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 km s$^{-1}$ in the *Gaia* Data Release 1 Tycho-Gaia astrometric solution (TGAS) 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 $R - R_\odot \sim 0.6$ 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 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: N-body simulations — methods: numerical — galaxies: structure — galaxies: kinematics and dynamics — The Galaxy: structure

1 INTRODUCTION

Milky way astronomy is currently entering an exciting era with the recent first data release (*Gaia* DR1, *Gaia* Collaboration et al. 2016a) from the European Space Agency (ESA)’s *Gaia* mission (Gaia Collaboration et al. 2016b). *Gaia* DR1 contains the Tycho-*Gaia* Astrometric Solution (TGAS, Michalik et al. 2015; Lindegren et al. 2016) which provides positions, parallaxes and proper motions ($\alpha, \delta, \pi, \mu_\alpha, \mu_\delta$) 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 years 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 6 dimensional phase space measurements, TGAS can be cross-matched with ground based spectroscopic surveys such as the Radical Velocity Experiment (RAVE, 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 (APOGEE, Majewski et al. 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 (Prieto et al. 2016; Hunt et al. 2016; Monari et al. 2016b).

In this *Letter*, we present a 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 which 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 summarise 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, $\pi$, and proper motions ($\mu_\alpha$, $\mu_\delta$), but does not include any ra-
Note that the current observational data suggest that the Sun rotates faster than the circular velocity at the Solar radius by about $V_0 = 12.24$ km s$^{-1}$ (Schönrich et al. 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 $(l, b) = (180^\circ, 0) \pm (10^\circ, 5^\circ)$ (right hand grouping) and $+v_l$ for stars within the area of $(l, b) = (0, 0) \pm (10^\circ, 5^\circ)$ (left hand grouping). 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 Galactic rotation velocity, $v_\text{rot}$. 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 $(l, b) = (180^\circ, 0)$ and $(0, 0)$, provides comparable information to $v_\text{rot}$, with respect to the Solar motion. We define $v_l = 4.74047 \mu_1 \cos(b)/\pi$, where $\mu_1 = \mu_1 \cos(b)$ 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 $(l, b) = (180^\circ, 0) \pm (10^\circ, 5^\circ)$. 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, $v_\text{rot}$, and higher $-v_l$ indicates faster $v_\text{rot}$. 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’).

### 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 et al. 2012; Rocca-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 et al. 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 \( (l, b) = (180^\circ, 0) \). 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.

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 (ISM). The spiral perturbation is of the form given in Cox & Gómez (2002), with the pattern speed and 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. 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 \( l = 180^\circ \) 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 \( l = 0^\circ \) 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 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 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 Figure 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 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 $v_t$ 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 $v_t$ remains constant with distance makes either of these explanations unlikely.

Gaia DR2 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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