IS THE MILKY WAY ELLIPTICAL?

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ABSTRACT

We show that two significant anomalies in the kinematics of the Galaxy, viz. the low value of the axis ratio of the velocity ellipsoid of old stars in the solar neighbourhood and the difference in apparent rotation curves between distant stars and HI gas, can be explained if the gravitational potential in the Galactic plane is elliptical. In the best-fit model, the isopotential curves have an axis ratio of 0.92, roughly constant with radius, and the mean circular speed is $200\,\mathrm{km\,s^{-1}}$.

1. INTRODUCTION

Galaxy halos are unlikely to be round if they are formed by dissipationless collapse (Dubinski & Carlberg 1991). Galactic disks embedded in such halos will experience a non-axisymmetric gravitational field Ψ, which to first order we can characterise as an elliptical perturbation on a circular potential

$$\Psi(R,\phi) = \Psi_0(R) + \tfrac{1}{2}\epsilon(R)v_c(R)^2 \cos 2(\phi - \phi_b). \qquad (1)$$

We might hope to detect signatures of this perturbation in the shapes and kinematics of galactic disks. Here we focus on available evidence for our own Galaxy; for results concerning possible ellipticity in other galaxies, see Franx & de Zeeuw (1992) and references therein.

We will consider a simple 'standard' model, in which the axisymmetric component has constant circular speed v_c, $\Psi_0 = v_c^2 \ln R$, and the ellipticity of the equipotentials $\epsilon > 0$ is also constant. The angle ϕ_b is the Galactocentric azimuth of the minor axis of the potential. It is convenient to work with the combinations

$$c_\Psi = \epsilon \cos 2\phi_b \quad \text{and} \quad s_\Psi = \epsilon \sin 2\phi_b. \qquad (2)$$

Local constraints on c_Ψ and s_Ψ have been discussed elsewhere (Kuijken and Tremaine 1991, Kuijken 1992). By way of summary, we present the local results, and predictions for the 'standard' model, in Table 1. They imply

$$s_\Psi = 0.01 \pm 0.04, \qquad c_\Psi = 0.12 \pm 0.04, \qquad (3)$$

i.e. the Sun lies near the minor axis of the equipotentials, which have an axis ratio of 0.88 ± 0.04. This number is sensitive to radial gradients in v_c or ϵ, which are assumed zero in the standard model.

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	Observed	±	Predicted
Oort constant A	$14.4\,\mathrm{km\,s^{-1}kpc^{-1}}$	1.2	$\frac{1}{2}(1 + c_\Psi)v_c/R_0$
Oort constant B	$-12.0\,\mathrm{km\,s^{-1}kpc^{-1}}$	2.9	$-\frac{1}{2}(1 + c_\Psi)v_c/R_0$
Oort constant C	$0.6\,\mathrm{km\,s^{-1}kpc^{-1}}$	1.1	$\frac{1}{2}s_\Psi v_c/R_0$
Oort constant K	$-0.35\,\mathrm{km\,s^{-1}kpc^{-1}}$	0.5	$-\frac{1}{2}s_\Psi v_c/R_0$
Radial LSR motion $\overline{v_R}$	$-1\,\mathrm{km\,s^{-1}}$	9	$s_\Psi v_c$
Azimuthal LSR motion $\overline{v_\phi}$	—	—	$(1 - c_\Psi)v_c$
Vertex deviation	$5.5°$	4.2	$-2s_\Psi$
Velocity ellipsoid σ_ϕ^2/σ_R^2	0.42	0.06	$(1 - 3c_\Psi)(0.66 \pm 0.06)$

Table 1. Local constraints on ellipticity.

For the remainder of this paper, we will set $s_\Psi \equiv 0$ and focus on constraints derived from distant tracers of Galactic rotation. In particular, we will re-interpret published determinations of the Galactic rotation curve (derived with the assumption of axisymmetry) from the viewpoint that the Galaxy may not be axisymmetric.

2. DEEP STELLAR RADIAL VELOCITY SURVEYS

An elliptical distortion affects classical methods for measuring the Galactic rotation curve. In an axisymmetric velocity field, the radial velocity with respect to the local standard of rest of 'tracer' stars at distance D towards Galactic longitude ℓ is given by

$$v_{\mathrm{rad}} = \left[\left(\frac{R_0}{R}\right)v_c(R) - v_c(R_0)\right]\sin\ell, \qquad (4a)$$

$$\text{with } R = \left(R_0^2 + D^2 - 2DR_0\cos\ell\right)^{\frac{1}{2}}. \qquad (4b)$$

In practice, the distance to the Galactic centre R_0 is only known with about 15% precision and the zero point of the distance scale of the tracer stars may be poorly calibrated, so it is best to leave R_0 as a free parameter in fits to $(D, v_{\mathrm{rad}}, \ell)$ data. A fit to $v_c = $ constant models is usually found to be adequate—but remember that with radial velocity data alone it is always possible to add an arbitrary term $v_c \propto R$ to the rotation curve. In the case of a linear rotation curve, constant-v_c fits return the value of $2AR_0$.

We have simulated two recent surveys of distant tracers $(D \lesssim R_0)$: the Cepheid survey of Caldwell & Coulson (1989) and the carbon star data of Schechter et al. (1989; this volume). We assumed that the Galaxy is of 'standard' elliptical form, with the Sun on a symmetry axis. For a range of ellipticities c_Ψ, we simulated radial velocity surveys sampled in a manner similar to these real stellar surveys, and fitted an axisymmetric model of the form of eq. (4) to these data, assuming constant v_c. The results for the two data sets are plotted in Figure 1; crudely, an ellipticity of $c_\Psi = 0.1$ leads to an overestimate of the circular speed of $\sim 25\%$. However, while these surveys are *sensitive* to ellipticity, they are not good *detectors* of it: the rms deviation of the best-fit axisymmetric

Method	v_c	Reference
HI tangent points: $\ell = 30°–90°$	$220\,\mathrm{km\,s^{-1}}$	Gunn *et al.* (1979)
HI tangent points: $\ell = 30°–90°$	$214\,\mathrm{km\,s^{-1}}$	Rohlfs *et al.* (1986)
HI tangent points: $\ell = 53°–90°$	$284\,\mathrm{km\,s^{-1}}$	Rohlfs *et al.* (1986)
HI tangent points: $\ell = 53°–90°$	$260\,\mathrm{km\,s^{-1}}$	Merrifield (1992)
HI scale heights: $R = R_0–2R_0$	$165\,\mathrm{km\,s^{-1}}$	Merrifield (1992)

Table 2. Determinations of v_c from gas kinematics.

model to radial-velocity data drawn from a Galaxy with intrinsic ellipticity as high as 0.2 is less than 2% of the circular speed!

3. ROTATION OF THE HI GAS

The other traditional tracer of large-scale Galactic structure is the neutral hydrogen 21cm line. This is diffuse emission, and so distance determinations are somewhat problematical, and necessarily less direct than they are for stars: somehow the kinematic information must be used to yield both a distance and a rotation curve simultaneously. Two methods have been used with success: the classical tangent-point method (Kwee *et al.* 1954) for the inner Galaxy ($R < R_0$), and the HI scale-height method (Merrifield 1992) outside the solar circle. Table 2 summarizes recent results from such analyses. Once again, we have simulated the effects of ellipticity on these data, and plotted the results in Figure 1. The most striking result is the low value of v_c derived by Merrifield; also, his value is sensitive to ellipticity in the *opposite* sense to the other results. This is a consequence of the radically different kinematic distance determination he uses.

4. ELLIPTICITY?

We have seen that determinations of the rotation curve of the Milky Way outside the solar circle (i) differ significantly, and (ii) are affected in different ways by any ellipticity present. It is therefore natural to ask if there is a value for the ellipticity with which these analyses can be reconciled. The answer is provided in Figure 1, where the determinations of the circular speed discussed above are shown corrected for a range of possible ellipticities. We see that, if the rotation curve is flat and the ellipticity of the potential constant with radius, an ellipticity of 0.08 is able to account for all of the discrepancy. This is the same value as was derived *independently* from the anomaly in the solar neighbourhood kinematics. A least-squares fit for the ellipticity and circular speed from the data shown in Table 1 and Figure 1 (assuming errors of $20\,\mathrm{km\,s^{-1}}$ for the latter) gives

$$v_c = 197 \pm 10\,\mathrm{km\,s^{-1}}, \qquad c_\Psi = 0.080 \pm 0.013, \qquad \chi^2 = 3.6\ (6\ \mathrm{d.o.f.}). \qquad (5)$$

When we relax the assumptions of a flat rotation curve and constant ellipticity, replacing both with power laws ($v_c \propto R^\alpha$ and $\epsilon v_c^2 \propto R^p$), we find

$$v_c = 184^{+19}_{-14}\,\mathrm{km\,s^{-1}}, \qquad c_\Psi = 0.08^{+0.04}_{-0.03}, \qquad \alpha = -0.1^{+0.1}_{-0.1}, \qquad p = 0.1^{+0.3}_{-0.6}, \qquad (6)$$

with $\chi^2 = 2.0$ (4 d.o.f.): the best-fit ellipticity is reasonably constant with
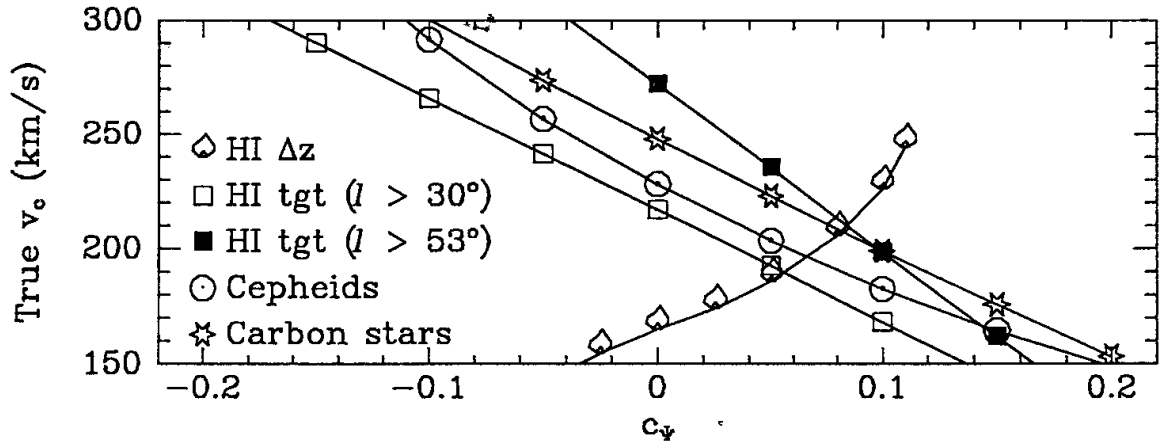
Figure 1. Determinations of the Galactic circular speed, corrected for different possible ellipticities c_Ψ.

radius. The best-fit axisymmetric model has $\chi^2 = 9$, with the best fits requiring, implausibly, that $\alpha \simeq -0.45$, much steeper than in other galaxies.

5. SUMMARY

We have shown that discrepancies between different measurements of the Galactic rotation curve outside the solar circle can be understood as the effect of an elliptical distortion in the gravitational potential. The same distortion also explains a different anomaly, namely the low value of the axis ratio of the velocity ellipsoid in the solar neighbourhood.

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