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On the Solar Velocity

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The recent *Gaia* data release (Gaia Collaboration et al. 2018a) provides astrometry for over a billion sources, of which more than seven million also have line-of-sight velocities, permitting their full 3D heliocentric velocities to be determined. To put these velocities in a *galactocentric* reference frame requires knowledge of the velocity of the Sun with respect to the Galactic center, $\mathbf{v}_\odot$, while decomposing them into galactocentric cylindrical coordinates, (V_R, V_ϕ, V_z), also requires knowledge of R_0, the distance to the Galactic center (GC). In this note we highlight the implications of the recent contribution by the GRAVITY collaboration (Gravity collaboration et al. 2018) in the determination of $\mathbf{v}_\odot$.

Traditionally $\mathbf{v}_\odot$ has been derived by decomposing it into the solar motion, $\mathbf{u}_\odot$, the velocity of the Sun with respect to the solar neighborhood defined by local stellar samples, and the velocity of the local standard of rest (LSR), $\mathbf{v}_{LSR}$:

$$\mathbf{v}_\odot = \mathbf{u}_\odot + \mathbf{v}_{LSR}. \tag{1}$$

Consistent with the assumption of axisymmetry, $\mathbf{v}_{LSR}$ is typically assumed to correspond to the circular velocity at the Sun's location. Such an approach was taken, for example, by Gaia Collaboration et al. (2018b) when mapping the (V_R, V_ϕ, V_Z) velocity fields from *Gaia* astrometry and line-of-sight velocities. However, in clear contradiction with the assumptions made, the resulting velocity maps clearly show large scale non-circular streaming motions in the plane.

More recent definitions of the LSR allow for a non-axisymmetric Galaxy, so that $\mathbf{v}_{LSR}$ includes the non-circular streaming motions at the Sun, but the difficulty of estimating $\mathbf{v}_{LSR}$ essentially means that its uncertainty is of the order of the magnitude of the streaming motions ($\approx 10\,\mathrm{km\,s^{-1}}$), significantly larger than the uncertainties in $\mathbf{u}_\odot$ and dominating the uncertainty of any estimate of $\mathbf{v}_\odot$ based on Eq. 1.

Recently the GRAVITY collaboration used observations of the star S2 orbiting SagA*, assumed to be at the center of the Galaxy, to determine the distance to the GC to be $R_0 = 8.122 \pm 0.033\,\mathrm{kpc}$. It should be noted that this estimate of R_0 is absolute, being based on positional and spectroscopic observations of a resolved binary, and that its precision is nearly an order of magnitude better than earlier determinations (Bland-Hawthorn & Gerhard 2016).

The first consequence of knowing R_0 is the immediate improvement in the decomposition of velocities in a galactocentric coordinate system. (See Figure 1.)

In addition, as pointed out by Reid & Brunthaler (2004), a direct measure of R_0 allows the determination of the component of $\mathbf{v}_\odot$ orthogonal to the line-of-sight to the GC via the measured proper motion of SagA* which, assuming that SagA* is stationary at the GC, is just the apparent reflex motion of $\mathbf{v}_\odot$. Thanks to the exceptional precision of R_0 the uncertainty of this velocity component is now of the order of $1\,\mathrm{km\,s^{-1}}$. Others have already applied this in new derivations of the circular velocity curve of the Milky Way (McGaugh 2018; Eilers et al. 2018).

However, a closer inspection of the GRAVITY results reveals an additional hidden treasure for Galactic studies. Among the fitted parameters is the parameter $\dot{z}_0 = 1.9 \pm 3\,\mathrm{km\,s^{-1}}$, a correction to the assumed $\mathbf{v}_\odot$ velocity component toward SagA* modelled as $(\dot{z}_0 + 11\,\mathrm{km\,s^{-1}})$, using $\mathrm{U}_\odot = 11\,\mathrm{km\,s^{-1}}$ based on Schönrich et al. (2010). (Private communication, F.Eisenhauer.) This velocity component results in a systematic Doppler shift in the spectroscopic observations of S2, and introduces a delay in the arrival times of the observations due to the changing distance between the observer and the SagA*-S2 system (i.e. the Rømer effect). In any case, as $\mathrm{U}_\odot$ is fixed, their determination of the component of $\mathbf{v}_\odot$ toward the GC is effectively independent of the solar motion.

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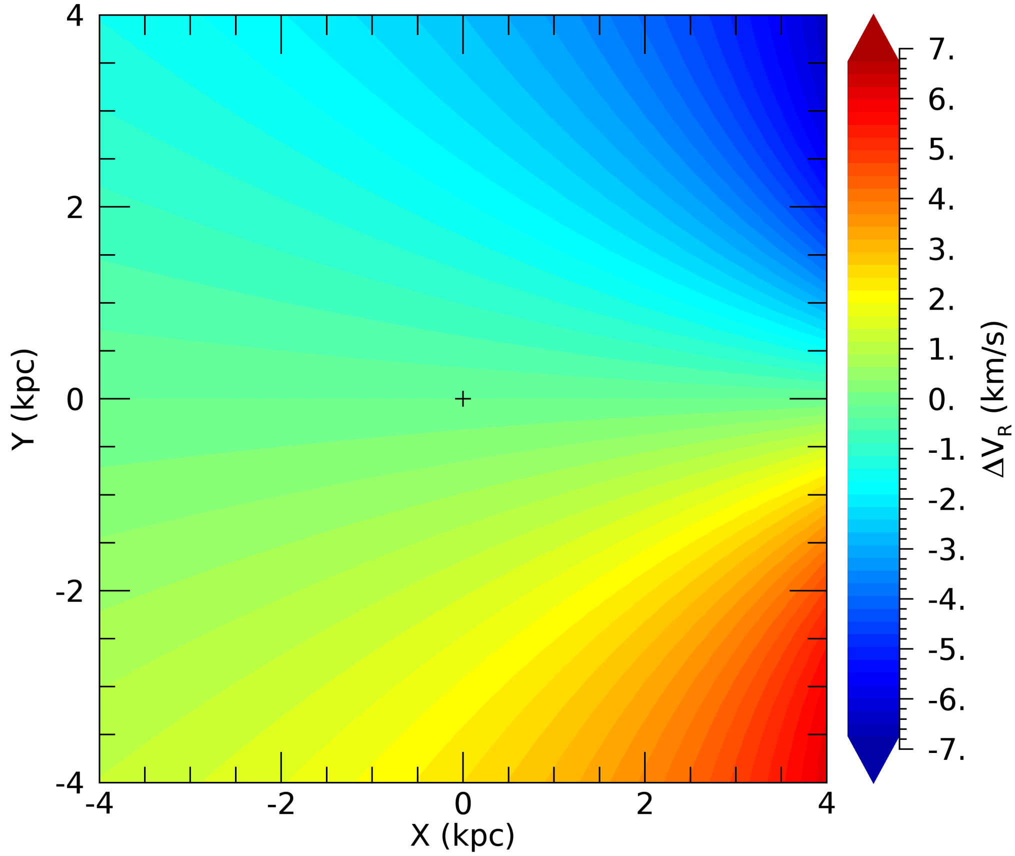

Figure 1. The systematic error in V_R, with respect to heliocentric position (X-axis toward the GC and Y-axis in the direction of Galactic rotation), assuming $R_0 = 8.34$ kpc in the case that the true $R_0 = 8.122$ kpc, for a constant circular velocity $V_0 = 240\,\mathrm{km\,s^{-1}}$. The systematic error in V_ϕ will be of the same magnitude but opposite sign.

Combining the above GRAVITY results with the proper motion of SagA* from Reid & Brunthaler (2004), we find for $\mathbf{v}_\odot$:

$$\begin{aligned} V_{R,\odot} &= -12.9 \pm 3.0 \ \mathrm{km\,s^{-1}} \\ V_{\phi,\odot} &= 245.6 \pm 1.4 \ \mathrm{km\,s^{-1}} \\ V_{Z,\odot} &= 7.78 \pm 0.09 \ \mathrm{km\,s^{-1}} \end{aligned} \tag{2}$$

Again, we stress that this estimate of $\mathbf{v}_\odot$ is independent of $\mathbf{v}_{LSR}$ or of the solar motion.

Now that we have determined $\mathbf{v}_\odot$ independently of $\mathbf{v}_{LSR}$, we can estimate $\mathbf{v}_{LSR}$ using $\mathbf{v}_\odot$ and the solar motion by Schönrich et al. (2010):

$$\begin{aligned} V_{R,LSR} &= 1.8 \pm 3.1 \ \mathrm{km\,s^{-1}} \\ V_{\phi,LSR} &= 233.4 \pm 1.5 \ \mathrm{km\,s^{-1}} \\ V_{Z,LSR} &= 0.53 \pm 0.38 \ \mathrm{km\,s^{-1}} \end{aligned} \tag{3}$$

Interestingly the radial component is not significantly different than zero, so that the typical assumption of the LSR being in circular motion, with a circular velocity of $233.4\,\mathrm{km\,s^{-1}}$, seems to be justified. However, given the significant streaming motions seen by *Gaia*, this may be fortuitous, and should not necessarily be interpreted as evidence that the Milky Way is dynamically axisymmetric, nor that the solar neighborhood is in circular motion. Indeed, if instead the solar neighborhood was on a closed *elliptical* orbit, as might be expected for a non-axisymmetric galactic potential, then the near zero radial motion of the LSR would imply that there is significant non-circular streaming motion in the V_ϕ direction. Meanwhile, the small to non-existent vertical motion of the LSR indicates that there is no significant mean vertical motion at the Sun's position.

Finally, it should be noted that the uncertainties on $\mathbf{v}_\odot$ stated above do not take into account possible systematic errors that would result if SagA* is not at the GC and/or has significant peculiar motions with respect to the GC. Given the current precision of $\mathbf{v}_\odot$, such systematic errors may dominate, and it would be most useful to place upper limits on how far the position and velocity of SagA* might reasonably deviate from these assumptions.

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