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The boxy bulge and stellar bar of the Milky Way

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Abstract. We describe the boxy bulge, long stellar bar and elliptical ring of the Galaxy. This model has largely evolved from NIR survey work by many teams and differs from other models with a monolithic ellipsoidal bulge. We maintain that the structure of the inner Galaxy can only be properly studied by adequately sampling the entire Galactic plane for $|l| < 30°$, $|b| < 1.5°$, and that the bulge is best studied at least 3° from the plane. We briefly report a slight radially outwardly increasing metallicity gradient along the bar and reaffirm de Vaucouleurs & Pence's (1978) suggestion that the Galaxy is probably of morphological type SAB(rs)bc II.

Keywords. Galaxy: bulge, Galaxy: stellar content, Galaxy: structure

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1. From Central Explosion to Non-axisymmetric Potential

In the 1950s Oort and others posited an "explosive event" at the Galactic Centre to explain various spiral features that had unusually high radial velocities when measured at 21 cm (Oort 1977). Although a bar was first mooted by de Vaucouleurs (1964; Vaucouleurs & Pence 1978) and attempts to model the gas flow with elliptical orbits, the possibility of a central bar could not progress further until the advent of sensitive, high-resolution ground-based point-source surveys in the near infrared (DENIS and 2MASS) and space-borne surveys (*IRAS*, *MSX* and *COBE*). Gerhard (1996) reviews the observation and modelling of atomic and molecular gas in the inner Galaxy. Here, we concentrate on work done in the near- and mid-infrared wavelength ranges to determine the overall structural properties of the boxy bulge and its related long stellar bar.

2. The Boxy Bulge

Blitz & Spergel (1991) examined a 2.4 μm surface-brightness map of the Galactic bulge region by Matsumoto *et al.* (1982) and confirmed the peanut-shaped bulge tantalizingly revealed in a *COBE* publicity photograph. Dwek *et al.* (1995) established the boxy nature of the bulge, finding an opening angle ($\phi_{\rm bulge}$) of $20° \pm 10°$ and axial ratios $(a : b : c) = (1 : 0.33 \pm 0.11 : 0.23 \pm 0.08)$.

Traditionally, determining Galactic structure from visible star counts has been vitiated by severe extinction in the Galactic plane (see Paul 1993). With a factor ten (in magnitudes) less extinction in the K-band, near-infrared sky surveys have largely overcome this problem, although the patchiness of the extinction still remains a problem close to the plane. Garzón *et al.* (1993), in their Two Micron Galactic Survey (TMGS), mapped approximately 75 deg^2 in the bulge region ($10° > |b| > 2°$, $|l| < 15°$—the plane was avoided because of the patchy extinction and the spiral arm contribution).

López-Corredoira *et al.* (1997 [L97], 2000 [L00]) derived the upper end of the bulge K-band luminosity function, finding a sharp drop at $M_K = -8.0$ mag (compared with the disc). The star counts contained bulge and disc populations so a model disc (from Wainscoat *et al.* 1992 [W92]) was subtracted from the total counts. The equation of stellar statistics reduces to a Fredholm equation of the first kind†, in which either the density function may be regarded as the kernel and the luminosity function as the unknown function, or vice versa. The method is iterative, the density function being first the unknown and the luminosity function the kernel, their roles switching back and forth in successive stages of the iteration. L00 made the approximation that the bulge luminosity function is independent of position at distances from the plane between 250 pc and 1200 pc and set it as the kernel of the integral equation. They then set the W92 bulge density function as the unknown at the start of the iteration. The equation was then inverted and an improved value of the density function obtained. Since the density function is sensitive to noise, only the highest-density regions of the TMGS were used in the inversion. The luminosity function was then set as the unknown and the density function as the kernel for another round of iterations (the luminosity function stabilizes after three iterations). Lucy's (1974) statistical method was used to carry out the iterations.

The resulting K luminosity function shows a sharp drop for $M_K < -8$ mag and falls considerably below that of the disc (Frogel & Whitford 1987 show that the brightest bulge stars are up to 2 mag fainter than the brightest disc stars). The K luminosity function was extended up to $M_K = -2.8$ by López-Corredoira, Cabrera-Lavers & Gerhard (2005 [L05]) using the more sensitive 2MASS survey, this time over the bulge area $|l| < 20°$, $2.25° < b < 12.25°$. the availability of both K_s and H Enabled L05 to make an approximate extinction correction to the counts ($m_e = m_{K_s} - 1.77[H - K_s]$). The inversion routines described above were this time applied by prior subtraction of first an exponential disc and second an exponential disc truncated at $R = 4$ kpc (i.e. a disc with a central hole). LO5 applied an ellipsoidal model (their figure 1) but found that a boxier model of the form $t = [x^4 + (x_2/a)^4 + (x_3/b)^4]^{1/4}$ produced a better fit to the isocontours (see their figure 4). The axial ratios they find from the boxy model (1:0.5:0.4) is fairly close to axisymmetry and they give an opening angle $\phi_{\rm bulge} = 20°$–$35°$—considerably greater than the bulge opening angle derived from radio work. Indeed, some workers find much wider values for $\phi_{\rm bulge}$ (e.g. Sevenster *et al.* 1999, in modelling the distribution of OH/IR stars at $b = \pm 3.25°$, report $\phi_{\rm bulge} \sim 44°$ and Valllenari *et al.* (this conference), using 2MASS bulge fields at $30° > l > 17°$, $-6° < b < 3°$, set $\phi_{\rm bulge}$ as high as $53° \pm 11°$). Cabrera-Lavers *et al.* (2007 [C07]) stress that, in the first quadrant the maximum stellar density along the line of sight does not in general coincide with the major axis of an ellipsoidal stellar distribution. For narrow features such as the long stellar bar the difference is slight, but for the bulge, the difference in distance could amount to as much as a kiloparsec. When this effect is corrected for, the uncorrected value for $\phi_{\rm bulge}$ reported in C07—$23.1° \pm 3.2°$—is lowered to $12.6° \pm 3.2°$ (for the boxy geometry reported by L05, C07 calculate $\phi_{\rm bulge} = 14.2^{+3.0}_{-3.5}$ deg). A further point to make here is that bulge properties should be studied by dealing with the $|b| < 1.5°$ region separately since the in-plane region of the bulge seems to have a different stellar distribution from that of the rest of the bulge. We emphasize that all the errors cited here for the opening angle of the bulge are purely statistical. Any attempt to derive the opening angle of the bulge is heavily fraught with unknown systematic errors. In reality, the value of $\phi_{\rm bulge}$ cannot yet be determined with certainty although it probably lies somewhere in the range 10°–35°.

† A Fredholm equation (see Trumpler & Weaver 1953) is a linear univariate integral equation of the form $F(x) = G(x)U(x) + \lambda \int_a^b U(y)K(x,y)dy$, where F, G and K are known functions, a, b and the parameter λ are constant, and U is the unknown function. For a Fredholm equation of the first kind, $G(x) = 0$. The function $K(x,y)$ is the "kernel" of the integral equation.

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3. The Long Stellar Bar

The above-described inversion techniques relied on separating the disc and bulge star counts so that the Galactic plane was avoided because of problems with spiral arms and patchy extinction. The opening angle of the boxy bulge (and that produced by simpler triaxial ellipsoids) agrees fairly well with the radio results for the inner ~2 kpc, ϕ being in the range 10°–35°. For $|b| < 1.5°$, however, the situation changes dramatically. Hammersley *et al.* (2000 [H00]), López-Corredoira *et al.* (2001 [L01], 2007 [L07]), Benjamin *et al.* (2005 [B05]) and C07 find that NIR source counts in the plane of the first quadrant reveal a difference in opening angle between the bulge and a further feature, which they conclude is a stellar bar extending beyond the outer limits of the bulge, that cannot be accounted for by the errors—the various opening angles of the stellar bar reported by these two groups being in close concordance ($43° \pm 7°$, H00; $44° \pm 10°$, B05; $43° \pm 1.8°$, C07). For a review of the literature on the long-bar hypothesis, see C07 and L07. Here, I concentrate almost exclusively on the work done on the long bar by the IAC team.

Hammersley *et al.* (1994), examined Two Micron Galactic Survey (TMGS) star counts and identified intense peaks in the counts along the Galactic plane at $l = 27°$ and $l = 21°$, which, they argued, could not be caused solely by anomalously low extinction. They used these peaks to determine the nature of the peaks in the DIRBE maps at $35° < l < 15°$, which they concluded were due to a barlike feature rather than to a ring or spiral arms. The intensity of the peak at $l = 27°$ suggested the possibility of an end-of-bar star formation region. Garzón *et al.* (1997) and López-Corredoira *et al.* (1999), determined from spectra taken at the 2.5 m Isaac Newton Telescope that a significant number of the sources were red supergiants. H00 revisited the long bar hypothesis, this time measuring the distance to several points along the bar using the red clump method with H–$(J-H)$ colour–magnitude diagrams, compiled from observations taken at the 1.52 m Carlos Sánchez Telescope (Teide Observatory, Tenerife) using the CAIN infrared camera. They found a revised bar opening angle ($\phi_{\rm bar}$) of $43° \pm 7°$. Similar results were obtained by Picaud, Cabrera-Lavers & Garzón (2003), who used the same equipment but with $K_{\rm s}$–$(J-K_{\rm s})$ colour–magnitude diagrams and simulations from the Besançon model of the Galaxy (Robin *et al.* 2003), and by L01, using the DENIS survey (this time covering the southern part of the Galactic plane). L01 set the far end of the bar at $l = -13°$ and interpreted a solitary strong peak at $l = -22°$ as a stellar ring, or pseudo-ring, seen tangentially (corresponding to the so-called 3 kpc ring—actually a 4 kpc ring). The north–south asymmetry in the star counts found by L01 using DENIS was confirmed by B05 using the more sensitive GLIMPSE.survey They detected 25% more sources in the north but did not explore the plane in the longitude range $|l| < 10°$. L01. With the Two Micron All Sky Survey (2MASS), which covered the entire plane, L01 found a very clear N–S asymmetry in the star counts for $K_{\rm s} < 9.0$ mag for the region $|b| < 0.25°$, $|l| < 30°$ and confirmed an earlier claim by Calbet *et al.* (1996) of heavier extinction at negative l.

The N–S asymmetry is particularly evident in *MSX* $m_{8.7\,\mu{\rm m}} < 6.0$ mag source counts for $|b| < 0.5°$ (see figure 2 of L07). There is a clear plateau that slopes downwards from $l = 27°$ to $l = -13°$ and a prominent peak at $l = -22°$ (which they interpret as the elliptical ring seen tangentially). Interestingly, between the negative-l end of the bar and the $l = -22°$ peak, the counts drop almost to disk level, indicating an absence of stars. The bulge+bar+truncated inner disc model proposed by C07 is summarized in their figure 21. L07 calculate a size for the long bar of 7.8 kpc × 1.2 kpc × 0.2 kpc. They estimate the star density (for $M_{K_{\rm s}} < -6.1$ mag) of around 7.5×10^{-5} pc^{-3}, about a third that of the bulge (assuming similar populations for both components).

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González-Fernández *et al.* (submitted), took low resolution ($R = 500$) HK_s spectra of selected sources at $l = 7°$, $12°$, $15°$, $20°$, $26°$ and $27°$ ($b = 0°$), using the 3.7 m Telescopio Nazionale Galileo (La Palma, Spain). They derive the metallicities of the sources from the Na I, Ca I and CO equivalent widths in the K_s spectra, using the empirical scale for luminous red giants obtained by Ramírez *et al.* (2000) and Frogel *et al.* (2001). At $l = 7°$ the mean metallicity corresponds to that of the bulge (e.g. Mollá *et al.* 2000), whereas for the most external fields ($l = 26°$ and $l = 27°$) the mean metallicities are closer that of the inner disc (e.g. Rocha-Pinto *et al.* 2006). For intermediate longitudes, there is a steady decrease towards the bulge between these two extremes. González *et al.* interpret this metallicity distribution as further evidence for the existence of a long stellar bar bridging the inner disc and outer bulge. The combination of long stellar bar and triaxial/boxy bulge seems to be fairly common among barred galaxies.

In summary, the boxy bulge and long stellar bar are misaligned and the bar is contained in an elliptical ring. De Vaucouleurs & Pence's (1978, see their figure 6) suggestion that the Galaxy is of morphological type SAB(rs)bc II might not be too wide of the mark.

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