Astron. Astrophys. 360, 111–119 (2000)

ASTRONOMY
AND
ASTROPHYSICS

A survey of selected areas in the galactic plane with ISOCAM⋆,⋆⋆

M.J. Burgdorf[1], **M. Cohen**[2], **S.D. Price**[3], **S. Ott**[1], **M.P. Egan**[3], **T. de Graauw**[4], **R.F. Shipman**[3,4], **S. Ganesh**[5,6], **C. Alard**[5], **and F. Schuller**[5]

[1] ISO Data Centre, Astrophysics Division, Space Science Department of ESA, Villafranca del Castillo, P.O. Box 50727, 28080 Madrid, Spain
[2] Radio Astronomy Lab., 601 Campbell Hall, University of California, Berkeley, CA 94720, USA
[3] Phillips Lab./GPOB, 29 Randolph Rd., Hanscom AFB, MA 01731-3010, USA
[4] SRON, Lab. for Space Research, P. O. Box 8009, 9700 AV Groningen, The Netherlands
[5] Institut d'Astrophysique de Paris, CNRS, 98bis Bd Arago, 75014 Paris, France
[6] Physical Research Laboratory, Navarangpura, Ahmedabad 380009, India

Received 10 November 1999 / Accepted 11 April 2000

Abstract. Seven 11.6' × 11.6' fields along the inner Galactic plane were imaged by the Infrared Space Observatory's ISOCAM camera to investigate the large scale properties of the Galaxy. We present results from this GPSURVEY program at wavelengths of 10 and 15 μm as well as some complementary observations from the ISOGAL project at 7 μm. Point source detection is complete to a limiting flux of about 10 mJy. There is generally good agreement between the observed source counts and that predicted by the SKY 5 multiwavelength Galactic structure model. However, some discrepancies were found at certain Galactic longitudes, particularly near the Galactic center. Indications of the nature of the excess sources are inferred from the colour histograms.

Key words: surveys – stars: statistics – Galaxy: stellar content – Galaxy: structure – infrared: general – infrared: stars

1. Introduction

The determination of the spatial distribution of stars in our Galaxy is a problem with a long history (Paul 1993). A fundamental difficulty in this "classical" stellar statistics is the extinction of star light caused by interstellar dust which limits star counts at visible wavelengths to relatively high Galactic latitudes or small windows near the plane. As this extinction decreases with increasing wavelength, radio and infrared observations were used in order to investigate the Galactic structure at large distances and close to the Galactic plane. From these observations it was inferred that our Galaxy is a mildly barred spiral (de Vaucouleurs & Pence 1978).

Detailed characterizations of the global distribution of stars in our Galaxy were studied by using plausible models of the near- and mid-infrared sky. A lot of work has been done during the last few decades in order to impose constraints on models of stellar distribution, with observations from the ground (Two Micron Sky Survey, Neugebauer & Leighton 1969), with balloon experiments (Hayakawa et al. 1981) and from the *Spacelab 2* Infrared Telescope (Kent et al. 1991). More recently the Two Micron Galactic plane Survey TMGS (Garzón et al. 1993) covered a large area to K $\leq$ 9.5 but, unfortunately, the survey does not have the multicolour observations necessary to classify and separate the mix of normal late type, AGB and other evolved stars it preferentially detects. This need for a more sensitive near infrared survey to study the morphology of the inner Galaxy is a fundamental rationale for conducting the DEep Near Infrared Survey DENIS (Epchtein 1997) and the 2 Micron All Sky Survey 2MASS (Skrutskie 1997).

At mid-infrared wavelengths our knowledge is mainly based on star counts from the IRAS Point Source Catalog. Unfortunately the IRAS data products are often confusion limited along the Galactic plane owing to a combination of high source density and shadowing effects due to detector response and data processing. This "confusion" degraded IRAS' detection limit over much of the inner plane to fluxes of 1 Jy or greater. Therefore, only the most luminous of stars in the Galactic plane could be detected at large distances by IRAS, biasing the sample.

Observations from the GPSURVEY experiment with ISOCAM are used, as described below, to check the validity of models for the mid-infrared point source sky at lower fluxes. ISOCAM was the camera aboard the European Space Agency's Infrared Space Observatory (ISO) which was launched in November 1995 and ended its life in April 1998 when all helium was lost. A description of the ISO satellite can be found in Kessler et al. (1996) and of its camera in Cesarsky et al. (1996).

We chose for the comparison between observation and theory a recently modified version of the SKY model (Wainscoat et al. 1992; Cohen 1995; 1994). The model populates the physical and geometric components of the Milky Way System (namely

Send offprint requests to: M.J. Burgdorf (mburgdor@iso.vilspa.ese.es)

⋆ ISO is an ESA project with instruments funded by ESA Member States (especially the PI countries: France, Germany, the Netherlands and the United Kingdom) and with the participation of ISAS and NASA.

⋆⋆ This is paper number 5 partially based on data from the ISOGAL project to appear in a refereed journal.

Table 1. Central positions of rasters performed with ISOCAM

Proposal and OSN	latitude b	longitude l	ISO Rev.	Filters
ISOGAL7N 50	$-0.^\circ 3$	$-30.^\circ 1$	474	LW2
ISOGAL7N 49	$+0.^\circ 7$	$-30.^\circ 0$	474	LW2
ISOGAL7N 51	$+0.^\circ 3$	$-29.^\circ 9$	484	LW2
ISOGAL7N 52	$-0.^\circ 8$	$-29.^\circ 8$	474	LW2
ISOGALNE 51	$-0.^\circ 3$	$-30.^\circ 1$	87	LW3
ISOGALNE 52	$\pm 0.^\circ 0$	$-30.^\circ 0$	315	LW3
GPSURVEY 5	$\pm 0.^\circ 0$	$-15.^\circ 7$	289	LW3, LW7
ISOGAL7N 13	$\pm 0.^\circ 0$	$-\ 6.^\circ 0$	491	LW2
ISOGALNE 11	$\pm 0.^\circ 0$	$-\ 6.^\circ 0$	315	LW3
GPSURVEY 6	$+0.^\circ 1$	$-\ 6.^\circ 0$	301	LW3, LW7
ISOGAL8C 30	$+3.^\circ 0$	$-\ 0.^\circ 1$	837	LW2
ISOGAL7C 14	$+3.^\circ 0$	$-\ 0.^\circ 1$	498	LW3
GPSURVEY 7	$+3.^\circ 1$	$\pm\ 0.^\circ 0$	301	LW7
GPSURVEY 1	$-0.^\circ 1$	$+\ 5.^\circ 2$	148	LW3, LW7
GPSURVEY 2	$+0.^\circ 3$	$+15.^\circ 9$	148	LW3, LW7
GPSURVEY 3	$+0.^\circ 6$	$+28.^\circ 1$	152	LW3, LW7

disk; bulge; spiral arms, spurs and Gould's Belt; a 4 Kpc molecular ring; and halo), with different types of sources, each of which has an individual characteristic space density and intrinsic brightness. All these constituents and also the interstellar extinction curve are represented by analytical expressions. Extinction variations, however, are at the wavelengths considered in this paper a negligible issue, and none of our lines of sight goes through any of the off- or on-plane dark clouds that TMGS has found (Hammersley et al. 1999).

The authors tested their ab initio statistical model extensively against IRAS source counts and extended its synthetic spectral library from 2.0 to 35.0 μm. This range covers in particular the ISOCAM filters LW2, LW3 and LW7 that are the basis of the investigation in hand. The model parameters have been verified with published source counts at other wavelengths (Cohen 1993). The GPSURVEY observations are compared to the SKY 5 mid-infrared predictions in the following Sects. The model adequately accounts for the observations in most directions. In two regions of the Galactic plane, however, the model underpredicts the observations, indicating either a local geometric deficiency or missing populations of sources in the model.

2. Observations

The observing strategy of the GPSURVEY program consisted of sampling a number of critical positions in the Galactic plane with ISOCAM raster scans. The positions of the fields analyzed are given in Table 1.

Each raster consisted of 6×6 images, separated by 100″ in spacecraft y- and z-axis. This way we covered an area of 133 arcmin^2 in an observation of two hours duration. The images were taken with the Astronomical Observation Template CAM01 (general observation) using filters LW3 and LW7. They cover the wavelength ranges 12–18 μm and 8.5–10.7 μm, respectively. The pixel field of view was 6 ″.

The GPSURVEY field at $l = -6.^\circ 0, b = +0.^\circ 1$ has been observed also as part of the ISOGAL program in filters LW3 and LW2 (5.5–8.5 μm). These data provided us with the opportunity to obtain additional information on the colours by cross-identification of LW2, LW3 and LW7 sources and to check the reliability of the source extraction in filter LW3. The ISOGAL rasters were performed with a different step size than those in GPSURVEY (90″ and 150″, oriented towards north) and also the integration times were shorter. Hence the comparison between ISOGAL and GPSURVEY data could be used to show that those instrumental effects which are related to the observing conditions (e.g. pixel-memory effects) had a negligible effect on the result. We have also pulled up several ISOGAL observations of areas near $l = -30°, b = -0°$ in order to check whether the source statistics change on small angular scales.

3. Data processing

The starting point of the data processing were Auto Analysis Results from the pipeline version 7. For the extraction of point sources we used an algorithm developed for the ISOGAL project (Alard 2000). It contains inter alia corrections for the distortion of the ISOCAM field of view and for transient effects. For the conversion of the flux values from engineering units to Jansky we used the following factors (Blommaert 1998):

$$S_{LW2}(mJy) = (ADU/G/s)/2.32 \quad (1)$$

for filter LW2,

$$S_{LW3}(mJy) = (ADU/G/s)/1.96 \quad (2)$$

for filter LW3 and

$$S_{LW7}(mJy) = (ADU/G/s)/1.33 \quad (3)$$

for filter LW7, assuming central wavelengths of 6.7, 14.3 and 9.6 μm, respectively.

The flux density S is then converted into magnitude mag with the formulae

$$mag(LW2) = -2.5 \times log(S_{LW3}/90.36\ Jy) \quad (4)$$

$$mag(LW3) = -2.5 \times log(S_{LW3}/19.64\ Jy) \quad (5)$$

$$mag(LW7) = -2.5 \times log(S_{LW7}/42.22\ Jy). \quad (6)$$

The source lists produced this way form the basis of the results presented in the following section.

In each GPSURVEY field we detected more sources in filter LW7 than in filter LW3, as expected because of the shorter wavelength. Therefore it was possible to check the completeness of the LW3 source list by means of cross-identification with LW7. We found for 86% of the sources stronger than 10 mJy in LW3 a source at the same position in LW7, hence the source extraction worked in a satisfactory way down to that flux level.

This finding was confirmed by a comparison of the source lists generated from the GPSURVEY and ISOGAL rasters on a common area at $l = -6.^\circ 0, b = +0.^\circ 1$: In spite of the different observing strategy (see previous Sect.) only one GPSURVEY source was not found in the ISOGAL field. The rms difference between the GPSURVEY and the ISOGAL fluxes for a single source is 19%, thus confirming the error estimated from repeated observations of a similar field by Omont et al. (1999).

Table 2. Comparison of GPSURVEY and ISOGAL source counts, $l = -6\,\mathrm{deg}$.

flux level in LW3 mag	GPSURVEY deg^{-2}	ISOGAL deg^{-2}
5.5	620 ± 190	610 ± 80
6	900 ± 230	900 ± 100
6.5	1410 ± 280	1558 ± 130
7	2310 ± 360	2160 ± 150
7.5	3270 ± 430	3250 ± 190
8	3940 ± 470	4600 ± 220

Table 3. Comparison of source counts from adjacent directions, $l = -30\,\mathrm{deg}$

flux level in LW3 mag	ISOGAL (b=-0°.3) deg^{-2}	ISOGAL (b=0°.0) deg^{-2}
5.5	263 ± 50	290 ± 40
6	394 ± 60	464 ± 50
6.5	680 ± 70	622 ± 60
7	936 ± 90	948 ± 70
7.5	1446 ± 110	1569 ± 90
8	2165 ± 130	2655 ± 120

The average of the ISOGAL fluxes from all 70 sources seen in this particular area is 3% lower than the average of the GPSURVEY fluxes; this difference is barely significant. Table 2 shows a comparison between the cumulative star counts of GPSURVEY and ISOGAL for this field. As the area observed with ISOGAL was larger, its Poisson errors to the source counts are smaller. ISOGAL and GPSURVEY give very similar results.

Another check of the reliability of the flux values obtained with the ISOGAL point source extractor was performed by determining the influence of different data processing techniques for transient correction, flat-fielding, deglitching and dark-correction on the derived average point source fluxes. We found that results obtained with different reduction methods varied by less than 12% for sources brighter than 10 mJy and not too close to the edges of the raster, where only part of the point spread function is seen. In addition to these semi-automatic methods we also performed spot-checks on single sources with the ISOCAM Interactive Analysis software (Ott et al. 1997).

4. Results

Fig. 1 shows the number of point sources as a function of flux for all fields from Table 1.

The star counts from the ISOCAM observations are in good agreement with the SKY 5 model for 4 of the 7 main directions that we examined, viz. $l = -30°, l = -16°, l = 5°$ and $l = 29°$. For the comparison with the model we only used the inner 64 arcmin^2 of each GPSURVEY field, where 80% of the area has been observed in 4 different raster positions. This way we increased the reliability of the source detection and created a dataset with rather homogeneous signal to noise ratio. Trustworthy results can only be stated for fluxes above 10 mJy, where the measured signal is at least five times the rms noise. This is the minimum needed to derive a sound number–flux-density relationship (Murdoch et al. 1973). At lower fluxes we find in several plots the effect of Malmquist bias: Noise in the images was mistaken for sources by the point source extractor, causing systematically too high source counts. On the other side the number of sources found at fluxes above several hundred mJy is too small for reliable statistics. As GPSURVEY and ISOGAL fields had to be chosen away from bright sources in order to avoid saturation of the detectors, objects with very high fluxes might be systematically underrepresented in our samples and were therefore excluded from our discussion.

The area at $l = -30°, b = 0°$, was used as a check of reproducibility: The results from 5 ISOGAL fields which were up to 1°.5 apart from one another are plotted in Figs. 1a to 1f. It can be seen that very similar numbers were obtained from these observations (see also Table 3).

The field at $l = -6°.0, b = +0°.1$ has the highest source density among the 7 directions in GPSURVEY: 5000 deg^{-2} in LW3. This value, however, is still clearly smaller than the formal confusion limit of 8000 deg^{-2} at 15 μm (Omont et al. 1999). We find for this field good agreement between the model and observations in LW2 and LW3, although for the case of the latter filter there is a slightly steeper decrease of log N as a function of log S than the model predicts. In LW7, however, there are more sources than expected. In order to obtain information about the nature of the sources causing the discrepancies to the model we made colour histograms for the "problematic" directions $l = 16°, l = 0°$ and $l = -6°$ (see Fig. 2), which showed in the case of the field at $l = -6°.0, b = +0°.1$ an excess of observed sources with colour indices [9.62]-[15] between 0.6 and 1.2. In order to test the ability of the model to predict colours correctly we made also the colour histogram from the source counts in filters LW2 and LW3, where no significant discrepancy to the model was found. Here the agreement between observation and model is much better (see Fig. 2b).

At position $l = 15°.9, b = 0°.3$ we detected a factor of two more objects in LW7 and about 60% more in LW3 than the model predicts. Therefore we replaced the circular molecular ring in the model by the more realistic assumption of a non-uniform ellipse orientated with major axis offset by 30° from the line of sight to the Galactic Centre (Simonson & Mader 1973). Ruphy et al. (1997); Ruphy (1996) found that this ring gives a better fit to DENIS star counts than a uniform, circular pattern. Fig. 3 shows that this modification of the model produces a greatly improved agreement with the observations at $l = 15°.9, b = 0°.3$. Even with the modified model there is still a small surplus of sources with colour indices [9.62]-[15] between 0.6 and 1.2 (see Fig. 2c), but considering the large error bars in the observed source counts the deviations are not very significant. At $l = -6°.0, b = +0°.1$, however, the large discrepancies between observed and modelled source counts stand also with the assumption of an elliptical molecular ring. It is therefore necessary to further constrain the details of both the geometry, interstellar extinction and stellar populations of the ring by the abundant observations of TMGS, MSX, DENIS and, now, by GPSURVEY and ISOGAL images too.

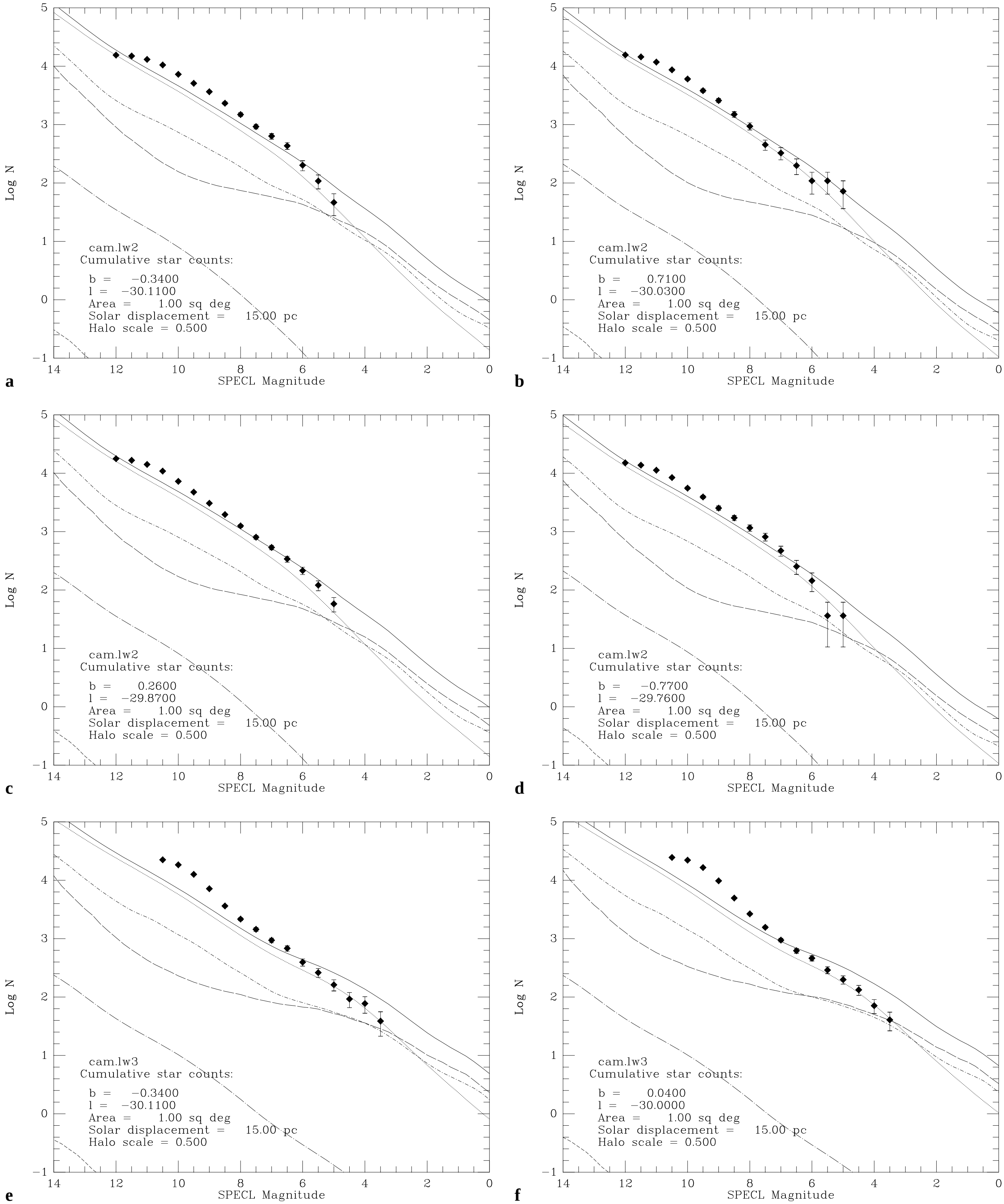

Fig. 1a–u. Comparison of SKY 5 predictions and observed cumulative star counts at 6.75 μm (filter LW2), 9.62 μm (LW7) and 15 μm (LW3) for various fields observed with GPSURVEY and ISOGAL. The filter and the position for each area are given in each plot. Poisson error bars are shown, appropriate to the actual number of sources observed in each bin. The source counts are only for medium fluxes free of systematic errors (see main text for details). Diamonds, observed star counts; solid line, total model prediction; dots, disk; short dashed, bulge; long dashes, arms; short dashed-dotted, mol. ring; long dashed-dotted, halo.

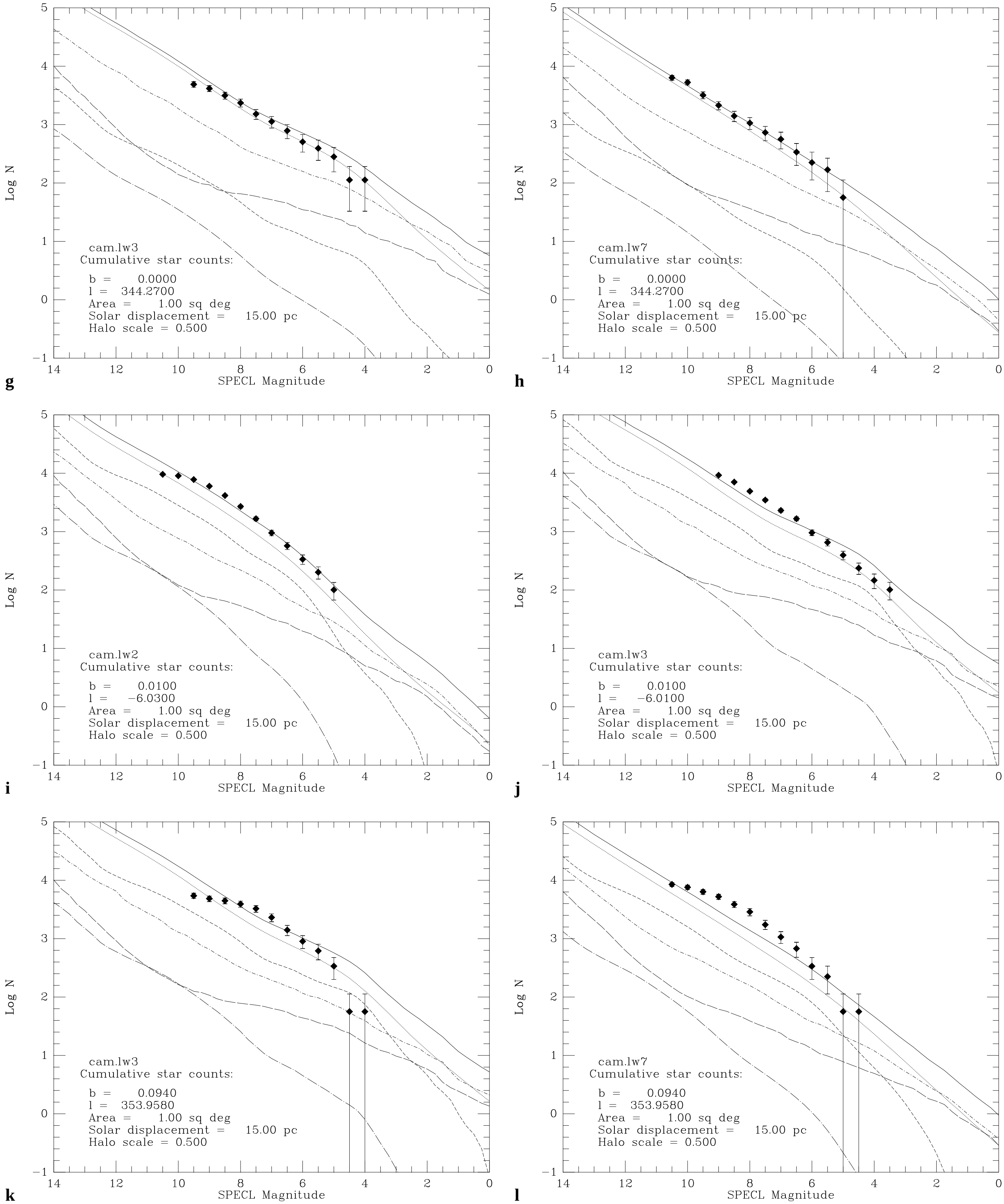

Fig. 1a–u. (continued)

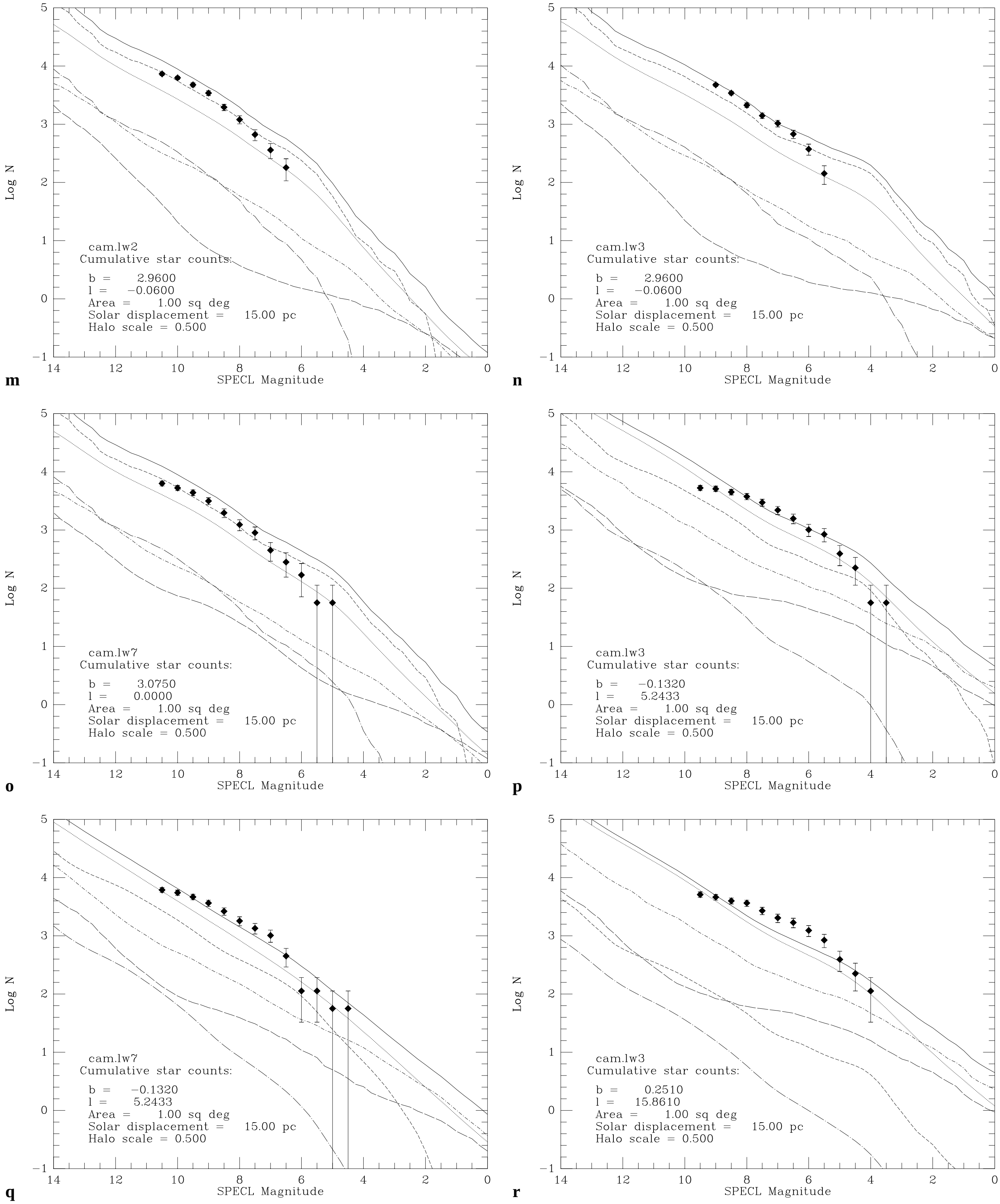

Fig. 1a–u. (continued)

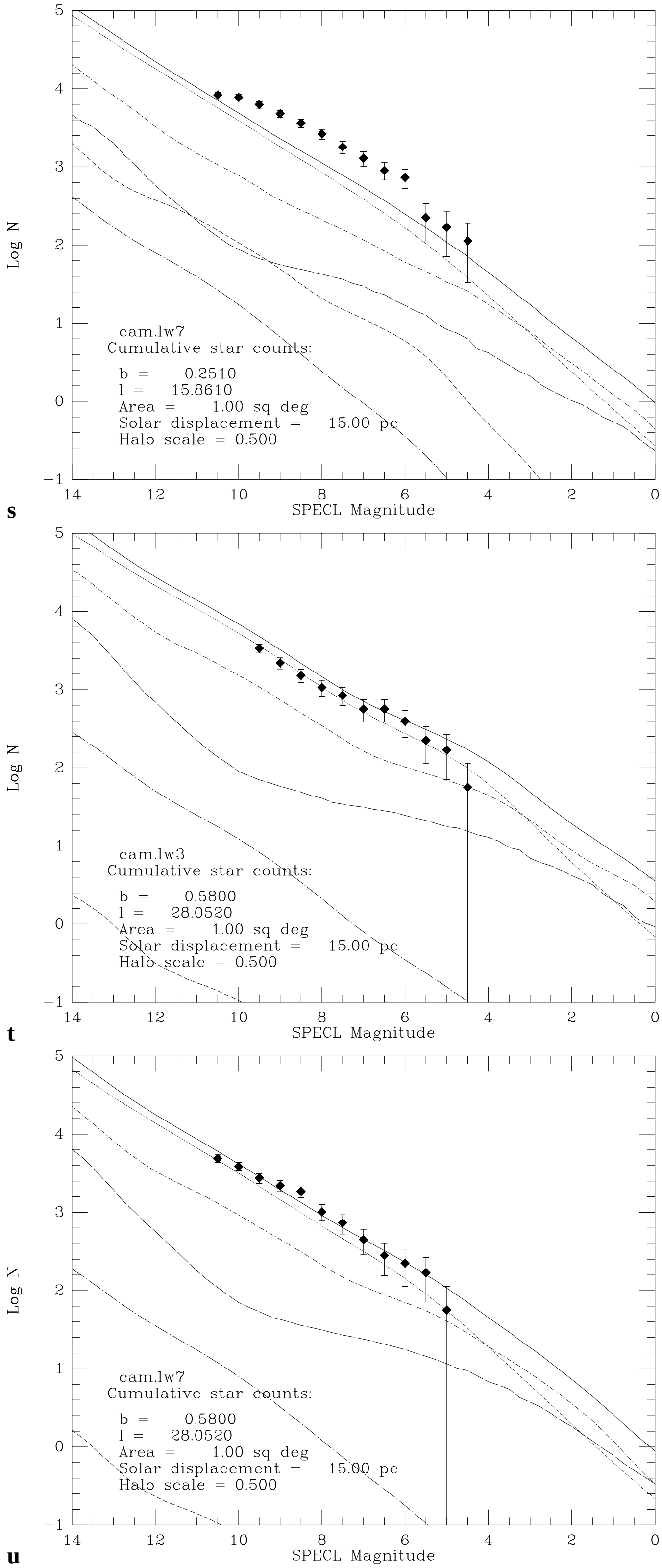

Fig. 1a–u. (continued)

For the raster outside of the Galactic plane at $l = -0°, b = 3°$ the original model reproduces correctly the star counts in LW3 except for fluxes stronger than 100 mJy, where again the observed slope of the log N vs. log S plot is steeper than expected. In LW2 and LW7, however, we observed significantly fewer sources than the model predicted. Here the histogram of measured colour indices [6.75]-[15] shows a deficit between 0.2 and 0.6 but an excess at higher values when compared to the model (see Fig. 2d).

5. Conclusions

For most of the fields we probed in the Galactic plane we found that SKY 5 describes the point source sky correctly down to fluxes of 10 mJy. The accuracy of this check is essentially limited by the Poisson statistics of the numbers found in the fields with size $692'' \times 692''$. Challenging exceptions to this general agreement are the directions from $l = -6\overset{\circ}{.}0$ to $l = 15\overset{\circ}{.}9$ in the Galactic disk as well as $l = -0\overset{\circ}{.}1, b = 3\overset{\circ}{.}0$, the only field observed where the contribution from the bulge is dominant.

Hammersley et al. (1994) have claimed the presence of a star formation region that extends from $l = 15°$ to $l = 28°$ in the Galactic plane. In the same region, in particular at $l = 15°$, a giant branch is present, too, which is formed of old sources (Hammersley et al. 1997). It is likely that the young and the old sources stem from the same feature in the inner galaxy. This feature could be caused by an elliptical thin ring or by a stick-like bar with a half-length of 4 kpc. Whereas the ring would have a major peak for both young and old sources at the tangential point ($l = 27°$) that falls rapidly inwards, a bar would be expected to have far fewer young than older stars in the middle of the bar. The excess of sources with colour indices [9.62]-[15] between 0.6 and 1.2 seen in GPSURVEY corresponds to AGB stars and normal M giants, hence the ISOCAM measurements support a bar far more than a ring.

Various bar models state that the asymmetry introduced by a centrally concentrated bar with its major axis in the first quadrant results in higher number counts at large positive longitude ($l \geq 10°$) and small negative longitude ($\mid l \mid \leq 10°$) (Binney et al. 1991; Dwek et al. 1995; Freudenreich 1998; see Unavane & Gilmore 1997 for a summary). This is confirmed by our source counts in field $l = -6\overset{\circ}{.}0$ which lie above the predictions of SKY 5 with the assumption of an axially symmetric bulge. Also the comparison of the GPSURVEY fields at the same distance but opposite sides from the Galactic centre reflects the number count asymmetries expected from the bar models.

The area around $l = -0°, b = 3°$, where two overlapping fields have been observed in three filters, probes mainly the star population of the Galactic Bulge. The fact that we find both excesses and deficits of stars, depending on their colour, shows that the situation is here more complicated than in the Galactic Disk and that there is a basic disagreement between the ISOCAM observations and the SKY 5 model. An analogous result was found for the TMGS by López-Corredoira et al. (1997) and Hammersley et al. (1999). A detailed analysis of ISOCAM data taken at a nearby field in the inner Galactic Bulge has been published by Omont et al. (1999; 1997); Omont (1999).

Summing up it may be said that in general the agreement between SKY 5 and the ISOCAM observations at selected fields

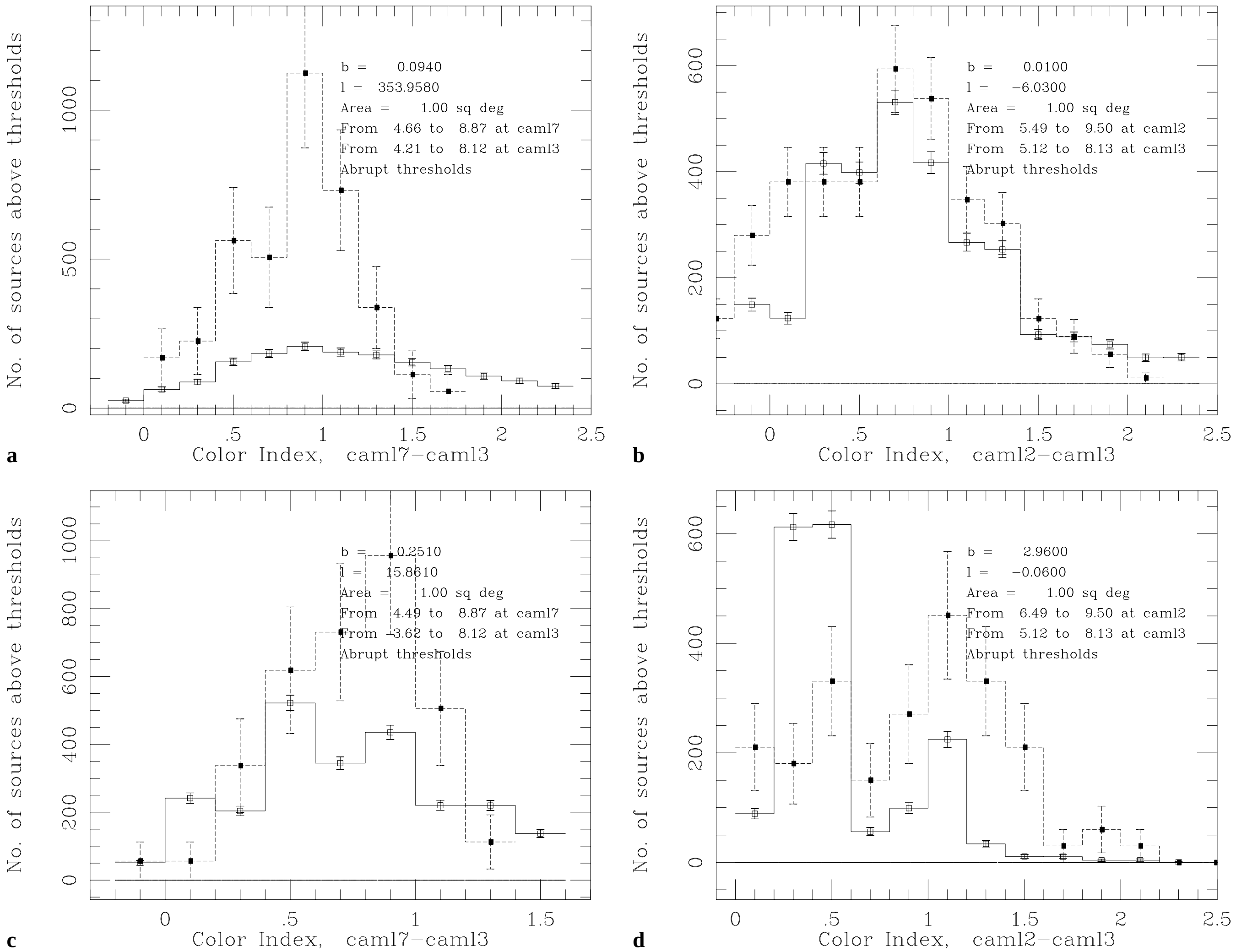

Fig. 2a–d. Colour histograms for the three fields of the GPSURVEY program where discrepancies between modelled and observed source counts were found. Only sources with a flux stronger than 10 mJy in either filter were considered. The colour index and the position for each area are given in each plot. Poisson error bars are shown, appropriate to the actual number of sources observed in each bin. Solid line, total model prediction; short dashed, observed number of point sources. For the field at b = +0°.3, l = +15°.9 the modified SKY 5 model (elliptical instead of a circular ring) was used.

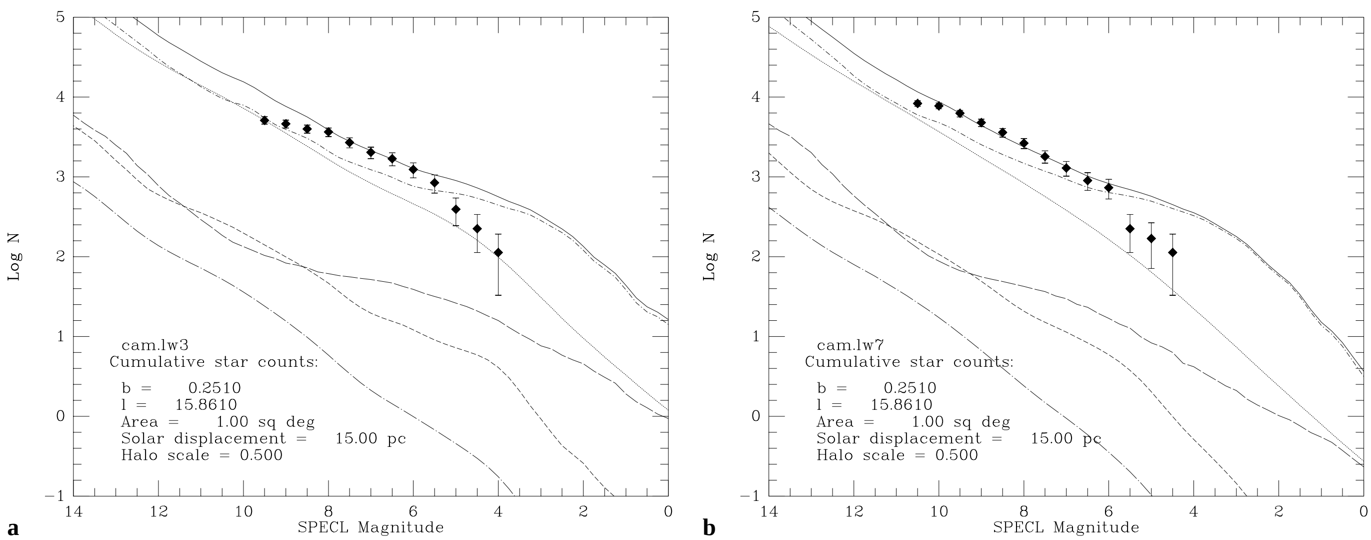

Fig. 3a and b. Comparison of predictions from a modified SKY 5 model (elliptical instead of a circular ring) and observed cumulative star counts at 9.62 μm and 15 μm for the field centered at b = +0°.3, l = +15°.9. Details as for Fig. 1.

in the Galactic Plane is very good. Deviations by 60% or more were only seen in connection with the bulge, whose geometry is more complicated than assumed in the model, and with a bar in the centre of our Galaxy, which is not included in the model.

Acknowledgements. We thank Professor A. Omont for valuable discussions and comments. The ISOCAM data presented in this paper was analysed using 'CIA', a joint development by the ESA Astrophysics Division and the ISOCAM Consortium. The ISOCAM Consortium is led by the ISOCAM PI, C. Cesarsky, Direction des Sciences de la Matière, C.E.A., France.

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