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Map of the Galaxy in the 6.7-keV emission line

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ABSTRACT

We study the two-dimensional surface brightness distribution of the Galactic X-ray background emission outside the central degree around Sgr A* in the 6.7-keV line as measured by the Proportional Counter Array spectrometer of the *Rossi X-ray Timing Explorer* observatory. The use of the emission line instead of continuum (3–20 keV) radiation and application of time-variability filtering to the long data set allows us to strongly suppress the contamination of the Galactic ridge X-ray emission (GRXE) map by bright point-sources. The surface brightness in the 6.7-keV line demonstrates very good correspondence with the near-infrared surface brightness over the whole Galaxy, supporting the notion that the GRXE consists mostly of integrated emission from weak Galactic X-ray sources. We find compatible linear correlations between near-infrared and 6.7-keV surface brightness for the bulge and disc of the Galaxy. This indicates that the populations of weak X-ray sources making up the GRXE in the disc and in the bulge are not significantly different.

Key words: radiation mechanisms: general – stars: binaries: general – Galaxy: bulge – Galaxy: disc – Galaxy: general.

1 INTRODUCTION

Galactic ridge X-ray emission (GRXE: e.g. Cooke, Griffiths & Pounds 1970; Bleach et al. 1972; Worrall et al. 1982; Warwick et al. 1985) – X-ray radiation concentrated to the Galactic plane and unresolvable into bright (>0.1–1 mCrab) point sources – has a prominent spectral feature at energy ∼6.7 keV (Koyama et al. 1986, 1989) that is typical of hot, optically thin plasma emission. As the energy resolution of X-ray detectors increased, more emission lines were found, additionally hinting at a thermal origin of the GRXE.

The hypothesis of a truly diffuse origin of the GRXE has met a number of practically unresolvable difficulties (see e.g. Tanaka 2002, for a review). The main problem is that the GRXE is apparently emission of optically thin plasma with temperatures up to >5–10 keV. Such hot diffuse plasma cannot be bound to the gravitational potential or magnetic field of the Galaxy and should form a continous outflow with a very large energy loss rate ($\sim10^{43}$ erg s^{-1}). To sustain stationary X-ray extended emission, this energy must somehow be supplied throughout the whole Galaxy.

The alternative explanation of the GRXE being cumulative emission of a large number of weak point X-ray sources emitting a strong 6.7-keV line (e.g. Worrall & Marshall 1983; Mukai & Shiokawa 1993) has also faced difficulties due to the failure of X-ray telescopes (including the modern *Chandra* and *XMM–Newton*) to resolve the GRXE (Sugizaki et al. 2001; Hands et al. 2004; Ebisawa et al. 2005).

A solution to all these problems has apparently been found recently through studies of the GRXE morphology. As the knowledge of the GRXE surface brightness distribution in the Galaxy progressively improved (e.g. Koyama et al. 1986; Yamauchi & Koyama 1993; Yamauchi et al. 1996; Revnivtsev 2003; Revnivtsev et al. 2006), it finally became possible to demonstrate that the GRXE closely follows the near-infrared (NIR) emission of the Galaxy, which is in turn a good tracer of the stellar mass density (Revnivtsev et al. 2006). It was consequently proposed that X-ray emissivity is proportional to stellar mass density. The determined unit-stellar-mass emissivity proved to be in good agreement with the cumulative emissivity of X-ray sources (cataclysmic variables and coronal stars) in the solar neighbourhood (Sazonov et al. 2006; Revnivtsev et al. 2006). These findings imply that the GRXE represents integrated emission of weak ($L_X < 10^{34}$ erg s^{-1}) Galactic X-ray sources.

Despite the significant progress made in understanding the GRXE morphology, Revnivtsev et al. (2006) could not construct a two-dimensional map of the GRXE of reasonable quality. The main limiting factor was severe contamination by bright X-ray sources. This in particular precluded a study of the GRXE distribution in the Galactic plane. However, the prominent emission line at energy ∼6.7 keV makes it possible to get rid of (or at least strongly diminish) the contribution from bright sources. Indeed, luminous X-ray binaries do not typically exhibit an emission line at this energy. At most they show a fluorescent emission line at ∼6.4 keV, but its equivalent width is approximately 10 times smaller than that

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of the 6.7–6.9-keV emission lines present in the GRXE. The contribution of the fluorescent line will therefore be important only from very bright sources. The 6.7-keV line has been successfully used in studying the GRXE by e.g. Yamauchi & Koyama (1993) in application to GINGA/LAC data. Here we would like to apply the same method to *Rossi X-ray Timing Explorer* Proportional Counter Array (*RXTE*/PCA) data, which provide better sensitivity and angular resolution.

One can consider three distinct spatial components of the GRXE: Galactic disc, Galactic bulge/bar, and the central cusp of extended emission. The focus of the present Letter will be on the former two components, which are distributed widely over the sky spanning over 100° in Galactic longitude and ∼3°–8° in Galactic latitude. *RXTE* observations ideally suit such a study.

The central surface brightness cusp of the GRXE (Koyama et al. 1996; Muno et al. 2004; Neronov et al. 2005) has a size of only 5–10 arcmin, meaning that X-ray instruments with good angular resolution should be invoked to study this component. However, when studying the GRXE on large scales one needs wide sky coverage and large grasp (collecting solid angle multiplied by effective area) to be able to detect flux from regions of low X-ray surface brightness.

2 ANALYSIS

2.1 General approach

In comparison with the work of Revnivtsev et al. (2006), the available *RXTE* data allow us to make improvement in two directions.

(i) Flux and time-filtering. Regular and numerous *RXTE* observations of the Galactic bulge and inner Galactic disc regions (e.g. Swank & Markwardt 2003) have covered a long period of time, much longer than the typical variability time-scale of bright X-ray binaries. Therefore, although the time-averaged map of the inner Galaxy is dominated by the emission of bright point sources (the large fraction of them being transients), by filtering out time periods when bright sources are present at particular positions on the sky it is possible to construct a map that is almost free from contamination.

(ii) ∼6.7-keV emission line flux measurements. The GRXE contains lines of ionized iron at energies ∼6.7–6.9 keV with a very large eqivalent width (∼1 keV), which is not typical of any type of luminous X-ray binaries. The equivalent width of the emission line intrinsic to the GRXE has been shown to be very stable across the Galactic disc and bulge (e.g. Tanaka 2002; Revnivtsev 2003). For these reasons the 6.7-keV line may be regarded as a reliable indicator of the GRXE.

2.2 Data

We use data of the PCA spectrometer of the *RXTE* observatory. This instrument presents a number of advantages for our study: it combines a large (∼6400 cm^2) total effective area with moderate energy resolution ∼18 per cent at energies 6–7 keV, while its instrumental background is well understood and can be accurately subtracted from the total detector count rate (e.g. Markwardt, Jahoda & Smith 2002).

We analyzed all observations performed in slew or scan mode from 1996 March until 2005 March. A large part of the data used is associated with a series of dedicated Galactic bulge and plane scans.[1] These scans cover an approximately square-like region ∼15° × 15° around the Galactic Centre (see e.g. Revnivtsev 2003) and two rectangular regions in the inner Galactic plane. In total, these scans cover the inner Galaxy from $l \sim -25°$ to $l \sim +21°$. The rest of the Galaxy is covered by occasional scans and slews.

The data were analyzed using standard tasks of the HEASOFT 6.0.2 package (http://heasarc.gsfc.nasa.gov/docs/software/lheasoft/). Only Standard2 data (129 energy channels, 16-s time-resolution) from the first layers of anodes of the detectors were used because of the higher quality of the background subtraction possible for data from these layers. The total exposure time of the observations used is ∼30 Ms.

The data were rearranged into spatial bins of different size. In the region ∼20° around the Galactic Centre the bin size was chosen to be 0°.5 × 0°.5. Further away from the Galactic Centre the bin sizes were increased to 5° × 1° (the longer dimension being along the Galactic plane).

Within these bins we searched for strong flux variability and selected only those time-intervals when the detected flux was lower than the certain limit. The value of this limit was calculated as the 4σ excess above the most probable value of the flux. Such data selection allows us to effectively filter out observations that are significantly contaminated by transient bright X-ray binaries. In order to demonstrate this we present in Fig. 1 the fluxes and spectra (the time-averaged spectrum and the one obtained after application of the time filter) measured by *RXTE*/PCA at $l = -2°.5$, $b = -2°.5$. It can be seen that in this particular case time-filtering has decreased the level of contamination by a bright point source (X-ray nova IGR J17464−3213) by an order of magnitude.

Upon applying time-filtering we constructed the energy spectrum for every spatial bin.

To approximate the spectral continuum we used the model of a photoabsorbed power-law. The centroid of the line was fixed at the value $E_{\rm line} = 6.66$ keV (see e.g. Koyama et al. 1989; Revnivtsev 2003, for the results of approximation of GRXE spectra measured by instruments with moderate energy resolution) and the width of the line was fixed at a value of $\sigma = 0.3$ keV. Although such a representation of the complex of emission lines at 6.4–6.9 keV (see e.g. Tanaka 2002) is clearly an oversimplification, it provides a good approximation to the observed set of lines for the limited energy resolution of the PCA spectrometer (see Fig. 1).

The flux in the broad Gaussian emission line inferred from the spectral approximation will be used below for mapping the GRXE.

Even after the application of all our methods aimed at reducing the contamination from bright point sources, some spatial bins remain polluted. The strongest contamination comes from sources that themselves exhibit powerful emission lines at 6.7–6.9 keV (e.g. thermal plasma emission). In the Galactic Centre region such sources are the Ophiuchus galaxy cluster and the intermediate polar V2400 Oph (both are located at $l \sim 0°$, $b \sim 8°$), in the Galactic plane strong contamination comes from the star η Carinae ($l \sim -75$). We excluded these spatial bins from our subsequent analysis.

Below there will be presented measurements of the extended emission in terms of surface brightness. For conversion of the flux measured by PCA to intensity we assumed uniform surface brightness within the PCA field of view (∼1° radius) and adopted the solid angle of the PCA collimator to be 0.975 square degrees (Jahoda et al. 2006).

[1] More detailed information about the Galactic Centre scans can be found at http://lheawww.gsfc.nasa.gov/users/craigm/galscan/main.html

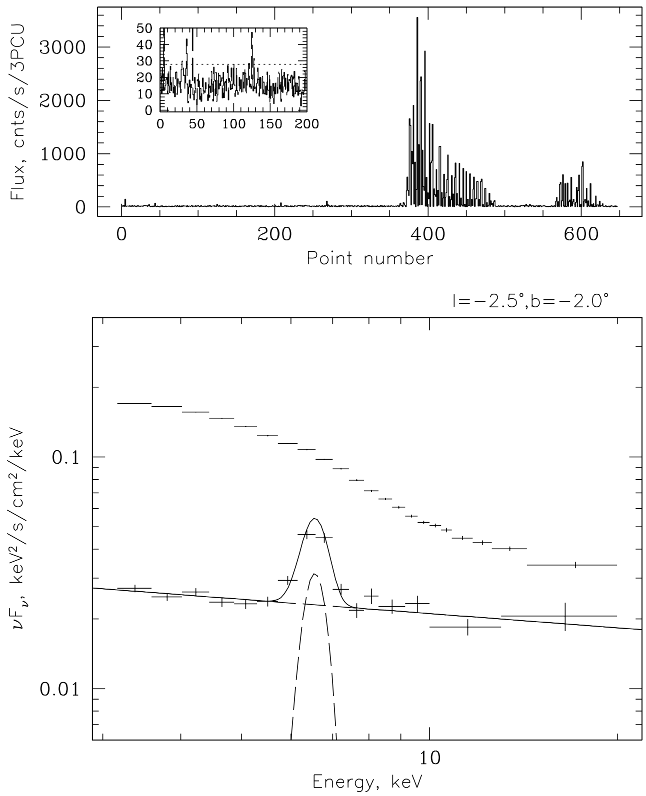

Figure 1. Upper panel: history of flux measurements made by *RXTE*/PCA within the 0°.5 × 0°.5 region centered at $l = -2^\circ.5$, $b = -2^\circ.0$. Strong contamination by a transient bright X-ray source is obvious. The flux thresholds that was used for data filtering are schematically shown in the inset. Lower panel: energy spectrum measured by *RXTE*/PCA within the same region. The upper spectrum was obtained by collecting all data, while the lower spectrum was obtained by collecting only data that passed the flux filtering as shown above. The lower spectrum is approximated by a model, which is later used for extraction of emission line fluxes: a power law with a broad Gaussian emission line centered at $E_{\rm line} = 6.66$ keV with a fixed width $\sigma = 0.3$ keV.

2.3 Systematics

The spectrometer PCA of the *RXTE* observatory is a well-calibrated instrument (see e.g. Jahoda et al. 2006), so no significant systematical problems are expected during the data analysis. The accuracy of the PCA instrumental background subtraction is very good, ∼1 per cent of the average PCA background count rate, or $\sim 1\text{–}2 \times 10^{-12}$ erg s^{-1} cm^{-2} in the energy band 3–20 keV. For the GRXE this translates into a flux of the broad ($\sigma = 0.3$ keV) Gaussian line $dF_{\rm line} \sim 5\text{–}8 \times 10^{-6}$ photon s^{-1} cm^{-2} deg^{-2}. Therefore, in our case this uncertainty practically never dominates over Poissonian count statistics.

There are two main uncertainties associated with our analysis: (i) unfiltered contribution from bright point sources and (ii) spatial confusion due to the relatively fast (∼0°.5–1° per the 16-s time-bin) motion of the PCA field of view.

We managed to reduce the influence of the first problem by filtering out those spatial bins for which the measured equivalent width of the 6.7-keV emission line was significantly (more than twice) different from equivalent width (EW) ∼850 eV, which was measured in the (high-quality) average GRXE spectrum by Revnivtsev (2003). Such deviations of the equivalent line width indicate that the contribution of non-GRXE emission is important.

The spatial confusion problem appears in those regions where the surface brightness of the GRXE exhibits sharp features. In such cases, due to the fast motion of the PCA field of view, the flux measured by PCA may be ascribed to the wrong region. For PCA, with its ∼1°-radius field of view, this problem is particularly important within a few degrees of Sgr A* because of the sharp increase of the 6.7-keV line surface brightness toward it. Since our analysis becomes unreliable within the ∼1° region around Sgr A*, we do not consider it here.

The confusion problem may also lead to distortions in our surface brightness map near the Galactic plane due to the relatively large surface brightness gradients in this region. Given that the exponential vertical scaleheight of the GRXE around the Galactic plane is ∼1°–2° (see e.g. Valinia & Marshall 1998; Revnivtsev et al. 2006) and assuming an angular velocity of the PCA field of view of ∼1°/16s, we can estimate that the uncertainty of flux measurement can reach ∼10–15 per cent. This uncertainty should be taken into account in comparing the observed X-ray surface brightness with e.g. the surface brightness of the Galaxy in the NIR. In our subsequent analysis we quadratically added a 10 per cent systematic uncertainty to allow for confusion.

2.4 NIR surface brightness data

In the present paper we compare the GRXE map with the stellar density distribution in the Galaxy for which the best tracer is the NIR surface brightness.

The map of the Galaxy in the NIR spectral band was obtained using data of *Cosmic Background Explorer* Diffuse Infrared Background Experiment (*COBE*/DIRBE) observations [the zodi-subtracted mission average map provided by the Legacy Archive Microwave Background Data Analysis (LAMBDA) archive of the Goddard Space Flight Center, http://lambda.gsfc.nasa.gov]. In order to reduce the influence of the interstellar reddening we considered the DIRBE spectral band 4.9 μm.

We applied the simplest corrections to the NIR map of the Galaxy obtained by *COBE*/DIRBE. We removed the extragalactic background component determined by averaging measurements at $|b| > 20^\circ$. We assumed that the intrinsic NIR colour temperature (i.e. the ratio of the intrinsic surface brightnesses $I_{1.2\ \mu\rm m}$ and $I_{4.9\ \mu\rm m}$) of the Galactic disc and bulge/bar is uniform and its true value can be derived at high Galactic latitudes where interstellar reddening is negligible. Then the foreground extinction map can be expressed as

$$A_{4.9\ \mu\rm m} = \frac{-2.5}{A_{1.2\ \mu\rm m}/A_{4.9\ \mu\rm m} - 1} \times \left[\ln\left(\frac{I_{1.2\ \mu\rm m}}{I_{4.9\ \mu\rm m}}\right) - \log\left(\frac{I^0_{1.2\ \mu\rm m}}{I^0_{4.9\ \mu\rm m}}\right)\right].$$

Here the A values are the reddening coefficients at different wavelengths. We used the interstellar reddening values from Lutz et al. (1996) and Indebetouw et al. (2005). The applied correction of course removed only the main effects of interstellar extinction on the *COBE*/DIRBE map. Therefore, we do not expect that the obtained *COBE*/DIRBE map and profiles have accuracy better than ∼10 per cent.

3 RESULTS

In Figs 2 and 3 we demonstrate the correlation between the 6.7-keV line intensity and the NIR surface brightness. These results strongly support the finding of Revnivtsev et al. (2006), that the

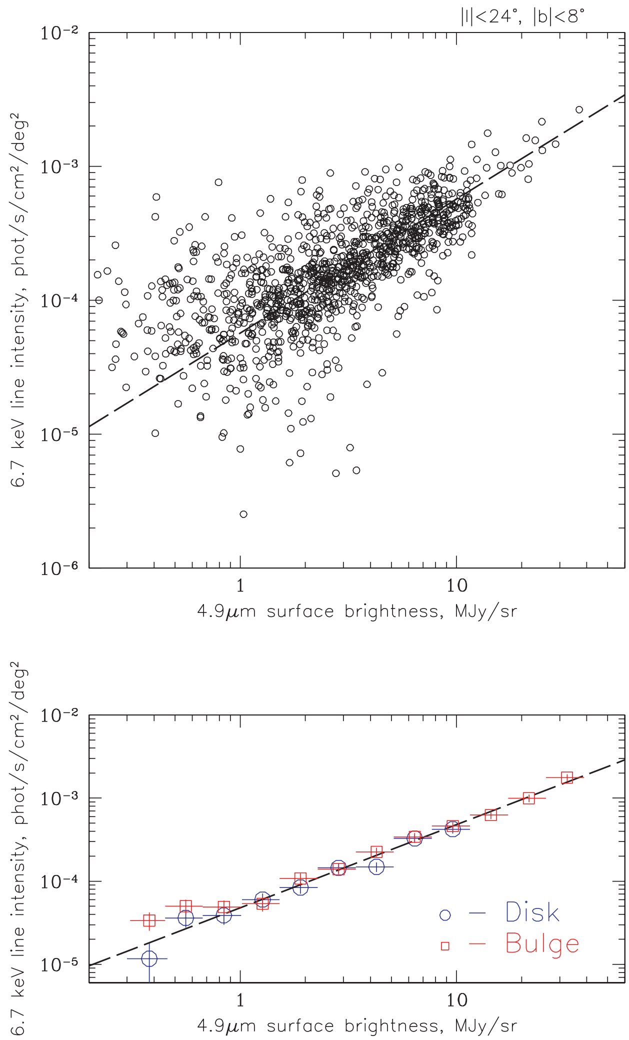

Figure 2. Correlation of NIR (DIRBE 4.9 µm, corrected for interstellar reddening) and 6.7-keV emission line surface brightness in the inner Galaxy. Upper panel: points are measurements of X-ray and NIR intensities in small, 0°(5 × 0°)5, spatial bins, so that the X-ray statistics is rather limited. The uncertainties of the 6.7-keV line fluxes are different for different points, but in general the scatter around the linear approximation is compatible with the errors involved. The correlation $I_{6.7\,\mathrm{keV\,line}}$[photon s^{-1} cm^{-2} deg^{-2}] = 4.7×10^{-5} $I_{4.9\,\mu\mathrm{m}}$ [MJy sr^{-1}] is shown by the dashed line. Lower panel: measurements of the X-ray line intensity averaged within NIR flux bins. Data for the Galactic disc ($|l| > 10°$) and bulge ($|l| < 3°$) are shown by open circles and squares, respectively. The dashed line is the same best-fitting linear correlation as the one presented in the upper panel.

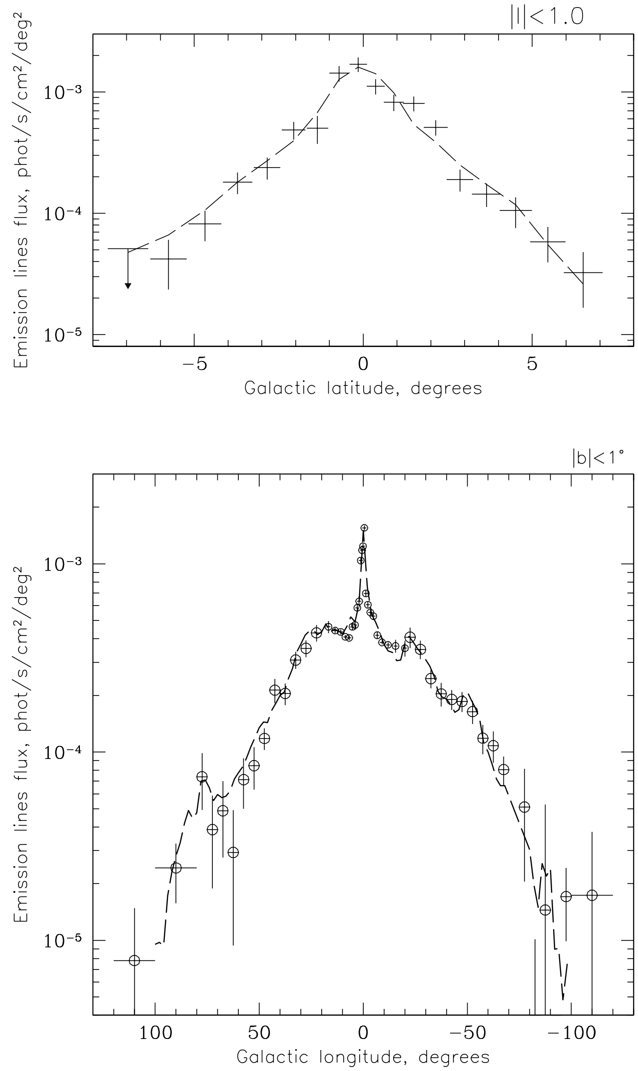

Figure 3. Profiles of the surface brightness of the Galaxy in the 6.7-keV emission line measured by *RXTE*/PCA. Upper panel: profile perpendicular to the Galactic plane at $|l| < 2°$. Lower panel: profile along the Galactic plane at $|b| < 1°$. On both panels the dashed lines show the profile of the surface brightness of the Galaxy at 4.9 µm measured by *COBE*/DIRBE.

GRXE surface brightness traces the NIR one. With respect to that work, a significant improvement is achieved in the Galactic plane region. It can be seen that the Galactic bulge and plane regions of the GRXE have the same proportionality to the NIR emission. This indicates that there is no significant difference in the populations of weak X-ray sources that constitute the GRXE in the plane and in the bulge. Note that a similar result has been obtained via a study of the hard X-ray emission of the Galactic ridge with the *International Gamma-Ray Astrophysics Laboratory* (*INTEGRAL*: Krivonos et al. 2006).

In order to visualize the distribution of the 6.7-keV surface brightness in the inner Galaxy we present a false-colour two-dimensional map in Fig. 4 and compare it with the maps of Galactic emission in the 3–20 keV energy band and in the NIR band. In constructing the 6.7-keV map we increased the statistics of flux measurements in the 6.7-keV line by using adaptively sized spatial bins.

4 SUMMARY

(i) We built a map of the Galaxy in the ~6.7-keV line, the characteristic emission line of the Galactic X-ray background (GRXE). The use of only this line instead of a broad-band X-ray flux allowed us to strongly suppress the contamination from bright point sources. As a result we achieved a very good coverage of the inner Galaxy ($|l| < 25°$) and followed the Galactic ridge emission up to $|l|$ ~100°–120°.

(ii) We demonstrated that the surface brightness of the Galaxy in the 6.7-keV line corresponds very well to its NIR surface brightness. This shows that the GRXE volume emissivity is proportional to the stellar mass density in the Galaxy.

(iii) We showed that the proportionality between the 6.7-keV surface brightness and NIR one is the same for the bulge and disc of the Galaxy.

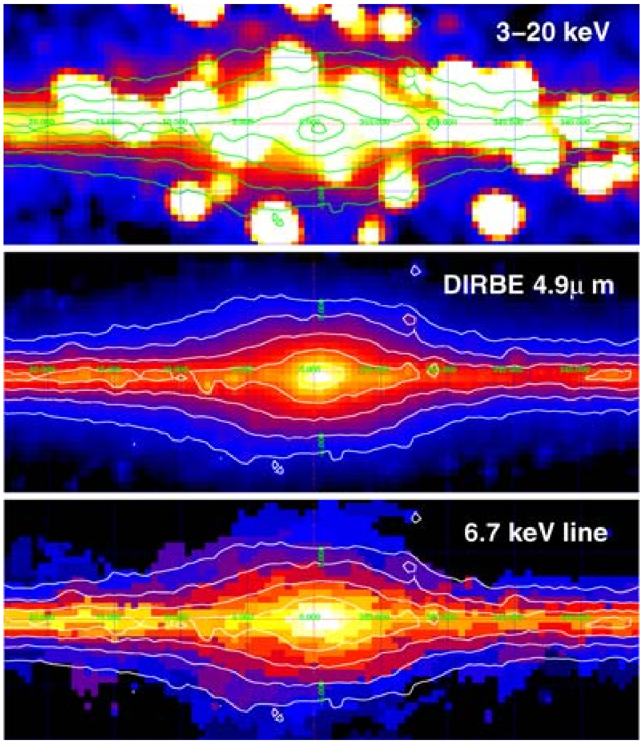

Figure 4. Top: time-averaged map of the inner Galaxy in the energy band 3–20 keV obtained with *RXTE*/PCA. The domination of bright point sources is evident. The contours are iso-brightness contours of the NIR emission of the Galaxy (see middle panel) Middle: near-infrared surface brightness map of the Galaxy (*COBE*/DIRBE 4.9-μm data, corrected for reddening) Bottom: Map of the surface brightness of the inner Galaxy in the 6.7-keV emission line. The white contours are iso-brightness contours of NIR emission.

(iv) The aforementioned observational facts along with the value of unit-stellar-mass X-ray emissivity measured in the solar neighbourhood (Sazonov et al. 2006) provides further evidence that the bulk of the GRXE is made up by faint Galactic X-ray point sources.

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REFERENCES

Bleach R. D., Boldt E. A., Holt S. S., Schwartz D. A., Serlemitsos P. J., 1972, ApJ, 174, L101
Cooke B. A., Griffiths R. E., Pounds K. A., 1970, in Gratton L., ed., Proc. IAU Symp. 37, Non-Solar X- and Gamma-Ray Astronomy. Reidel, Dordrecht, p. 280
Ebisawa K. et al., 2005, ApJ, 635, 214
Hands A. D. P., Warwick R. S., Watson M. G., Helfand D. J., 2004, MNRAS, 351, 31
Indebetouw R. et al., 2005, ApJ, 619, 931
Jahoda K., Markwardt C. B., Radeva Y., Rots A. H., Stark M. J., Swank J. H., Strohmayer T. E., Zhang W., 2006, ApJS, 163, 401
Koyama K., Makishima K., Tanaka Y., Tsunemi H., 1986, PASJ, 38, 121
Koyama K., Awaki H., Kunieda H., Takano S., Tawara Y., 1989, Nat, 339, 603
Koyama K., Maeda Y., Sonobe T., Takeshima T., Tanaka Y., Yamauchi S., 1996, PASJ, 48, 249
Krivonos R., Revnivtsev M., Churazov E., Sazonov S., Grebenev S., Sunyaev R., 2006, A&A submitted (astro-ph/0605420)
Lutz D. et al., 1996, A&A, 315, L137
Markwardt C., Jahoda K., Smith D. A., 2002, http://lheawww.gsfc.nasa.gov/users/craigm/pca-bkg/bkg-users.html
Mukai K., Shiokawa K., 1993, ApJ, 418, 863
Muno M. P. et al., 2004, ApJ, 613, 326
Neronov A., Chernyakova M., Courvoisier T. J., Walter R., 2005, A&A submitted (astro-ph/0506437)
Revnivtsev M., 2003, A&A, 410, 865
Revnivtsev M., Sazonov S., Gilfanov M., Churazov E., Sunyaev R., 2006, A&A, 452, 169
Sazonov S., Revnivtsev M., Gilfanov M., Churazov E., Sunyaev R., 2006, A&A, 450, 117
Sugizaki M., Mitsuda K., Kaneda H., Matsuzaki K., Yamauchi S., Koyama K., 2001, ApJS, 134, 77
Swank J. H., Markwardt C. B., 2003, AAS, HEAD Meeting No. 7
Tanaka Y., 2002, A&A, 382, 1052
Valinia A., Marshall F. E., 1998, ApJ, 505, 134
Warwick R. S., Turner M. J. L., Watson M. G., Willingale R., 1985, Nat, 317, 218
Worrall D. M., Marshall F. E., 1983, ApJ, 267, 691
Worrall D. M., Marshall F. E., Boldt E. A., Swank J. H., 1982, ApJ, 255, 111
Yamauchi S., Koyama K., 1993, ApJ, 404, 620
Yamauchi S., Kaneda H., Koyama K., Makishima K., Matsuzaki K., Sonobe T., Tanaka Y., Yamasaki N., 1996, PASJ, 48, L15

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