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TRACING THE HERCULES STREAM WITH GAIA AND LAMOST: NEW EVIDENCE FOR A FAST BAR IN THE MILKY WAY

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Abstract. The length and pattern speed of the Milky Way bar are still controversial. Photometric and spectroscopic surveys of the inner Galaxy, as well as gas kinematics, favour a long and slowly rotating bar, with corotation around a Galactocentric radius of 6 kpc. On the other hand, the existence of the Hercules stream in local velocity space was classically interpreted as the signature of a short and fast bar with corotation around 4 kpc. This follows from the fact that the Hercules stream looks like a typical signature of the outer Lindblad resonance of the bar. Here, by combining the TGAS catalogue of the Gaia DR1 with LAMOST radial velocities, Monari et al. have confirmed that the position of Hercules in velocity space as a function of radius in the outer Galaxy is very well described by fast bar models with a pattern speed no less than 1.8 times the circular frequency at the Suns position.

Keywords: Galaxy: kinematics and dynamics, Galaxy: disc, Galaxy: structure

1 Introduction

To a first approximation, axisymmetric dynamical models (e.g. Cole & Binney 2017) describe the distribution and kinematics of stars in the Milky Way. However, it is now well established that the Milky Way contains prominent non-axisymmetric structures, in particular the bar and the spiral arms in the Galactic disc. The presence of non-axisymmetries reflects also in the velocity distribution of stars. In particular, in the Solar neighbourhood this would appear as an homogeneous ellipsoid, with a tail for low tangential velocity stars, if the Galaxy were a pure axisymmetric disc in differential rotation. However, substructures in local velocity space space have been known for a very long time and called 'moving groups'. It has been shown (e.g. Famaey et al. 2005) that the most prominent of these moving groups are not disrupted open clusters keeping coherence in velocity space. Therefore, alternative mechanisms have to be invoked for their formation like the resonant interaction between the stars and the bar or the spiral arms. In particular, Dehnen (2000) has shown that the Hercules moving group, could be a direct consequence of the Sun being located just outside of the bar's outer Lindblad resonance (OLR). This resonance occurs at the radius $R_{\rm OLR}$ where stars make two epicyclic oscillations while making one retrograde rotation in the frame of the bar, hence

$$\kappa + 2\,(\Omega - \Omega_{\rm b}) = 0, \tag{1.1}$$

where $\Omega(R)$, $\kappa(R)$, and $\Omega_{\rm b}$ are the Galaxy's circular frequency, epicyclic frequency, and the bar's pattern speed respectively (see Binney & Tremaine 2008).

This is at odds with new studies of the stellar photometry (Wegg & Gerhard 2013; Wegg et al. 2015) and stellar and gas kinematics (Portail et al. 2015; Sormani et al. 2015; Li et al. 2016; Portail et al. 2016) of the Galactic centre which favour a long bar (extending to $R \sim 5$ kpc), oriented at an angle of $\phi_b \sim 27^\circ$, and with a pattern speed $\Omega_{\rm b} \sim 40$ km s^{-1} kpc^{-1}, placing the bar corotation at about 6 kpc from the Galactic centre (Portail et al. 2016), and the OLR way beyond the Solar neighbourhood.

A way to check whether the OLR or CR explanation holds is to investigate how the Hercules feature in velocity space varies with the position in the Galaxy (e.g. Antoja et al. 2014). The Gaia mission provides a

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unique opportunity to test this in the Galactic disc. One first step is to cross-match the recent Gaia DR1/TGAS catalogue with existing spectroscopic surveys and trace the position of Hercules in velocity space as a function of Galactocentric radius. In particular Monari et al. (2017c) combine TGAS with the LAMOST DR2 catalogue (Liu et al. 2014). I summarise this work in this contribution. In Sect.

2 Cross matching TGAS and LAMOST

Monari et al. (2017c) cross match the TGAS catalogue (providing Right Ascension α, the declination δ, the parallax π, and the proper motions μ_α and μ_δ) with the LAMOST DR2 A, F, G and K type stars catalogue (Liu et al. 2014), from which we obtain the line–of–sight velocity $v_{\rm los}$. They select stars with fractional parallax error $\sqrt{\sigma_\pi^2+(0.3{\rm mas})^2}/\pi<0.2$, (where the use of the 0.3 mas systematic uncertainty is recommended in Gaia Collaboration et al. 2016), obtaining a total 49,075 stars, mostly distributed towards the anti–centre of the Milky Way (while, the spectroscopic survey RAVE, for example, focuses on the central parts).

3 Analysis

The observables $(\alpha,\delta,\pi,\mu_\alpha,\mu_\delta,v_{\rm los})$ are transformed to the cylindrical Galactocentic coordinates $(R,\phi,z,v_R,v_\phi,v_z)$ using fundamental parameters of our Galaxy derived by Reid et al. (2014), and a value of the radial motion of the Sun with the respect of the Local Standard of Rest of $U_\odot=10$ km s^{-1} (e.g. Bovy et al. 2015).

It is then studied the distribution of stars in the (R,v_ϕ) plane, shown in Fig. 1 (left panel). In this space, Hercules appears as the clump of stars localized between $v_\phi\sim190$ km s^{-1}, and $v_\phi\sim200$ km s^{-1}, slightly detached from the main velocity mode at higher v_ϕ. The valley between Hercules and the main velocity mode (the 'gap'), appears only for stars with $v_R>0$ (right panel). This is due to the fact that Hercules is composed by stars moving outwards in the Galaxy (e.g. Dehnen 1998; Famaey et al. 2005).

Assuming that the Hercules gap in the (R,v_ϕ) plane corresponds to stars with guiding radii at the position of the OLR ($R_{\rm OLR}$), one can write how the tangential velocity of these stars ($v_{\rm OLR}$) as

$$v_{\rm OLR}=\frac{R_{\rm OLR}v_{\rm c}(R_{\rm OLR})}{R}, \tag{3.1}$$

where $v_{\rm c}(R_{\rm OLR})$ is the circular speed of the Galaxy at the OLR. As we move outwards in R, $v_{\rm OLR}$ becomes lower, and the number of stars that is affected by the OLR becomes smaller, which eventually leads to the disappearance of the Hercules moving group. This is in good agreement with theoretical models of perturbed disc DF described by Monari et al. (2016, 2017b). Hercules, however, can be traced it at larger R and lower $v_{\rm OLR}$, using the v_ϕ distribution shown in Fig. 2.

One can describe the circular velocity curve as a power-law $v_{\rm c}(R)=v_0(R/R_0)^\beta$. In the right panel of Fig. 1 the corresponding $v_{\rm OLR}(R)$ for three values of $R_{\rm OLR}$ was overplot, using $\beta=-0.3,0,0.3$, and $\Omega_{\rm b}=1.89\Omega_0$. This value of the pattern speed $\Omega_{\rm b}$ was found by Antoja et al. (2014) using the RAVE catalogue which mostly probes regions with $R<R_0$, and still nicely follow the shape of the gap even for $R>R_0$, without *any* tuning of the parameters to obtain a good fit. This is also confirmed when looking at the saddle points in the v_ϕ distributions in Fig. 2.

4 Conclusion

The traditional explanation that the Hercules moving group is a signature in local stellar kinematics of the Galactic bar's OLR (Dehnen 2000) is at odds with the slowly rotating long bar models favoured by stellar and gas kinematics in the inner Galaxy. This would mean that an alternative explanation, e.g. based on spiral arms or the bar's corotation (Pérez-Villegas et al. 2017) is necessary.

One way to test whether Hercules is indeed linked to the OLR of the bar is to trace its position and shape in velocity space as a function of position in the Galaxy. Monari et al. (2017c) made a first step in this direction, combining the TGAS and LAMOST DR2 catalogues, and found out that the rotational velocity of the Hercules moving group is indeed closely following the prediction of older models (obtained with different data) placing the Sun just outside the OLR of the bar. At this pattern speed, the corotation of the bar is close to $R\sim4$ kpc, and its OLR is at $R\sim$7 kpc.

Alternative explanations, necessary to account for a slowly rotating bar with corotation around $R\sim6$ kpc, should also reproduce the position of Hercules in velocity space and its variation with position in the Galaxy

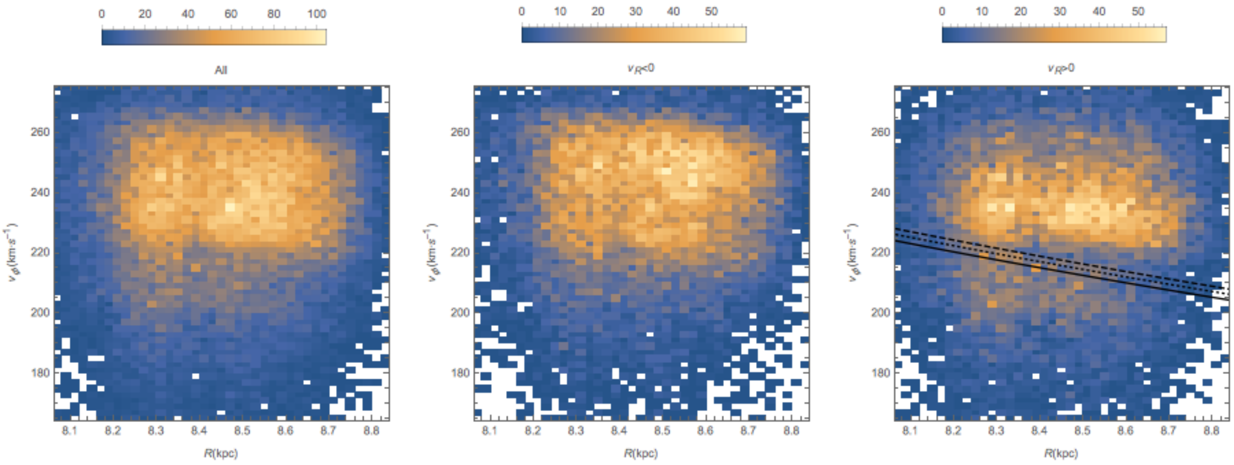

Fig. 1. Distribution of stars in TGAS+LAMOST in the (R, v_ϕ) plane from Monari et al. (2017c). Stars with parallax accuracy $\sqrt{\sigma_\pi^2 + (0.3\text{ mas})^2}/\pi < 0.2$ are selected. The bin size is 20 pc in R, and 2 km s^{-1} in v_ϕ, and the units of the color bar indicate the number of stars per bin (the white bins are empty). The left panel represents the whole sample, the central panel stars with $v_R < 0$, and the right panel stars with $v_R > 0$. The different curves in the right panel correspond to different models of $v_{\rm OLR}$ with $\Omega_{\rm b} = 1.89\Omega_0$: the solid curve has a flat $v_{\rm c}(R)$ ($\beta = 0$), the dashed curve has an increasing $v_{\rm c}(R)$ ($\beta = 0.3$), and the dotted curve a decreasing $v_{\rm c}(R)$ ($\beta = -0.3$).

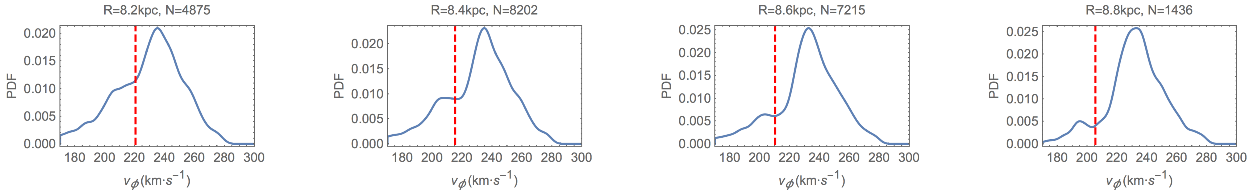

Fig. 2. Distribution of stars in v_ϕ, for stars with $v_R > 0$ and $R_i - \Delta R < R < R_i + \Delta R$, where $R_i = 8.2$ kpc, 8.4 kpc, 8.6 kpc, and 8.8 kpc, and $\Delta R = 0.1$ kpc. The PDFs are obtained using Gaussian kernels of bandwidth 3 km s^{-1}. The red dashed line corresponds to $v_{\rm OLR}(R_i)$ for $\Omega_{\rm b} = 1.89\Omega_0$, and $\beta = 0$, indicating the theoretical gap between the high- and low-velocity modes in v_ϕ. From Monari et al. (2017c)

as the fast bar models do. The way that the position of the Hercules gap in v_ϕ varies in R indicates its origin linked to a single resonance radius. This excludes models of perturbers with varying pattern speed with radius, like the corotating spiral arms.

Models of the star counts in the inner Galaxy shows the existence of a long, flat structure reaching out to $R \sim 5$ kpc. If the bar is fast, this structure could for example be a loosely wound spiral coupled to the end of the bar.

The debate on the origin of the Hercules moving group is yet to be settled, as recent N-body models (Pérez-Villegas et al. 2017) suggest that Hercules could also have an origin related to orbits trapped to the bar's corotation. To settle this debate, the upcoming Gaia data releases will have the greatest importance, to trace precisely the shape of the velocity distribution of the stars at different locations in a large volume of the Galaxy. Necessary will also be the use of more refined models to describe the star's distribution function under the effect of non-axisymmetric perturbers, especially in the vicinity of resonances (Monari et al. 2017a).

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