Stars with fast Galactic rotation observed in *Gaia* TGAS: a signature driven by the Perseus arm?

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ABSTRACT

We report on the detection of a small overdensity of stars in velocity space with systematically higher Galactocentric rotation velocity than the Sun by about $20 \, \mathrm{km \, s^{-1}}$ in the *Gaia* Data Release 1 *Tycho–Gaia* astrometric solution data. We find these fast Galactic rotators more clearly outside of the Solar radius, compared to inside of the Solar radius. In addition, the velocity of the fast Galactic rotators is independent of the Galactocentric distance up to $R - R_0 \sim 0.6$ kpc. Comparing with numerical models, we qualitatively discuss that a possible cause of this feature is the co-rotation resonance of the Perseus spiral arm, where the stars in the peri-centre phase in the trailing side of the Perseus spiral arm experience an extended period of acceleration owing to the torque from the Perseus arm.

Key words: methods: numerical – Galaxy: structure – galaxies: kinematics and dynamics – galaxies: structure.

1 INTRODUCTION

Milky Way astronomy is currently entering an exciting era with the recent first data release (*Gaia* DR1, Gaia Collaboration et al. 2016b) from the European Space Agency (ESA)'s *Gaia* mission (Gaia Collaboration et al. 2016a). *Gaia* DR1 contains the *Tycho–Gaia* Astrometric Solution (TGAS, Michalik, Lindegren & Hobbs 2015; Lindegren et al. 2016) that provides positions, parallaxes and proper motions (α, δ, π, μ_α, μ_δ) for around 2 million stars using data from the *Tycho*-2 catalogue (e.g. Perryman & ESA 1997; Høg et al. 2000) to provide a baseline of approximately 30 yr upon which to calculate astrometric values for stars in common between *Tycho*-2 and *Gaia*. This enables us to explore local dynamics in unprecedented detail (e.g. Bovy 2016). Additionally, to provide the full six-dimensional phase space measurements, TGAS can be cross-matched with ground-based spectroscopic surveys such as the Radial Velocity Experiment (Steinmetz et al. 2006) in the Southern hemisphere and/or the Large Sky Area Multi-Object Fibre Spectroscopic Telescope (LAMOST, Zhao et al. 2012) and the Apache Point Observatory Galactic Evolution Experiment (Majewski, APOGEE Team & APOGEE-2 Team 2016) in the Northern hemisphere to gain radial velocity measurements for stars in both catalogues. This has already been demonstrated to grant new insights into stellar

dynamics (Allende Prieto, Kawata & Cropper 2016; Hunt, Bovy & Carlberg 2016; Monari et al. 2016b).

In this Letter, we present the first detection of a small group of stars in the TGAS data whose Galactocentric rotation velocity is systematically higher than the Sun, independent of radius. Hereafter, we call these stars fast Galactic rotators that appear clearly only outside the Solar radius. In Section 2, we describe our treatment of the data and the observed feature. In Section 3, we compare the data with numerical models and qualitatively discuss that the fast Galactic rotators found in the TGAS data could be interpreted as a signature of the co-rotation resonance of the Perseus arm. In Section 4, we summarize the results.

2 FAST GALACTIC ROTATORS IN THE TGAS DATA

We analyse the rotation velocity of stars from the *Gaia* DR1 TGAS data. The TGAS catalogue provides parallaxes, π and proper motions (μ_α, μ_δ), but does not include any radial velocity information that would allow us to calculate Galactocentric rotation velocity, v_{rot}. Such radial velocities can be obtained for a subset of stars by combining TGAS with spectroscopic surveys (e.g. Hunt et al. 2016; Monari et al. 2016b), but here we choose to analyse TGAS data on their own. We can for instance examine the velocity in the direction of Galactic longitude, v_l, which at $(l, b) = (180°, 0)$ and $(0, 0)$,
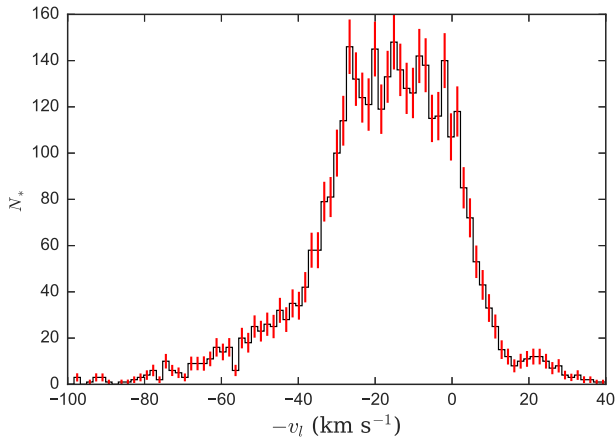
Figure 1. Histogram of $-v_l$ (km s^{-1}) for stars within the line-of-sight area of $(l, b) = (180°, 0) \pm (10°, 5°)$ and with $\sigma_\pi/\pi \leq 0.15$.
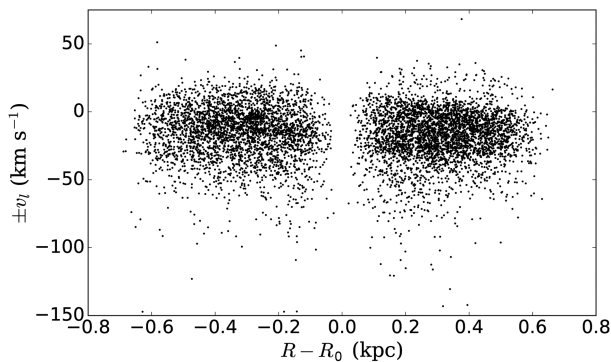

Figure 2. $-v_l$ (km s^{-1}) against $R - R_0$ for stars within the line-of-sight area of $(l, b) = (180°, 0) \pm (10°, 5°)$ (right-hand grouping) and $+v_l$ for stars within the area of $(l, b) = (0°, 0) \pm (10°, 5°)$ (left-hand grouping).

provides comparable information to v_{rot}, with respect to the Solar motion. We define $v_l = 4.74047\mu_{l*}/\pi$, where $\mu_{l*} = \mu_l \cos(b)$ is the proper motion for the longitude direction in true arc.

Fig. 1 shows the histogram of $-v_l$ (km s^{-1}) for stars within the line-of-sight area of $(l, b) = (180°, 0) \pm (10°, 5°)$. In this Letter, we limit our sample to only stars whose fractional parallax error is less than 15 per cent, i.e. $\sigma_\pi/\pi \leq 0.15$. Along this particular line-of-sight, $-v_l$ roughly corresponds to the rotation velocity with respect to the Sun, v_{rot} and higher $-v_l$ indicates faster v_{rot}. The error bars are 1σ and were calculated using the bootstrapping technique, taking 1000 samples with replacement. There is a small, but clear 'bump' around $-v_l = 20$ km s^{-1}, which corresponds to a group of stars with $-v_l$ about 20 km s^{-1} faster than the Sun (hereafter we call this group of stars 'fast Galactic rotators'). Note that the current observational data suggest that the Sun rotates faster than the circular velocity at the Solar radius by about $v_\odot = 12.24$ km s^{-1} (Schönrich, Binney & Dehnen 2010). In addition, the mean rotation of the stars is slower than the circular velocity by the asymmetric drift. Therefore, these fast Galactic rotators are rotating significantly faster than the mean rotation of the stars.

Fig. 2 shows $-v_l$ (km s^{-1}) against $R - R_0$ for stars within the line-of-sight area of $(l, b) = (180°, 0) \pm (10°, 5°)$ (right-hand grouping) and v_l for stars within $(l, b) = (0°, 0) \pm (10°, 5°)$ (left-hand grouping), i.e. positive velocity is in the direction of Galactic rotation for both samples. Here, R is the Galactocentric radius of stars and R_0 indicates the Solar radius. These fast Galactic rotators,

with $-v_l \sim 20$ km s^{-1}, are clearly visible above the bulk of the sample in the right-hand grouping, i.e. outside of the Solar radius. On the other hand, the fast Galactic rotators are missing from the left-hand group at $(l, b) = (0, 0) \pm (10°, 5°)$, i.e. inside of the Solar radius.

This is to our knowledge, the first discovery of these fast Galactic rotators just outside of the Solar radius and the signature extends at least from $R - R_0 = 0.1$ to 0.6 kpc. We checked that the parallax and proper motion errors of the fast Galactic rotators are not systematically high compared to the other stars in the sample. We also checked that the 'excess astrometric noise' is not high for these stars. In other words, they are unlikely to be binary stars (see Lindegren et al. 2016). In the next section, we will present one possible cause of this feature, namely that this could be an indication of the co-rotation resonance of the Perseus spiral arm.

3 SIGNATURE DRIVEN BY THE PERSEUS SPIRAL ARM?

The kinematics of the Milky Way, along with other spiral galaxies, is likely heavily influenced by the spiral arms themselves. In this section, we qualitatively compare the data with numerical models and propose that the fast Galactic rotators found in the TGAS data can be driven by the Perseus spiral arm, as one possible mechanism.

Lin & Shu (1964) proposed a solution to the so-called 'winding dilemma' by treating the spiral structure as density wave features that rotate rigidly with a pattern speed that is constant with radius, irrespective of the rotation velocity of the stars themselves. However, N-body simulations have as of yet been unable to reproduce spiral arms as long-lived single modes (e.g. Sellwood 2011; Dobbs & Baba 2014), instead showing spiral arm features which are short-lived but recurrent with pattern speeds that match the rotation of the stars, i.e. co-rotating at all radii (e.g. Sellwood & Carlberg 1984; Grand, Kawata & Cropper 2012; Roca-Fàbrega et al. 2013). One of the interpretations of the N-body simulations is that while the spiral arm features themselves are transient, their evolution in configuration space may be driven by several spiral modes present in the disc that are in fact longer-lived standing wave oscillations (lasting for about 10 rotations) similar to the original density wave theory (e.g. Minchev et al. 2012; Roškar, Debattista & Loebman 2013; Sellwood & Carlberg 2014).

We therefore consider two types of the numerical models, an N-body model from Kawata et al. (2014) and a test particle model with rigidly rotating spiral arms from Monari et al. (2016a), and analyse the rotation velocity distribution in the direction of $(l, b) = (180°, 0)$. Note that these models are both also analysed in Grand et al. (2015).

The details of the numerical simulation code and the galaxy model of the N-body model are described in Kawata et al. (2014). The galaxy is set up in isolated conditions and consists of a gas and stellar disc but no bulge component. The model shows transient spiral arm features, co-rotating with the stars at all radii as discussed in Kawata et al. (2014). We examine a snapshot at an earlier time from this model with a strong spiral arm as shown in Kawata et al. (2014) (K14a) and a snapshot at a later time from this model with a weak spiral arm as shown in Grand et al. (2015) (K14b). A comparison of this galaxy to the Milky Way including measurement of its age/velocity dispersion, bar strength and the pitch angle of the spiral arms are given for K14a in Hunt et al. (2015) and for K14b in Grand et al. (2015). We assume a solar radius of $R_0 = 8$ kpc for both K14a and K14b.

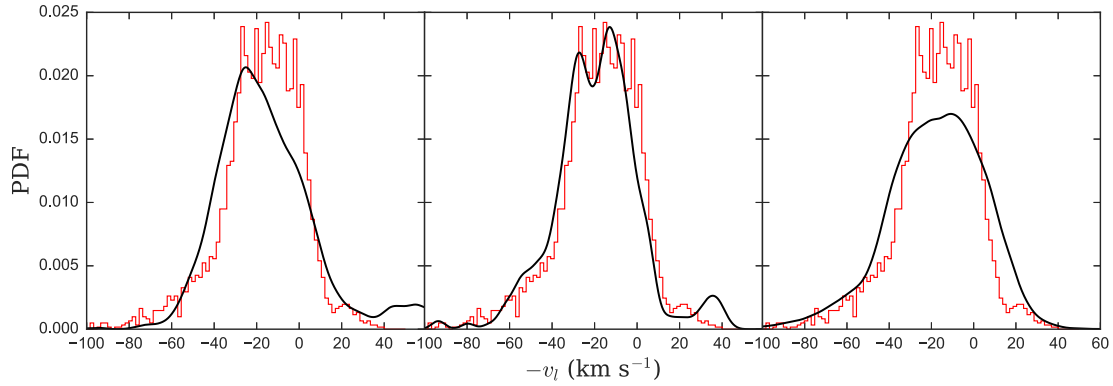**Figure 3.** PDF for v_{rot} (km s^{-1}) for model particles in K14a (left), K14b (centre) and M16 (right) for the line of sight $(l, b) = (180, 0)$ on the near trailing side of the spiral arm. Overlaid on a histogram of v_l (km s^{-1}) constructed from the TGAS data. v_{rot} and v_l are roughly equivalent at $(l, b) = (180, 0)$.

The test particle model we use is model S2 from Monari et al. (2016a), henceforth M16. The details of the model are given in Monari et al. (2016a). The gravitational potential used is comprised of an axisymmetric part (Model 1 from Binney & Tremaine 2008), along with a rigidly rotating two armed spiral perturbation. The axisymmetric component consists of two spherical components, a dark halo, a bulge and three disc components; thin, thick and interstellar medium. The spiral perturbation is of the form given in Cox & Gómez (2002), with the pattern speed and pitch angle derived by Siebert et al. (2012). The co-rotation radius of the spiral arm is 11.49 kpc. We assumed the Solar radius of $R_0 = 8$ kpc.

Although we wish to compare v_l directly between the TGAS data and our models, our models are too low resolution to analyse the velocity distribution in such a small area that we explore in Section 2. Thus, we expand the selection of the model particles to cover a 1 kpc cube such that $0 < R - R_0 < 1$ kpc and $-0.5 < y, z < 0.5$ kpc, where the y-direction is the direction of rotation and the z-direction points towards the North Galactic Pole. For the models, we have six-dimensional position and velocity information, and therefore we do not need to use $-v_l$ as a proxy for the rotation velocity with respect to the Sun, v_{rot}, as we did for the TGAS data. Hence, we directly analysed the rotation velocity of the i-th particle with respect to the observer as $v_{rot, i} = v_{\phi, i} - v_{circ} - v_{\odot}$, where $v_{\phi, i}$ is the Galactocentric rotation velocity of the i-th particle, v_{circ} is the circular velocity of the model disc at R_0 and $v_{\odot} = 12.24$ km s^{-1} (Schönrich et al. 2010) is the solar proper motion assumed.

Fig. 3 shows the probability distribution function (PDF) for v_{rot} for model particles in K14a (left), K14b (centre) and M16 (right) for the line of sight $(l, b) = (180°, 0)$, overlaid on a histogram of $-v_l$ of the TGAS data as shown in Fig. 1. The line shows the distribution of v_{rot} of the model particles in the volume described above. The left-hand and central panels of Fig. 3 show clearly a small secondary high velocity peak in the distribution at approximately 50 and 25 km s^{-1}, respectively. In contrast, the PDF of M16 in the right-hand panel shows little structure in the distribution of v_{rot}. There is no evidence of a separate peak for the high velocity population. Instead it exhibits a more symmetric spread of the rotation velocity, which clearly contradicts the observed distribution.

The strong arm model K14a in the left-hand panel is also clearly inconsistent with the data, because K14a shows fast Galactic rotators with $v_l \approx 50$ km s^{-1} that is much faster than the observed fast Galactic rotators. Model K14b in the central panel also overestimates the velocity of the fast Galactic rotators. However, the comparison between Models K14a and K14b suggests that the

velocity of the 'bump' of the fast Galactic rotators gets slower with a weaker arm. Therefore, it is likely an indication that the arm in Model K14b is still too strong compared to the spiral arms of the Milky Way, and it is reasonable to assume that a weaker arm would reproduce the data nicely. It is pleasing to note that apart from a slight offset of the location of the fast Galactic rotators, Model K14b is in good agreement to the data, including the slight double peak in the main distribution and a sharper cut-off in the faster rotation side compared to the tail in the slower rotation side.

In Kawata et al. (2014) we showed that these fast Galactic rotators observed in the N-body models are caused by stars which are initially close to apo-centre phase on the leading side of the spiral arm and are decelerated by the arm. After the spiral arm has overtaken these stars, they are accelerated by the spiral arm while approaching their peri-centre phase, which leads to a group of fast Galactic rotators on the trailing side of the spiral arm. This is because the spiral arms seen in N-body simulations are co-rotating and thus the stars can stay close to the spiral arm for an extended period of time. This can cause them to be significantly accelerated on the trailing side of the spiral arm.[1] In other words, this feature is driven by the co-rotation resonance of the spiral arm. In M16, we do not find any feature, because the co-rotation radius ($R_c = 11.49$ kpc) is far away from the assumed Solar radius.

At $l = 180°$, the Perseus arm is located approximately 2 kpc outwards from the Sun (e.g. Reid et al. 2009). Thus, we are observing the trailing side of the Perseus arm. Therefore, we speculate that the fast Galactic rotators found in the TGAS data could be the stars driven by the co-rotation resonance of the Perseus arm in the way described above. On the other hand, at $l = 0$ the Perseus arm is further away and therefore the influence of the arm is not strong enough to induce the fast Galactic rotators. If so, the Perseus arm could be co-rotating and transient as observed in N-body simulations. However, this feature could perhaps be equally well explained by classic spiral density wave theory where the spiral arm features are rigidly rotating and there is a specific co-rotation radius. For example, if there is a density wave with co-rotation radius just outside the Solar radius, we would also expect to observe these fast Galactic rotators

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[1] Note that as demonstrated in Grand et al. (2012) the non-linear growth of the spiral arm is resulting from a mechanism similar to swing-amplification (Julian & Toomre 1966), but which differs in terms of the evolution and occurs at a wide range of radii.
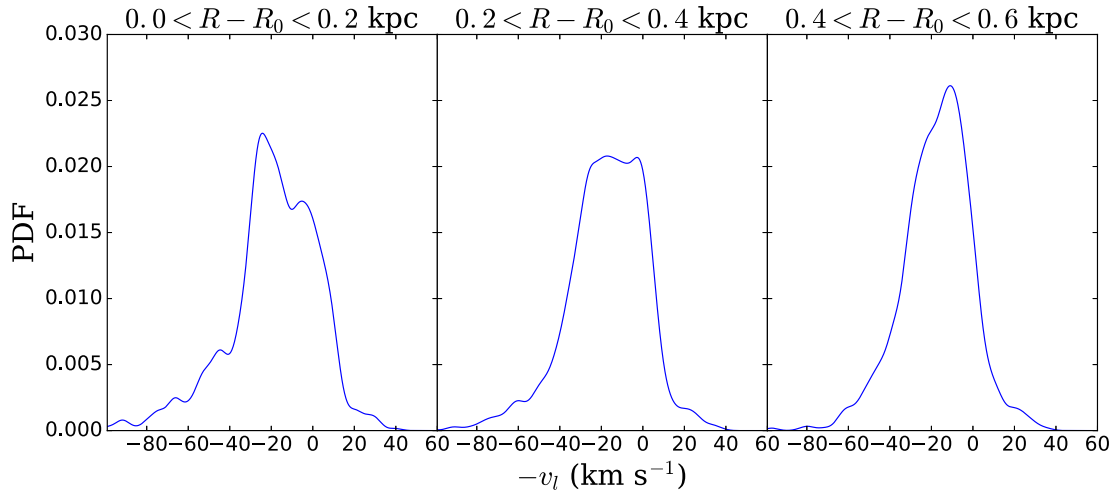
Figure 4. PDF for $-v_l$ (km s^{-1}) for $0.0 < R - R_0 < 0.2$ kpc (left), $0.2 < R - R_0 < 0.4$ kpc (centre) and $0.4 < R - R_0 < 0.6$ kpc (right).

outside the Solar radius. However, the overdensity in velocity space would move with radius at a given azimuth.

To distinguish these theories of the dynamics of spiral structure, we need to measure the rotation velocity distribution at different radii of the Perseus arm itself, as discussed in Kawata et al. (2014) and Hunt et al. (2015). If the Perseus arm is like the co-rotating spiral arms seen in *N*-body simulations, we expect that the feature found in this Letter will be observed on the trailing side of the Perseus arm at different radii, i.e. different l, because the spiral arm features are co-rotating at all radii. Unfortunately, the volume where TGAS provides accurate enough parallax and proper motion is too small for us to analyse the rotation velocity distribution at different l.

However, we can measure the 'bump' feature of the fast Galactic rotators with varying radius up to approximately 0.6 kpc. Fig. 4 shows the distribution of $-v_l$ (km s^{-1}) for $0.0 < R - R_0 < 0.2$ kpc (left), $0.2 < R - R_0 < 0.4$ kpc (centre) and $0.4 < R - R_0 < 0.6$ kpc (right). Although the variation in the structure of the velocity distribution is clear, the position of the bump of fast Galactic rotators around $-v_l = 20$ km s^{-1} does not alter velocity with increasing distance. The constant rotation speed of the feature for $0.0 \leq R - R_0 \leq 0.5$ kpc can also be seen in fig. 3 of Monari et al. (2016b) at $v_\phi \sim 275$ km s^{-1}. They assume a Solar Galactocentric rotation speed of 254.6 km s^{-1} and hence this is consistent with the 20 km s^{-1} fast Galactic rotators observed in this Letter. The combination of the non-variation of the feature with distance and the fact that it is also observed in the TGAS+LAMOST data shown in Monari et al. (2016b) make it unlikely to be a feature of noise alone.

If this feature were caused by a single resonance, e.g. relating to the bar, it would be expected to vary with distance in a fashion similar to the *Hercules* stream, as shown in Monari et al. (2016b). Note that we also observe the *Hercules* stream in Fig. 2 as an overdensity defined by a gap going from $-v_l \sim -30$ km s^{-1} at $R - R_0 \sim 0.1$ kpc to $-v_l \sim -45$ km s^{-1} at $R - R_0 \sim 0.3$ kpc and then fading away, although it is not clearly visible in Fig. 1 because the gap varies with radius.

4 SUMMARY

Analysing the newly released *Gaia* TGAS data, we found a group of stars which have systematically high rotation velocity just outside of the Solar radius. We compare them with snapshots of an *N*-body

simulation and a test-particle simulation with spiral arms and find that these fast Galactic rotators can be explained by peri-centre phase stars being accelerated by the Perseus arm for an extended period, owing to the co-rotation resonance. This supports the scenarios of the Perseus arm being either a transient and co-rotating spiral arm like seen in *N*-body simulations or a density wave whose co-rotation radius is just outside of the Solar radius. From the current data, we cannot distinguish between these two possibilities, although the non-variation of the feature in velocity space with respect to radius does not argue in favour of a single co-rotation radius.

There are also other possible explanations for this feature not necessarily linked to non-axisymmetric patterns such as spiral arms, for example, these fast Galactic rotators could also be made of high eccentricity stars triggered by an interaction event in the outer disc, whose peri-centre of their orbits is close to the Solar radius, hence at high rotational velocity. Although in this case, the location of the bump in v_l would be expected to vary with distance, as it would if it is a resonance feature of the bar or of a single static spiral density wave. The fact that the feature in v_l remains constant with distance makes either of these explanations unlikely.

Gaia Data Release 2 will allow us to examine stellar dynamics over a much larger area of the Galaxy and with far greater accuracy. We will be able to probe different lines of sight using *Gaia* radial velocities and also observe the far leading side of the Perseus arm. This information will provide a crucial test for these competing spiral arm models as demonstrated in Hunt et al. (2015).

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