

## Observational Evidence for a Bar in the Milky Way

Konrad Kuijken

*Kapteyn Institute, PO Box 800, 9700 AV Groningen, Netherlands*

**Abstract.** Evidence from a variety of sources points towards the existence of a bar in the central few kpc of the Galaxy. The measurements roughly agree on the direction of the bar major axis, but other parameters (axis ratio, size, pattern speed) are still poorly determined. Current dynamical models are limited by the quality of hydro simulations, the degeneracy of stellar orbit models, stellar-kinematic data and the significant lopsidedness of the central kpc. Microlensing promises new constraints on the mass distribution in the bulge/bar region.

### 1. Introduction

Our vantage point inside the Milky Way disk offers us the possibility of a unique insight into the structure of at least our galaxy; however this same location causes many unique problems. It is undoubtedly useful to compare the Milky Way with other, more distant spiral galaxies, but this rarely happens on an equal footing: sometimes the Milky Way serves as a local well-understood calibrator for the external galaxies, other times it is the other galaxies which provide inspiration and guidance necessary for us to be able to interpret the observations of our own Galaxy. Though the study of the dynamics of the inner regions of the Milky Way may be said to be still in the 'borrowing from other galaxies' phase, the many data being gathered make it likely that eventually we will be able to 'give' as well.

This review covers the mounting evidence that the center of the Galaxy harbors a bar with a size of a few kpc. Early evidence for a bar (§2) was championed mostly by de Vaucouleurs, but received little following until interest was rekindled about five years ago by results from near-infrared surveys. Since then, many detections of a barred distortion, broadly consistent with each other (at least as regards direction of the bar major axis) have appeared. They fall into two broad categories, those based on photometric data (surface photometry and star counts, §3) and those based on kinematics of stars and gas (§4). More recently, the gravitational microlensing searches in the direction of the Galaxy bulge have turned up many more events than had been originally expected based on a simple axisymmetric model for the Milky Way. A bar may significantly enhance these expected rates, and may well be required to explain the microlensing data (§5). This review ends with a wish list of some observations which might help constrain the bar parameters in the future (§6).

Table 1. Properties of the Galaxy with a bearing on its Hubble type, according to de Vaucouleurs (1970). Each property/morphological type pair at stage Sbc is assigned a score of +1 (good agreement), 0 (indifferent), or -1 (conflict).

Criterion	(a)	(b)	(c)	(d)	(e)	(f)	Sum
A(s)	-	-	-	-		-	-5
AB(s)	-	-	-	-	+	-	-4
B(s)	-	-	-			-	-4
B(rs)		+	+			+	+3
B(r)		+		+			+2
AB(r)	+	+					+2
A(r)				-		-	-2
A(rs)			+	-	+	-	0
AB(rs)	+	+	+			+	+4

<sup>a</sup>High spiral arm multiplicity

<sup>b</sup>Inner ring diameter of 6 kpc

<sup>c</sup>Broken ring structure

<sup>d</sup>Radio structure of the nucleus

<sup>e</sup>Yerkes spectral type

<sup>f</sup>Non-circular HI motions

## 2. Early Evidence

De Vaucouleurs (1964, 1970) early on suggested that the Milky Way was in fact a barred spiral. His argument relied on comparing many morphological features of the Milky Way with other spirals of different revised Hubble types, the crucial step in this analysis being to associate the HI feature known as the 3-kpc arm (also interpreted in terms of a bar by Kerr 1967) as part of a broken HI ring. For a list of properties, he gave each of the subtypes (r, rs, s) and (A, AB, B) a score reflecting their goodness of fit for the Milky Way, and obtained an overall score by a simple unweighted sum (see Table 1). The best fit was the completely mixed type SAB(rs)bc: a galaxy with fairly weak rings and a bar with not-quite grand design spiral structure. It is interesting, and reassuring, that this conclusion does not appear to be dominated by a single column in Table 1 (though three of the six diagnostics pertain to the 3-kpc expanding arm). There thus appeared to be a good case for taking this suggestion seriously.

However, much of the effort in understanding Galactic structure in subsequent years was focused on the problem of maintaining spiral density waves, and the idea that the Milky Way had a bar fell out of fashion. Only in the last five years has it returned into favor.

## 3. Photometric Evidence

Because the Galaxy is virtually edge-on, we cannot see a bar directly. However, unless the bar happens to be aligned along or perpendicular to the sun-Galactic

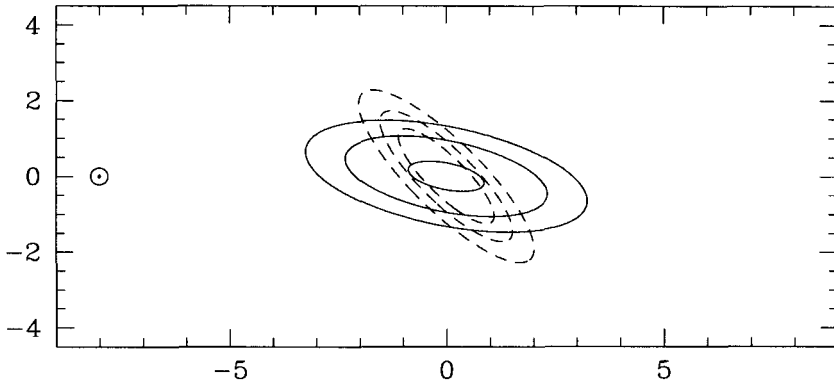


Figure 1. The bar models 'G2' (solid lines) and 'E3' (dashed) of Dwek et al. (1995) projected onto the Galactic plane. Contours are spaced at factors of 3 in mid-plane density; the outermost contour corresponds to  $3 \times 10^6 L_{\odot}/\text{kpc}^{-3}$ . The position of the sun ( $R_0 = 8\text{kpc}$ ) is indicated, and galactic longitude increases counterclockwise from the right.

center line, a bar will create systematic differences between points at equal and opposite longitudes: if the major axis of the bar lies in the first quadrant, for instance, (longitude  $0 < \ell < 90^\circ$ ) then objects in that quadrant will on average be closer to the sun than those in the fourth quadrant. Such effects can show up both in surface brightness and in star counts.

### 3.1. Surface Photometry

Blitz & Spergel (1991), in their search for non-axisymmetric structure in the Milky Way, analyzed the near-IR data of Matsumoto et al. (1982) and showed that there were indeed systematic differences between positive and negative longitudes near the Galactic center. They showed that these could be understood as a perspective view of a bar: the near side (in the first quadrant) would appear more vertically extended on the sky than the far side, and the surface brightness of the near side should be greater, both as observed. Furthermore, in the innermost regions the asymmetry in surface brightness is actually reversed, and this feature too is reproduced in the data.

Superior data from the DIRBE experiment on the COBE satellite have confirmed and sharpened this result. After dereddening the near-IR data, Dwek et al. (1995) derive a best-fit model 'G2' for the emissivity of the bar of the form

$$\rho(x, y, z) \propto e^{-s^2/2} \quad (1)$$

where (assuming the sun is 8kpc from the Galactic center)

$$s^4 = \left[ \left( \frac{x}{1490\text{pc}} \right)^2 + \left( \frac{y}{580\text{pc}} \right)^2 \right]^2 + \left( \frac{z}{400\text{pc}} \right)^4 \quad (2)$$

and  $(x, y, z)$  are Galactic coordinates rotated by  $13^\circ 4'$  about the Galactic minor ( $z$ -) axis. This functional form implies an ellipsoidal shape for the bar projected onto the galactic plane, but makes boxy bulge isophotes as seen from earth, as observed. (To some at this conference, the boxy isophotes are already strong evidence for a bar!). The axis ratios are 2.6:1:0.7. There are still uncertainties in this deprojection, which was derived as a least-square fit to a fairly restricted set of models—it will be hard to do better given the usual problems associated with recovering a three-dimensional emissivity from a two-dimensional surface brightness map. For instance, model 'E3', a triaxial version of Kent's (1992) modified Bessel function model fits almost as well as G2, but with major axis position angle  $40^\circ$  (this model does have the unsatisfactory feature that the  $z:y$  axis ratio is greater than 1). Further uncertainty arises from the correction for the disk contribution to the surface brightness. A sketch of both bar models is shown in Figure 1.

### 3.2. Star Counts

Counts of individual objects also reveal left-right asymmetries of the Galactic center region. All such data sets show an effect in the same direction: objects at positive longitudes appear brighter and therefore are presumably closer. These data sets include SiO masers (Nakada et al. 1991, Izumiura et al. 1994), IRAS AGB stars (Weinberg 1992), IRAS Miras (Whitelock & Catchpole 1992), the OGLE red clump stars (Stanek et al. 1994), and OH/IR stars (Sevenster, these proceedings). Furthermore, the globular clusters also appear to show a bar-like distortion (Blitz 1993). Typical magnitude offsets are 0.2–0.5, the best-measured one being that of the OGLE group ( $0.37 \pm 0.03$ ). For comparison, the Dwek et al. (1995) G2 model would allow at most a 0.2 magnitude offset between brightness of objects at positive and negative longitudes within  $6^\circ$  of the galactic center (Figure 2).

While all these studies agree on the sign of the asymmetry, the agreement mostly ends there: the magnitude offset between positive and negative  $\ell$  varies considerably from survey to survey (though part of the effect may be due to small number statistics in some of these data sets, and different depths of the different samples). Also, the results of the bulge surface photometry imply a very much smaller bar than the IRAS AGB counts of Weinberg: the former extends out to longitudes of about  $10^\circ$ , and the latter out to about  $40^\circ$ . It is therefore quite possible that the Milky Way in fact contains *several* bars.

It is interesting to note that, had we not known about bars in other galaxies, we might not have chosen to interpret these left-right asymmetries in such terms. On the sky, the asymmetries suggest a lop-sided ( $m = 1$ ) distortion instead, and it might have seemed far-fetched to attribute these to perspective effects of an inherently  $m = 2$  bar.

### 4. Kinematic Evidence

Bars also show up as kinematic distortions of the velocity fields of stars and gas, since the closed orbits in a pattern-rotating barred potential are no longer circular, but rather elongated along or perpendicular to the bar. Resonances (chiefly inner and outer Lindblad and corotation) affect the orbit structure profoundly.

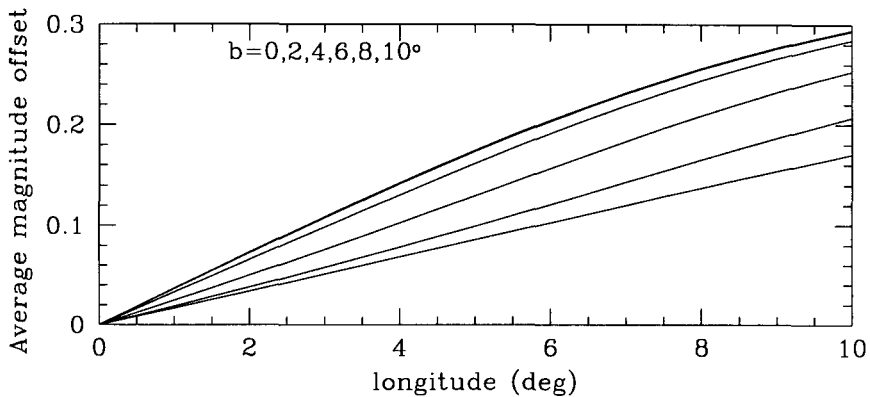


Figure 2. The average magnitude offset between objects at galactic coordinates  $(\ell, b)$  and  $(-\ell, b)$  in the Dwek et al. (1995) bar model. Different curves correspond to different latitudes: (top to bottom)  $b = 0, 2, 4, 6, 8, 10^\circ$ .

Some closed orbits are self- or mutually intersecting, making them unsuitable as gas orbits and consequently generating gaps and shocks in the gas distribution (see the review by Athanassoula, these proceedings), and the distribution of stellar orbits follows similar behavior. Unlike photometric signatures (except perspective effects discussed above), these kinematic effects of a bar are also visible in edge-on systems, and so provide a means of detecting bars in such galaxies.

Both the kinematics of gas and stars could reveal evidence for a bar in the Milky Way, but each have their problems when it comes to quantifying bar parameters. Gas, because it tends to dissipate down to the closed, non-intersecting orbits, delineates the orbit structure and hence the potential most clearly, but the most striking features are associated with the resonances where hydro-dynamic effects are a major factor. It is still very difficult to model all the relevant processes at these locations well. Stellar orbits, on the other hand, are dominated by gravitational forces, but because of the absence of dissipation the accessible orbits are much more varied. It is still an unsolved problem to derive the gravitational potential from observed radial velocity distributions in stationary elliptical galaxies, and the barred galaxy problem, which also involves unknown figure rotation, is even more complicated. Therefore, though it is possible to rule out axisymmetric models on the basis of kinematic data, producing a unique bar model is a considerably harder problem.

#### 4.1. Gas Kinematics

The distribution of gas within  $5^\circ$  of the Galactic center is complicated. Significant features for our purposes are:

- Large forbidden CO and HI velocities
- A fast outwards decline in HI tangent point velocities

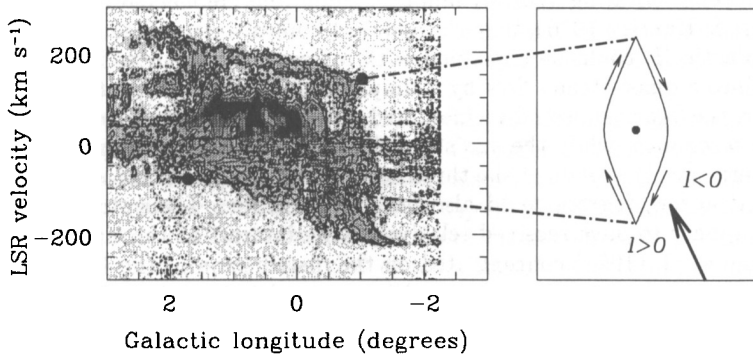


Figure 3. Left: the distribution of CO emission in longitude and radial velocity, from the Bell Labs. survey. Emission at  $b = -3'$  is shown. Contours are drawn at brightness temperatures of 1, 2, 4, 8, and 16 K. Note the parallelogram-shaped envelope of the emission. Right: a model for the parallelogram, from Binney et al. (1991). The cusped orbit is viewed from the direction of the thick arrow, and gas streams around the orbit as indicated.

- A *very* lopsided CO distribution
- A dramatic change in the CO kinematics near longitudes  $+1.7$  and  $-1^\circ$ .
- A tilted (by  $\sim 7^\circ$  projected onto the sky) HI (and maybe CO) plane.

The CO velocity structure, from the Bell Labs survey (Bally et al. 1987, 1988) is shown in Figure 3.

The forbidden velocities (negative velocities in the first quadrant, positive ones in the fourth) imply non-axisymmetry, assuming the gas to be a dynamically cold tracer of the potential. However, per se they say little about the nature of this deviation from circularity: in particular, local expanding features in the gas may cause features similar to those observed (e.g. Oort 1977, Uchida et al. 1994).

So far, no coherent *dynamical* model has been formulated which addresses all observed features (but see Weinberg's paper in these proceedings). However, several analyses have focused on subsets of these observations. All these investigations have centered on single-bar models, though reality may well be more complex.

Liszt & Burton (1980) have modelled the kinematics of the HI in the central few kpc as a tilted, elliptically streaming disk (an earlier fit as an expanding disk was equally successful, if less plausible). Their model successfully fits the observed distribution of HI in position on the sky and radial velocity, though it offers no dynamical origin for this disk. If the ellipticity is caused by a bar, then the least satisfactory aspect of this model is the absence of pattern rotation. It seems plausible, though, that a pattern speed could fairly simply be accommodated in such a kinematic model.

Mulder & Liem (1986) attempted to construct a global model for the HI. Using non-selfgravitating hydrodynamical simulations (pioneered in this context by Sanders & Huntley 1976), they showed that a multitude of kinematic features in the Galactic HI could be explained with a simple model in which a gas disk is forced into a quasi-steady flow by a simple model for a weak, rotating bar. In particular, the 3kpc arm could be identified with shocked material near the inner Lindblad resonance, while the sun's position near corotation (implying quite a slow pattern speed) explained the three nearby spiral arms. Forbidden velocities in the central few degrees could also be accounted for. Their striking results, however, appear to have received relatively little interest at the time.

Binney et al. (1991) concentrated on the distribution of the CO and other molecular gas at  $b = 0$  (Figure 3), and interpreted it in terms of a dynamical model in which the gas is allowed to move on closed, non-intersecting orbits only. No attempt was made to address the tilt of the inner plane. They identify the striking parallelogram shape of the orbit with the smallest orbit outside the inner Lindblad resonance which does not intersect itself—gas further in will strongly dissipate kinetic energy and end up inside the ILR on an ' $x_2$  disk'. The parallelogram orbit is cusped, and seen from a fairly narrow range of angles, its projection into the longitude-velocity plane takes on the observed shape. Because this orbit is strongly affected by the resonances, the pattern speed of the Binney et al. model is very well constrained, with corotation around  $2.4 \pm 0.5$  kpc. Furthermore, the parallelogram projection of the orbit only appears from viewing angles of the bar about  $16^\circ$  off end-on. The distribution of HI at larger radii is consistent with the closed orbits outside corotation, as is the radial dependence of the model bar density with that of the observed bulge light.

In spite of these successes, a worrying aspect of this model is the left-right asymmetry of the parallelogram. The data show such an effect in the sense expected from perspective, but it is much more pronounced than expected from the model. Rigorous modelling of the observed asymmetry (the cusps of the orbit appear at longitudes  $\sim +1.7^\circ$  and  $-1^\circ$ ) implies that the cusps of the parallelogram orbit lie at radius  $\sim R_0/5 \simeq 1.6$  kpc. An orbit of this size would have to be aligned within  $6^\circ$  of the line of sight, and would have to be very slender if we were indeed viewing it down its sides. A more plausible, if perhaps less elegant, explanation invokes some lopsidedness to the central kinematics, which spoils the perspective of the bar orbit. Such a component may be needed anyway to explain the rather large velocity difference of the gas deduced to lie near the cusps: this gas should have zero velocity in the bar frame.

The dynamics of the tilt of the inner gas are a puzzle. It may have consequences for the bar analysis: when Liszt & Burton (1980) restrict their model to the Galactic plane (rather than the tilted inner disk plane), velocity crowding of the gas mimicks the observed distribution of CO very nicely. It therefore appears that the identification of the parallelogram with a specific CO orbit is not unique, and a more detailed consideration of the CO distribution out of the galactic plane is required. (Initial suggestions by Blitz & Spergel (1991) that the stellar emission is tilted in the same direction as the gas were shown by the COBE data to have been an artifact of extinction. The stellar distribution is consistent with being aligned with the Galactic plane).

Weiner & Sellwood (1995) have concentrated on fitting the kinematics of the HI, particularly the sharp falloff of the tangent point velocity, outside longitudes

4°. They use a hydrodynamic code to model the steady-state behavior of the gas. Their results appear inconsistent with the findings of Binney et al.: they find that only bars seen over 30° off end-on can generate forbidden velocities over a sufficiently large longitude range. Their best-fit model also has a significantly larger corotation radius of 3.6kpc.

The differences between the various analyses of the gas kinematics partly reflect differences between the kinematics of the different tracers, possibly due to nongravitational effects, but to some extent also is an indication of the collisionality of the interstellar medium: it remains a gross simplification to model gas as perfect tracers of the closed non-intersecting orbits in a smooth, pattern-rotating potential. For instance, the lop-sided distribution of the central gas distribution is possibly a transient feature (e.g., a fluctuation associated with the relatively small number of large clumps in the central few 100pc, or the result of a dynamical instability or interaction) whose amplitude raises concerns about fitting equilibrium bisymmetric models to the dynamics. An investigation by Jenkins & Binney (1994) shows that stochastic processes in the gas distribution will indeed cause lopsidedness, but they have difficulty reproducing effects as dramatic as those observed. Quite possibly, self-gravity or low-temperature cooling (neither of which is included in their calculations) can make a substantial difference here.

Future refinements of the analyses of the observed gas dynamics may well be inspired on observations of the CO distributions in other barred galaxies (see reviews by Turner and by Kenney, these proceedings), which may establish when molecular gas does and does not trace the closed orbits allowed by the potential.

#### 4.2. Stellar Kinematics

Given the possible problems with the dynamics of the gas, to what extent can stellar dynamics help?

At the moment, the answer is, unfortunately, not very much. The large velocity dispersions in the bulge region wash out signatures of non-axisymmetry, which only large numbers of stars sampled at a range of longitude or integrated-light velocity distributions (see Kuijken & Merrifield 1995 or Merrifield, these proceedings) can overcome.

Apart from the difficulty of getting sufficiently detailed observations, there is also a theoretical bottleneck: we do not know what the velocity distributions in realistic galactic bars actually look like, because there are large families of possible combinations of stellar orbits which can be combined to make the same bar. Whereas gas modelling can be simplified by considering closed orbits, this constraint is not available in the case of stars. Ideally, it should be replaced by a further observational phase-space measurement: distance down the line of sight and/or proper motions. In any case, just about the simplest axisymmetric model that can be constructed for the bulge, an oblate isotropic rotator, appears to fit all available stellar-kinematic data (Kent 1992), including recently published M giant samples (Blum et al. 1995). This good fit is not evidence against a bar, but rather an illustration of the difficulty of detecting a bar in the stellar kinematics of the bulge. The strongest feature in radial velocity data that argues in favor of a bar is the bimodality of the OH/IR stars: in addition to a hot 'bulge' population, the central degree or so contains quite a cold stellar disk, whose kinematics are similar to those of the inner CO gas (Lindqvist et al. 1992). It



is possible that these stars were formed from the gas that lives inside the inner Lindblad resonance (an ' $x_2$  disk').

The most detailed model constructed for the Milky Way's stellar bar is that of Zhao (these proceedings). Analysis of the Spaenhauer et al. (1992) sample of stars with proper motion in Baade's Window (Zhao, Spergel & Rich 1994) shows possible signatures of triaxiality (vertex deviations of metal-weak and metal-poor stars incompatible with axisymmetry), but since the sample is small the statistical weight of this study is rather low. Similar analyses of larger samples in different parts of the bulge currently offer the best hope of understanding the bar dynamics from stellar kinematics.

Long-range perturbations of the stellar kinematics by the quadrupole field of a bar may also be detectable. Perturbation formulae for the stellar velocity field, as well as the velocity dispersions, in a barred, pattern-rotating potential, have been derived by Kuijken & Tremaine (1991). Weinberg (1994) has shown that the resonances of a bar with a decreasing pattern speed will trace out a characteristic signature across a disk, and he finds some evidence in the kinematics of old K giants for such a feature.

### 4.3. The Pattern Speed from Stellar Kinematics

A particularly important product of stellar kinematics might be the measurement of the pattern speed  $\Omega_p$  of the bar. Such measurements can be made in model-dependent ways by identifying certain morphological features (typically of the gas) with resonances, or less so via an integral constraint derived from the continuity equation (Tremaine & Weinberg 1984, TW). The TW method involves integration along a given line of the velocity component perpendicular to it. It was originally formulated for application to moderately inclined external barred galaxies, in which case it requires measurement of mean radial velocity along a line parallel to the major axis. In that form it is inapplicable to edge-on galaxies such as our own, but two modifications are: the first involves integration of heliocentric radial velocities around the galactic equator (Kuijken & Tremaine 1991) and the second integration of transverse velocities down a single line of sight near the Galactic center. Neither variant is currently practical, however: the second requires accurate distances and proper motions at  $b = 0$ , whereas the first would rely on full longitude coverage in the densest parts of the galactic plane, with complete radial velocity coverage. Nevertheless, future large near-infrared surveys may one day allow these measurements to be made.

## 5. Gravitational Microlensing Evidence

Microlensing of stars by foreground objects which pass at very small projected impact parameters has recently developed from an elegant curiosity to a new tool in galactic structure research. As shown by Refsdal (1964), if a foreground object of mass  $m$  at distance  $x$  from us passes within a radius

$$R_E(x) = 2\sqrt{Gmx(1-x/L)/c} \propto m^{1/2} \quad (3)$$

from the line of sight to a source at distance  $L > x$ , the source will be magnified ('microlensed') by a factor  $> 1.34$ . Since in general the lens will move with

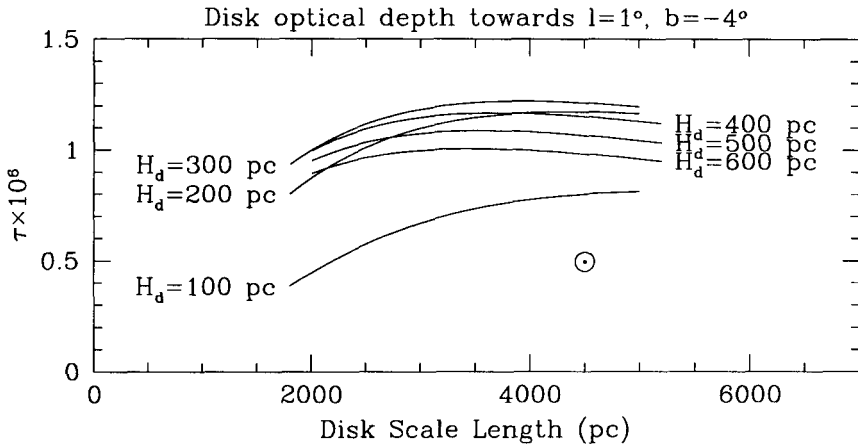


Figure 4. The optical depth of bulge stars to microlensing by a double exponential disk  $\rho \propto \exp(-R/a - z/H_d)$ , constrained to produce a maximum rotation speed below 180km/s. The sun symbol shows the optical depth due to a less than maximal disk, consistent with the measurements of Kuijken & Gilmore (1991).

respect to the line of sight, the brightening will only last for a certain time, typically of the order of 1-100 days (depending on the lens mass). The average number of lenses in the ‘microlensing tube’  $R(x) < R_E(x)$  is called the optical depth  $\tau$ , and depends on the number density  $\nu$  of lenses along the line of sight:

$$\tau = \int_0^L \nu(x) \pi R_E(x)^2 dx \propto m^0 \bar{\rho} \tag{4}$$

where  $\bar{\rho}$  is a mean mass density in lenses.  $\tau$  therefore depends only on the mass density in lenses, not on the masses of individual lenses (but the detectability does depend on  $m$  via the timescale of typical events).

Whereas the detection rate for microlensing towards the Magellanic clouds may be disappointingly low (Alcock et al. 1995a), the ‘control experiments’ towards the Galactic bulge have surprisingly turned up many more events than had initially been expected: the optical depth to the average bulge star is about  $3 \times 10^{-6}$  (Udalski et al. 1994, Alcock et al. 1995b). Along the line of sight towards Baade’s Window, a double exponential disk can produce at most  $\tau_D < 1.2 \times 10^{-6}$ , with a more likely number being less than half that (Figure 4).

The early calculations were based on axysymmetric models, and on the assumption that the bulge stars were only lensed by foreground disk and halo objects. It was later realized (Kiraga & Paczynski 1994) that bulge stars are so common that lensing of a far-side bulge star by one on the near side contributes a significant signal ( $\tau_B \sim 0.7 \times 10^{-6}$  if one uses the Kent model for the bulge). This signal is enhanced further if the bulge is extended along our line of sight, for then the near-side stars are in a fatter part of the microlensing tubes for lensing of the far-side bulge stars. The effect can be as much as a factor of two if

the bulge has the axis ratio of the Dwek et al. (1995) model, raising the optical depth to bulge sources to around  $1.2 \times 10^{-6}$ . The numbers are still a little low, and larger numbers of microlensing events will have to be analyzed before it is clear whether there still is a problem or not.

Further constraints on bulge-bulge lensing can be derived by searching for a systematic offset between the (unmagnified) brightnesses of lensed stars with the general population. If far-side bulge sources are systematically lensed more often than near-side ones, the lensed sources should be systematically fainter. The magnitude of the offset can be used to constrain the axis ratio and orientation of the bar (Stanek 1995, and these proceedings).

## 6. Conclusions and Wishlist of Further Observations

It is clear that a variety of lines of evidence point towards the existence of non-axisymmetric structure in the central few kpc of the Milky Way. Equally impressive is the lack of evidence to the contrary! While the precise details have not yet been characterized, rapid progress is being made, partly driven by the need to understand the new microlensing data. Major stumbling blocks at the moment are the difficulty of realistically simulating hydrodynamical processes.

In conclusion, it seems useful to compile a list of observations which may help pin down the nature and parameters of the bar. These include:

- *To see the bar in stellar kinematics.* Proper motions of samples of stars throughout the bulge will greatly help define the orbit structure, and hence the gravitational potential and pattern speed of the bar.
- *An optical depth map of the bulge region.* As shown by Kiraga (1994), such a map provides an entirely separate constraint on the mass distribution in the central regions.
- *evolutionary history of the bulge as traced by stellar abundances and their ratios.* Such data can be used to constrain the star formation history of the bulge/bar, and combination with kinematic data ultimately will allow the evolutionary relation between the bar, bulge (if indeed they are separate) and disk to be addressed.
- *Self-gravitating hydrodynamic simulations of gas flow in barred potentials* will help address issues related to central lopsidedness, stability and possible tilts.

## References

- Alcock, C. et al. 1995a, preprint astro-ph/9506113  
 Alcock, C. et al. 1995b, ApJ, 445, 133  
 Bally, J., Stark, A. A., Wilson, R. W., & Henkel, C. 1987, ApJS, 65, 13  
 Bally, J., Stark, A. A., Wilson, R. W., & Henkel, C. 1988, ApJ, 324, 223  
 Binney, J., Gerhard, O. E., Stark, A. A., Bally, J., & Uchida, K. I. 1991, MNRAS, 252, 210  
 Blitz, L. 1993, in Back to the Galaxy, S. S. Holt & F. Verter, New York: AIP, 98

- Blitz, L. & Spergel, D. N. 1991, *ApJ*, 379, 631
- Blum, R. D., Carr, J. S., Sellgren, K., & Terndrup, D. M. 1995, *ApJ*449, 623
- de Vaucouleurs, G. 1964, in *The Galaxy and The Magellanic Clouds*, F. J. Kerr & A. W. Rodgers, Sydney: Aust. Acad. Sci., 88
- de Vaucouleurs, G. 1970, in *The Spiral Structure of Our Galaxy*, W. Becker & G. Contopoulos, Dordrecht: Reidel, 18
- Dwek, E. et al. 1995, *ApJ*, 445, 716
- Izumiura, H. et al. 1994, *ApJ*, 437, 419
- Jenkins, A. & Binney, J. 1994, *MNRAS*, 270, 703
- Kent, S. M. 1992, *ApJ*, 387, 181
- Kerr, F. J. 1967, in *IAU 31*, H. van Woerden, 239
- Kiraga, M. 1994, *Acta Astron.*, 44, 241
- Kiraga, M. & Paczynski, B. 1994, *ApJ*, 430, L101
- Kuijken, K. & Gilmore, G. 1991, *ApJ*, 367, L9
- Kuijken, K. & Merrifield, M. R. 1995, *ApJ*, 443, L13
- Kuijken, K. & Tremaine, S. D. 1991, in *Dynamics of Disk Galaxies*, B. Sundelius, Göteborg: Göteborg Univ. Press, 71
- Lindqvist, M., Winnberg, A., Habing, H. J., & Matthews, H. E. 1992, *A&AS*, 92, 43
- Liszt, H. S. & Burton, W. B. 1980, *ApJ*, 236, 779
- Matsumoto, T. et al. 1982, in *The Galactic Center*, G. Riegler & R. Blandford, New York: AIP, 48
- Mulder, W. A. & Liem, B. T. 1986, *A&A*, 157, 148
- Nakada Y., Deguchi, S., Hashimoto, O., Izumiura, H., Onaka, T., Sekiguchi, K., & Yamamura, I. 1991, *Nature*, 353, 140
- Oort, J. H. 1977, *ARA&A*, 15, 295
- Refsdal, S. 1964, *MNRAS*, 128, 295
- Sanders, R. H. & Huntley, J. M. 1976, *ApJ*, 209, 53
- Spaenhauer, A., Jones, B. F., & Whitford, A. E. 1992, *AJ*, 103, 297
- Stanek, K. 1995, *ApJ*, 441, L29
- Stanek, K. Z., Mateo, M., Udalski, A., Szymanski, M., Kaluzny, J., & Kubiak, M. 1994, *ApJ*, 429, L73
- Tremaine, S. D. & Weinberg, M. D. 1984, *ApJ*, 282, L5
- Uchida, K. I., Morris, M. R., Serabyn, E., & Bally, J. 1994, *ApJ*, 421, 505
- Udalski, A. et al. 1994, *Acta Astron.*, 44, 165
- Weinberg, M. D. 1992, *ApJ*, 384, 81
- Weinberg, M. D. 1994, *ApJ*, 420, 597
- Weiner, B. J. & Sellwood, J. A. 1995, in *Unsolved Problems of the Milky Way*, L. Blitz, in press
- Whitelock, P. & Catchpole, R. 1992, in *The Center, Bulge and Disk of the Milky Way*, L. Blitz, Dordrecht: Kluwer, 103.
- Zhao, H., Spergel, D. N., & Rich, R. M. 1994, *AJ*, 108, 2154