Near infrared star counts as a test of Galactic bar structure

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ABSTRACT

We present survey data in the narrow-band L filter (nbL), taken at UKIRT, for a total area of 277 arcmin\textsuperscript{2}, roughly equally divided between four regions at zero Galactic latitude and longitudes $\pm 4.3^\circ$ and $\pm 2.3^\circ$. The 80 per cent completeness level for these observations is at roughly magnitude 11.0. This magnitude limit, owing to the low coefficient for interstellar extinction at this wavelength ($A_{\text{nbL}}=0.047A_V$), allows us to observe bulge giants. We match the nbL-magnitudes with DENIS survey K magnitudes, and find 95 per cent of nbL sources are matched to K sources. Constructing colour-magnitude diagrams, we deredden the magnitudes and find evidence for a longitude dependent asymmetry in the source counts. We find that there are $\sim 15$ per cent and $\sim 5$ per cent more sources at the negative longitude than at the corresponding positive longitude, for the fields at $\pm 4.3^\circ$ and $\pm 2.3^\circ$ respectively. This is compared with the predictions of some Galactic bar models. We find an asymmetry in the expected sense, which favours gas dynamical models and the recent deconvolution of surface photometry data (Binney et al. 1991; Binney, Gerhard & Spergel 1997), over earlier treatments of photometric data (e.g. Dwek et al. 1995).

Key words: Galaxy: stellar content – ISM: dust, extinction – Galaxy: structure – Stars: statistics – Stars: infrared – Galaxy: bar – extraterrestrial intelligence

1 INTRODUCTION

An extremely dense stellar cluster and probable bar dominate the central kiloparsec of the Galaxy. This cluster may be the remnant of a core about which the galaxy grew or may be the product of a long-lived bar in the disk feeding gas into central star forming regions. Neither its history and nature, nor its relationship to the bulge, halo and disk are well known.

As an example, the cluster changes its luminosity density profile by 2 in the power law index in some unobserved region between the central few arcsec and the optically observable region some degrees away.

How and where? And are more complex spatial distributions possible? For example, in M31, the nearest similar spiral, the central region shows two luminosity maxima, neither of which corresponds to the centre of the larger scale gravitational potential, or is understood. (van der Marel et al. 1997)

In practice, to observe the central regions of our own Galaxy, because of the high extinction in the disk in the line of sight, it is necessary to work at infrared wavelengths, at which the dust is more transparent, or to use wavelengths very different from optical wavelengths where dust does not impede out view (e.g. radio frequencies). In the former case, we use stars as tracers of structure, and in the latter case, we trace gas, or young stars with associated HII regions.

In doing this, many studies have suggested the existence of a central kiloparsec-scale bar. Gas dynamical data has been used by Binney et al. (1991) and Blitz & Spergel (1991) to derive the existence of a bar with its long axis pointing towards the first quadrant ($\ell > 0$). In terms of near infrared surface photometry, the measurements made by the COBE satellite have been the most extensive. The DIRBE instrument on board mapped the whole sky at near to far infrared wavelengths from 1.25 $\mu$m to 240 $\mu$m using the DIRBE with a beam of 0.7 $\times$ 0.7$^\circ$.

This data has been used, among others, by Dwek et al. (1995) whose best fit model suggests a boxy-bar in the centre of our Galaxy with an inclination of about 19$^\circ$ to our line of sight, the long axis again being in the first quadrant. The latest and most sophisticated use of the DIRBE data has been by Binney, Gerhard & Spergel (1997), who do a full three-dimensional deconvolution of the apparent light intensity and dust distribution. Binney, Gerhard & Spergel (1997) also find a bar with its long axis in the first quadrant, inclined at about 20$^\circ$. This is near the limit of what is possible with surface photometry data of low spatial resolution, as demonstrated recently by Zhao (1997).

Other investigations have used tracer populations to
constrain the nature of the bar - for example, Weinberg (1992) and more recently Nikolaev & Weinberg (1997) use IRAS source to confirm that there is a large scale asymmetry in their distribution, consistent in geometry with a bar-like structure.

Any bar-like structure will be centrally concentrated, and a relatively small survey concentrating on sources near the centre will have enough statistical weight to show up longitude dependent asymmetries, if they exist. The only moderately sized, multicolour, higher resolution survey, covering about $2^\circ \times 0.5^\circ$ around the Galactic centre, is by Catchpole, Whitelock and Glass (1990). It was performed in the J, H and K bands up to a limiting magnitude of K=12. While almost the entire J map was dominated by heavy interstellar extinction, those at H and K show progressively more detail of the inner region. They show clear changes in spatial structure for different populations, suggesting that analysis of low resolution data will necessarily be problematic.

For the galactic centre this means that M and late K giants can be reached in K but not at the shorter wavelengths as the extinction will be too strong (up to 5 magnitudes in J [Catchpole, Whitelock & Glass 1990] leading to an expected apparent J magnitude of $\approx 16.5$ mag; [Wainscoat et al. 1992]). We also expect that essentially all I and most J objects seen in the plane will be disk objects.

Recently, a high resolution survey in near infra-red bands called DENIS (Deep Near Infra Red Southern Sky Survey) has been initiated. It aims to map the whole of the southern sky in J,K and with 3 arcsecond pixels. (Epchtein 1997; Fouqué et al. 1997). The calibration and flat-fielding of images is reported in Borsenberger (1997), and the source extraction and astrometry that we use come from the accompanying paper 1 (Unavane et al. 1997). In that paper we reported techniques for removing the effects of foreground disk asymmetries in the colour-magnitude diagrams, and used a statistical approach to understanding asymmetries. The usefulness of the three wavebands was somewhat limited since only K reliably penetrates the densest dust regions in the plane towards the centre of the galaxy. A source by source dereddening - necessary because of the high spatial frequency structure in extinctive clouds - was not possible.

Here we present complementary nbL data taken at UKIRT, which match to DENIS K data. A source by source dereddening is carried out, from which we deduce the existence of central longitude asymmetries consistent in direction with some Galactic bar models.

We present first the high-quality 1996 data, and subsequently a brief description is given of the problematic 1995 data.

2 THE OBSERVATIONS

The locations of the regions observed in nbL are indicated in figure 3. Also indicated on this figure are the DENIS rasters for the region. The region enclosed by the dotted box shows the set of UKIRT observations made in July 1995, which were severely affected by a fault in the data acquisition software. The regions observed in July 1996 achieved the expected magnitude limits and were reduced using standard techniques. For comparison, the beamsize of the COBE/DIRBE survey (0.7”) is shown in the same figure.

2.1 Why nbL (3.6 μm)?

From the colour magnitude diagram in figure 2.1, it can be seen that by far the brightest sources are the late type III sources (i.e. M giants), which reach absolute L magnitudes of about 0.7. If we assume the distance to the centre of the galaxy to be 8kpc, this corresponds to an apparent magnitude at that distance of 7.5. The extinction coefficient in nbL (3.6μm) is only $\approx 40$ per cent of the value in magnitudes present at K, and $<5$ per cent that at V. Thus, using an estimate of 1.9 magnitudes of extinction per kpc in the disk at visual magnitudes (Schmidt-Kaler, 1976), the above magnitude is increased to about 8.4. Assuming a limiting magnitude of 12 in the nbL observations, this suggests that source as faint as $m_{L} = -3.4$ should be detected (i.e. all bright K giants and all M giants should be detected).

In addition, as explained in the next paragraph, this wavelength regime is a bridge between shorter wavelength surveys (I,J,K) and longer wavelength surveys (7μm, 15μm) which are being carried out near-simultaneously.

Furthermore, and a not unimportant factor when observing from the surface of the Earth, the atmosphere has a transparent window at this wavelength.

2.2 Choice of fields for observation

Part of the mission of the ISO spacecraft, launched in November 1995, was to map selected regions of the Galactic Plane at 7μm and 15μm. The project, called ISOGAL, has provided and will continue to provide, high resolution (6 arcsecond pixels) images which penetrate deep into the Galactic Plane, by observing at these wavelengths where extinction by dust is very small. The choice of nbL fields is made so as to coincide with some ISO fields, since the amount of information about an astronomical source can be increased manifold with colour information.

Furthermore, the DENIS survey is producing images in I,J and K, for the whole of the southern sky, which includes all of the Galactic Plane within several tens of degrees of the centre. (see Epchtein 1997; paper 1). The nbL observations also have full coverage at these DENIS wavelengths, again allowing invaluable colour information to be deduced.

Also, following on from paper 1, we choose fields at equal and opposite longitudes at a given latitude to test for longitude asymmetries in the inner disk/bulge. The expected maximum contrast for most Galactic bar models falls between $4^\circ$ and $6^\circ$ in longitude - fields for observations in this region would be best at discriminating models.

Furthermore, to avoid corresponding positive and negative longitude pairs with very different extinctions in the line of sight, we choose fields with similar intergrated luminosities in the J and K bands, and hence in (J-K) colour also. These wavelengths sample dust extinction in the line of sight in the disk, and it is to minimize these asymmetries that we make our choice. We base this on the COBE/DIRBE maps by choosing equal and opposite longitude pairs which most
nearly show the same fluxes and colour. Figure 2.2 shows the J,K and (J-K) contours for the central few degrees of the Galactic bulge. The chosen fields for observation are marked by asterisks, and some contours are emphasized to show that they pass as nearly as possible, given the various other constraints, through these fields.

3 THE 1996 OBSERVATIONS

An enlargement showing the pattern of the 1996 observations is indicated in figure 3. The area of each field was calculated by noting the perimeter points and applying the formula for the area of a region bounded by n given, ordered perimeter points \((x_i, y_i)\) (where \((x_{n+1}, y_{n+1}) \equiv (x_1, y_1)\)):

\[
A = \frac{1}{2} \sum_{i=1}^{n} \left| x_i y_{i+1} - x_{i+1} y_i \right|
\]

The correction for spherical geometry is negligible for fields of this size.

3.1 At the telescope - data acquisition

The observations were carried out at UKIRT during the first half of each night on 3rd and 4th July 1996, during photometric conditions. Cloud coverage prevented further observations.

The instrument used was IRCAM3 (Infra Red Camera). IRCAM3 is a cooled 1-5μm camera with a 256 × 256 InSb array. The basic plate scale is ~0.286 arcsec per pixel, giving a maximum field of 73 arcsec. Standard J,H,K, nbL, L' and narrow band M photometric filters are available for use. In these observations, the nbL filter was chosen (narrow band L). The central wavelength of this filter is 3.60μm, with a FWHM of 0.06μm. The profile is shown in figure 2.1.

The mode of observation, which had been tested in the previous run in July 1995 (see below), was adopted. The mode allowed us to achieve a limiting magnitude of nbL ~ 12-13. A major difficulty, and one which becomes more difficult as the wavelength is further increased above 3.6μm, is the very high sky background level, caused primarily by a blackbody-type emission from the sky, upon which are superimposed sky emission lines.

For example, the peak pixel value of an 8th magnitude source is no more than 140 counts in the typical exposures that we use, over a background count of about 40000. This is a signal of only a few parts in a thousand, thus requiring a very precise sky subtraction. As can be seen, a long stare mode observational technique would immediately saturate the detectors, and no signal from the sources would be seen.

The adopted method of observation was as follows:

- Each raster of observation consisted of a slightly-overlapping grid of 3 × 3 images, and was preceded by one dark frame.
- Each of these images is the sum of 167 exposures, each of 0.12 second duration. The short duration of each individual exposure is essential to avoid saturation of the detector. Hence, the total exposure time per image was 20.04 seconds.

The individual exposures are not delivered, but are coadded by an on-line transputer array (ALICE) and the final image is delivered.

The time taken for the observations associated with each raster was about 10 minutes, after taking account of the overhead times in multiple detector readouts, and telescope slewing.

Furthermore, at regular times during the observing period (in our case, after every 3 rasters) a standard star raster was taken, which consisted of 5 images, each image taken in just the same way as above, and an associated dark frame. The chosen standard star was HD161903, which has an nbL magnitude of 7.00, at \((\alpha_{2000}, \delta_{2000}) = (17^h45^m43.3^s, -1^o47'34'')\) or \((l, b) = (23.64, 13.73)\).

The observing pattern is indicated in the sketch in figure 3.1. The resulting data taken away from the telescope thus consisted of several rasters, each containing 9 images, and a dark frame associated with each one. In addition, several standard star rasters, consisting of 5 dithered images and associated dark frame, are also taken.

3.2 At the computer - data reduction

A standard technique for reducing this data was employed. Below is the procedure adopted for each raster:

(i) Dark subtraction - from each image in a raster, the dark frame was subtracted.

(ii) A flat field image was created by median-filtering the set of 9 object images. (5 images in the case of the standard star) The technique of using a "sky" frame devoid of sources fails in these crowded Galactic centre regions. The flat field image is divided by the median of all the pixel values in it, to normalize it.

(iii) Flat fielding - the dark subtracted images are divided by the normalised flat field image.

(iv) Pretty picture production - the 9 images can be mosaiced to form a pretty picture for display purposes.

(v) Source extraction - all images were filtered using a moving block median, and sources more than 2.3σ above the background noise were flagged, by use of the SExtractor program (Bertin & Arnouts 1996). The photometry was then carried out on the unfiltered images by using a 7 pixel radius aperture for the source, and an annulus between 7 and 11 pixels from the source centre for the sky background to be subtracted from it.

(vi) Airmass correction - using the airmass information in the header, and the standard value for the airmass correction at the UKIRT site (0.09 magnitudes per airmass), all the raw magnitudes were corrected.

(vii) Absolute photometry - the corrected standard star photometry was used to determine the offset between instrumental and true magnitude. The correction was applied to all extracted sources. A very stable mean zero point of 18.78±0.03 magnitudes was derived.

(viii) Approximate astrometry - The positions of sources were calculated assuming that the pixel scale was 0.286 arcseconds per pixel and by using the header information about the image centres.
(ix) Absolute astrometry - see below

Table 5.3 shows the numbers of sources found in each of the fields.

### 3.3 Photometric error and completeness

The random uncertainty in magnitude was assessed empirically by comparing the magnitude of the same object when it appeared fully twice (or more) in neighbouring images. Figure 3.3 shows, in the upper panel, the difference in magnitude between measurements of the same object from overlapping images. A clipped gaussian was fitted to the distribution in several magnitude ranges for this diagram, to give values \( \sigma_{m_1-m_2} \) representative of this random scatter in magnitude differences. This \( \sigma \) represents the standard deviation of the difference of two like distributions. Hence the standard distribution for individual magnitude measurements is given by \( \sigma_m = \sigma_{m_1-m_2}/\sqrt{2} \). The result is shown in the lower panel of figure ??.

Completeness was assessed by the addition of artificial stars to the images. Two images were used - one from the first of the two nights of observation which was judged by eye and by image background statistics to be particularly noisy after reduction, and one from the second of the two nights which was judged to be particularly clean. The ellipticity, orientation, and full-width at half-maximum values for the stellar sources were averaged for each image, and used to create artificial stars with these same parameters. In each case, magnitudes for artificial stars ranging from 10.00 to 13.50 in 0.25 magnitude intervals were used, with never more than 25 artificial stars being added to each image. Hence, a total of 30 modified images were created (15 for each original image), and were each reduced in the same way as described above for the untouched images.

The fraction of retrieved images for each magnitude range is shown graphically in figure 5.3. The fall below 90 per cent completeness occurs for both images at about magnitude 11.0, with a difference of no more than 0.25 magnitudes between the two images. Unlike the DENIS images (paper 1), there is essentially no problem with crowding in these fields, since the pixel size used is small (0.286 arcseconds) and the sources are seldom within a few arcseconds of one another. As a result, there is little difference in completeness levels if the positional tolerance of matches of recovered images is made tighter, or looser.

### 3.4 Absolute positions

An absolute reference frame was established by the use of a source extraction of a plate scan matched to GSC stars. (See paper 1). This optical reference frame cannot be applied directly to the L band images, because in the directions of high extinction towards which the fields lie, it is impossible to establish with any certainty in which the L sources in the images (which usually number at most a dozen) correspond to optical sources. Moreover, despite the generous overlaps between images, expected to enable a precise mosaicing to be carried out, there remain problems in very many of the images due to random telescope motions which cannot be corrected because of a lack of common sources in the overlaps.

The method finally employed to fix the positions involves the use of the DENIS results in the same regions. For each of the nbL fields, we have corresponding DENIS I, J and K images (see figure 5.2). A "step-up" method can be used. The sufficient similarity in sources between 0.6\( \mu \)m and 1.25\( \mu \)m can be used to match up optical and J images. This puts the J images on the same astrometric reference frame as the optical images. From there, the K images can be mapped onto the J images by source matching, and finally the nbL sources can be matched to the K sources.

This final procedure was carried out by eye for each of the 288 images in the 1996 observations.

### 4 THE 1995 OBSERVATIONS

The observations were obtained during the first 1996 half of the nights of 7, 8 and 9 July 1995, at UKIRT using the narrow-band L filter. Reference is made to these observations in an earlier article (Unavane & Gilmore 1997).

Five regions were imaged in the same manner as for the subsequent 1996 observations. The pixel size was 0.286 arcseconds, and the exposure time for each image was a total of 20 seconds. The flat fielding was not carried out in the standard way, due to technical difficulties which plagued the acquisition transputer array. Furthermore, two out of the three half-nights allocated were marred by thin cloud. The electronic noise in the image consisted of both systematic pixel value shifts and random noise. Each image was inspected for the nature of the systematic shifts, and an attempt was made to interpolate over such rows and columns using "good" neighbouring data. The small pixel size helped to retain adequate resolution nevertheless. The density of cloud was empirically corrected for by finding a correlation between the sky background and the varying apparent magnitude of the standard star.

The magnitude zero points were taken from observing the standard star HD161903 as in the 1996 observations. Perhaps unsurprisingly, the completeness and photometric precision were below expectation. A limiting magnitude of about 9.5 was achieved for the nights when electronic faults dominated uncertainties, and of about 11.0 when only cloud dominated the uncertainties. Random photometric scatter was estimated by comparing the magnitudes obtained from neighbouring images. Scatter of up to 0.5 magnitudes is present in most of the observations. It is interesting to note that the empirical method of correcting for cloud, though it may have severe systematic uncertainties associated with it, seems to work better than the method for correcting electronic noise.

The locations, and labels for the regions are given in table 1. Also included are the area of the fields, and an indication of the relative numbers of sources per unit area in the fields. The number counts are shown in figure 5.2.

Apart from noise at bright magnitudes due to low number statistics, the populations appear to follow similar trends, until nbL > 8.5 where the fields A, C and E, show a significant excess. This may plausibly be due to regions of lesser extinction in these fields. The final col-
umn in Table 1 gives the number count as log(\(\text{number of sources/magnitude/deg}^2\)) interpolated to L=7.5 after a linear fit between 6.0 and 9.0. The central field, A, has a significantly higher count, by about a factor of two, than the other fields.

5 ANALYSIS

5.1 Extinction coefficient

The extinction coefficient associated with this filter may be calculated by convolving its profile with the reddening curve. Using the parametrization of the reddening curve of Mathis (1990) between 1.0 \(\mu\)m and 3.8 \(\mu\)m in paper 1 (\(\frac{\Delta(2)}{A_V} = 1.484 - 5.60109x + 8.395624x^2 - 4.5947083x^3\) where \(x = log(\lambda/\mu\text{m})\)), we find that the coefficient is given by \(A_{\text{nlL}} = 0.047A_V\). Convolving in the UKIRT sky makes no appreciable difference, since this part of this region of the infrared spectrum is relatively free of strong lines. Compared with DENIS-K, for which the value is \(A_K = 0.112A_V\), we see that the extinction is only \(\sim 40\) per cent of the K-value in the band nbL, and \(< 5\) per cent of the value in the visible.

5.2 The 1995 observations

We note that the 1995 fields B and C, which are at latitudes of \(\pm 1\)° and \(\pm 1.5\)° respectively, show a significant difference in counts, with the field at \(\ell = -1\)° being more populous by a factor of \(\sim 1.6\), and that the fields D and E, which we would expect to show number counts falling off steeply, as \(R^{-1.8}\) (King, 1989), have a very similar number count.

In both cases, extinction along the line of sight may play a crucial role. Calculation shows that in the former case, in order to make the regions B and C display comparable counts would require a relative shift in L of \(\sim 0.7\) magnitudes, which corresponds to a difference in extinction, in the visual band, between the two lines of sight of \(\Delta A_V \sim 12\). For the latter case, on integrating along the line of sight the expected \(R^{-1.8}\) bulge distribution, we would predict number counts different by a factor of \(\sim 2.3\), corresponding to \(\Delta A_V \sim 11\).

These values of \(\Delta A_V\) of \(\sim 12\) correspond to differential reddening \(\Delta(J - K) = 2.0\) and \(\Delta(K - L) = 0.6\), using the values of \(A_X\) derived above. These values are large enough to be tested by multicolour observations in the various fields, in order to disentangle the effects of reddening from those of stellar distribution.

5.2.1 Combining with DENIS-K

We use the photometric and astrometric reductions of DENIS data described in paper 1. Only data in regions B and E contained sufficiently reliable images suitable for matching to DENIS data. The matching between sources led to only 26 per cent and 18 per cent matches in regions B and E respectively, reflecting the poor quality of data acquired in this run. Compare this to the 1996 data where \(\gtrsim 95\) per cent of L sources are matched with K sources (see later). No attempt was made to understand the selection effects in this matching.

The resulting colour magnitude diagrams are shown in figure 5.2.1.

By tracing a fiducial colour-magnitude (K-nbL)-(K) locus for K and M giants placed at a distance of 8 kpc (Garwood & Jones 1987), we can estimate the extinction to the sources. This method assumes that the objects are all bulge objects, and that they are all giant stars. A rough calculation based on a recently derived photometric model of the galaxy by Binney, Gerhard & Spergel (1997) suggests that inward of 3kpc from the centre, no more than 12 per cent of sources are disk sources (see paper 1). Each source can be traced back along a reddening vector to the fiducial locus.

Figure 5.2.1 suggests a near constant extinction for region E of \(A_V\) between about 10 and 15, bearing in mind the large scatter in the L-band photometry for this field. In the case of region B, however, we clearly see a larger spread of extinction values between \(A_V = 5\) and \(A_V = 35\). The field-size for these K and L sources is only some tens of arcmin², yet even on that scale, there is a wide range of extinction present. Mapping this extinction suggests an essentially random distribution in this region.

This is consistent with the known molecular cloud distribution near this region. (Liszt, 1988). Sgr D, centred near \((\ell, b) \sim (1.1°, -0.1°)\), has a concentration of molecular gas in its vicinity, as does Sgr B (centred near \(0.6°, -0.1°\)) and the overlap of these molecular cloud regions undoubtedly leads to the surprisingly patchy extinction pattern.

Nevertheless, these admittedly poor quality observations serve to indicate that although the technique of dereddening sources by using multi-band observations is conceptually simple, the direction of the fields must be carefully chosen to avoid regions such as region B which have very different reddening on scales of a few tens of arcminutes.

For the 1996 observations, fields were chosen which were further out, to avoid the worst Galactic centre molecular cloud complexes, and allow a better characterisation of the stellar distributions.

5.3 The 1996 observations

Figure 5.3 shows the resulting number counts for the four regions at \(\ell = +3°\), \(\ell = +2°\), \(\ell = -2°\), and \(\ell = -4°\). The raw counts in each case are given in panel (a). It is clear that there is no large difference between number counts at like positive and negative longitudes. Panel (b) shows the same data corrected for incompleteness according to the completeness levels derived in the previous section. The completeness level used was equal to the mean of the completeness levels derived in the two separate experiments indicated in figure 3.3.

Absolute astrometry and cross matching to DENIS K data were carried out as described above. In establishing the absolute positions of the sources, a cross-matched catalogue of the L and K sources was made. More than 95 percent of sources detected in L were matched by sources in K.
6 REDDENING CORRECTIONS

The almost complete matching between K and L sources suggests that the K band observations penetrate as much of the dust as do the L band observations. Since the extinction coefficient in L is less than half that at K, we deduce that the central bulge, which dominates the source counts, is reached in both bands.

Plotted in figure 1 are the resulting colour-magnitude diagrams. Shown in each case, as dotted lines, is an unreddened giant branch displaced to a distance of 8kpc. The differences in reddening along the line of sight to these fields, and within the fields are clearly seen. The fields at \( \ell = 4^\circ \) and \( \ell = -4^\circ \) suggest that extinction is greater by some 0.6 in K-L (9 in \( A_V \)) at \( \ell = 4^\circ \) by comparison of the location of the observed giant branches. The fields at \( \ell = +2^\circ \) and \( \ell = -2^\circ \), on the other hand, show more nearly similar observed mean giant branch colours.

A simple approach to assessing number counts unaffected by reddening is to trace back points in the (K)-(K-nbL) diagram so that they lie on the fiducial giant branch. Thus, for each source, a value \( A_{K-nbL} \) is established by tracing back along the reddening line until the giant branch locus is reached. This value of \( A_{K-nbL} \) is converted to a value \( A_{nbL} \) using \( A_{nbL} = 0.723A_{K-nbL} \).

These dereddened number counts are shown in figure 1. Points at the incomplete, fainter magnitudes are included weighted by the completeness function. All points which would give a negative value for \( A_V \) are rejected. These account for \( \lesssim 10 \) per cent of the sources, and can be attributed to photometric and/or matching errors. The results for the mid-magnitude bins are shown in table 1.

7 BAR STRUCTURE

A bar-like structure in the central regions of the Galaxy would show up as a positive longitude /negative longitude asymmetry. Most bar models to date agree roughly as to the orientation of the bar in suggesting that the nearer end is in the quadrant \( \ell > 0^\circ \). This means that the counts are higher at small negative longitudes (\( |\ell| < 6^\circ \)) than at the corresponding positive longitudes due to the geometry of the viewpoint. For the Dwek et al. (1995) models the percentage difference in surface luminosity from the bar, assuming no extinction, reaches a maximum value in this region at \( \sim 4^\circ \), when the flux from negative longitudes is greater by \( \sim 30 \) per cent than at the corresponding positive longitude. The value is reduced to about \( 20 \) per cent greater at \( \ell = \pm 2^\circ \).

Figure 2 shows the values of table 1 value superposed on the diagram of bar asymmetries in number counts expected for the various bar models. Note that the asymmetries which are shown in figure 2 are not direct photometric asymmetries, but rather the asymmetries resulting from a numerical integration using the models derived from photometry. They are number count contrasts expected for tracer populations. For our observations, which do not extend beyond \( \ell = \pm 4.3^\circ \), the difference in distance modulus to the two sides of the bar that we see is typically less than a few tenths of a magnitude, and we use the nbL-band number counts as a tracer population.

Note also that the photometric models we use for comparison are derived from observations at higher latitudes than the ones at which we are observing, where the reddening is lower, which inevitably means that they are more reliable there. Derivation of bulge structure from these data in the mid-plane, where uncertainties in the removal of effects due to dust are greater, are less reliable, which emphasises the value of resolved number count studies such as this one.

In all of these directions, close as they are to the disk plane, there will be contamination by disk sources. We make an estimate based on the Galactic model of Binney, Gerhard & Spergel (1997) for the contrast between disk and bulge in the inner disk. For sources inward of 3kpc from the centre, observed from the sun, and for longitudes of \(< 5^\circ \), the number count contrasts vary strongly only with latitude (because of the thinness of the disk), and are typically 10–12 per cent for \( |b| < 0.1^\circ \). The actual central asymmetries are thus likely to be greater than those seen here (by about 2 and 4 percentage points at \( \ell = \pm 4^\circ \) and \( \ell = \pm 2^\circ \) respectively) due to the diluting effect of the disk. We thus find that we favour the photometric model of Binney, Gerhard & Spergel (1997) and the dynamical models of Binney et al. (1991) and Blitz & Spergel (1991) over the Dwek et al. (1995) photometry.

L band imaging clearly has the potential to penetrate regions of severe extinction - visual extinction of \( A_V = 30 \) magnitudes becomes only \( A_{nbL} = 1.4 \). Regions near the centre of the galaxy are obscured by patchy extinction clouds with \( A_V \) as high as \( \sim 40 \). In order to more fully study these regions, multiband K and L band imaging will be important, to disentangle the extinction patterns from the distribution patterns; even J and H observations can suffer too much extinction in some of these regions to allow reliable source detection. As we show, a nearly complete match can be made between L objects and K objects down to limiting magnitudes of about 11, suggesting that both bands penetrate sufficiently to see as many sources as there are to be seen.

Moreover we see an asymmetry consistent with bar models. Although the statistical weight of our results is poor (we achieved less than half the survey observations in nbL that we were hoping for) we show that this method - of surveying in K and L bands - does allow the central regions of the Galaxy to be reached reliably in the plane.

To date, derivations of bar structure have depended on observations well out of the plane due to the overwhelming problem of patchy extinction. We show that with suitably penetrating wavelengths (K and L), direct evidence in the Galactic plane of dereddened number count asymmetries can be found. Direct determination of the spatial structure of the inner Galaxy is feasible with this technique.

* For the Dwek et al. (1995) models, we use their ‘best-fit’ models

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E3 and G2, which come from the fit to 2.2μm surface intensity, with an imposed radial 2.4kpc cut-off.
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