LETTER TO THE EDITOR

The intricate Galaxy disk: velocity asymmetries in Gaia-TGAS

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ABSTRACT

We use the Gaia-TGAS data to compare the transverse velocities in Galactic longitude (coming from proper motions and parallaxes) in the Milky Way disk for negative and positive longitudes as a function of distance. The transverse velocities are strongly asymmetric and deviate significantly from the expectations for an axisymmetric Galaxy. The value and sign of the asymmetry changes at spatial scales of several tens of degrees in Galactic longitude and about 0.5 kpc in distance. The asymmetry is statistically significant at 95% confidence level for 57% of the region probed, which extends up to ~1.2 kpc. A percentage of 24% of the region studied shows absolute differences at this confidence level larger than 5 km s⁻¹ and 7% larger than 10 km s⁻¹. The asymmetry pattern shows mild variations in the vertical direction and with stellar type. A first qualitative comparison with spiral arm models indicates that the arms are unlikely to be the main source of the asymmetry. We briefly discuss alternative origins. This is the first time that global all-sky velocity asymmetries are detected in the Milky Way kinematics, beyond the local neighbourhood, and with a purely astrometric sample.

1. Introduction

The scientific community studying the Galaxy welcomed with much expectation the publication of the first Gaia data (Gaia Collaboration et al. 2016a,b) in September of 2016. Even with the limitations of the first release, the Gaia data possesses exciting possibilities for new discoveries on the formation, evolution and current structure of the Milky Way. The Tycho-Gaia astrometric solution (TGAS, Michalik et al. 2015) is the largest astrometric sample to date and comprises proper motions and parallaxes of unprecedented accuracy for two-million stars.

Following the approach proposed in Antoja et al. (2016) (hereafter A16), here we compare the transverse velocities in Galactic longitude (i.e., coming from proper motions and parallaxes) for negative and positive Galactic longitudes as a function of distance with the Gaia-TGAS data. Once the solar motion is subtracted, the data reveals clear large-scale velocity asymmetries that are signatures of the non-axisymmetry in the Galaxy.

This discovery adds up to recent findings of the intricateness of the Galactic disk. For instance, there is multiple evidence of radial and vertical velocity gradients and wave-like motion in the disk (e.g., Siebert et al. 2011; Widrow et al. 2012). Also, Carlin et al. (2013) found asymmetric vertical and radial velocities for different azimuths in the direction of the anti-centre. Recently, Box et al. (2017) found evidence of non-zero values of the local divergence and radial shear while measuring the Oort’s constants with TGAS, but restricted to a local sample (~200 pc). So far these detections have been either very local, limited to the directions probed with the particular ground-based survey, or detected primarily in radial velocity data. Thanks to Gaia, this is the first time that we detect global all-sky velocity asymmetries, beyond the local neighbourhood and with a purely astrometric sample.

We describe the data in Section 2, and the method in Section 3. We show our results on the velocity asymmetry in Section 4. We perform tests to assess the limitations and robustness of our results in Section 5. In Section 6, we conclude and comment on the possible origin of the detected asymmetry.

2. The data

We use proper motions from Gaia-TGAS (Gaia Collaboration et al. 2016a,b) and the distance estimations from Astraatmadja & Bailer-Jones (2016). These were obtained in a Bayesian way from the TGAS parallaxes using different priors: i) an isotropic prior with an exponentially decreasing space density with increasing distance with a short scale length (hereafter dist1), ii) with a longer scale length (dist2), and iii) an anisotropic prior derived from the observability of stars in a Milky Way model (dist3). We also compare the results with the inverse of the parallax as a distance estimator.

We select different layers in Z. We assume a Sun’s height above the plane Z₀ = 0.027 kpc (Chen et al. 2001). Our primary sample is a disk layer with |Z| < 0.1 kpc and has 936861 stars. We further divide our primary sample into groups of different spectral types and luminosity classes obtained from the catalogue of Pickles & Depagne (2010) that we cross-match with TGAS using the Tycho2 ID. We will study young main sequence stars (OBAV, 66446 stars), main sequence stars (FGK M, 509874 stars) and giant stars (KMIII, 126988 stars).

For these samples we compute the observed transverse velocity in the longitude direction (hereafter transverse velocity)
was called the symmetric Galaxy, \( V \), where the distance on the plane for the primary sample (Section 2) using error in \( \mu_V \) 2011; Pasetto et al. 2012, but see discussion in Section 5). A symmetric Galaxy is Gaussian centred at 0 with a sigma derived from the actual data. We did 500 bootstrap of the median \( V_\ell \) at each bin, obtaining effectively 124750 bootstrapped \( V_\ell(+) - V_\ell(-) \) (combinations without repetition) for each pair of bins, from which we computed \( \sigma \). Given the measured \( V_\ell(+) - V_\ell(-) \) and the assumed distribution under the null hypothesis, we find that 71% of bins deviate from axial symmetry at 95% level (p<0.05). By combining all the individual p values with the Fisher’s method, we infer that the hypothesis of axial symmetry can be rejected with a p value < 0.001.

The asymmetry is such that the median velocity difference oscillates between -15 and 18 km s\(^{-1}\) and a median absolute deviation (MAD) of 2.7 km s\(^{-1}\) (considering all bins). The median asymmetry is minimum (1.4 km s\(^{-1}\)) for the distance between 0.2 and 0.4 kpc, and maximum (8.8 km s\(^{-1}\)) at a distance between 1.2 and 1.4 kpc. It is minimum (1.2 km s\(^{-1}\)) at longitudes of \( \pm 5^\circ \) and maximum (15 km s\(^{-1}\)) at longitudes of \( \pm 105^\circ \). A percentage of 47% of all bins probed show absolute differences larger than 2 km s\(^{-1}\) that are statistically significant at 95% level, 24% larger than 5 km s\(^{-1}\), and 7% larger than 10 km s\(^{-1}\). All these numbers indicate that the fraction of the solar suburbs with kinematics showing signs of non-axisymmetry is quite large.

The differences in transverse velocity of Fig. 1 show a pattern of a scale of several tens of degrees and about 0.5 kpc in distance. We observe a large region of negative differences (blue colours) in the range \( |\ell| \sim [70, 180]^\circ \). The positive differences (red colours) are mostly located at close distances, and in the inner and outer disk directions at the farthest distances probed.

Figure 2 shows the velocity asymmetries for different layers in Z as indicated in the legends. The asymmetry extends at least up and down in the plane to \( |Z| \approx 300 \) pc. Beyond this height it loses significance due to the lack of data. We find a mild dependence in Z. The region with negative asymmetry for \( |\ell| \geq 70^\circ \) is present at all Z. But there is a large region with positive asymmetry at \( |\ell| \leq 70^\circ \) only present at the higher Z probed. Beyond \( |Z| > 100 \) pc the asymmetry seems to be dominated by a duality of positive and negative asymmetry, while most of the small scale pattern is significant only at low Z. We do not find differences with small changes in the Z\(_0\) assumed.

Figure 3 shows the velocity asymmetries for the different stellar groups described in Section 2.1 except for the FGKV since it looks essentially as Fig. 1. Interestingly, the large blue region of negative differences appears for all sub-samples but the asymmetry differs substantially in the inner Galaxy (\( |\ell| \leq 70^\circ \)) it is negative for the OBAV group, it is both positive and negative for the FGKV group, and it is mostly positive for the KMIII group at the furthest distances (there is not enough statistics at closer distances for this group). The median velocity asymmetry (for statistically significant bins) is largest for the KMIII group (8 km s\(^{-1}\)), followed by the OBAV (7 km s\(^{-1}\)) and the FGKV (5 km s\(^{-1}\)).

### 3. The method

Our procedure consists of comparing the median velocity of symmetric Galactic longitudes, that is \( \ell \) and \(-\ell\), in bins of longitude and distance on the Galactic plane (\( \ell, d \cos(b) \)). That is:

\[
V_\ell(+) - V_\ell(-) = k \delta d \mu_\ell, (\ell > 0) - k \delta d \mu_\ell, (\ell < 0) - 2U_\odot \sin |\ell|, \tag{2}
\]

where the \( V_\odot \cos \ell \) term from equation (1) cancels out. In an asymmetric Galaxy, \( V_\ell \) is symmetric in \( \ell \) and, therefore, we expect that \( V_\ell(+) - V_\ell(-) = 0 \). Non-null values of \( V_\ell(+) - V_\ell(-) \) show the contribution of the non-axisymmetries. Note that asymmetries in the Galactic radial and azimuthal velocities may both contribute. This methodology has the advantage of being model-independent. Only an assumption on \( U_\odot \) is required. We assume \( U_\odot = 9 \) km s\(^{-1}\) (similar to determinations of Coskunoglu et al. 2011; Pasetto et al. 2012) but see discussion in Section 5. Asymmetries in \( \delta d \mu_\ell \equiv k \delta d \mu_\ell \) are postponed to a forthcoming paper.

We estimate the 95% confidence band of \( V_\ell(+) - V_\ell(-) \) with bootstrapping. We only consider bins with at least 5 stars (thus 10 stars in the pair \( \ell > 0 \) and \( \ell < 0 \)). The typical dispersion of the bootstrapped median \( \delta d \mu_\ell \) (indicative of the precision of the median) is of 0.3 and 0.9 km s\(^{-1}\) at a distance of 0.5 and 1 kpc, respectively. This is much smaller than the individual stellar errors (Section 2) due to the large number of stars in each bin.

### 4. Tangential velocity asymmetry

In Fig. 1 we plot \( V_\ell(+) - V_\ell(-) \) as a function of longitude and distance on the plane for the primary sample (Section 2) using \( 1 \) Note that this is the same quantity plotted in figure 6 of A16, which was called \( \Lambda - \Delta \alpha \) there. Note also that in A16 we used larger bins in distance and a different vertical range in the plots.

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**Fig. 1.** Difference between the median transverse velocity in Galactic longitude as a function of longitude and distance for symmetric Galactic longitudes \( \ell > 0 \) and \( \ell < 0 \). We use bins of \( 5d \cos(b) = 0.2 \) kpc and \( \Delta \ell = 10^\circ \). We plot a grey cross in bins where \( V_\ell(+) - V_\ell(-) \) is statistically consistent with 0 with a 95% confidence, i.e. where the observations are compatible with an axisymmetric Galaxy. The grey region shows bins with insufficient data (we require at least 5 stars in each \( \ell > 0 \) and \( \ell < 0 \) bin). We have fixed the colour scale to 20 km s\(^{-1}\).
pattern is the same in 90%, 81% and 91% of the significant bins when comparing dist1 with 1/π, dist2 and dist3, respectively.

**Parallax accuracy.** As recommended in Arenou et al. (2017), a possible parallax bias of ~0.3 mas that could be non-uniform in the sky has to be considered in the analysis of TGAS data. Here we see that the distances with this systematic error taken into account from (Astraatmadja & Baile-Jones 2016) slightly shorten the distance scale but do not change the asymmetry. We have also repeated our calculations using 1/π and correcting for a systematic bias, that is effectively adding or subtracting 0.3 mas to the parallax. We show here two cases where we add -0.3 mas for ℓ > 0 and +0.3 mas for ℓ < 0, and the reverse (Fig. 4 bottom panels). Note that these are the worse case scenarios with the bias contributing maximally to the velocity asymmetry in equation (4). In these cases the asymmetry pattern changes slightly, especially in the directions to the inner and outer Galaxy, but is overall preserved. We conclude that the presumed bias in parallax can not be responsible for the global velocity asymmetry observed. Note also that the negative sign of the asymmetry at ℓ ~ 100° does not change even under the more extreme systematic considered here. This is, therefore, a very robust result that models of the asymmetry must reproduce.

**Correlation between parallax and proper motion.** The astrometric correlations can be of up to ±1 in certain sky regions in the TGAS data (see figure C.1 in Arenou et al. 2017). However, the velocity asymmetry is not induced by these correlations. We have tested this by, first, adding uncorrelated noise equal to 3 times the standard errors reported in the catalogue, which is enough to break the correlations. We only observe slight changes, that might well be due to introducing larger errors and not to the correlations, but the overall asymmetry pattern is preserved. Secondly, we have added extra correlated noise using the individual reported standard errors and setting all astrometric correlations

\[ i, j \rightarrow \rho_{ij} = \pm 1 \] (keeping its original sign). This does not increase the observed velocity asymmetry.

**Sky coverage, completeness, extinction.** The TGAS catalogue is incomplete and has a non-uniform sky coverage (e.g., see figure 5 of Arenou et al. 2017). Due to this and to extinction, there are differences in the number of observed stars in the sym-

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**Fig. 4.** Same as Fig. 1 but for dist3 (first top panel), assuming \( U_p = 14 \) km s\(^{-1}\) (second top panel), correcting for an assumed systematic bias in the parallax of +0.3 mas for ℓ > 0 and of −0.3 mas for ℓ < 0 (first bottom panel), and the reverse bias (second bottom panel). The bottom panels are cut at 1 kpc where the error in distance starts to be larger than the bin size.
metric bins \((\ell, d \cos(b))\) and \((-\ell, d \cos(b))\). However, these will not bias the median transverse velocity but only change its precision, assuming there are no additional selection effects. Besides, if in the pairs of bins there was a difference in the vertical distribution of stars (for instance a different median \(Z\) at positive and negative longitudes), the measured asymmetry could be due to a different \(V_r\) as a function of \(Z\), which is expected in an axisymmetric galaxy. However, the velocity changes with \(Z\) in the thin layer that we select (200 pc) are much smaller than the velocity asymmetry that we measure: taking equation 13 of [Bond et al. (2010)], the velocity at \(Z = 0\) would change only by 1 km s\(^{-1}\) at \(Z = 100\) pc.

Assumption of \(U_0\). Ideally, one should fit the value of \(U_0\) at the same time of a non-axisymmetry model to the observed velocity asymmetry. Here our analysis requires an assumption for \(U_0\) (equation (2)). However, note that a different \(U_0\) can not smooth out completely the asymmetry at all Galactic longitudes because the term \(-2U_0 \sin \ell\) has always the same sign. It will only modify the pattern and sign of the asymmetry. E.g., if we use \(U_0 = 14 \) km s\(^{-1}\) (Schönrich 2012), the asymmetry becomes negative everywhere (Fig. 4 (top right panel) reaching values down to \(-25\) km s\(^{-1}\) and with 34% of the bins with asymmetries as large as \(10\) km s\(^{-1}\), but does not disappear. On the other hand, one can estimate a value of \(U_0\) from the data by averaging the quantity \(U_0 = \frac{\sum \sigma_{\mu_\ell} (\ell) - \sigma_{\mu_\ell} (\ell=0)}{2 \sin \ell}\) for all bins (i.e. supposing that \(V_r(+) - V_r(-) = 0\), in other words, that there is no net contribution from non-axisymmetries). This value is \(U_0 \approx 8.3 \pm 0.6\) km s\(^{-1}\), and thus, for our choice of \(U_0 = 9\) km s\(^{-1}\) the total net asymmetry is the smallest one compared to other values.

To conclude, with the information currently available to us on the quality and limitations of the Terascale data and of our method, the measurement of the velocity asymmetry is robust.

6. Discussion and conclusions

We have detected velocity asymmetries when comparing the median transverse velocity in Galactic longitude for positive and negative longitudes using the Gaia-Terascale catalogue following a model-independent approach. The sign of the velocity differences follows a pattern that depends on the distance and direction. The velocity asymmetry reaches values larger than 10 km s\(^{-1}\) for 7% of the region studied. This asymmetry, which extends to all distances and directions probed, indicates that the stellar motion in the disk is highly non-axisymmetric.

Part of the asymmetry (in the direction of the outer disk) is present for all the stellar types considered here. This points towards a common dynamical origin of the asymmetry. The differences seen for the young sample (not yet phase-mixed) can be due to imprints of the velocities at birth or structures such as the Gould’s belt [Lesh 1998, Comeron & Torra 1994]. The differences when comparing dwarfs with giant stars could be due to the same perturbation acting different on different mean ages.

Regarding the magnitude of the asymmetry, the values that we find are similar to previous determinations of streaming motion. For example, star-forming regions deviate from rotation typically by 10 km s\(^{-1}\) [Reid et al. 2014, Honma et al. 2012, Ryl et al. 2012]. In external galaxies, radial streaming motions of 7 km s\(^{-1}\) are observed [Rix & ZastRzsky 1995]. For the Milky Way, velocity gradients in the radial direction are of 3 km s\(^{-1}\) kpc\(^{-1}\) [Siegfert et al. 2011] and fluctuations with amplitude of 10 km s\(^{-1}\) have been measured [Bovy et al. 2015].

In A16, we studied the asymmetries in transverse velocity for a series of disc simulations with spiral structure. Some models followed the Tight-Winding-Approximation (TWA) and some were N-Body models. The magnitude of the typical velocity asymmetries of the models were of the order of \(\sim 2\) km s\(^{-1}\) but up to 10 km s\(^{-1}\), thus, resembling those found here (see also Faure et al. 2014, Grand et al. 2016 for alternative but similar predictions). However, the spatial scales of the variations of the asymmetry patterns were larger in distance compared to the data, except for the model of transient arms. Also the particular pattern of the observed asymmetry and, in particular, its sign does not follow what we saw in the vast majority of models that were built to resemble the spiral structure of the Galaxy (see figure 6 of A16 but note the different range of distance). However, a quantitative fit of the model exploring the whole range of spiral parameters is necessary to draw definitive conclusions (Antoja, Roca-Fàbregas et al. in preparation).

This asymmetry could also be attributed to the Galactic bar that can deviate the velocities from axisymmetry by about 5-10 km s\(^{-1}\) near the Sun [Monari et al. 2014, Bovy et al. 2015], thus compatible with the data here. A perturbation from a satellite could excite breathing or other disk modes [Gómez et al. 2013, Widrow et al. 2014] but little attention is put on its effects on the in-plane velocities. An elliptic potential induced by a non-spherical halo can also perturb the in-plane velocities [Kuijken & Tremaine 1994]. How well these other models reproduce the observed asymmetry needs to be investigated. Several agents may contribute simultaneously to it, creating a quite intricate Galaxy disk. We hope to decipher it with the advent of new data (Gaia DR2 and follow-up surveys) and models that combine internal and external agents driving the evolution of the Milky Way disk.

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