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Vertical velocity patterns in the Milky Way disc: RAVE-Gaia streaming motions

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Abstract. Using data from the Radial Velocity Experiment (RAVE) and the Tycho- Gaia astrometric solution catalogue (TGAS), we study the vertical velocity (Vz) patterns in the Milky Way disc. We search in particular for variation in velocity with distance above and below the disc midplane. In contrast to previous suggestions of a breathing mode seen in RAVE data, our results support a combination of bending and breathing modes, likely generated by a combination of external or internal and external mechanisms.

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

1. RAVE-TGAS

Using RAVE (Steinmetz *et al.* 2006) radial velocities, TGAS proper motions (Lindegren *et al.* 2016) and the distance estimate inferred from TGAS trigonometric parallaxes by Astraatmadja & Bailer-Jones (2016) or distances obtained by McMillan *et al.* (2017) by combining TGAS parallaxes with spectrophotometric data, we compute the vertical velocity fields and compare our results to the velocity fields obtained by Williams *et al.* (2013). The superior parallaxes and proper motions obtained by the ESA Gaia mission (Gaia Collaboration *et al.* 2016a) should yield marked improvements on the velocity fields.

For comparison purposes, the left panel of Fig. 1 shows the vertical velocity field obtained by Kordopatis *et al.* (2013), which is very similar to the one obtained by Williams *et al.* (2013), both make use of a compilation of proper motion catalogues. The resulting velocity fields differ mainly from Williams *et al.* (2013) in being based on the full RAVE sample instead of only red-clump stars. This allows for a better comparison to the velocity fields obtained with our RAVE samples. When using the McMillan distances, we exclude stars with an error of $\sigma_d/d > 20\%$ to exclude uncertain velocities from our velocity fields. We join these distances to the radial velocities from RAVE and TGAS proper motions to form the RAVE-TGAS-McMillan data set with 45,945 stars. The middle panel of Fig. 1 shows the median values of V_z as a function of galactic position for the RAVE-TGAS-McMillan set. The right panel shows the corresponding velocity fields for the RAVE-TGAS-ABJ set.

In contrast to previous results suggesting a breathing mode perturbation in the extended solar neighbourhood, our analysis supports a combination of breathing mode at $R < 8\,\text{kpc}$ and bending mode at $R > 8\,\text{kpc}$, a combination not previously reported in the literature. Inwards of the solar radius, a bar and/or spiral perturbations could have induced the breathing mode; alternatively, this could be due to a satellite perturbation.

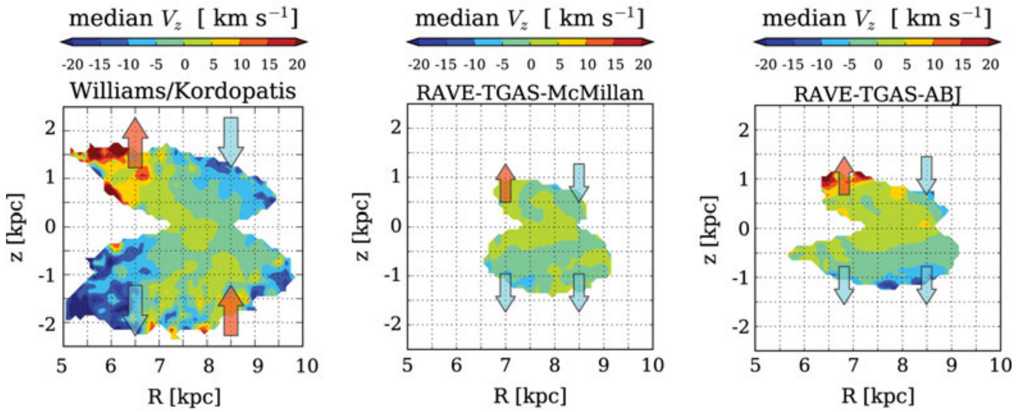

Figure 1. Maps of median vertical velocity. The velocity maps are displayed in $(0.1\,\mathrm{kpc})^2$ pixels covering up to 3 kpc from the Sun. Each pixel is smoothed by computing the median velocities over a box of $(0.2\,\mathrm{kpc})^2$ with a minimum of 50 stars. The arrows in the left panel show the direction of vertical motion consistent with a breathing mode in the Williams/Kordopatis sample. The middle panel employs RAVE radial velocities, TGAS proper motions and the McMillan *et al.* (2017) distances with $\sigma_d/d > 20\%$, while the right panel employs the distances derived by Astraatmadja & Bailer-Jones (2016) using the Milky Way prior. The arrows in the middle and right panel show the signatures of a breathing mode perturbation inside and a bending mode outside R_0.

On the other hand, the bending mode at $R > 8\,\mathrm{kpc}$ is consistent with an external perturbation, for example caused by the Sagittarius dwarf galaxy or a dark matter subhalo passing through the disc. A combination of breathing and bending mode can be seen as a superposition of waves existing simultaneously in the Milky Way disc.

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