On the characterization of the Galactic warp in the Gaia era

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The disk of our Galaxy is known to have a warp in the ISM (Kerr, 1957; Hartmann & Burton, 1997) that is also seen in the stellar component (e.g. Lopez-Corredoira et al. 2002).

The line of nodes roughly coincides with the Galactic Center-Sun line.
TEST TOOL:
A Gaia mock catalogue of warped stellar populations
Recipe for making a warped population in statistical equilibrium
Recipe for making a warped population in statistical equilibrium

- Choose the stellar population
  
  We consider OB, A and RC stars. Take into consideration their velocity dispersion and local surface density.
Recipe for making a warped population in statistical equilibrium

• Choose the stellar population

• 3D Galactic potential
Recipe for making a warped population in statistical equilibrium

- Choose the stellar population
- 3D Galactic potential

Allen & Santillan (1991) potential consisting of a Miyamoto-Nagai disk, a spherical bulge and a massive spherical halo.
Recipe for making a warped population in statistical equilibrium

- Choose the stellar population
- 3D Galactic potential
- A geometric warp model: tilted rings
Recipe for making a warped population in statistical equilibrium

- Choose the stellar population
- 3D Galactic potential
- A geometric warp model: tilted rings

\[ \Psi(r; r_1; r_2; \psi_{\text{max}}, \alpha) = \psi_2((r - r_1)/(r_2 - r_1))^\alpha, \quad r > r_1 \]

The tilt is applied beyond \( r_1 \). The resulting warp is such that the tilt angle increases as a power law whose exponent is \( \alpha \) and such that at \( r_2 \) it has a value equal to \( \Psi_2 \).
Recipe for making a warped population in statistical equilibrium

• Choose the stellar population
• 3D Galactic potential
• A geometric warp model: tilted rings

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This warp model is applied to the disc potential.
Recipe for making a warped population in statistical equilibrium

• Warp the Galactic disk potential adiabatically
Recipe for making a warped population in statistical equilibrium

- Warp the Galactic disk potential adiabatically

\[ \psi_2 = \psi_2(t) \]
Recipe for making a warped population in statistical equilibrium

- Warp the Galactic disk potential adiabatically

\[ \psi_2 = \psi_2(t) \]

\[ \psi_{\text{max}} \]

\[ T/P \]

n = 1/8  n = 1/2  n = 2  n = 4

Impulsive \leftrightarrow Adiabatic
After considering Drimmel extinction map and Gaia selection function.
What is the best way to detect and characterise the warp within the Gaia observational constrains?

After considering Drimmel extinction map and Gaia selection function
Great Circle Cell Counts Methods
The GC3 Methods

**GC3: Great Circle Cell Counts Method**

It relies on the fact that the orbits of stars in a stream in a spherical potential are confined to a plane that contains the galactic center.

\[ |\hat{L} \cdot \hat{r}_*| \leq \delta_r \]

Pole vector: \( \hat{L} \)
Star position vector: \( \hat{r}_* \)
both unit vectors.

**MGC3: Modified Great Circle Cell Counts**

They add the extra requirement that the velocity vector lies within the great circle band.

\[ |\hat{L} \cdot \hat{v}_*| \leq \delta_v \]
How this method is useful for detecting the warp?

Poles corresponding to each radius bin

Courtesy of C. Mateu
How this method is useful for detecting the warp?

Poles corresponding to each radius bin

Courtesy of C. Mateu
How this method is useful for detecting the warp?
Results
Results after Applying Gaia selection function and Gaia errors

Abedi et al. 2014 (MNRAS.442.3627A)
KINEMATIC SIGNATURE OF THE WARP
Looking at the vertical velocities

A test particle orbiting in a warped galactic disk
Both are corrected for the vertical motion of the Sun
SIMULATIONS VS. OBSERVATIONS I: 
**UCAC4 CATALOG**
The fourth United States Naval Observatory (USNO) CCD Astrograph Catalog, UCAC4, is an all-sky astrometric catalog with more than 105 million of stars with proper motions. It is complete to R=16. It also contains 2MASS magnitudes (Zacharias et al. 2013).

We choose the Red clump giants using the method from Cabrera-Lavera et al. 2007.
**SIMULATIONS VS. OBSERVATIONS**

Our warp model
(affected by Gaia selection function)

Note that the $\mu_b$ is corrected for the vertical motion of the Sun.
Residual spin of Hipparcos/Tycho-2 system wrt extragalactic inertial reference frame

Bobylev (2010)

$$(\omega_1, \omega_2, \omega_3) = (-0.11, 0.24, -0.52) \text{ mas/yr}$$

Federov et al. (2011)

$$(\omega_1, \omega_2, \omega_3) = (0, 0, -1.8) \text{ mas/yr}$$
What should be the spin axis for which the observations match with the model?

Least squares fit

\[(\omega_1 g, \omega_2 g) = (-0.09, -1.55) \text{ mas yr}^{-1}\]
Residual rotation of Hipparcos/Tycho-2 system wrt extragalactic inertial reference frame

<table>
<thead>
<tr>
<th>Method/Solution</th>
<th>$\omega_1$</th>
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<td>Bobylev (2010)</td>
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<td>$0.24 \pm 0.10$</td>
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<td>Fedorov et al. (2011)</td>
<td>$\sim 0$</td>
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<td>LSF, outliers removed</td>
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Spin vector in Equatorial coordinates

Spin vector in Galactic coordinates
Residual rotation of Hipparcos/Tycho-2 system wrt extragalactic inertial reference frame

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Spin vector in Equatorial coordinates

Spin vector in Galactic coordinates
Conclusions

* We have made a kinematical model for the Galactic warp.

* We have used the GC3 methods to search for and characterise the warp. We find that it is a very efficient and robust method.

* We look for the kinematic signature of the warp in real data using UCAC4 proper motion catalogs. Correcting for the rotation of the inertial reference frame and any other systematics is very crucial for our work.

Abedi et al. 2014 (MNRAS.442.3627A)