 | 10-20 | 20-30 | 30-40 | 40-50 | 50-60 | 60-90 |
|-------|-------------------------------------|------|------|------|------|------|------|------|
| 3-4   |                                    | 0.24 | 0.22 | 0.18 | 0.19 | 0.13 | 0.12 | 0.15 |
| 4-5   |                                    | 0.28 | 0.29 | 0.26 | 0.21 | 0.17 | 0.17 | 0.16 |
| 5-6   |                                    | 0.41 | 0.37 | 0.35 | 0.30 | 0.24 | 0.22 | 0.23 |
| 6-7   |                                    | 0.58 | 0.55 | 0.50 | 0.43 | 0.33 | 0.32 | 0.32 |
| 7-8   |                                    | 0.80 | 0.77 | 0.70 | 0.60 | 0.47 | 0.44 | 0.45 |