The soft gamma-ray emission of the Milky Way resolved in compact sources

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Since the seventies, the Milky Way is known as an abundant source of gamma-ray photons[1]. It has further been progressively confirmed that the emission is mainly diffuse in nature, resulting from interstellar processes[2]. However, in the soft gamma-ray domain, the lack of sensitive, high resolution observations did not allow for a clear estimate of the contribution from compact sources[3,4]. Even the

best imaging experiment[5] revealed a few point sources that could account for about 50% of the total Galactic flux[6]. Understanding this emission is of utmost importance to pin down the most relevant particle acceleration processes and gain insight into the physical and chemical equilibrium of the interstellar medium[7]. A major problem appeared since theoretical studies faced considerable difficulties to account for such an intense emission[4-7,9]. Here we present the results of observations in the soft gamma-ray domain that combine high sensitivity and high resolution over a large field of view. These reveal numerous compact sources. We show that they account for the entirety of the Milky Way's emission leaving at most a minor role to diffuse processes. The long standing problem of the interstellar soft gamma-ray emission is therefore solved.

There are two main processes that can lead to an interstellar soft gamma-ray emission. The first and the most natural is inverse Compton scattering of high-energy (GeV) cosmic-ray electrons on the ambient photon field. However, the electrons required to account for the bulk of the Galactic emission would also produce radio-synchrotron emission in the Galactic magnetic field at a level much higher than the one actually observed[10]. The second assumes the presence of a few hundred keV electron-population radiating through bremsstrahlung interactions with the interstellar gas. Since these electrons would lose their energy primarily through ionization and Coulomb collisions, the total power required to compensate for their energy losses is of the order of 10^{41}-10^{43} ergs/s[8]. This power, comparable or higher than that of the cosmic ray protons, would affect the interstellar medium ionization equilibrium and give rise to an excessive dissociation of the interstellar molecules. In the light of the above arguments outlining the improbability of an interstellar origin for the galactic soft-gamma ray emission, and taking into account the spectral shape of this emission, the hypothesis of a major point source contribution was put forth[8,11].

The INTEGRAL gamma-ray observatory[12], launched in October 2002, carries two major co-aligned coded-mask instruments: the IBIS imager[13] and the SPI spectrometer[14]. To lessen the instrumental background contribution, both experiments are actively shielded. Coded mask imaging acts as a high-pass spatial-frequency filter, strongly attenuating structures larger than the instrument's angular resolution which is 13' for IBIS and 2.6° for SPI. This makes IBIS with its ISGRI[15] photon counting gamma-camera very well suited to measure the emission from compact sources. Below 100 keV, the IBIS/ISGRI sensitivity reaches the millicrab level.

INTEGRAL observed the Galactic centre region in the spring and fall of 2003 as part of its core programme (guaranteed time) and during two target of opportunity observations. The total observing time amounts to about $1.5\ 10^6$ s in the central part of the survey. Figure 1 shows an IBIS/ISGRI mosaicked image produced using the standard analysis software[16]. Sources have been detected and removed one by one from the most to the least significant and obtained a list of 91 excesses above 6 sigma. Catalogued counterparts were searched for each of these sources using SIMBAD at the Centre des Données Stellaires de Strasbourg. All but 26 were identified with known sources. Forty of the identified sources are accreting binary systems with low mass companions as expected in a region rich in old stars such as the Galactic bulge. The remaining sources of known type are: 7 high-mass systems, 2 radio pulsars, 2 plerionic Supernova remnants (SNRs), 1 millisecond pulsar, 1 soft gamma-ray repeater and 1 Seyfert 1 galaxy. This leaves 11 sources of unknown type. The known binaries contribute to the total source flux at levels of 86%, 78%, 77% and 74% respectively in the 20-40, 40-60, 60-120 and 120-220 keV bands. The global spectrum of the other sources is thus significantly harder possibly indicating a new emerging population of hard sources. One could consider that some of the unidentified sources are highly absorbed such as IGRJ16318-4848[17] discovered during the course of this survey. A significant contribution from plerions and pulsars could also be considered since their spectra are much harder than the average.

Since diffuse emission is washed out during the standard imaging process, its contribution can be estimated by comparing the data before and after this processing. This entails comparing the ISGRI count rate and the combined intensity of detected sources. The count rate is due to the internal background, the cosmic diffuse background (CDB), the galactic diffuse emission and point sources. If the ISGRI count rates can be corrected for the internal background variations and the contribution from the known point sources removed, one should be left with a Galactic emission, possibly diffuse, and an isotropic contribution; the latter composed of the CDB and the constant internal background.

The internal background has a hard spectrum and fully dominates the count rates above 500 keV. One can therefore use the high-energy ISGRI count-rate to predict the variable part of the internal background. The relation between the count rate in each energy range and that above 500 keV can be derived from high latitude observations devoid of galactic emission. The variable part of the internal background has been subtracted from each observation window to produce corrected count rates. The contribution of each detected source was computed applying the IBIS angular response to the intensity at the source position in the field of view. To convert intensities to source count rates, a conversion factor was derived from Crab nebula observations.

Galactic maps of the difference between the corrected and the source count-rates were built. Each sky bin has been assigned the average of the count rates of all observations pointing within it. The resulting map has a resolution of the order of the field of view (19° FWHM). These residuals contain an isotropic emission and a Galactic contribution. Their respective importance was fitted on the latitude profile of the residuals. The fitted count rate of this residual Galactic emission is 8.6 ± 3.0 s^{-1}, 0.2 ± 1.1 s^{-1}, 0.7 ± 1.3 s^{-1}, -0.7 ± 0.6 s^{-1}, respectively in the 20-40, 40-60, 60-120 and 120-220 keV bands. A Galactic diffuse component contribution of 13 % of the total Galactic emission appears below 40 keV. There is no indication of an interstellar emission beyond. We note however that at high energy (> 120 keV) the uncertainty becomes large compared to the total source contribution.

Figure 2 displays the longitude profile of the corrected count rate together with that from the detected sources. The Crab nebula and the equally bright accreting black hole Cygnus X-1 dominate the longitude profiles. At low energy, the galactic centre is not much less significant but weakens faster with energy. Although the general agreement between both profiles is very good particularly at low energies, one can note significant discrepancies. Since our source list is complete only over the central Galactic radian, some of these discrepancies may be due to missing sources. Other discrepancies may be ascribed to inaccurate or inappropriate response functions. In particular, above ~ 100 keV, the passive shield is not anymore fully opaque while this was assumed in our computation of the source contribution. Latitude profiles of the corrected count rates are given in figure 3. The diffuse Galactic contribution at the 13% level revealed in the fitting procedure is clearly apparent on the top profile. This emission could be due to weaker sources and/or interstellar emission. It is peaked both in latitude and longitude and its ~ 10° radius is reminiscent of the Galactic bulge strongly populated with low mass X-ray binaries (LMXBs).

At high energy (E>120 keV), the large systematic uncertainties reflect the limitations of the method. It is assumed that the corrected count rates are only due to emission within the field of view but the passive shield is not anymore opaque at these energies.

In this regard, we note that SPI, using a large anticoincidence system is much better shielded at high energy. Strong et al.[19] have made a preliminary attempt to estimate the Galactic diffuse emission, separating only the 4 brightest sources near the Galactic centre. One may wonder what would have been the effect of the 43 sources detected in the simultaneous ISGRI data. Taking advantage of the summed spectra of the 4 sources measured by both instruments a cross calibration can be extracted. The total Galactic emission measured by SPI can be obtained by summing the "diffuse" and source spectra given in figure 2 of the Strong et al. paper. The sources detected in the ISGRI data contribute to 86% of the Galactic emission observed with SPI between 100 and 200 keV, giving a heuristic estimate of the source contribution in this energy range.

It appears that the Galactic soft gamma-ray emission is fully dominated by compact sources even if a little room still exist for interstellar emission. The difference with the X-ray domain (< 10 keV) is particularly remarkable[20]. It seems that between 10 and 20 keV a complete change in the mechanisms at the origin of the Galactic emission must occur. However, one should temper this conclusion bearing in mind the vast difference in spatial resolution between the X-ray and gamma-ray experiments. A few arcmin wide feature will appear as diffuse to Chandra and as a point source to IBIS. Below 40 keV the remaining 13% not accounted for by the detected compact sources could be due to weak bulge sources or to the same mechanism at work below 10 keV. Interstellar processes can still contribute to the soft gamma-ray emission of the Galaxy but at such a low level or in so restricted areas that the power supply, ionisation or molecule dissociation problems are alleviated.

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Acknowledgements: This paper is based on observations with INTEGRAL, an ESA project with instruments and science data centre funded by ESA member states (especially the PI countries: Denmark, France, Germany, Italy, Switzerland, Spain), Czech Republic and Poland, and with the participation of Russia and the USA. The authors acknowledge CNES for its indefectible support during the ISGRI development.

Competing Interests statement: The authors declare that they have no competing financial interests.

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Figure 1: IBIS/ISGRI view of the Galactic centre region.

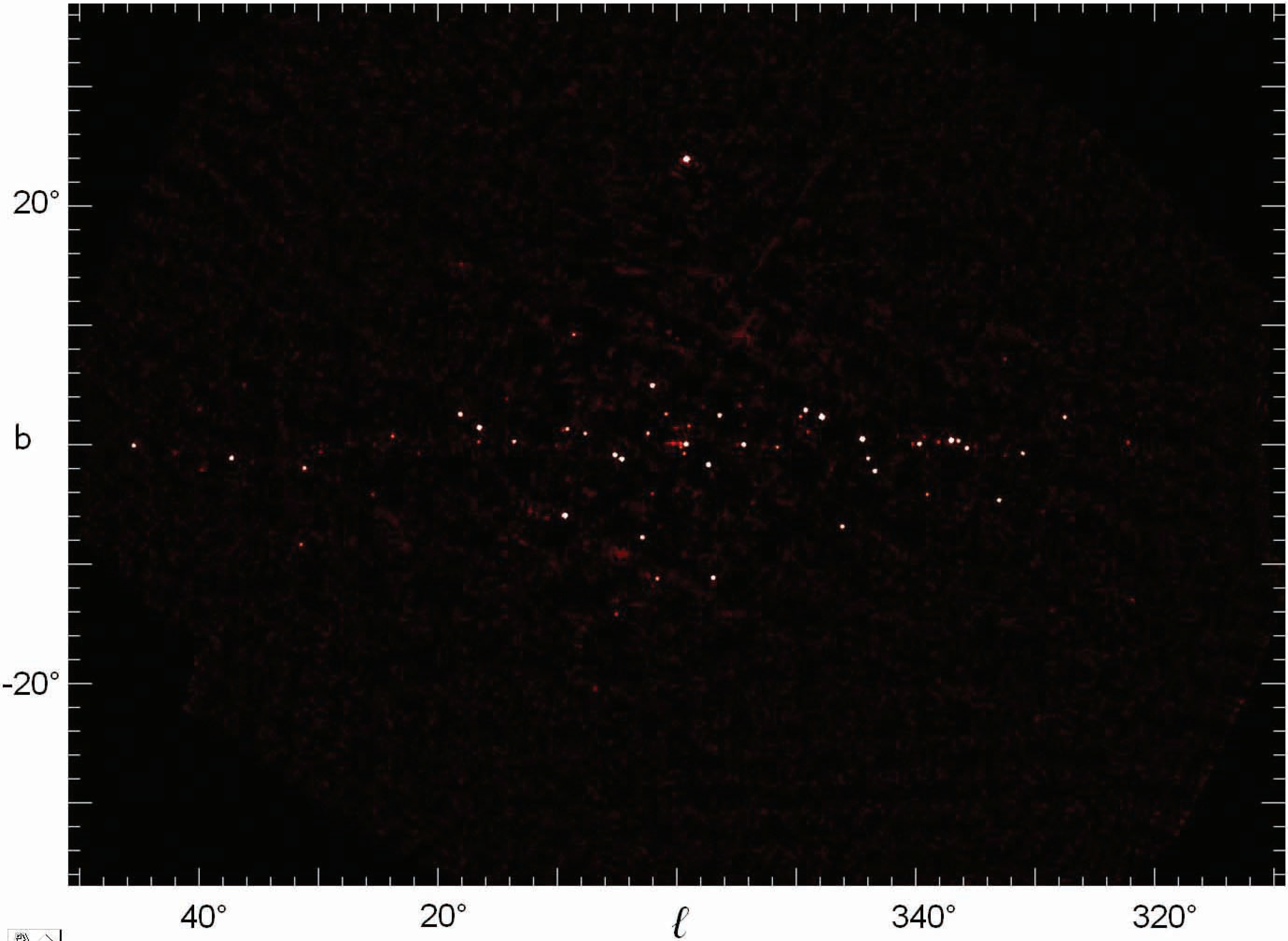
ISGRI galactic map of the central part of the Milky Way in the 20-60 keV energy-band. Most of the 91 sources detected in this image lay in the Galactic plane. The Galactic bulge, the region around the Galactic centre (ℓ=0°, b=0°), is densely populated, especially with LMXBs. This map is a mosaic of about 2000 images resulting from the IBIS standard analysis[16] of 2.2 ks pointed observations. The standard analysis deconvolves detector images with the mask pattern, detects the significant peaks and subtracts the PSF side-lobes in the resulting sky images. ISGRI[15], the low-energy camera of IBIS uses 16384 independent CdTe detectors operating between 15 keV and 1 MeV. With the IBIS mask 3.2 m above, it provides a 13’ angular resolution over a 19°x19° FWHM field of view and has a sensitivity close to 1 mCrab below 100 keV for a 10^6 s observation. The average point source location accuracy is a few arcmin[17].

Fig2: Longitude profile of the Galactic emission (|b|<5°)

Comparison between the background-corrected detector count-rate (black circles) and the estimated count rate from the detected sources (red triangles) as a function of longitude for each energy band. These profiles were produced averaging the corrected count rates of all pointings lying in the same longitude bin, with |b|<5°. The resulting angular resolution is then given by the instrument’s field of view. Since the variable internal background dominates all other components above 500 keV, the count rate above that energy can be used to predict and subtract the internal background in each energy range. This correction has been calibrated using the relation between the count rates in each energy range and that above 500 keV during high latitude observations (pointing at |b|>30°), which are deprived of Galactic and point source emission. The contribution of the Galactic emission above 500 keV does not significantly bias the background subtraction. Even if the total Galactic flux above 500 keV were at the Crab level, the bias introduced in the correction would never exceed 0.3 s^{-1}; which is negligible, at least below 120 keV. The total point-source count rate profile is estimated for each pointing correcting for acceptance and attenuation effects due to the source position in the field of view. The flux obtained through the imagery is then calibrated on the background corrected crab count rate. The error bars are due to the systematic uncertainties introduced during this process. The constant isotropic background obtained by fitting the latitude distribution (see figure 3) has been added to the source count rate.

Fig3: Latitude profiles of the Galactic emission in the central regions ($|\ell|$<20°)

These profiles have been produced the same way as the ones shown in Fig. 2. They show background corrected count rates (black circles), and source contribution (red triangles), in the Galactic central regions. The interstellar emission is believed to be distributed as a 5° FWHM gaussian along the Galactic plane[3]. Such a gaussian has been convolved with the IBIS field-of-view and the resulting Galactic distribution has a width around 15°. To estimate the amount of residual emission compatible with Galactic emission, we fitted the latitude profile of the difference between corrected count rate and source count rate, with the previously defined Galactic distribution and an isotropic component. The latter have been added to the source count rate in each profile to see the amount of residual emission. A contribution of 14% is visible under 40 keV (panel a). Sco X-1 (b ~ 20°) is not well accounted for because of the inaccuracies of the response model at large angles. No significant emission is seen at higher energies. In the 120 to 220 keV band, the systematic errors due to the background subtraction and the source count rate normalisation limit the significance of the result.


20°
b
-20°
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ℓ
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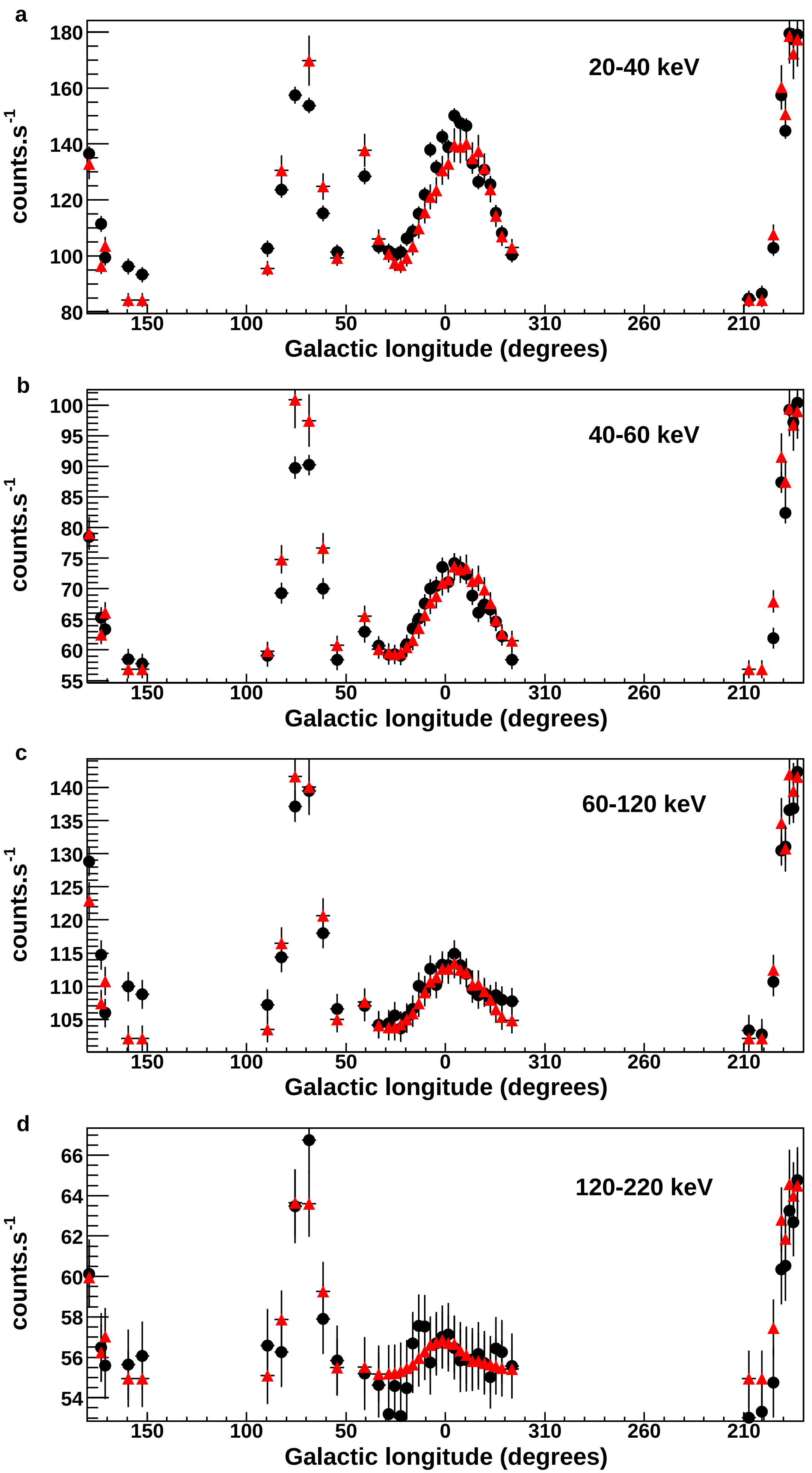
320°


a
20-40 keV
counts.s^{-1}
80
100
120
140
160
180
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50
0
310
260
210
Galactic longitude (degrees)
b
40-60 keV
counts.s^{-1}
55
60
65
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75
80
85
90
95
100
150
100
50
0
310
260
210
Galactic longitude (degrees)
c
60-120 keV
counts.s^{-1}
105
110
115
120
125
130
135
140
150
100
50
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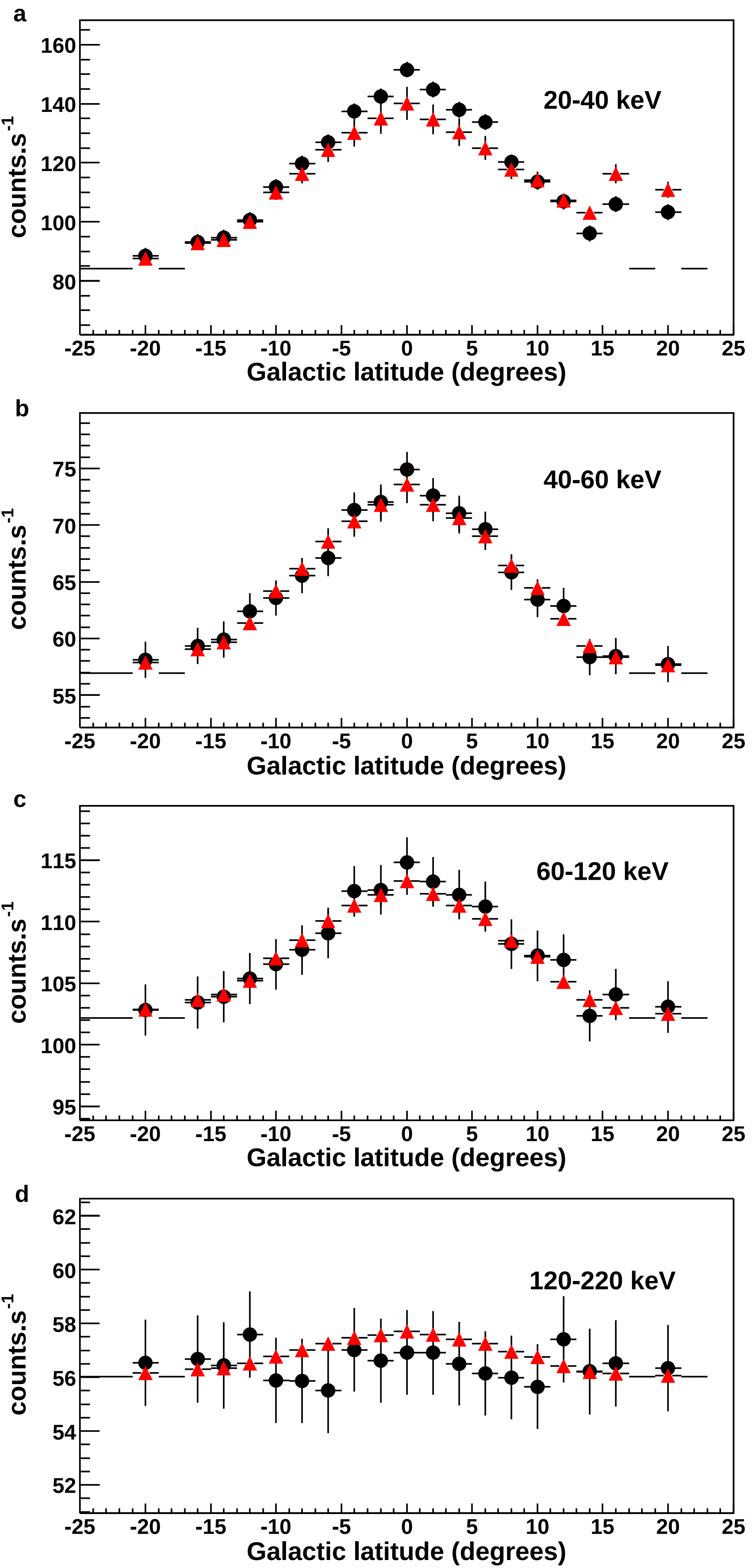
310
260
210
Galactic longitude (degrees)
d
120-220 keV
counts.s^{-1}
54
56
58
60
62
64
66
150
100
50
0
310
260
210
Galactic longitude (degrees)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20-40 keV
counts.s^{-1}
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140
120
100
80
-25
-20
-15
-10
-5
0
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10
15
20
25
Galactic latitude (degrees)
b
40-60 keV
counts.s^{-1}
75
70
65
60
55
-25
-20
-15
-10
-5
0
5
10
15
20
25
Galactic latitude (degrees)
c
60-120 keV
counts.s^{-1}
115
110
105
100
95
-25
-20
-15
-10
-5
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15
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25
Galactic latitude (degrees)
d
120-220 keV
counts.s^{-1}
62
60
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-25
-20
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Galactic latitude (degrees)