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Pattern speeds in the Milky Way

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Abstract. A brief review is given of different methods used to determine the pattern speeds of the Galactic bar and spiral arms. The Galactic bar rotates rapidly, with corotation about halfway between the Galactic center and the Sun, and outer Lindblad resonance not far from the solar orbit, R_0. The Galactic spiral arms currently rotate with a distinctly slower pattern speed, such that corotation is just outside R_0. Both structures therefore seem dynamically decoupled.

Key words. Galaxy: structure – Galaxy: kinematics and dynamics – Galaxy: fundamental parameters – Galaxy: disk – Galaxy: bulge – Galaxies: spiral

1. Introduction

The Milky Way is a barred spiral galaxy with a boxy barred bulge (e.g., Dwek et al. 1995; Binney et al. 1997), extending to ~ 2 kpc, and an in-plane bar, reaching to ~ 4 kpc (e.g., Benjamin et al. 2005; Cabrera-Lavers et al. 2007). The disk is probably of Freeman type II, with an exponential profile outside ~ 4 kpc (López-Corredoira et al. 2004; Benjamin et al. 2005), and a centrally flat or decreasing profile inside this radius. The Galaxy probably has a four-armed spiral pattern in the gas and young stars, but only two of these may be present in the density distribution of old stars (see e.g., Drimmel 2000; Martos et al. 2004).

2. Pattern speed of the Galactic bar

The most direct determination of the bar's pattern speed has been through applying a modified version of the Tremaine-Weinberg continuity argument to a sample of ~ 250 OH/IR stars in the inner Galaxy (Debattista et al. 2002). The quantity actually measured is the difference between the pattern rotation velocity and the circular velocity at the local standard of rest (LSR). This depends on the Galactic constants R_0, V_0 and the peculiar radial velocity $u_{\rm LSR}$ of the LSR. The result is sensitive to $u_{\rm LSR}$; however, HI absorption measurements show that the HI gas between the Sun and the Galactic center moves at a common radial velocity $-0.23 \pm 0.06\ \rm km\,s^{-1}$ (Radhakrishnan & Sarma 1980), so the most natural assumption is that $u_{\rm LSR}$ is zero to this level. Debattista et al. (2002) applied the method to a subsample of $\sim$ 250 sufficiently bright and long-lived OH/IR stars (see Sevenster 2002) to ensure an approximately complete and relaxed sample. The resulting value of the pattern speed is $\Omega_p = 59 \pm 5 \pm 10\,(\rm sys)\ km\,s^{-1}\,kpc^{-1}$ for $R_0 = 8$ kpc, $V_0 = 220\ \rm km\,s^{-1}$, and for other values of the Galactic constants, $\Omega_p = (V_0/R_0) + 31.5 \pm 5 \pm 10\,(\rm sys)\ km\,s^{-1}\,kpc^{-1} - (18/R_0)\,u_{\rm LSR}$. The main part of the signal comes from stars at low b and around $l \sim 30°$, i.e., probably

Send offprint requests to: Ortwin Gerhard disk stars coupled to the bar, perhaps near inner spiral arm tangent points or in an inner ring around the bar (see Sevenster & Kalnajs 2001). More frequently, the pattern speed of the bar has been estimated from comparing the gas flow in hydrodynamic simulations with the observed Galactic CO and HI *lv*-diagrams. These simulations generally reproduce a number of characteristic features in the *lv*-plot very well, but none reproduces all the observed features. Thus the derived pattern speeds vary somewhat. Englmaier & Gerhard (1999) obtain $\sim 60\ \mathrm{km\,s^{-1}\,kpc^{-1}}$ (for 'standard' $R_0 = 8$ kpc, $V_0 = 220\ \mathrm{km\,s^{-1}}$) from placing the corotation radius $R_{\rm CR}$ outside the 3 kpc arm and inside the molecular ring, and matching mainly to the spiral arm tangents; Fux (1999) obtains $\sim 50\ \mathrm{km\,s^{-1}\,kpc^{-1}}$ ($R_{\rm CR} = 4-4.5$ kpc) from a comparison to several reference features in the CO *lv*-plot; Weiner & Sellwood (1999) obtain $42\ \mathrm{km\,s^{-1}\,kpc^{-1}}$ ($R_{\rm CR} = 5.0$ kpc) from matching the extreme HI velocity contour; Bissantz et al. (2003) obtain $55-65\ \mathrm{km\,s^{-1}\,kpc^{-1}}$ ($R_{\rm CR} = 3.4 \pm 0.3$ kpc) from models with separate bar and spiral pattern speeds and matching the spiral arm ridges in the CO emission and the positions of molecular clouds and HII region in the *lv*-diagram; Rodríguez-Fernández & Combes (2008) obtain $30-40\ \mathrm{km\,s^{-1}\,kpc^{-1}}$ and $R_{\rm CR} = 5-7$ kpc from models with a second nuclear bar and matching to the Galactic spiral arm pattern. From these results, we may take as combined estimate for the bar pattern speed from gas dynamics $\Omega_p = 52 \pm 10\ \mathrm{km\,s^{-1}\,kpc^{-1}}$ or $R_{\rm CR} = 3.5-5.0$ kpc (for 'standard' $R_0 = 8$ kpc, $V_0 = 220\ \mathrm{km\,s^{-1}}$; roughly $R_{\rm CR} \propto R_0$). A third estimate for the bar pattern speed comes from determining the length of the bar and assuming that, like in external galaxies the Galactic bar is a fast bar, i.e., $\mathcal{R} = R_{\rm CR}/R_{\rm B} = 1.2 \pm 0.2$ (Aguerri et al. 2003). The length of the NIR bar from COBE is $R_{\rm B} \simeq 3.5$ kpc (Binney et al. 1997; Bissantz & Gerhard 2002), whereas the length of the 'long bar' from starcounts is $R_{\rm B} \simeq 4.0$ kpc (Benjamin et al. 2005; Cabrera-Lavers et al. 2007). This results in a rather wide range of $R_{\rm CR} = 3.5-5.6$ kpc or $\Omega_{\rm b} \sim 35-60\ \mathrm{km\,s^{-1}\,kpc^{-1}}$. A final method is based on the interpretation of star streams observed in the stellar velocity distribution function (VDF) in the solar neighborhood as due to resonant orbit families near the outer Lindblad resonance (OLR) of the Galactic bar. Near the OLR there are two elongated families of periodic orbits (anti-aligned inside and aligned outside OLR), so an observer located near the points in the disk where these cross may see two stellar streams at different velocities (Kalnajs 1991). The associated non-periodic orbits from both families can generate two streams in observations from a range of radii and bar angles. Using a series of backward integration test particle simulations to match the observed VDF, Dehnen (2000) estimates $\Omega_{\rm b} = 1.85 \pm 0.15 V_0/R_0$ ($51 \pm 4\ \mathrm{km\,s^{-1}\,kpc^{-1}}$ for the 'standard' $R_0 = 8$ kpc and $V_0 = 220\,\mathrm{km\,s^{-1}}$). Mühlbauer & Dehnen (2003) expanded on this model and show that if the OLR of the bar lies slightly inside the solar circle and the Sun lags the bar by $\sim 20°$, three observed facts can be explained: the lack of significant radial motion of the LSR, the vertex deviation of $\sim 10°$ for the old stars, and the observed ratio of velocity ellipsoid $(\sigma_2/\sigma_1)^2 = 0.42 < 0.5$. Minchev et al. (2007) show that the observed value of the Oort C constant as a function of velocity dispersion can also be explained in this model, if $\Omega_{\rm b} = 1.87 \pm 0.04 V_0/R_0$ ($51.5 \pm 1.5\,\mathrm{km\,s^{-1}\,kpc^{-1}}$ for 'standard' R_0, V_0). This work suggests that the Galactic bar is important for the velocity distribution near the Sun. Chakrabarty (2007) agrees with this conclusion but concludes that spiral arm perturbations need to be included, and criticizes the backward integration simulations of Dehnen (2000). Her best estimate for bar corotation and pattern speed are $R_0/R_{\rm CR} \simeq 2.1 \pm 0.1$ and $\Omega_{\rm b} \simeq 57.5 \pm 5\ \mathrm{km\,s^{-1}\,kpc^{-1}}$.

Rather than considering the response of disk particles to a bar-like perturbation, Fux (2000) analyzes a fully self-consistent N-body simulation of a barred galaxy scaled to the Milky Way. This simulation shows multiple, time-dependent streams in many places in the disk, and in particular often displays a Hercules-like stream outside corotation. This stream is made of particles on 'hot' orbits with Jacobi energy just above its value at the 1-2-Lagrange points. While this explanation of the Hercules stream is different from the OLR scattering mechanism, it also places the OLR of the bar (at 7.7 kpc) near R_0 (assumed 8 kpc in his model). Stellar kinematic data over larger portions of the Galactic disk will be needed to identify the correct mechanism and redetermine the final range of Ω_b.

3. Spiral arm pattern speed

It is not a priori clear whether the rotation of the Galactic spiral pattern can be described by a constant, single pattern speed, and for how long this approximation is valid. However, a useful first step is to see whether this assumption is consistent with available data.

Here the most direct method relies on the birthplaces of the observed open clusters. These are obtained from their current locations in the disk by rotating them backwards in time along their orbits according to their known ages, using a model for the local circular speed in the disk. If open clusters are born in spiral arms, the distribution of birthplaces for some age bin should be spiral-like, and by comparing the spiral patterns obtained from different age bins, the rotation rate of the pattern can be estimated. Dias & Lépine (2005) did this (i) by simple backward circular rotation for a sample of 599 clusters, and (ii) by integrating the full orbits backwards for a sample of 212 clusters with radial velocities, proper motions, distances and ages. They find that indeed most open clusters are born in spiral arms, that the spiral arms approximately rotate like a rigid body, and that $\Omega_{sp} = 24 - 26\ \mathrm{km\,s^{-1}\,kpc^{-1}}$, so $R_{CR,sp} = (1.06 \pm 0.08)R_0$. Bissantz et al. (2003) computed gas flow models in realistic Galactic potentials with different pattern speeds for the bar and spiral pattern. Compared to single pattern speed models where the corotation radius forms a rigid barrier for the gas flow, gas may flow inwards through R_{CR} along arms passing through this region in models with two pattern speeds. In the *lv*-plot, two pattern speeds models therefore show regions with low gas content at radii around the bar's corotation radius. Similar voids are present in the observed *lv*-diagram. While this argues for a lower pattern speed for the spiral arms than for the bar, the gas flow models have so far not been accurate enough for this signature to reliably constrain the second pattern speed. In the Bissantz et al. (2003) simulations, both models with $\Omega_{sp} = 20$ and $40\ \mathrm{km\,s^{-1}\,kpc^{-1}}$ are consistent with the data. Martos et al. (2004) considered the self-consistent response of the Galactic disk to the two-armed *K*-band spiral pattern proposed by Drimmel (2000), as a function of its pattern rotation Ω_{sp}. They find that dynamical consistency is sensitive to Ω_{sp}, with the best results for $\Omega_{sp} = 20\ \mathrm{km\,s^{-1}\,kpc^{-1}}$. Using gas-dynamical simulations, they find that the gaseous response to this two-armed pattern is a pattern of four arms which resembles the Galactic pattern inferred from the tangent points seen in various tracers (e.g. Englmaier & Gerhard 1999).

A relatively large literature exists on determining the spiral arm pattern speed by fitting a kinematic model to the kinematics of OB stars and Cepheids. The fitted models allow for solar motion, Galactic rotation including values for R_0, V_0 and Oort constants, and the kinematic response to an assumed spiral arm perturbation. Ω_{sp} and other free parameters are obtained from the fit. Older determinations from OB and Cepheid stars (see Fernández et al. 2001) give $\Omega_{sp} = 20 - 30\ \mathrm{km\,s^{-1}\,kpc^{-1}}$. One study is by (Mishurov & Zenina 1999) who model Cepheid radial and Hipparcos proper motions, obtaining $\Omega_{sp} - \Omega_0 = 0.4 - 2.2\ \mathrm{km\,s^{-1}\,kpc^{-1}}$ and $R_{CR,sp} - R_0 = 0.1 - 0.4$ kpc, for $\Omega_0 = 27.5\ \mathrm{km\,s^{-1}\,kpc^{-1}}$ and $R_0 = 8$ kpc. Fernández et al. (2001) fit a kinematic model to the Hipparcos O, B, and Cepheid velocities, finding $\Omega_{sp} = 30\ \mathrm{km\,s^{-1}\,kpc^{-1}}$. Lépine et al. (2001) investigate a superposition of $m = 2$ and $m = 4$ modes for the Galactic spiral pattern and fit parameters of this model and the Galactic constants to the Cepheid kinematics. They obtain similar values for the pattern speeds of both modes, with $\Omega_{sp,m=2} - \Omega_0 = 0.15 \pm 0.5\ \mathrm{km\,s^{-1}\,kpc^{-1}}$ and $\Omega_{sp,m=4} - \Omega_0 = 0.18 \pm 0.1\ \mathrm{km\,s^{-1}\,kpc^{-1}}$, indicating that the Sun is within 0.2 kpc of the corotation resonance of the pattern. Quillen & Minchev (2005) investigated the effect of a rotating spiral pattern on the velocity distribution of old stars in the solar neighborhood. They find that two families of orbits can be caused by spiral density waves if the Sun is near the inner 4:1 resonance. This gives $\Omega_{sp} \sim 18\ \mathrm{km\,s^{-1}\,kpc^{-1}}$ but the match of the observed VDF near the Sun is not as good as in the bar-driven models. Chakrabarty (2007) simulated the effects of the bar *and* spiral arms on the VDF. She did not find a clear best-fit model, but constrains $\Omega_b \simeq 57.5 \pm 5\ \mathrm{km\,s^{-1}\,kpc^{-1}}$ and $\Omega_{sp} \simeq (17-28)\ \mathrm{km\,s^{-1}\,kpc^{-1}}$.

4. Conclusion

The Galactic bar rotates rapidly, with corotation about halfway between the Galactic center and the Sun, and OLR not far from the solar orbit, R_0. To recapitulate, for $R_0 = 8$ kpc, $V_0 = 220\ \mathrm{km\,s^{-1}}$: direct determination favors a fast pattern speed for the bar, $\Omega_b = 59 \pm 5 \pm 10\,(\mathrm{sys})\ \mathrm{km\,s^{-1}\,kpc^{-1}}$. Hydrodynamic models from a number of papers give best fits to CO *lv*-plots for $\Omega_b \simeq 52 \pm 10\ \mathrm{km\,s^{-1}\,kpc^{-1}}$. The velocity distribution of old stars in the solar neighborhood seems influenced most by the bar, and somewhat by the spiral arms. Modeling this gives $\Omega_b \simeq 50 - 60\ \mathrm{km\,s^{-1}\,kpc^{-1}}$. Taking all constraints together, the most likely range is $\Omega_b \simeq 50 - 60\ \mathrm{km\,s^{-1}\,kpc^{-1}}$, corresponding to bar corotation at $R_{CR} \simeq 3.5 - 4.5$ kpc. The Galactic spiral arms rotate with a distinctly slower pattern speed. Open cluster birthplace analysis and the velocity field of nearby young stars indicate that the current corotation of the spiral pattern is just outside R_0. These tracers cover the last $10^7 - 10^8$ yr, and result in $\Omega_{sp} \simeq 25 \pm 2\ \mathrm{km\,s^{-1}\,kpc^{-1}}$. Investigations of the stellar velocity distribution in the solar neighborhood allow a wider range, $\Omega_{sp} \simeq (17 - 28)\ \mathrm{km\,s^{-1}\,kpc^{-1}}$. This corresponds to a backward time-scale more like $\sim 10^9$ yr. Hydrodynamic models also favor a second, slower pattern speed for the spiral arms in the disk. The Galactic bar and spiral pattern thus seem to be dynamically decoupled.

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