# Chapter 2

# Is the Milky Way a Barred Spiral Galaxy?

# MORPHOLOGY OF THE GALACTIC BULGE FROM COBE DIRBE OBSERVATIONS

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## 1. Introduction

The Diffuse Infrared Background Experiment (DIRBE) on-board the Cosmic Background Explorer (*COBE*) satellite has provided striking new images of the Galactic bulge at effective wavelengths of 1.25, 2.2, 3.5, and $4.9\mu$ (Hauser 1993, plate 3; Arendt et al. 1994; Weiland et al. 1994). The bulge, defined here as the spheroid within the $|l| < 20°$ and $|b| < 10°$ region around the Galactic center, and its stellar content have been subjects of considerable interest since they contain important clues about the dynamical and star-formation history of our Galaxy. The morphology of the Galactic bulge is much harder to ascertain than that of bulges in many external galaxies, because of our location in the Galactic plane amid the obscuration by interstellar dust. In spite of this difficulty, there has recently been an accumulating body of evidence that the stellar distribution in the bulge is bar shaped, i.e. that the bulge is not rotationally symmetric in the plane of the disk (see Blitz 1993 for a review of the subject). The existence of a bar in our Galaxy would have important implications for the dynamics of the Galaxy. A bar would provide a mechanism for sweeping gas from the disk into the Galactic center "feeding" a central black hole (e.g. Shlosman, Frank, & Begelman 1989). It would also provide a mechanism for generating spiral arms, and a basis for estimating the mass of the halo relative to that of the disk (e.g. Combes & Sanders 1981 and references therein).

The evidence for a bar at the Galactic center is drawn from: (1) stellar and gas dynamics in the Galactic center region (Liszt & Burton 1980; Bahcall, Schmidt, & Soneira 1982; Vietri 1986; Binney et al. 1991; de Zeeuw 1992; Binney & Gerhard 1993); (2) asymmetries in the photometric image of the bulge (Blitz & Spergel 1991, based on the $2.4\mu$ image obtained by

*L. Blitz and P. Teuben (eds.), Unsolved Problems of the Milky Way*, 61–69.

Matsumoto et al. 1982; and Weiland et al. 1994, from DIRBE images at 1.25, 2.2, 3.5, and 4.9$\mu$); (3) the analysis of stellar tracers of the large-scale Galactic structure (Habing et al. 1985; Rowan-Robinson & Chester 1987; Blanco 1988; Nakada et al. 1991; Whitelock & Catchpole 1992; Weinberg 1992a,b); (4) the excess of gravitational microlensing events in the direction of the Galactic bulge over earlier theoretical expectations (Paczynski et al. 1994); (5) the presence of a hotspot off-center from the Galactic center in the 1.8 MeV COMPTEL sky map (Chen, Gehrels, & Diehl 1994); and (6) the asymmetric distribution of bulge red clump stars detected by the OGLE (Stanek et al. 1994). However, the exact morphology of the bar, its orientation with respect to the disk are still issues that need to be resolved.

## 2. DIRBE Observations

The DIRBE images of the Galactic center region provide a new, and much improved data base, in terms of spatial and simultaneous wavelength coverage, and in sensitivity, for studying the bulge. After the subtraction of radiation scattered and emitted by interplanetary dust and emission from the galactic disk, and including a correction for interstellar extinction, the DIRBE data show a longitudinal asymmetry in the intensity maps of the bulge, and a flattening of the light distribution in the north and south polar regions of the bulge, giving it a "boxy" appearance (see Weiland et al. 1994 for a detailed description of the unveiling of the bulge morphology).

The 1.25, 2.2, 3.5, and 4.9$\mu$ data used in this investigation are a specially processed subset of the DIRBE data consisting of DIRBE weekly-averaged maps, selected at 2 week intervals over a 6 month period to achieve complete sky coverage. (Weiland et al. 1994). The calibration applied is preliminary, and the same as that used in the publicly-released DIRBE Galactic Plane Maps. To prepare the data for comparison with bulge models, we: (1) subtracted a simple empirical model describing the intensity of the interplanetary dust emission and scattering component; (2) created extinction corrected maps for $|l| > 3°$ at 1.25, 2.2, and 3.5$\mu$, and for $|l| > 2°$ at 4.9$\mu$; and removed the emission of the Galactic disk. Details of these procedures, and a discussion on the related uncertainties can be found in Dwek et al. (1994).

## 3. Bar Models and Their Characteristics

### 3.1. MATHEMATICAL CHARACTERIZATION OF THE BULGE

The calculated intensity of light from the bulge region in a given direction is given by an integral of the volume emissivity of the sources along the line of sight. We assumed that the volume emissivity can be described by an analytical function subjected to three consecutive rotations: the first, a counterclockwise rotation by an angle $\alpha$ around the z-axis, giving rise to a longitudinal asymmetry in the projected intensity; the second, a clockwise rotation by an angle $\beta$ around the new y-axis, tilting the source distribution out of the Galactic plane and giving rise to both longitudinal and latitudinal asymmetries in the projected intesity; and the third, a roll, defined here as a counterclockwise rotation of the bar by angle $\gamma$ around the new x-axis. Such a rotation is degenerate for prolate spheroids, but will change the projected intensities for triaxial systems.

### 3.2. AN OBLATE SPHEROID MODEL

Before resorting to triaxial models, we examined to what extent the bulge can be approximated by an axisymmetric distribution of sources such as an oblate spheroid. Such a simple model will provide a first order estimate of the minor-to-major axis ratio of the system. The latter quantity is of great interest, since it contains clues to the dynamical history of the formation of the bulge (Statler 1987; Combes & Sanders 1981; Combes et al. 1990; Raha et al. 1991; Sellwood 1993). We therefore adopted an axisymmetric Gaussian-type function to describe the source density distribution in the bulge, and calculated the apparent intensity of this density distribution as seen by an observer located at a distance D from the Galactic center. The results showed that in spite of the relatively good agreement between this model and the data, it fails to account for the observed longitudinal asymmetry of the bulge. The asymmetry is apparent in the DIRBE data (Weiland et al. 1994; Figure 3a in Dwek et al. 1994), which shows the systematic deviations of the data from the longitudinal symmetric model at positive Galactic longitudes. This led us to examine various triaxial models for the bulge.

### 3.3. TRIAXIAL BULGE MODELS

We have selected from the literature several functional forms, previously chosen to fit the observed surface brightness profile of the Galactic bulge or bulges in external galaxies, to characterize the source distribution of the Galactic bulge. Some functions have been used to describe an axisymmetric source distribution, and their radial coordinate was modified to allow for a triaxial bulge morphology. The various functions considered for the density distribution of bulge sources fall into three categories which characterize their general behavior: Gaussian-type functions (G), exponential-type functions (E), and power-law type functions (P). For a list of the various functional forms and their equations see Dwek et al. (1994).

In these functional forms, the bulge is characterized by its axes x0, y0, and z0; by its normalization constant $\rho0$; and by its orientation, which is characterized by three rotation angles described before: the in-plane rotation, out-of-plane tilt, and out-of-plane roll. We determined the best fitting model by a search for the minimum reduced chi-square in the multidimensional space spanned by these parameters. The results of the modeling efforts are discussed below.

## 4. The Resulting Bulge Morphology

### 4.1. GENERAL RESULTS

Table 1 in Dwek et al. (1994) presents the parameters and their $1\sigma$ statistical uncertainties of the best fitting models for the $2.2\mu$ intensity with no roll, for the various triaxial functional forms discussed above (see also Figure 1). Not surprisingly, considering the flattened appearance of the bulge, the best fitting models have intrinsically a "boxy" geometry which flattens the shape of the bulge both in the z direction and in the Galactic plane. Models which have "exponential" radial density distributions generally fit as well as the Gaussian functions, with the exception of model E1 used by Blitz & Spergel (1991) which was somewhat worse. The "power law" functions generally fit relatively poorly, since they have difficulty in fitting the outer portions of the bulge.

### 4.2. BULGE AXIS RATIOS

The scale lengths and densities have different meanings for the different functional forms and therefore cannot be directly compared to each other. However, a quantity that can be compared between the different functional forms is the ratio of various axes. The results show that regardless of the functional form and the wavelength of the observations, $x0/y0 = 3\pm1$, $z0/y0 = 0.7\pm0.3$, $z0/\mathrm{sqrt}(x0^2 + y0^2) = 0.74\pm0.4$. The latter ratio is somewhat larger than that derived for an axisymmetric bulge model or from the observed drop-off in the projected intensities along the x and z axes of the bulge (Weiland et al. 1994). The average axis ratios derived here translate to axial ratios of $\{x0\text{: } y0\text{: } z0\} = \{1\text{: } 0.33\pm0.11\text{: } 0.23\pm0.8\}$. Another quantity of interest is the bulge triaxiality, defined here as the ratio $T = [1 - (y0/x0)^2]/[1 - (z0/x0)^2]$ . Note that T is equal to 0 and 1 for oblate and prolate spheroids, respectively. The triaxiality of the bulge is in the range: $T = 0.81 - 0.94$, close to that of a prolate spheroid.

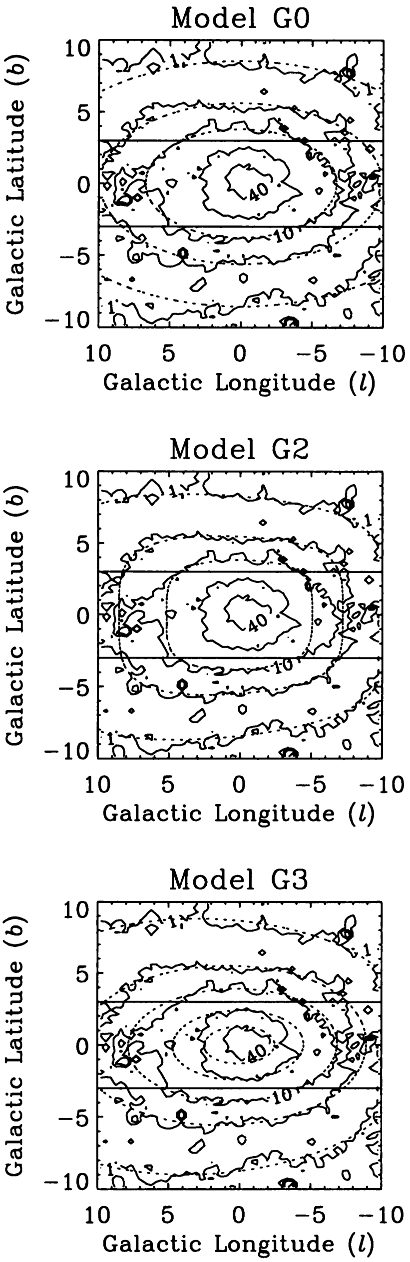

*Figure 1.* Comparison of the DIRBE observations (solid contours) with the projected $2.2\mu$ intensity of selected models (dotted contours).

## 4.3. BULGE ORIENTATION

The rotation and tilt angles are defined in the same way for each model, and also allow for a direct comparison between the various models. The best fitting models G2 and E3 give values of $\alpha = 74$ and 50°, respectively. The rotation angles of all models lie in the range $\alpha = 50 - 90°$, with an average of $\alpha = 65°$ if the power law functions are excluded, and with a $\pm 15°$ uncertainty reflecting the variance of the different models. Binney et al. (1991) have argued from studies of the kinematics of the H I, CO and CS gas in the central region of the Galaxy that the flow of the gas is dominated by a bar which should have a viewing angle of $16 \pm 2°$. Weinberg (1992a), on the other hand, suggested a viewing angle of $36 \pm 10°$ for the bar. These "viewing" angles correspond to values of $\alpha = 74 \pm 2°$ and $\alpha = 54 \pm 10°$, respectively, in our notation (see Figure 2 in Dwek 1994). The Binney et al. kinematic model therefore favors the Gaussian-type function G2 which has $\alpha = 70.7 \pm 4.4°$, over the functional form E3 that was used by Kent et al. which gives $\alpha = 49.8 \pm 9.4°$. Weinberg's model, however, favors the modified Bahcall & Soneira function, G3, which has a value of $\alpha = 59.0 \pm 9.5°$.

From an observed tilt in the streamlines of the H I and CO gas located within 2 kpc of the Galactic center, Liszt & Burton (1980) argued that the bulge should be tilted out of the Galactic plane as well. The data allow for an out-of-plane tilt of the bulge; however, at $2.2\mu$ the tilt angles of the various models are small, typically less than 0.6°, and are never larger than $3\sigma$ from zero. Results from 3.5 and $4.9\mu$ suggest that the tilt may be increasing with wavelength; however, the tilt angle is always less than 2°. Such small tilt angles could be caused by a non-uniform distribution of foreground stars. Our conclusion is therefore consistent with that reached by Weiland et al. (1994), who found no evidence for a tilt in the data. Blitz & Spergel argued from the Matsumoto et al. data that the bar should be tilted by as much as 7°. Tilting any of the models by that amount will produce a longitudinal difference map that is inconsistent with the DIRBE data. The difference between our result and that of Blitz & Spergel can probably be attributed to the improved data used in the current modeling effort, especially the improved correction for interstellar extinction.

## 4.4. THE EFFECT OF A ROLL

We have examined the effect of a roll, initially surpressing any tilt of the bulge, on two select functional forms, E1 and G2 in the notation of Dwek et al. (1994), and found that the roll had a minor effect on the quality of the fit of the function G2, and actually worsened the fit to the data. The effect of the roll was most dramatic for the function E1. By rolling the function by ≈ 45° the projected intensity attained an almost "boxy" character, distinctly different from its otherwise elongated appearance. The effect of the roll on E1 is peculiar to that function because of its definition of the radial coordinate. Similar results for these models were obtained for cases in which all three angles were allowed to vary simultaneously. Again, the 45° roll preferred by model E1 represents the peculiar definition of its radial coordinate, rather than an intrinsic roll of the Galactic bulge.

## 5. Conclusions and Comparison to Previous Work

We have modeled the Galactic bulge morphology and derived its luminosity and mass using the DIRBE observations of its projected surface brightness in the $|l| < 10°$, and $|b| > 3°$ region at $2.2\mu$, and in the $|l| < 10°$, and $|b| > 2°$ region at 3.5, and $4.9\mu$. The main results of the paper, and their relation to previous investigations can be briefly summarized as follows:

1) The bulge is a bar with its closest edge in the first Galactic quadrant. Even though an axisymmetric oblate spheroid provides a reasonable fit to the observed intensity, it fails to reproduce the longitudinal asymmetry observed in the DIRBE data (Weiland et al. 1994). This reconfirms the results of Weiland et al. and previous photometric studies of the bulge (Blitz & Spergel 1991), as well as studies of stellar populations and stellar and gas kinematics in the Galactic center region.

2) Triaxial models provide an improved fit to the data, and produce a longitudinal asymmetry in the projected intensity maps. Of the list of triaxial models studied (see Dwek et al. 1994) the Gaussian-type models (G1-G3), and the triaxial version of the modified spheroid used by Kent, Dame, & Fazio (1991), model E3, provided the best fits to the data.

3) Triaxial models produced axis ratios of $\{x0{:}y0{:}z0\} = \{1{:}\ 0.33\pm0.11{:}\ 0.23\pm0.08\}$. Thus the bulge resembles a prolate spheroid with a triaxiality between 0.81 and 0.94. For comparison, Vietri (1986) derived axis ratios of $\{1{:}0.7{:}0.4\}$ from dynamical constraints on model G3.

4) Comparison of the results of model E2 with the fit of Whitelock & Catchpole to the population of bulge Mira variables suggests that the IRAS selected Mira distribution is significantly flatter than the population of bulge K and M giants. This morphological discrepancy is puzzling considering the widely held view that M stars evolve into Miras. However, the difference in the morphology of these two populations probably arises from the fact that the IRAS Miras used in their analysis form an incomplete sample of all Miras with respect to their periods and spatial distribution.

5) The in-plane rotation angle $\alpha$ (see Figure 2 in Dwek et al. 1994) is between 50 - 80°, the range of values reflecting the variance between the different models. This corresponds to a range of viewing angles (the angle between the solar radius and the bar's major axis) between 10 - 30°.

This range is consistent with the value of 16 ± 2° suggested by Binney et al. (1991), and the value of 36 ± 10° suggested by Weinberg (1992a). The models most consistent with Binney et al. are G1 and G2, whereas Weinberg's results favor models G3 and E3. The bar could intrinsically be peanut-shaped but appears boxy because of the nearly end-on viewing angle (Combes & Sanders 1981).

6) The models are consistent with a slight tilt in the bar by an angle of about 0.6° at $2.2\mu$ and by an angle of about 2° at 3.5 and $4.9\mu$. However, these tilts are statistically insignificant, and can be accounted for by a non-uniform distribution of foreground stars.

7) A roll can affect the projected intensity of a given functional form. The effect of a roll was most noticeable for model E1, giving an intensity that was initially flattened along the galactic plane a "boxy" appearance.

## Acknowledgements

The National Aeronautics and Space Administration / Goddard Space Flight Center (NASA/GSFC) is responsible for the design, development, and operation of the Cosmic Background Explorer (*COBE*), under the scientific guidance of the COBE Science Working Group.

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