

The bulge luminosity functions in the MSX infrared bands

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Abstract. We use an inversion technique to derive the luminosity functions of the Galactic bulge from point source counts extracted from the Midcourse Space Experiment’s Point Source Catalog (version 1.2).

Key words. Galaxy: stellar content – Galaxy: structure – infrared: stars

1. Introduction

Information in the mid-infrared about the stars of the bulge has, until now, been restricted to the exploitation of IRAS data (e.g., Wainscoat et al. 1992). The new Point Source Catalogs (Egan et al. 1999) from the Midcourse Space Experiment (MSX; Mill et al. 1994, Johns Hopkins APL Technical Digest 1996, Price et al. 2001) provide far better spatial resolution, which considerably lessens the confusion due to high source density, and provides space-based satellite observations in six well-characterised filters. In the present paper we use the MSX data to analyse the stellar populations of the Galactic bulge in terms of their luminosity functions (LFs).

The MSX Point Source Catalogs (version 1.2, hereafter PSC1.2, obtained from NASA/IPAC) contain almost one third of a million sources confined solely to the domain $|b| < 5^\circ$, providing valuable probes of the bulge. Egan et al. (1999) provide detailed documentation for the PSC1.2. We have, in all cases, dealt only with sources of the highest quality (quality flags 3 or 4). These yield the most accurate radiometry and are unconfused.

Normally, the LF is measured in small regions of sky, such as Baade’s Window, assuming equal distance for all stars, but this is a poor approximation since it does not take into account the range in distances. Instead, we apply a technique developed by López-Corredoira et al. (2000) to deconvolve the density distribution and the luminosity function over wide areas that cover the bulge. We can derive stellar statistics from a large sample of stars and can calculate a rather accurate LF.

2. Luminosity functions

Using the inversion algorithms for the bulge’s stellar statistics equation on an infrared sky survey of fields towards the centre of the Galaxy, it is possible to obtain information about both the LF in the corresponding filter as well as the stellar density distribution. Once star counts are measured for each region, these can be inverted, producing as a result the density distribution along the line-of-sight and the LF. We refer the reader interested in the methodology to the complete explanation given by López-Corredoira et al. (2000) and outlined by López-Corredoira et al. (1997, 1998), who applied the procedure to K counts drawn from the Two Micron Galactic Survey.

In the present paper, instead of subtracting the star counts due to the disc using a model of the Galaxy, we evaluate it in the central regions from an extrapolation of the star counts in outer regions. Specifically, we used the region $(30^\circ - |b|) < |l| < 90^\circ$, $2^\circ < |b| < 5^\circ$, where the disc is the only component along the line-of-sight, to evaluate the disc star counts by fitting bi-cubic polynomial functions in the variables of Galactic longitude and latitude. The least-squares fits to the star counts for each magnitude and in each filter were carried out using the “E02DDF” routine of the NAG (1997) library. We extrapolated these functions into the central regions and subtracted them from the total star counts. By doing this, we remove the disc component and, because the bulge is defined as the excess over the extrapolation of the disc in the central regions of a galaxy, the star counts due to the bulge are the natural outcome of this operation.

We use only off-plane regions ($|b| > 2^\circ$) to avoid contamination by the spiral arms and other potential coplanar components such as a bar or the molecular ring. With the bulge star counts in the region within $|l| < (12^\circ - |b|)$, $2^\circ < |b| < 5^\circ$ (102 deg²), we derive the LFs for the four long-wavelength MSX bands with isophotal

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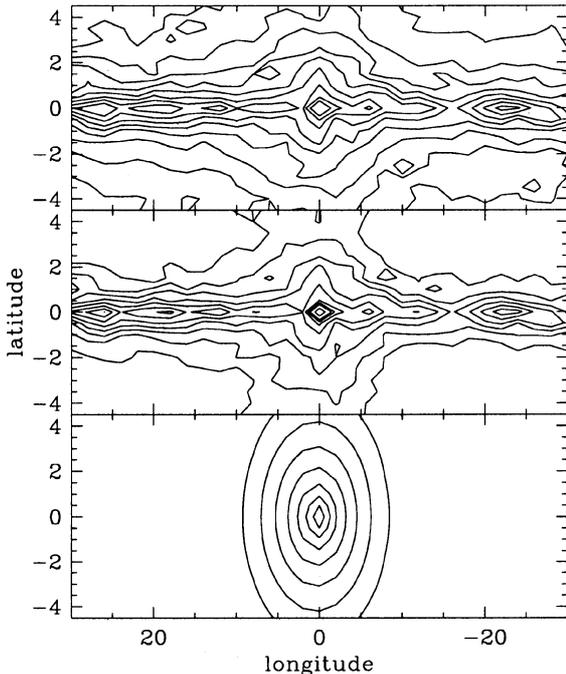


Fig. 1. Up: star counts in “Band-A” of MSX up to magnitude 5.4; contour step is 30 star/deg², first contour at 30. Mid: same star counts once the disc was subtracted; same contour step. Down: bulge, according to the inversion of the star counts, projected in the sky; same contour step. As can be observed, the asymmetry and other features agree with the result of the inversion in off-plane regions

wavelengths (λ_{iso}) of 8.28 (“A”), 12.13 (“C”), 14.65 (“D”), and 21.33 μm (“E”). Extinction is neglected in this region for these bands. The procedure could not be carried out for MSX’s short-wavelength narrow bands near 4.3 μm (“B₁” and “B₂”) because too few sources are detected to make adequate fits to the disc to remove this contaminant from the bulge by extrapolation.

The ranges of magnitude used for each of the four bands are shown in Table 1, along with the definition of in-band flux for zero magnitude. The limiting magnitude for completeness in the star counts is the upper limit of the selected range.

The stellar density distribution is obtained by inversion only for the band which provides the highest number of stars, i.e. that at 8.28 μm , and this density is used to obtain the LF in all bands by inversion. The density distribution by inversion is a posteriori fitted to a triaxial ellipsoid of axial ratios 1:0.36:0.23 with centre 8000 pc from the Sun, minor axis perpendicular to the plane, major axis in the plane, pointing nearly to the Sun with a small inclination of ~ 4 deg towards the first quadrant, with a density of stars

$$D(t) = K(t/3800)^{-0.9} \exp(-(t/3800)^{5.7}) \text{ star pc}^{-3}, \quad (1)$$

for t between 1500 and 4000 pc

$$t = \sqrt{x^2 + K_y^2 y^2 + K_z^2 z^2}$$

Table 1. Range of magnitudes used in the inversion for each filter and total number of stars due to the bulge, i.e. once the disc was subtracted, in the selected region: $|l| < (12 \text{ deg} - |b|)$, $2 \text{ deg} < |b| < 5 \text{ deg}$

Band	λ_{iso} (μm)	0^{m} irradiance (W cm^{-2})	Range used (mag)	Bulge stars
A	8.28	8.196E-16	2.0 to 5.4	4116
C	12.13	9.259E-17	0.0 to 3.0	1286
D	14.65	5.686E-17	0.0 to 3.0	1519
E	21.34	3.555E-17	-1.0 to 1.2	888

where x, y, z are the three axis; $K_y = 2.8$, $K_z = 4.4$ the two axial ratios (a/b and a/c); and K is an unknown constant. Note that the fitting distribution given in Eq. (1) is inferred entirely from MSX data with the procedure explained in López-Corredoira et al. (2000) which allows to obtain both the density and the luminosity function simultaneously.

This small-inclination model is the best fit, sufficient to yield the observed asymmetry of the bulge, in which the star counts at positive Galactic longitudes are higher than at negative Galactic longitudes (see Fig. 1). However, because the star count map we used is of quite low resolution (the density of bulge stars is only around 300 deg⁻² up to the limiting magnitude in the innermost bulge for Band-A; we used bins of $(\Delta l = 2^\circ) \times (\Delta b = 0.5^\circ)$), and the angle is strongly dependent on small variations in the position of the maximum projected star counts, we regard these numbers as a rough approximation.

The structural information is not totally reliable because we are using only a few thousand stars, insufficient for a statistically adequate inversion of the density distribution. However, as argued by López-Corredoira et al. (1997, 2000), the inversion to obtain the luminosity function is much less sensitive to Poissonian noise, and only weakly dependent on the density distribution because the dispersion in distance for bulge stars is relatively small. Therefore, our conclusions about the luminosity function are much more robust.

The LFs of the bulge stars for the four filters are shown in Fig. 2. The luminosity function for other bands than A are derived using the inversion procedure by López-Corredoira et al. (2000), but in these cases using a given density (1) to obtain the luminosity function instead of obtaining both the density and the luminosity function. The range of absolute magnitudes depends on the selected range in apparent magnitudes for each filter, and on the range of distances to the bulge stars. The error bars come from the dispersion of LFs in the different directions.

3. Comparison with “SKY” model

For comparison, we have also plotted in Fig. 2 the normalized LF of the “SKY” model (Cohen 1994, 1995; Cohen et al. 1994), which is a modified version of the model introduced by Wainscoat et al. (1992), but one whose changes do not significantly affect the bulge. To assemble the

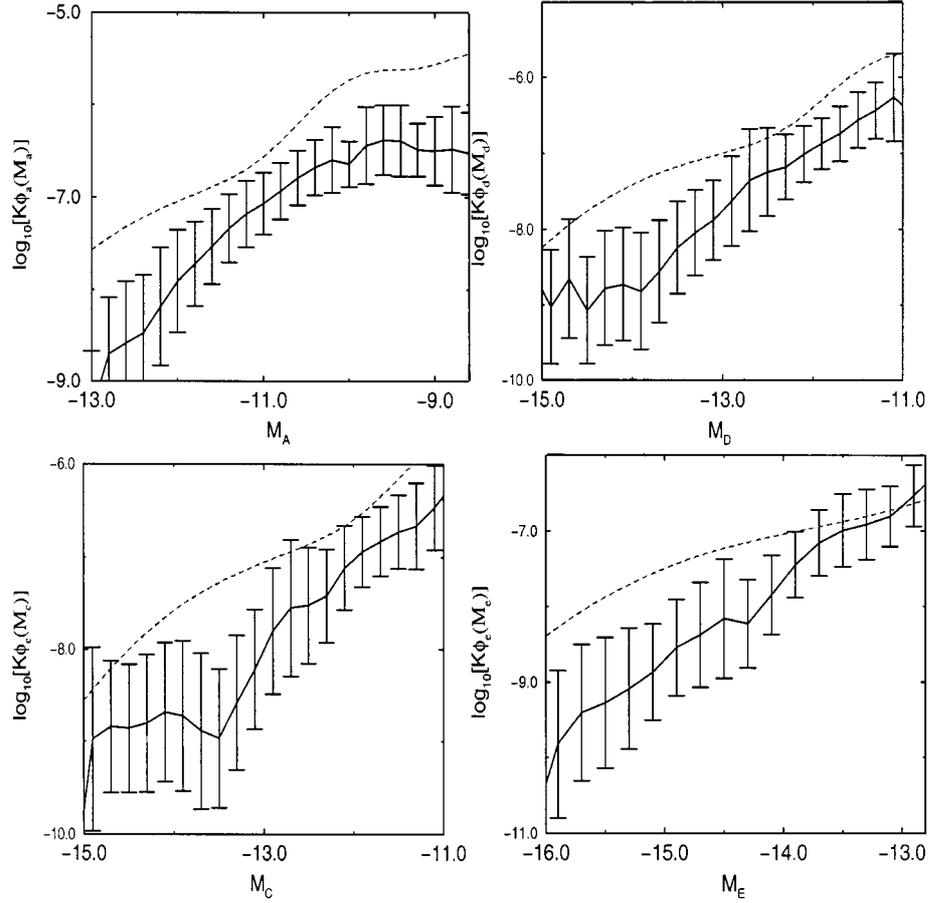


Fig. 2. Luminosity functions for bulge stars in the four long-wavelength MSX bands (solid line): A, C, D, E. ϕ is the normalized luminosity function, and K is an unknown constant. Dashed lines show for comparison the normalized luminosity functions of “SKY” model ($K = 1$)

Table 2. Average slopes of the plots in Fig. 2

Band	MSX Slope	SKY slope	Ratio of slopes (MSX/SKY)
<i>A</i>	0.56 ± 0.05	0.52 ± 0.02	1.08 ± 0.11
<i>C</i>	0.74 ± 0.05	0.61 ± 0.02	1.21 ± 0.09
<i>D</i>	0.78 ± 0.03	0.60 ± 0.02	1.30 ± 0.07
<i>E</i>	1.08 ± 0.03	0.51 ± 0.03	2.12 ± 0.14

Table 3. Number of stars (n) in the whole bulge for a limiting range of magnitudes

Band	Range of magnitudes	n from MSX	n from SKY	Ratio of n (MSX/SKY)
<i>A</i>	$M_A < -8.6$	$3.4 \cdot 10^4$	$7.8 \cdot 10^4$	0.44
<i>C</i>	$M_C < -11.0$	$1.4 \cdot 10^4$	$1.9 \cdot 10^4$	0.74
<i>D</i>	$M_D < -11.0$	$1.8 \cdot 10^4$	$2.7 \cdot 10^4$	0.67
<i>E</i>	$M_E < -12.8$	$1.0 \cdot 10^4$	$0.46 \cdot 10^4$	2.17

requisite data within SKY we first ran the model in its customised mode and generated tables of absolute magnitudes for all 87 categories of celestial source. These were then combined with the bulge mask (cf. Wainscoat et al. 1992) and the newest space densities.

Note that Fig. 2 compares SKY and MSX LFs only to show the differences in slope, rather than in absolute values; i.e., in each plot, the SKY LF shown corresponds to $K = 1$ but the LF derived from MSX data has been arbitrarily normalized ($K \neq 1$) for the comparisons. The differences in slopes of the MSX plots compared to those

of the SKY model are noteworthy, especially for Band-*E*, although one should recognize the uncertainties resulting from these inversions. The longer the filter wavelength, the steeper the slope of the MSX LF in comparison with those of the SKY model, as shown in Table 2, where the slope is s_λ such that

$$\phi_\lambda(M_\lambda) \approx C_\lambda \times 10^{s_\lambda M_\lambda} \quad (2)$$

in the range where we have calculated the LFs. The constants, C_λ , depend on the normalizations. The slopes are dependent on the magnitude range, but the ratio shown in the fourth column of the table should not be.

We can also compare the absolute counts. If we integrate the LFs over the whole volume of the bulge (see Sect. 6.5 of López-Corredoira et al. 2000), and multiply it by the total density of stars given by (1), assuming it is valid for all t , we obtain the results shown in Table 3, by comparison with the SKY model predictions. There is another clear trend, namely the increase, with increasing wavelength, in the ratio of the observed numbers of stars to those predicted. The absolute values of the ratios themselves are not important, since we used the approximation that (1) is valid for all t , but the trend of increasing ratio highlights a significant difference in stellar population with respect to that of the SKY model, which will be valuable for future refinements of SKY.

Bulge stars that contribute to the counts in our adopted ranges of magnitude are basically AGBs. The reddest AGBs are those obscured by the thickest dust shells while those nearer the faint limit of our adopted magnitude range have lower mass-loss rates. Since the slope of the luminosity function and the absolute number of stars are larger in MSX than predicted by SKY for larger wavelengths, we are led to the following suggestions about SKY: there is a deficit of weak mass loss AGB stars in “SKY”, for example, the objects discussed by Glass et al. (1999).

Source densities in the bulge are certainly high and, at densities above 500 sources deg^{-2} in filter A, confusion is sufficient to limit the completeness of PSC1.2 (Egan et al. 1999; their Sect. 7.1). PSC1.2 contains about 3300 confused sources over all longitudes for latitudes in the plane with modulus exceeding 2° (Egan et al. 1999; their Table 10). Therefore, we expect a significant underestimation of the total number of stars in our two selected bulge latitude ranges. Incompleteness in the differential counts from PSC1.2 can be seen in the inner Galaxy at around 200 mJy in filter A (Egan et al. 1999; their Figs. 31, 38), equivalent to $M_A \sim -8.5$. Thus, the combination of confusion and incompleteness might furnish an adequate explanation for the “flattening” of our derived LF at faint 8.28- μm magnitudes (Fig. 2) and the small ratio of $n(\text{MSX})/n(\text{SKY})$ in Table 3, although we are not sure about this to be the reason since confusion effects should be small at $M_A < -8.6$.

MSX’s band A is more than an order of magnitude more sensitive than the other bands. Consequently, we would expect the depth of coverage of the bulge in bands

C, D, E to be comparable to that of IRAS, and hence we expect few differences in completeness between MSX C, D, E and IRAS at 12 or 25 μm . Hence, we dismiss the scenario of an excess of AGBs with thick dust envelopes (strong mass loss).

The SKY model was originally guided by IRAS mid-infrared data although it has always been capable of handling the prediction of counts from *BVJHK* filters, as well as IRAS’s, and from user-supplied arbitrary passbands between 2.0 and 35.0 μm , hence its capability to operate equally well for these MSX filters. As Wainscoat et al. (1992) demonstrated, SKY fits the IRAS source counts well. The very red AGBs detected by MSX are also detected by IRAS, although not many of those with weak mass loss. It is possible that the pattern of excesses and deficits in LFs that we have described are compensated for, in predicting IRAS counts, but not for MSX whose deeper counts can probe specific populations better. The improvements delineated here will be applied to a future version of the SKY model.

The LFs established in this paper may be used to fit the population of bulge stars in any model. We do not pursue these fits here because it is not the aim of the present paper.

4. Conclusions

The LFs of the stellar population of the Galactic bulge in four infrared filters – 8.28, 12.13, 14.65 and 21.33 μm – have been calculated by means of a special technique of inversion. Based on the new MSX data, our inversion provides this information for the first time in the literature. It is of general value in the study of these stellar populations and will be implemented in a future version of the SKY model.

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