THE ASTROPHYSICAL JOURNAL, 379:631–638, 1991 October 1

DIRECT EVIDENCE FOR A BAR AT THE GALACTIC CENTER

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Received 1990 December 21; accepted 1991 April 11

ABSTRACT

The bar at the center of the Milky Way, long postulated from a number of different studies, is unambiguously detected in the 2.4 μm observations of the Galactic center of Matsumoto et al. We model the emission from a triaxial stellar bar and describe its distinctive signature. This signature is found in the data. The near side of the bar is in the first Galactic quadrant and the bar is tilted with respect to the Galactic plane in a sense consistent with the work of Sinha and of Liszt and Burton, who first proposed a tilted bar to explain the kinematics of the H I and CO at the Galactic center. The small extinction that is observed at latitudes greater than 3° at 2.4 μm cannot account for the asymmetries observed in the distribution of the infrared emission. The bar is distinct from the triaxial spheroid postulated by Blitz and Spergel as the source of the asymmetries in the H I distribution in the outer Galaxy.

Subject headings: galaxies: nuclei — galaxies: structure — galaxies: The Galaxy — infrared: sources

1. INTRODUCTION

What is the shape of our Galaxy? de Vaucouleurs (1964), noting the similarity between the magnitude of the noncircular radial velocities observed in barred spirals and the noncircular motions seen in the H I in the inner regions of the Milky Way, first suggested that the Milky Way is a barred galaxy. Recently, we proposed that the anomalous velocities of the 21 cm gas in the Milky Way beyond $0.5\varpi_0$ can be quantitatively understood if the gas moves in response to a gravitational potential with a significant quadrupole component (Blitz & Spergel 1991, hereafter Paper I). We found that the amplitude of the quadrupole varies approximately as ϖ^{-1} between $0.5\varpi_0$ and the solar circle and is truncated at $\sim 1.5\varpi_0$. Such a potential would arise if the Galactic spheroid were triaxial. The model requires the spheroid to be slowly rotating in order to reproduce the detailed kinematics of the H I.

Subsequently, we have sought to find direct evidence for the triaxiality of the spheroid. Various authors had previously suggested that the gas in the central few kiloparsecs of the Milky Way is responding to the forcing by a bar (Peters 1975; Sanders & Huntley 1976; Cohen & Few 1976; Liszt & Burton 1980; Cohen & Dent 1983; Yuan 1984; van Albada 1985; Gerhard & Vietri 1986; Mulder & Liem 1986). Recently, Binney et al. (1991) constructed a detailed dynamical model for the gas in the Galactic center based on a rapidly rotating bar. Although the evidence from gas kinematics is strong, no direct evidence for a bar has yet been found. In this paper, we present direct evidence from infrared observations for the existence of a bar; moreover, the bar is dynamically distinct from the triaxial spheroid of Paper I.

Figure 1 summarizes our proposed Galactic morphology. In the center of the Galaxy is a bar oriented with the long axis closest to the Sun in the first quadrant. The triaxial spheroid is a separate component indicated by the lightly shaded region encompassing the bar. The orientation of a gas orbit in the potential of the triaxial spheroid is shown by the dotted line in the figure. In our model, the spheroid is slowly rotating, thus, we expect that the gas orbits lie perpendicular to the long axis of the spheroid inside of the Inner Lindblad Resonance at 15 kpc.

We identify the bar with the peanut-shaped bulge clearly visible in the *COBE* images of the Galaxy (Hauser et al. 1990). In this paper, we will show that this peanut-shaped bulge is triaxial and we will refer to this component in this paper as a bar. We distinguish between the bulge and the spheroid by their different longitude extents. The triaxial quadrupole potential identified in Paper I could be due to either a triaxial spheroid composed of slowly rotating low metallicity stars or an oval thick disk. Observations of giants in the spheroid show that they are a metal-poor population, while observations of the central bulge of our Galaxy suggest that it is metal-rich (e.g., Gilmore, King, & van der Kruit 1989). In the near-infrared map of Hayakawa et al. (1981), the bulge and the spheroid are clearly seen as distinct structures in the large-scale maps of the infrared emission.

2. EVIDENCE FOR THE BAR

All-sky surveys in the infrared are powerful tools for exploring the structure of the bulge. Because dust absorption is greatly reduced in the IR, it is possible to probe regions of the inner Galaxy obscured at visible wavelengths. The successful launching and deployment of the *COBE* satellite promises to provide an unprecedented opportunity to study the bulge directly through the radiation emitted in the near-infrared by the old population of stars of which it is composed. Notably, the first photographic representation of the near-infrared emission from nearly the entire Galactic plane clearly shows the bulge of the Milky Way in what appears to be an elongated, perhaps "peanut" shape.

Although *COBE* will provide by far the best absolute measurements of the Galactic near infrared emission that have been obtained to date, and important survey of the Galactic

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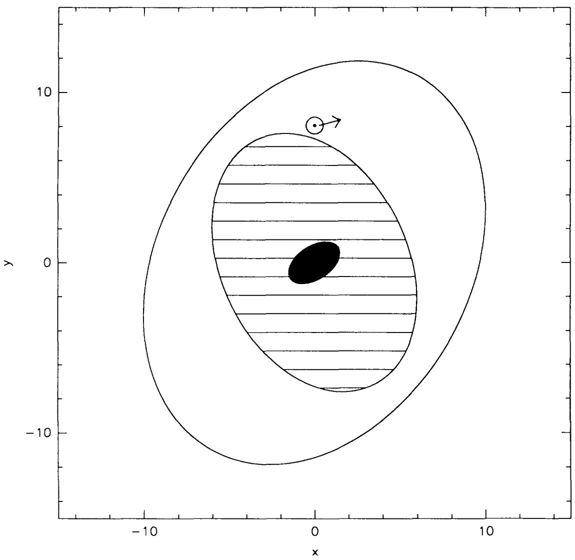

FIG. 1.—Schematic representation of our Galaxy model. In the center of the Galaxy is a triaxial bar that appears as a peanut-shaped bulge in the *COBE* image. The lightly shaded region is the triaxial spheriod whose r^{-3} density profile extends out beyond the solar circle. The solid line shows the orientation of a gas orbit in the potential of the triaxial spheroid. The arrow shows the direction of motion of the LSR.

center region has already been made with balloon observations by Matsumoto et al. (1982). To our knowledge, these observations have not been analyzed previously to determine whether a significant nonaxisymmetric component of the emission exists within the data. We provide such an analysis below, and show that there is *direct* evidence for a bar at the Galactic center. Furthermore, this bar is oriented in the direction implied by the work of Peters (1975), Sanders & Huntley (1976), Liszt & Burton (1980), and Mulder & Liem (1986) for a rapidly rotating bar. Moreover, Liszt & Burton (1980) argued implicitly that such a bar should be tilted with respect to the Galactic plane because of the tilt in the streamlines of the H I and CO observed within 2 kpc of the Galactic center. We find such a tilt in the sense predicted by their work.

Matsumoto et al. (1982), have produced a map of the 2.4 μm emission within 12° of the Galactic center in l and 10° of the center in b. The map is reproduced in Figure 2. The infrared emission is produced almost entirely by starlight, but its intensity can be attenuated somewhat by dust. This is seen most graphically in the three-color *COBE* photographic representation of the Galactic near-IR emission (Hauser et al. 1990); the disk is significantly reddened, but the bulge is not. Mastumoto et al. (1982) explicitly analyze their data for extinction using 3.4 μm data they obtained with the same balloon flight, and they find that the extinction correction is small at high $|b|$. Their analysis of the surface brightness as a function of latitude at $l = 0°$ shows a knee at $b = 2°$, which very likely represents the transition from the disk to the bulge. We therefore analyze their data only at latitudes greater than 3°, where the bulge emission can safely be analyzed in a single infrared color.

Before we present the analysis of their data, we wish to gain some understanding of the signature of the triaxial bulge or bar in the inner Galaxy. Because the scale length of the Galactic bar is a significant fraction of our distance to the Galactic center, triaxiality has a characteristic photometric signature, unless we lie along an axis in a symmetry plane. This signature is extremely difficult to detect in external systems, where the near side of the bar is not much closer than the far side of the bar.

Imagine that the stellar distribution in the Galactic center region has a barlike shape and the long axis of the bar is not oriented either parallel or perpendicular to the plane of the sky. Now, imagine two lines of sight in the plane of the Galaxy at longitudes $\pm l$; this situation is illustrated in Figure 3*a* which assumes that the near side of the bar is at positive longitudes. The line of sight at positive l intersects the major axis of the bar at smaller galactocentric radius than at $-l$; thus, due to the density gradient in the bar the integrated surface brightness along l is greater than along $-l$. However, along lines of sight very close to the center, represented in Figure 3*a* by $\pm l'$, the difference between the two lines of sight becomes very small, and the longer path length through the triaxial distribution at $-l$ makes the surface brightness along $-l'$ appear to be brighter than that along l'. Furthermore, the near side of the bar should appear to be thicker simply from geometric perspective, and it should have contours of surface brightness that are shaped as in Figure 3*b*.

In principle, one can distinguish between an oblate component and a triaxial component, and whether either distribution is tilted with respect to the Galactic plane. An oblate distribution of stars that is not tilted should simply result in folded maps that have a random distribution of positive and negative excesses.

To test the amplitude of this effect, we projected the bar onto the celestial sphere. We model the emission from the bar as

$$\rho(x, y, z) = \rho_0 \exp(-|x|/x_s - |y|/y_s - |z|/z_s), \quad (1)$$

where x, y, and z are the principal axes of the density distribution, x_s, y_s and z_s are the scale lengths of the distributions. We then project this into l, b coordinates and determine the surface brightness:

$$I(l, b) = \int \rho(x, y, z) ds \quad (2)$$

where s is a vector along our line of sight.

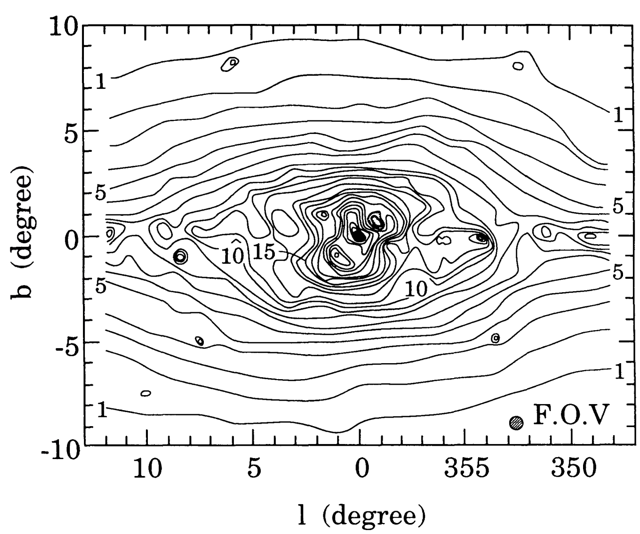

FIG. 2.—Contour map of 2.4 μm surface brightness of the region around the Galactic center taken from Matsumoto et al. (1982). The lowest contour and the contour interval are in steps of 1.0×10^{-10} W cm^2 μm^{-1} sr^{-1}.

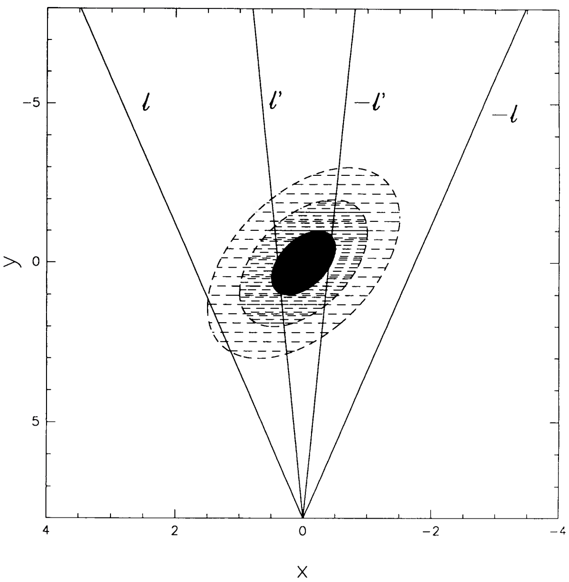

FIG. 3a

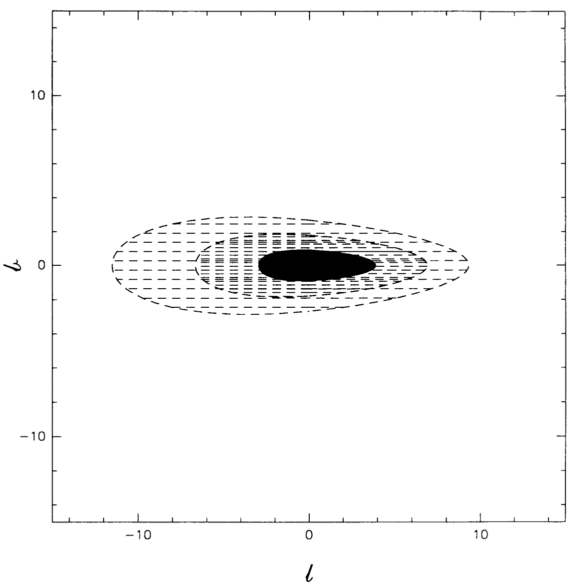

FIG. 3b

FIG. 3.—(*a*) This figure shows a bar viewed from the Galactic pole. Longitude increases counterclockwise. For a bar, whose near side is in the first quadrant, a line of sight at positive l intersects the bar at a smaller galactocentric radius than at $-l$. This effect is less pronounced closer to the Galactic center. (*b*) The bar of Fig. 3*a* is now shown as viewed from the Sun. Note that the near side of the bar is brighter at large positive l than at large negative l.

These asymmetries are manifest in "difference figures," where we fold the maps around either $l = 0$ or $b = 0$ and calculate the fractional difference in surface brightness:

$$\Delta I(l, b) = [I(l, b) - I(-l, b)]/I(l, b) , \quad (3a)$$

and

$$\Delta I(l, b)' = [I(l, b) - I(l, -b)]/I(l, b) . \quad (3b)$$

Figure 4 shows the fractional surface brightness difference for a model bar projected on the celestial sphere. We identify four features that must be present in differential surface brightness maps of a bar oriented obliquely to the Sun-center line, three of which are illustrated in Figure 4:

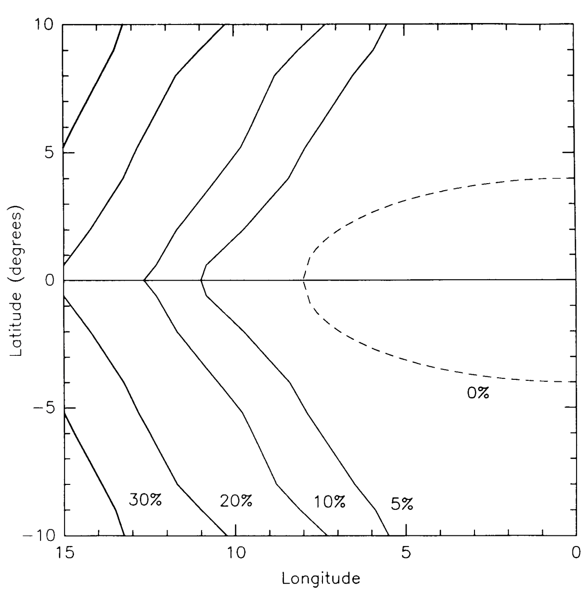

FIG. 4.—Percentage difference $100 \times \Delta I(l, b)$ (see eq. [3]) between the negative and positive longitudes for a model bar with $x_s = 1.0$ kpc, $y_s = z_s = 0.7$ kpc, $\theta = 45°$.

1. If the data are folded along $l = 0°$, that is, if one takes the difference between the emission on each side of the Galactic center, there should be excess emission along most of the length of the bar in the hemisphere that contains the nearer half. Furthermore, one expects the excess to be present at both positive and negative latitudes.
2. The value of $\Delta I(l, b)$ must increase with increasing longitude.
3. Close to $l = 0°$, there should be a sign change in the differential surface brightness such that the more distant portion actually appears to be brighter.
4. The near side of the bar (defined by the results from the above analysis) should show a larger angular scale height.

If the bar and the Galactic plane are not coplanar, that is the bar is tilted with respect to the plane of the disk, it should be evident from folding the data along the Galactic plane. In that case, there will be an excess of emission in one hemisphere, and a deficit in the other with the dividing line occurring at $l = 0°$. Note that this effect does not require the stars to have a barlike distribution, only that their distribution be aspherical. This is because, when projected on the sky, a flattened distribution produces a sinusoidal distribution of light in position angle on the sky.

Do maps of the galactic center show asymmetries similar to those seen in our projections of a bar? We have regridded the Matsumoto et al. (1982) data in 1° bins by interpolating from their published map shown in Figure 2. In this paper, we define colatitude and colongitude as those latitudes and longitudes that are at equivalent angles from the Galactic center. We also refer for simplicity to longitudes between $l = 348°$ and $l = 360°$ as negative longitudes. Figure 5 is a plot for the emission folded along $l = 0°$ for the Matsumoto et al. (1982) data. The striped region along the Galactic plane represents the disk emission excluded from the analysis. The estimated 1 σ uncertainty in the map is about 5%–7%. Except for a small patch

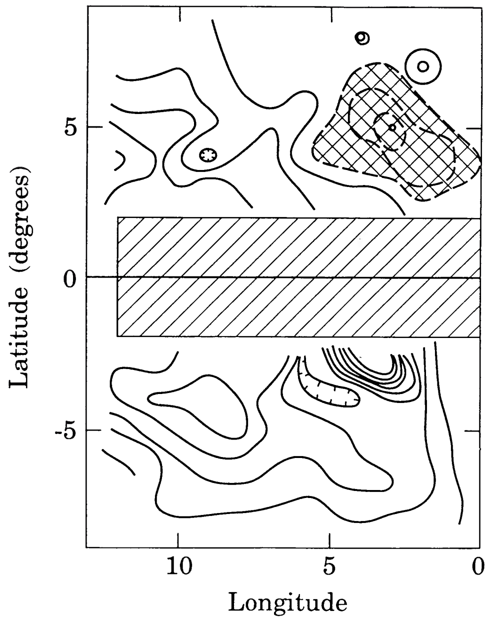

FIG. 5.—Absolute difference between the negative and positive longitudes for the Matsumoto et al. (1982) Galactic center data. The lowest positive contour and the contour intervals are in steps of 0.3×10^{-10} W cm^2 μm^{-1} sr^{-1}. Negative contours are indicated by cross-hatching.

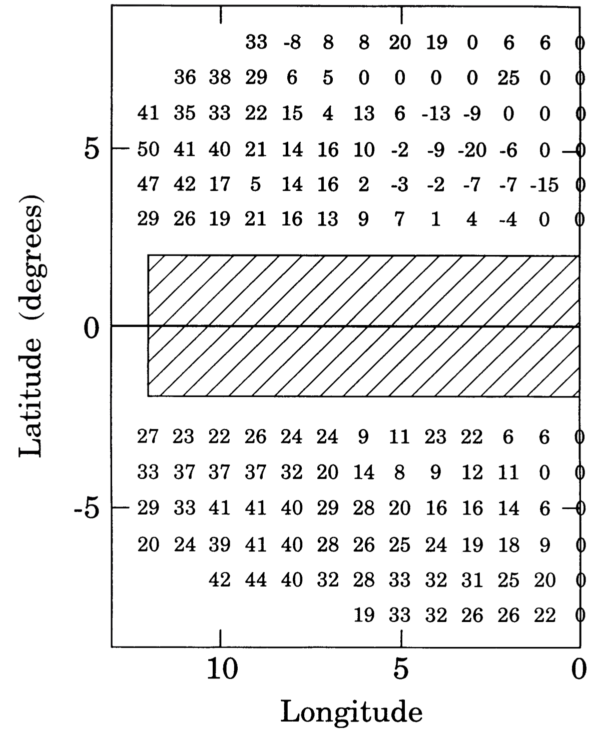

FIG. 6.—Percentage difference, $\Delta I(l, b)$ between the negative and positive longitudes for the Matsumoto et al. (1982) Galactic center data. The plot shows values plotted every degree; the resolution of the data is 0°5.

centered at $l = 3°$, $b = 5°$, there is a strong, coherent excess of emission at all locations at both positive and negative latitudes. We show below that the patch of negative emission is most likely the result of a tilt in the distribution of stars. This excess of emission shows that the distribution of stars is either asymmetric with respect to the Galactic center, a dynamically unstable situation, or that the distribution of stars is in the shape of a bar with the part of the long axis nearest the Sun occurring at positive longitudes. A plot of the excess as a percentage of the total emission at each position is shown in Figure 6. Note that there is a systematic increase in the percentage differential emission with longitude which is similar in magnitude to the simulation shown in Figure 4.

If the systematic trends in Figure 5 are due to a barred distribution of stars, then the latitude distribution at positive longitudes should have a systematically greater angular scale height than those at their colongitudes. The angular scale height, calculated by assuming that the latitude distribution is exponential, is shown for several longitudes in Figure 7. The straight lines are fits to the data which suggest that an exponential distribution is a reasonable approximation to the data. For each longitude, the centroid of the surface brightness is found as a function of latitude, and the angular scale height is determined from fits at each longitude. Figure 8*a* shows the angular scale height as a function of longitude and Figure 8*b* shows the differential angular scale height. At positive longitudes, the surface brightness distribution has a systematically larger angular scale height at positive longitudes than at negative longitudes, as expected for a bar. The *linear* scale height apparently increases with distance from the nucleus. If this did not occur, there would be no turn up in the angular scale height at negative longitudes. There are two discrepant points in Figure 8*b* that are due to the anomalously large scale heights measured from the Matsumuto et al. (1982) data at $l = -7°$ and $-8°$. Inspection of the Palomar prints indicates that these large values may be due to bright sources such as globular clusters at these two longitudes.

Consider now the small region of negative excess in Figure 5. If the Galactic bar were tilted by a small counterclockwise angle, then there would be more emission at a given location at positive b and negative l (and less at the corresponding colongitude), than there would be if the stellar distribution were not tilted. Thus when performing the folding shown in

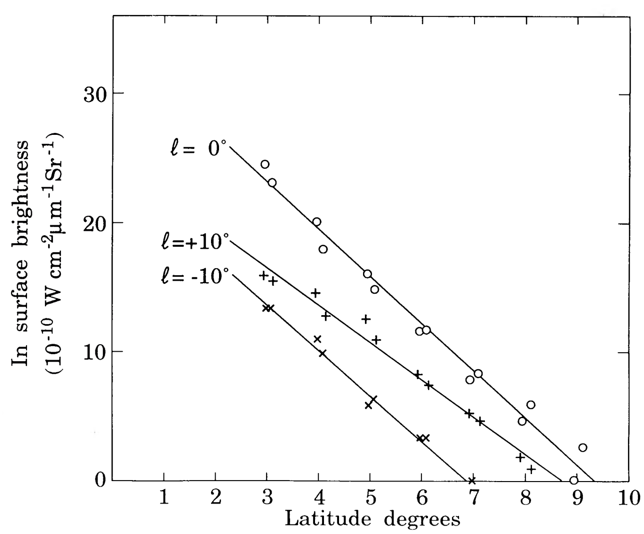

FIG. 7.—Plot of the ln of the surface brightness of the Matsumoto et al. (1982) data as a function of Galactic longitude for a few representative longitudes, and the lines showing a linear least-squares fit to the data. The plot shows that an exponential function is a satisfactory representation of the vertical distribution of surface brightness.

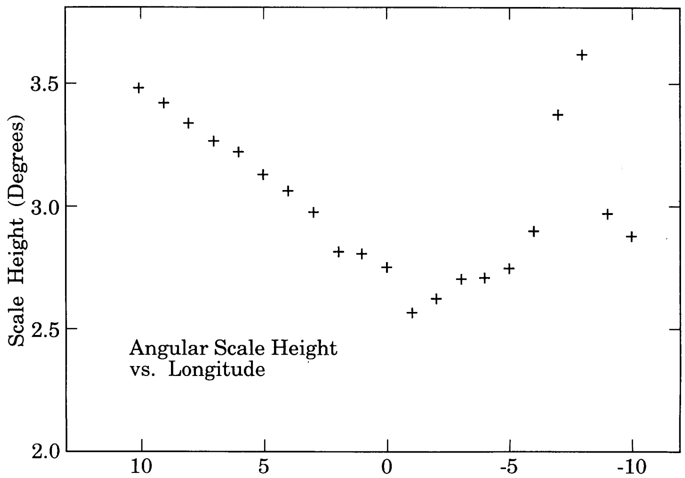

FIG. 8*a*

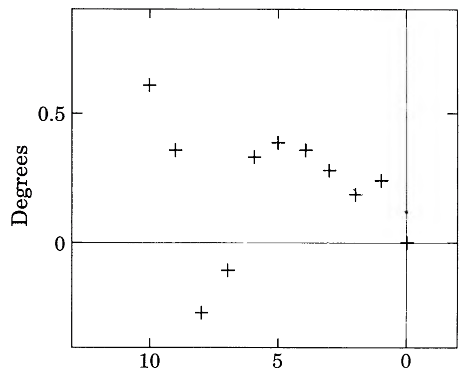

FIG. 8*b*

FIG. 8.—(*a*) Plot of the angular scale height as a function of Galactic longitude. The scale height was computed assuming an exponential surface brightness profile. (*b*) Plot of differential scale height as a function of Galactic longitude. The value at each point is the exponential scale height at longitude $-l$ subtracted from the scale height at l for the Matsumoto et al. (1982) data. Note that all but two values are positive, and that the data show a linear trend as is expected from geometrical effects of a bar with the near side located at positive longitudes.

Figure 5, there would be some locations where the effect of the tilt would overcome the greater apparent brightness of the near side of the bar. One would expect this to occur close to $l = 0°$, since the difference in apparent brightness of the bar between a longitude and its colongitude should be smallest there. We confirm this expectation with the simulation shown in Figure 9. This figure is produced in the same way as Figure 4, using the same axial scale lengths, but is tilted by 7° counterclockwise with respect to $b = 0°$ in the sense that the major axis is at positive latitudes at negative longitudes. The tilt produces a negative "hole" in the emission magnitude, extent and location as that shown in Figure 5.

The maps of differential surface brightness produced from the Matsumoto et al. (1982) data show conclusively that the stars in the inner portion of the Milky Way are arranged in a bar and that the bar has its near side at positive longitudes. All four criteria required of a bar are rigorously satisfied, but we find in addition, that the bar shows a small tilt with respect to $b = 0°$. These conclusions require only that there are no systematic effects in the data that mimic the derived distribution, a conclusion that can ultimately be checked with the *COBE* data. In § 3, we argue that extinction does not produce the results shown in the figures.

In Figure 10, we show $\Delta I(l, b)'$ computed from the Matsumoto et al. (1982) data. This demonstrates the tilt of the bar more directly. Clearly, there is excess emission at both positive l and negative b, as well as negative l and positive b. The excesses are clearly coherent over a large range in area and are not due to random fluctuations. For comparison, we show a plot of $\Delta I(l, b)'$ using the same tilt and model used to produce Figure 9. The results are shown in Figure 11, which shows a good agreement with the overall trend in Figure 10. Qualitatively, the tilt seen in the Matsumoto et al. (1982) data is also

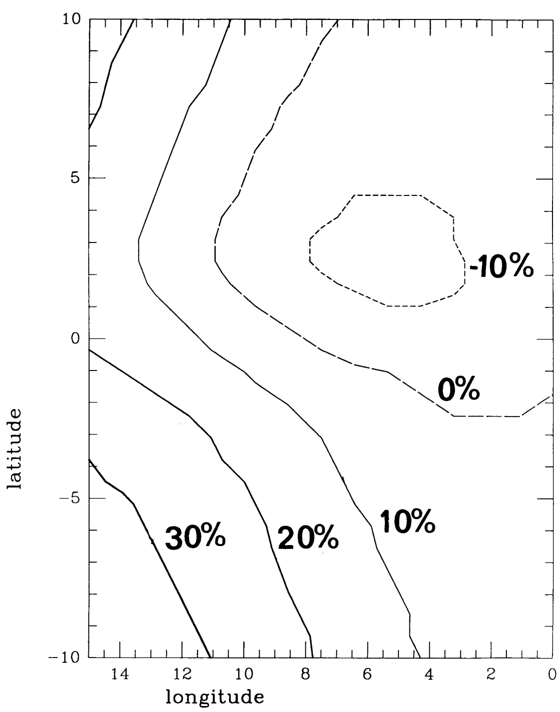

FIG. 9.—Fractional difference, $\Delta I(l, b)$ between the negative and positive latitudes for a model bar but with a counterclockwise tilt of the bar by 7°. The contours correspond to percentage intensity differences of 10%. Compare this to Fig. 6.

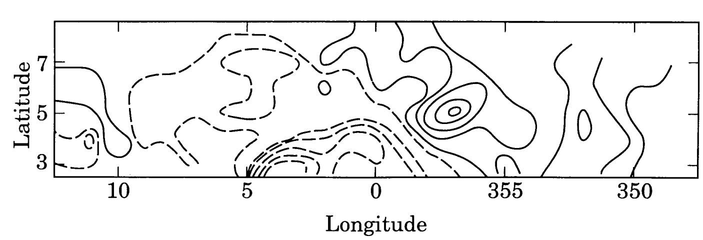

FIG. 10.—Absolute difference between the positive and negative latitudes for the Matsumoto et al. (1982) Galactic data. Negative contours are shown with dashed lines. The contour interval is 0.3×10^{-10} W cm^2 μm^{-1} sr^{-1}. Note the systematic change in sign from positive to negative longitudes.

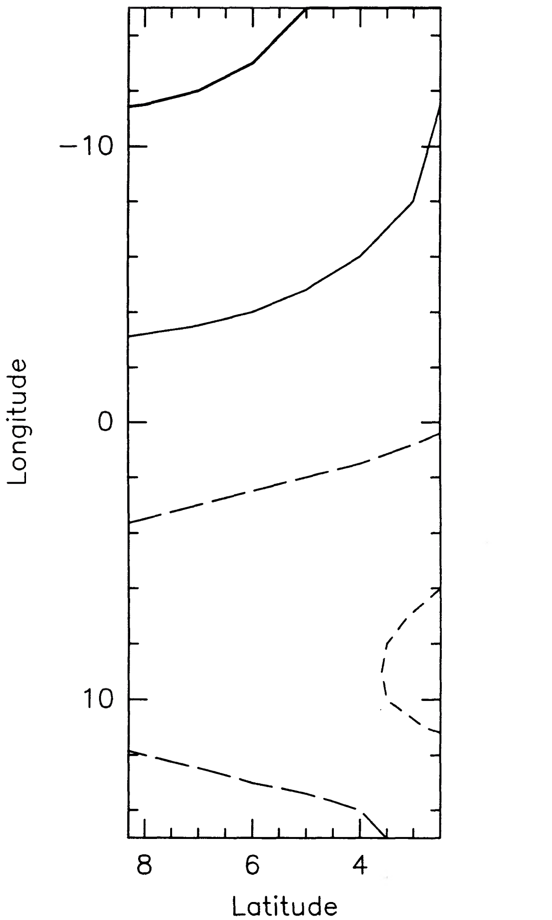

FIG. 11.—Fractional difference, $\Delta I'(l, b)$ (see eq. [3]), between the negative and positive latitudes for a model bar but with a counterclockwise tilt of the bar by 7°. Compare this to Fig. 8. The contours correspond to percentage intensity differences of 20% (*solid line*), 10% (*light solid line*), 0% (*long dashed line*) and −10% (*short dashed line*).

apparent in the smaller scale, but higher resolution 2.4 μm maps of Hiramoto et al. (1984). The tilt that we derive is consistent with the sense of the tilt of the streamlines of the 21 cm emission derived by Liszt & Burton (1980). A similar tilt was also found by Sinha (1979).

Another signature of the tilt is shown in Figure 12 which shows the centroid of the surface brightness distribution in b and each longitude. The surface brightness below, $|b| < 3$, was not used in the calculation of the centroid. The solid line, which is fit to all of points in the figure, implies an apparent tilt of 2°.6 in the plane of the sky. The dashed line, fit to the inner 5°, would imply an apparent bar tilt of 5°.5.

Careful analysis of the bulges of other galaxies reveal similar features. The bulge of M31 appears to be tilted with the respect to its disk (Ciardullo et al. 1988). A recent analysis of the gas flow in NGC 1832 suggests that the bar in this system is tilted with respect to the plane of the Galactic disk (Long 1990). In NGC 1832, the gas flow in the central 4 kpc shows significant noncircular motions and evidence for a ~10°–20° warp, analogous to what is seen in our own Galaxy.

The tilt between the bar and the disk is at first surprising. One would expect that bending waves would align the two systems in a few dynamical times (although we know of no careful analysis of the alignment rate.) This tilt may be due to the effects of the asymmetric orbits that can play an important role in a rotating barred potential (see, e.g., Pfenniger 1984).

In summary, the near infrared data show compelling evidence for a bar at the Galactic center, that the bar is tilted with respect to the plane, and that the near side of the bar is at small positive longitudes. The *COBE* data should be a significant improvement over the Matsumoto et al. (1982) results, and may provide data of sufficiently high quality to be able to determine or at least constrain the angle that the bar makes with the Sun-center line, and the radial density distribution of stars. Furthermore, the *COBE* data should make it possible to see clearly the link between the bar at the center of the Galaxy and the triaxial spheroid postulated in Paper I.

3. EXTINCTION EFFECTS

Can the observed asymmetries reported in § 2 be due primarily to extinction? The large column density of molecular gas observed toward the Galactic center presumably has a correspondingly large quantity of dust associated with it, assuming that the gas-to-dust ratio is comparable to the value obtained in the solar vicinity. We use the maps of Dame et al. (1987) to estimate the effect of the extinction due to the molecular gas in the disk along the line of sight to the Galactic center; the format of their plots is particularly useful in this regard. These maps show that the CO associated with the disk along the line of sight of the Galactic center is almost entirely confined to the Galactic plane. There is, however, a small amount of CO that extends to higher latitudes. Dame et al. (1987) show plots of this gas smoothed to a resolution of 0°.5, similar to the resolution of the infrared data. The most prominent feature is the plume of gas that extends upward from the Galactic plane to latitudes as large as 10°, but is confined within 2°.5 in l. The plume is consistent with the two-color reddening analysis of Matsumoto et al. (1982). In their paper, they attempt to correct for the extinction along the line $l = 0°$ and comment that the "correction for reddening is small at high Galactic latitude and anomalously low extinction exists at $b < 0°$." No reddening values are given in their paper. There is somewhat more CO at

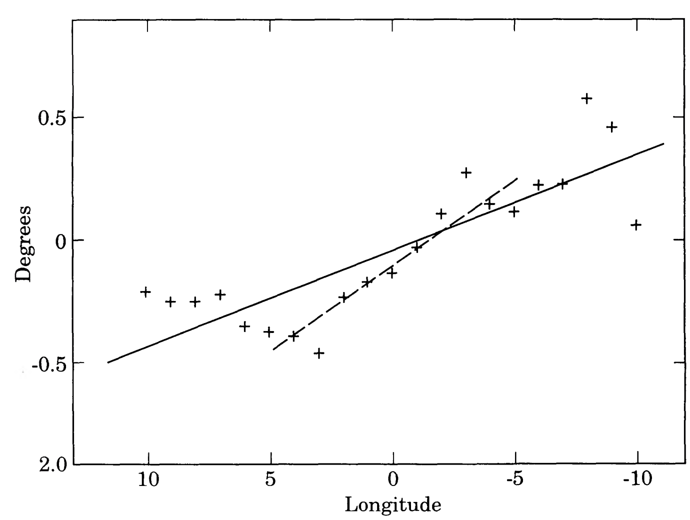

FIG. 12.—Centroid of the surface brightness distribution in latitude at each longitude. The surface brightness between $-3° < b < 3°$ was not used in the calculation of the centroid. The dashed line is fitted to the points with $|l| < 5°$. The solid line is fitted to the points with $|l| < 10°$.

positive longitudes than at the colongitudes, and the dust associated with this gas may contribute to the negative contours at $l < 2^\circ.5$ shown in Figure 6.

Except for this gas, there is no other CO in the region that we analyze that has an integrated line strength greater than 5 K km s^{-1}. The mean extinction is more than one order of magnitude smaller, judging from the spatial extent of the CO contours. Using the empirical conversion of CO integrated brightness to $N(H_2)$ of Bloemen et al. (1986), and the gas to extinction ratio of Savage & Mathis (1979), the maximum visual extinction along the line of sight due to the molecular gas is 1.3 mag. This corresponds to an extinction at 2.4 μm of only 0.13 mag (see, e.g., Johnson 1965).

Thus, if the excess emission seen at positive longitudes were due to extinction, the differential plots of Figures 6 and 9 would be plots of the extinction (with the signs reversed). An extinction of 0.13 mag corresponds to an attenuation of 15% in the surface brightness of the infrared emission, much smaller than most of the values plotted in Figure 5. Furthermore, this attenuation corresponds to the *maximum* extinction in the region, and that extinction is localized in two regions each no more than about 1 deg^2. The average value of the extinction due to the molecular gas is more than one order of magnitude less. The dust associated with the molecular gas therefore has only a neglible effect on the differential surface brightness plots of the Matsumoto et al. (1982) data.

That leaves only the extinction from the dust associated with the atomic hydrogen along the line of sight to the Galactic center since the column density of ionized gas should be negligible by comparison. It is possible to assess this contribution quantitatively by comparing the column densities at various longitudes and colongitudes using the data of Burton & Lizt (1978). Harvey Liszt has kindly provided a map of the velocity integrated H I emission in the Galactic center region, which shows that there is a small excess of H I column density at positive latitudes compared to negative latitudes, in agreement with the expectations from the infrared extinction measurements of Matsumoto et al. (1982). There is no systematic effect with longitude, however, and the mean excess of one position with that of its colongitude is about 600 K km s^{-1}. This is equivalent to an H I column density of 1×10^{21} cm^{-2}, or an A_v of 0.5 mag. At 2.4 μm, this corresponds to only 0.05 mag of extinction, far too low to have a significant effect on the overall structure in the folded maps of the Matsumoto et al. (1982) data. In any event, the distribution of differential extinction is quite patchy and does not at all resemble the structure of the folded maps. The extinction associated with the CO and H I taken together could however, be responsible for some of the apparently random structure seen in the maps.

Only one possibility remains: perhaps the gas-to-dust ratio is anomalous in various regions along the line of sight in such a way as to produce the observed structure in the infrared emission. This possibility would require a low gas-to-dust ratio along the line of sight. As first pointed out by Oort (1977), however, comparison of the extinction to the Galactic center with the total column density of gas seems to require that if there is an anomaly, it is in the opposite sense: there in less extinction toward the Galactic center by more than one order of magnitude than is obtained by assuming that the gas is axisymmetric and smoothly distributed about the center. A similar result was obtained from an analysis of the gamma-ray deficit toward the Galactic center by Blitz et al. (1985), although the deficit could also be due to the channeling of cosmic rays in a direction perpendicular to the disk in the central 500 pc of the Galaxy.

It therefore appears that extinction cannot be the cause of the infrared excess at positive longitudes, the larger angular scale height of the radiation at positive longitudes, or the tilt of the infrared distribution.

4. THE RELATIONSHIP OF THE BAR TO THE TRIAXIAL SPHEROID

The orientation of the bar that we derive is roughly perpendicular to the triaxial spheroid postulated in Paper I. Given the uncertainties, the photometry requires only that the long axes of the two distributions lie in different Galactic quadrants. Does it in fact make sense to speak of these two distinct populations, and is there any observational evidence for them?

We expect that at larger longitudes, where the spheroid dominates the surface brightness that the sign of the surface brighness distribution asymmetry should change. The differential surface brightness distribution from spheroid stars should show that the emission at *negative* longitudes is systematically brighter at locations where the light is no longer dominated by the bar. As is true for the bar, such an asymmetry in the spheroid stars should be visible in the near infrared. The best published survey made at 2.4 μm with sufficiently large sky coverage to detect the predicted asymmetry has been made by Hayakawa et al. (1981). At longitudes $345^\circ < l < 300^\circ$, the 2.4 μm surface brightness is clearly brighter and broader than at positive colongitudes. Because this asymmetry occurs at latitudes as large as 5° from the plane, it is unlikely to be due to spiral arms or any other nonaxisymmetric distribution of matter associated with the disk itself. This is the best direct evidence to date that the triaxial spheroid postulated in Paper I exists, is oriented as predicted, and is distinct from the bar.

There are however, other direct tests that should become available shortly. Again, the best near-infrared continuum data will be available from the *COBE* satellite, and an analysis similar to that done for the bar can be performed for the spheroid. Another data set that will also be capable of detecting a triaxial spheroid is composed of the OH/IR stars.

OH/IR stars should be good tracers of the dynamical structure of the bulge and spheroid. They are highly evolved stars, located at the tip of the asymptotic branch. Their progenitors are believed to be 1–3 $M_\odot$ main-sequence stars, and they are thought in turn to be the progenitors of planetary nebulae (e.g., Iben & Renzini 1983; te Lintel Hekkert & Zijlstra 1990). The *IRAS* satellite detected nearly 1000 AGB stars in the infrared. The double-peaked OH 1612 MHz maser line provides both accurate radial velocities, v_r and a measure of the shell expansion velocity, Δv. An analysis of these stars should therefore provide information not only on the distribution, but on the kinematics of the spheroid stars. te Lintel Hekkert et al. (1990), for example, concluded that the velocity dispersions and asymmetric drift of this sample are typical of thick disk stars.

In an axisymmetric galaxy, OH/IR stars, an older stellar population, should have the same distribution in both the northern ($l > 0$) and southern ($l < 0$) Galactic hemispheres. By symmetry, the integrals of motion in an axisymmetric galaxy are even functions of galactic longitude; because the OH/IR stars are an older dynamically phase-mixed stellar population, the two subsamples, $l < 0$ and $l > 0$, should be drawn from the same distribution function.

Although the sample of OH/IR stars is thought to be complete to 8 kpc in certain directions, it is not yet complete over the full longitude range of interest from $90° < l < -90°$. The size of the sample should ensure that once the sample becomes complete, it will be a good test of the triaxial spheroid distribution.

5. CONCLUSIONS

Analysis of the 2.4 μm from the Galactic center suggests that the bulge in the center of our Galaxy is triaxial and tilted relative to the plane of the Galaxy. The surface brightness distribution and the angular scale height are systematically greater in the north than in the south. The differential surface brightness distribution also has the characteristic signature of a bar-like distribution: a sign reversal near the origin. Furthermore, the differential surface brightness increases with Galactic longitude as required by our simulations of barlike distributions of stars. The deviations from this overall pattern are due to the tilt of the bar. Since our analysis focuses on the shape of the bulge for $|b| > 3°$, reddening is unlikely to be the source of the pronounced asymmetries.

Maps from balloon experiments (Hayakawa et al. 1981) of our Galaxy at 2.4 and 3.4 μm suggest that at intermediate latitudes ($3° < |b| < 5°$), the Galaxy is systematically brighter in the south than in the north at $|l| > 15°$. The results suggest that a population of stars of intermediate age, distinct from the bar population, has a triaxial distribution that is not aligned with the bar in the Galactic center. The distribution of stars outside the central region of the Galaxy is consistent with that required by the results of Paper I. Louis & Gerhard (1988) inferred similar misalignments in four of five galaxies that they studied.

The picture that is beginning to emerge is that the Galaxy has at least two triaxial components, misaligned with respect to one another. In Blitz & Spergel (1991), we argued that the spheroid was triaxial and slowly rotating implying that its corotation radius was at ~45 kpc. Spheroid stars seen in the local neighborhood are slowly rotating and metal-poor. Binney (1990) compares the spheroid proposed in Paper I to a small elliptical galaxy. On the other hand, the triaxial bulge appears to be metal-rich (Frogel 1988; Rich 1988). If it is the source of the noncircular motions seen in the 3 kpc arm and in the galactic center, then the bulge must be rapidly rotating (see, e.g., Mulder & Liem 1986; Yuan 1990; Long, Aguilar, & Ostriker 1990, Binney et al. 1991). These two systems may have distinct formation histories.

In this paper, we have referred to the central triaxial component, the dark shaded region of Figure 1 that corresponds to the peanut-shaped bulge so strikingly apparent in the *COBE* maps, interchangably as either a triaxial bulge or as a bar. If this component is indeed rapidly rotating as suggested by the gas kinematics, then these two designations may be equivalent. Bars viewed edge-on may appear as peanut-shaped bulges. This speculation is consistent with recent numerical work by Raha et al. (1990) and Combes et al. (1990) that found that flattened bars may be unstable to the firehose instability that leads to the formation of a peanut-shaped bulge. This hypothesis can be tested by detailed photometric and kinematic studies of external galaxies.

We would like to thank P. te Lintel Hekkert for providing us with a catalog of OH/IR stars and H. S. Liszt for a map of the differential H I emission. We would also like to thank J. Binney, D. Burstein. F. Combes, M. Hauser, I. King, K. Kuijken, P. te Lintel Herkkert, J. P. Ostriker, and M. Schwarzschild for useful discussion and comments on an earlier draft. L. B. is supported by AST89-18912. D. N. S. is supported by NSF grants AST88-58145 (PYI) and PHY88-05895 and by the A. P. Sloan Foundation.

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