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# Modelling the Milky Way with *Gaia*-TGAS

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**Abstract.** I summarize two recent projects involving the *Gaia*-TGAS data. Firstly, I discuss a detection of a lack of disc stars in the Solar neighbourhood with velocities close to zero angular momentum. We use predictions of this effect to make a measurement of the Solar rotation velocity around the Galactic centre, and also of $R_0$. Secondly, I discuss a detection of a group of stars with systematically high Galactic rotation velocity. We propose that it may be caused by the Perseus arm and compare the data with simulations.

**Keywords.** Galaxy: kinematics and dynamics, Galaxy: fundamental parameters

## 1. Introduction

The European Space Agency's *Gaia* mission (Gaia Collaboration *et al.* 2016a) gives us a new window on the dynamics of the Solar neighbourhood. *Gaia* DR1 (Gaia Collaboration *et al.* 2016b) contains the Tycho-Gaia Astrometric Solution (Michalik *et al.* 2015), a catalogue of $\sim 2 \times 10^6$ stars in common between *Gaia* and Tycho-2, the star mapper from *Hipparcos*, with positions on the sky, parallaxes and proper motions. We are entering an exciting era for Milky Way astronomy and astrophysics, and even from the first data release we are able to explore new facets of our Galaxy. In this work, I summarize two recent projects involving the *Gaia*-TGAS data. Please note that both works are described more fully in their respective publications.

## 2. Measuring the Solar motion with *Gaia*-TGAS and RAVE

In this Section, I summarize our recent work reporting on a detection of a dearth of stars with zero angular momentum in the Solar neighbourhood (Hunt *et al.* 2016), and describe how we used this feature to make a measurement of the Solar rotation velocity around the Galactic centre, $V_\odot$, and the distance to the Galactic centre, $R_0$.

The TGAS data provides only 5D phase space information, ($\alpha$, $\delta$, $\pi$, $\mu_\alpha$, $\mu_\delta$). However, we can cross match TGAS with ground based surveys, such as the Radial Velocity Experiment (RAVE; e.g. Steinmetz *et al.* 2006) or the Large sky Area Multi-Object fibre Spectroscopic Telescope (LAMOST; e.g. Zhao *et al.* 2012) to add line-of-sight velocities.

We cross matched TGAS with RAVE DR5, resulting in over 200,000 stars with the full 6D phase space information, allowing us to calculate tangential velocities, $v_Y$ (km s$^{-1}$. The left panel of Fig. 1 shows the distribution of $v_Y$ for stars within 700 pc, with a 'dip' visible around $v_Y = -240$ km s$^{-1}$. A feature like this was predicted by Carlberg & Innanen (1987), who suggest that a likely explanation is that the missing stars, which have zero angular momentum, plunge into the Galactic centre and are scattered onto highly chaotic orbits by interaction with the Galactic nuclear potential.

We modelled this effect by integrating test particles in a Milky Way-like potential and observing their orbits. We use the MWPotential2014 from galpy (Bovy 2015)

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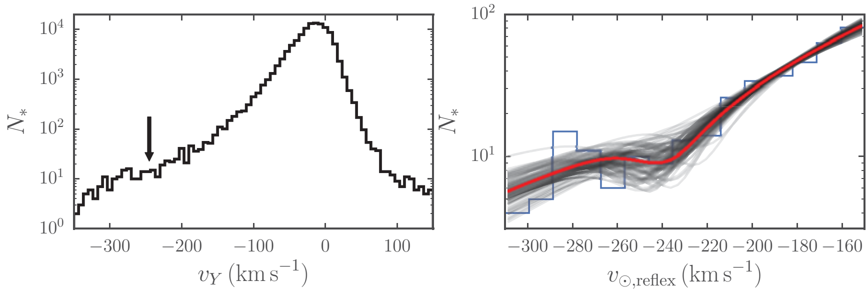


**Figure 1. Left:** Distribution of tangential velocities, $v_Y$ (km s$^{-1}$), with a 'dip' visible around $v_Y = -240$ km s$^{-1}$, marked with an arrow. **Right:** Tail of the $v_Y$ distribution overlaid with the best-fit model (red), and 100 MCMC samples (black). As shown in Hunt *et al.* (2016).

combined with a Plummer potential representing the Galactic nuclear potential. We created a function from the resulting distribution of stars which remained upon non-chaotic orbits (shown in Figure 3 in Hunt *et al.* 2016) by smoothly interpolating the model and combining it with an exponential.

We then fit this function to the distribution of disc stars in the range -310 km s$^{-1}$ $\leqslant v_Y < -150$ km s$^{-1}$. We also fit the exponential component alone and compared the likelihoods of the respective models. We determined that the data prefers the dip model at a significance of $2.7\sigma$. We explored the uncertainties on the model by performing a Markov Chain Monte Carlo (MCMC) analysis with EMCEE (Foreman-Mackey *et al.* 2013). We find $v_\odot = 239 \pm 9$ km s$^{-1}$, which also gives us $R_0 = 7.9 \pm 0.3$ kpc when combined with the proper motion of Sgr A$^*$. The right panel of Fig. 1 shows the tail of the $v_Y$ distribution overlaid with the best fit model (red) and the MCMC samples (black). We also performed the same analysis using TGAS+RAVE+LAMOST data. Here we use the bayesian distance estimates from Astraatmadja & Bailer-Jones (2016), whereas previously we used the RAVE spectrophotometric distance estimates. For this data set we find $v_\odot = 236 \pm 9$ km s$^{-1}$ at $3\sigma$. It is encouraging that the measurements are consistent.

*Gaia* DR2 will have the power to measure this feature, if real, with substantially increased precision. Assuming the errors decrease on the order of $\sqrt{N}$, we expect *Gaia* to enable us to constrain $v_\odot$ to within approximately 1 km s$^{-1}$. In turn, the error on $R_0$ would become dominated by the systematics. As such, any future exploration of this feature should take into account factors such as the Galactic bar, spiral arms, and giant molecular clouds, although the effects are expected to be small.

## 3. Searching for the Perseus arm with *Gaia*-TGAS

In this Section, I summarize our recent work reporting on a detection of a small group of stars in the TGAS data with systematically high Galactocentric rotation velocity as described fully in Hunt *et al.* (2017).

In Kawata *et al.* (2014) we showed that the distribution of $v_\phi$ is notably different for models which treat spiral structures as density waves, compared to $N$-body simulations which give rise to transient winding spirals arms, and in Hunt *et al.* (2015) we show that the final *Gaia* data release will easily enable us to observe the kinematic signatures of a co-rotating spiral arm, if present. Thus, we analyze the Galactocentric rotation velocity, $v_\phi$, of stars in TGAS. Here we wish to explore the distribution of velocities for stars in the direction of the Perseus spiral arm. In the direction of the Galactic anti-centre we can cross-match TGAS with LAMOST, but this results in very few stars. Thus we

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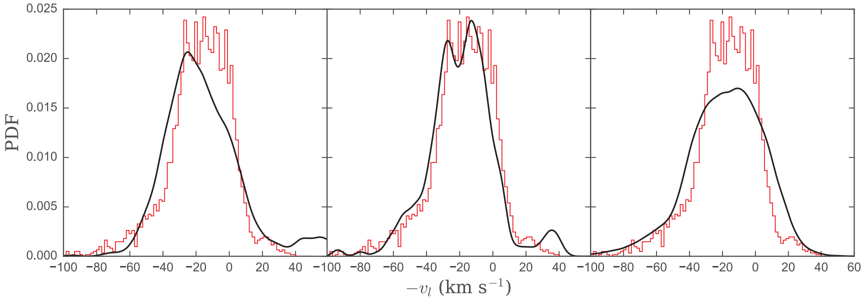


**Figure 2.** Distribution of $v_l$ (km s$^{-1}$) at $(l, b) = (180, 0) \pm 5$ deg (red) overlaid with three model predictions (black), originally shown in Hunt *et al.* (2017).

convert the proper motions $(\mu_\alpha, \mu_\delta)$ to $(\mu_l, \mu_b)$, because $v_l = 4.74\mu_l/\pi$ is analogous to Galactocentric rotation velocity when observing the line-of-sight $(l, b) = (180, 0)$ deg.

Fig. 2 shows the distribution of $v_l$ (km s$^{-1}$) at $(l, b) = (180, 0) \pm 5$ deg (red) overlaid with predictions from a $N$-body model with a strong spiral arm (left), an $N$-body model with a weak spiral arm (centre) and a test particle model with density wave like arms (right). The left and right panels of Fig. 2 show the strong arm model and the density wave model are not a good fit to the data. The centre panel is closer, but the high velocity 'bump' caused by the co-rotation of the $N$-body arm is still too strong compared with the data. We propose that a still weaker arm may reproduce the data nicely, as the strength of the arm effects the acceleration of the stars in the high velocity tail. Alternatively, the bump may be a resonance feature of a density wave like arm. Future *Gaia* data should enable us to better distinguish between the models.

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## References

Allende-Prieto, C,. Kawata, D. & Cropper, M. 2016 *A&A*, 596, 98
Astraatmadja, T. L., & Bailer-Jones, C. A. L. 2016 *ApJ*, 833, 119
Bovy, J. 2015 *ApJS*, 216, 29
Carlberg, R. & Innanen, K. A. 1987 *AJ*, 94, 666
Foreman-Mackey, D., Hogg, D. W., Lang, D., & Goodman, J. 2013 *PASP*, 125, 306
Gaia Collaboration *et al.* 2016 *A&A*, 595, 1
Gaia Collaboration *et al.* 2016 *A&A*, 595, 2
Hunt, J. A. S. *et al.* 2015 *MNRAS*, 450, 2132
Hunt, J. A. S., Bovy, J., & Carlberg, R. 2016 *ApJL*, 832, L25
Hunt, J. A. S., *et al.* 2017 *MNRAS*, 467, L21
Kawata, D., *et al.* 2014 *EAS*, 67, 247
Michalik, D., Lindegren, L. & Hobbs, D. 2015 *A&A*, 574, 115
Monari, G., Kawata, D., Hunt, J. A. S., & Fameay, B. 2017 *MNRAS*, 466, L113
Steinmetz, M., Zwitter, T. & Siebert, A. 2006 *AJ*, 132, 1645
Zhao, G., Zhao, Y-H., Chu, Y-Q., Jing, Y-P., & Deng, L-C. 2012 *RAA*, 12, 723