ORIGIN OF THE GALACTIC RIDGE X-RAY EMISSION: PUZZLE SOLVED?

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ABSTRACT

Origin of the Galactic ridge X-ray emission (GRXE) was a long standing problem of Xray astronomy. Explanations of the ridge emission by emission of a hot thermal plasma or by interaction of cosmic rays with interstellar matter were connected with serious problems. Latest studies of the ridge emission with highest sensitivity and finest spatial resolution X-ray telescopes (like CHANDRA) have not provided conclusive answer. We have studied the morphology of the Galactic ridge X-ray emission with Rossi Explorer and shown that the GRXE contains both disk and bulge/bar components, whose parameters very well agree with those of known stellar Galactic components. We have showen that the GRXE volume emissivity well traces well the stellar mass density in the Galaxy. Average Galactic unit stellar mass emissivity of the GRXE can be easily explained by average unit stellar mass X-ray emissivity in the Solar neighbourhood. Dominant contributors to the GRXE are accreting white dwarfs and coronally active stars. These types of X-ray sources are numerous, they might significantly contribute to the emission of X-ray emitting galaxies and should be taken into account in studies of extragalactic objects.

Key words: LaTeX; ESA; macros.

1. INTRODUCTION

There are two major large-scale extended features in the X-ray sky (above 2 keV): the almost uniform cosmic X-ray background (CXB, [11]) and an emission concentrated toward the Galactic plane – the Galactic ridge X-ray emission (GRXE, see e.g. [35]). While over the past two decades it has been firmly established that the CXB is a superposition of a large number of discrete extragalactic sources (namely active galactic nuclei, see e.g. [12]), the origin of the GRXE remained unexplained.

Exploration of the GRXE by different observatories has revealed that it is concentrated near the inner Galactic disk, extending tens of degrees in longitude and a few degrees in latitude [4, 35, 37, 38, 40], and probably has a central bulge-like component [41, 24]. The energy spectrum of the GRXE contains a number of emission lines of highly ionized heavy elements, indicating that the emission should be thermal with a temperature of up to 5–10 keV [15, 16, 32, 21]. The total GRXE luminosity has been estimated at $\sim$1–2$\times 10^{38}$ erg s^{-1} [41, 34].

The GRXE has been detected at least up to 20–25 keV energies [34, 24], and its spectrum in the 3–20 keV range consists of a continuum, which can be approximated by a power law of photon index $\Gamma \sim 2.1$, and powerful lines at 6–7 keV energies. Also a detection of GRXE at energies >40 keV (at Galactic longitude $l = 95$) was reported (e.g. [28, 34]), but it now appears that those CGRO/OSSE measurements were strongly contaminated by a few unresolved sources, including the active galactic nucleus IGR J21247+5058 recently discovered by the INTEGRAL observatory [18]. The IBIS telescope aboard INTEGRAL, capable of resolving point-like sources with flux >few$\times 10^{-11}$ erg s^{-1} cm^{-2} in crowded regions, has not detected the GRXE at energies above $\sim$40 keV and resolved 85% of it in the 20-40 keV energy band[17, 33].

Soon after discovery of the GRXE, it was proposed that it might consist of a large number of weak Galactic X-ray point sources, e.g. quiescent low-mass and high-mass X-ray binaries, cataclysmic variables, coronally active binaries, etc. [35, 36, 15, 22, 19]. However, it was not possible to draw a solid conclusion due to lack of detailed information about the space densities and X-ray luminosity distributions of these classes of X-ray sources.

Unless the GRXE is truly diffuse emission, it should eventually be possible to resolve it into a finite number of discrete sources. As the sensitivity of X-ray telescopes has been increasing, a progressively higher fraction of the GRXE has been resolved [35, 37, 29]. However, even the deepest observations of Galactic plane regions by the currently operating Chandra and XMM-Newton observatories, in which point-source detection sensitivities $F_x > 3 \times 10^{-15}$ erg

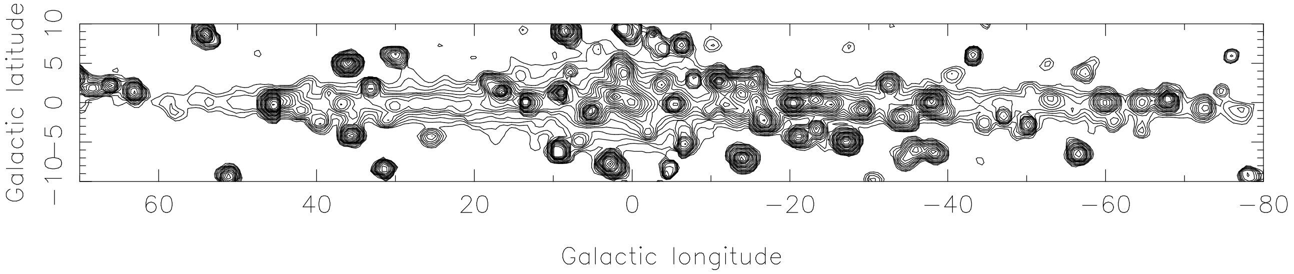

Figure 1. RXTE/PCA map of the sky around the Galactic plane in the energy band 3–20 keV. Contour levels are logarithmically spaced with a factor of 1.4, with the lowest contour corresponding to an intensity of 10^{-11} erg s^{-1} cm^{-2} deg^{-2}. This contour level shows statistically significant intensity on the sky everywhere on the plot, and the map clearly exposes many bright point sources and an underlying unresolved emission

s^{-1} cm^{-2} in the energy band 2–8 keV [6, 13, 7] were achieved, resolved not more than 10–15% of the GRXE. This was regarded as a strong indication of the GRXE being truly diffuse.

However, the hypothesis of diffuse origin of the GRXE meets strong difficulties [e.g. 15, 30, 31, 32]. The main problem is that the apparently thermal spectrum of the GRXE implies that the emitting plasma is so hot (∼5–10 keV) that it should be outflowing from the Galactic plane. A large energy supply is then required to constantly replenish the outflowing plasma.

Resolving the GRXE is additionally complicated by the fact that at fluxes near the present-day sensitivity limit ($\sim 10^{-15}$ erg s^{-1} cm^{-2}), extragalactic sources outnumber Galactic ones even in the Galactic plane (e.g. [7]). Since identification of weak sources detected in deep X-ray surveys of the Galactic plane is usually problematic and the CXB varies significantly on sub-degree angular scales, so far it has only been possible to place upper limits on the fraction of the GRXE resolved into Galactic X-ray sources (as mentioned above).

The only place where Galactic sources dominate over extragalactic ones is the inner $10'$ of the Galaxy [20], and Chandra has resolved up to 30% of the "hard diffuse" emission in certain parts of this region [21, region "Close" in this paper]. Moreover, the flux-number distribution of Galactic X-ray sources detected in this Galactic Center survey shows no cutoff down to the Chandra detection limit, implying that at least an order of magnitude deeper observations will be needed to resolve the bulk of the hard X-ray emission from the Galactic Center if the source flux-number distribution continues with the same slope to fluxes lower than presently accessible.

It is therefore worth considering alternative ways to solve the problem of the GRXE origin, in particular via studying its spatial distribution. The distribution of the GRXE over the sky is still poorly known, mainly because of its large extent (approximately 120° × 10°) and low surface brightness ($<$few$\times 10^{-11}$ erg s^{-1} cm^{-2} deg^{-2}). The investigation of the GRXE in the HEAO-1/A2 experiment [e.g. 14, 35] was significantly hampered by point source confusion, whereas instruments with much better spatial resolution were not able to cover a sufficiently large solid angle of the sky [e.g. 29, 13].

In this paper we present a brightness distribution of the GRXE measured in the 3–20 keV energy band by the RXTE/PCA instrument and show that this distribution closely follows the near-infrared brightness of the Galaxy, known to be a good tracer of the stellar mass distribution. We further compare the inferred Galactic ridge X-ray emissivity per unit stellar mass with the cumulative emissivity of point X-ray sources in the Solar neighborhood, determined by [27], and argue that the bulk of the GRXE is very likely composed of weak discrete sources of known types.

2. MAP OF THE GRXE

In Fig. 1 we present an X-ray intensity map of the sky around the Galactic plane convolved with the response of the PCA collimator (triangular shape with a radius ∼ 1°, see [25]). The contour levels on this map are logarithmically spaced with a factor of 1.4, and the lowest shown level corresponds to an X-ray intensity of $\sim 10^{-11}$ erg s^{-1} cm^{-2} deg^{-2}.

The map clearly exposes many bright point-like sources and an underlying unresolved emission – the GRXE. Henceforth we reserve the term "GRXE" to describe Galactic X-ray emission that cannot be resolved into discrete sources with flux higher than 10^{-11} erg s^{-1} cm^{-2}. We note that the exact value of the limiting flux is not important if it is in the range of $\sim 10^{-13-10.5}$ erg s^{-1} cm^{-2} , because the angular density of sources with such fluxes even in the Galactic plane is low and they do not contribute more than $< 10\%$ to the GRXE [29, 13].

The GRXE was given its name because it was originally detected as a prominent narrow (∼ 1–2°) band

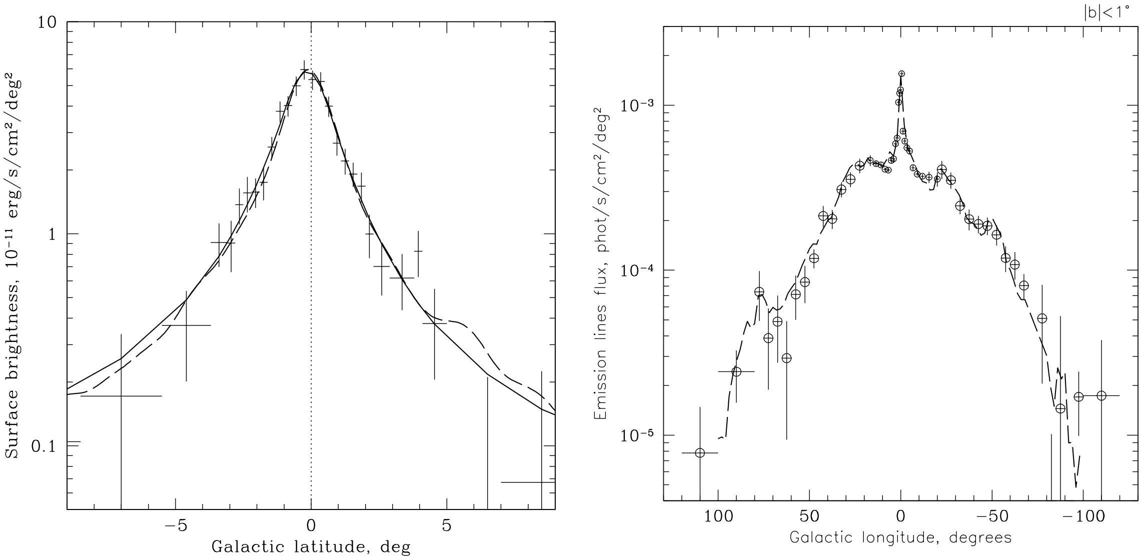

Figure 2. Left: the GRXE intensity profile in the ∼ 1°-wide band around $l = 20.2°$ perpendicular to the Galactic plane. The dashed line shows the near-infrared brightness distribution multiplied by a scaling factor. Right: GRXE profile (as measured in 6.7 keV characteristic emission line) along the Galactic plane at $|b| < 1°$. Dashed lines show the profile of the surface brightness of the Galaxy measured by COBE/DIRBE.

of unresolved emission along the Galactic plane [e.g. 2, 35]. However, it has since then become more evident that the unresolved X-ray emission of the Galaxy contains both a disk-like and a bulge-like component [41, 24]. The exponential scale height of the disk component of the GRXE is ∼ 1.5° [35, 37, 41], whereas it is much larger for the Galactic bulge – up to 3–5°[41, 24]. Both components can now be clearly seen on the RXTE map shown in Fig. 1.

It is natural to compare the inferred morphology of the GRXE disk and the bulge with the same components of the stellar distribution in the Galaxy. For this purpose we can use either models of the stellar density in the Galaxy[1, 3, 39, 8, 5, 9, 10] or existing near infrared maps of the Galaxy obtained by COBE/DIRBE.

Both comparisons show that the distribution of X-ray "background" emission on the sky is directly proportional to the near infrared brightness distribution of our Galaxy (see Fig.2 and 3).

Thus we conclude that the sky distribution of the GRXE surface brightness is directly proportional to the surface brightness distribution of the near infrared emission of the Galaxy which is known to be dominated by ordinary low mass stars, and we can state that the GRXE unit volume X-ray emissivity is proportional to the density of stars

Our estimates show that the ratio of X-ray luminosity to the mass of stellar association is $L_{\rm x}/M \sim (3.5 \pm 0.5) \times 10^{27}$ erg s^{-1} $M_{\odot}^{-1}$.

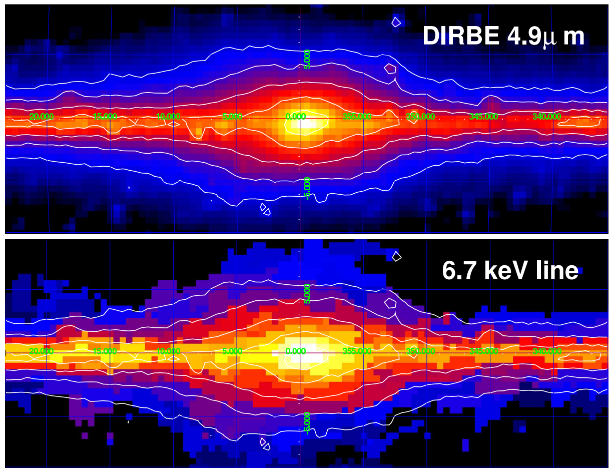

Figure 3. Top: Near-infrared surface brightness map of the Galaxy (COBE/DIRBE 4.9μm data, corrected for reddening) Bottom: Map of the surface brightness of the inner Galaxy in the 6.7 keV emission line. The white contours are iso-brightness contours of NIR emission.

It is interesting to note that the extinction-corrected COBE/DIRBE near-infrared (3.5μm) map of the sky should be nearly identical to the GRXE map upon scaling by a factor $I_{3-20{\rm keV}}(10^{-11}$ erg s^{-1} cm^{-2} deg$^{-2})/I_{3.5\mu{\rm m}}$(MJy/sr)=0.26. Figure 4 demonstrates that this is indeed the case. Subtracting the rescaled near-infrared map from the observed X-ray brightness map of the Galaxy (Fig. 4, upper panel) leaves only point-like X-ray sources (Fig. 4, lower panel).

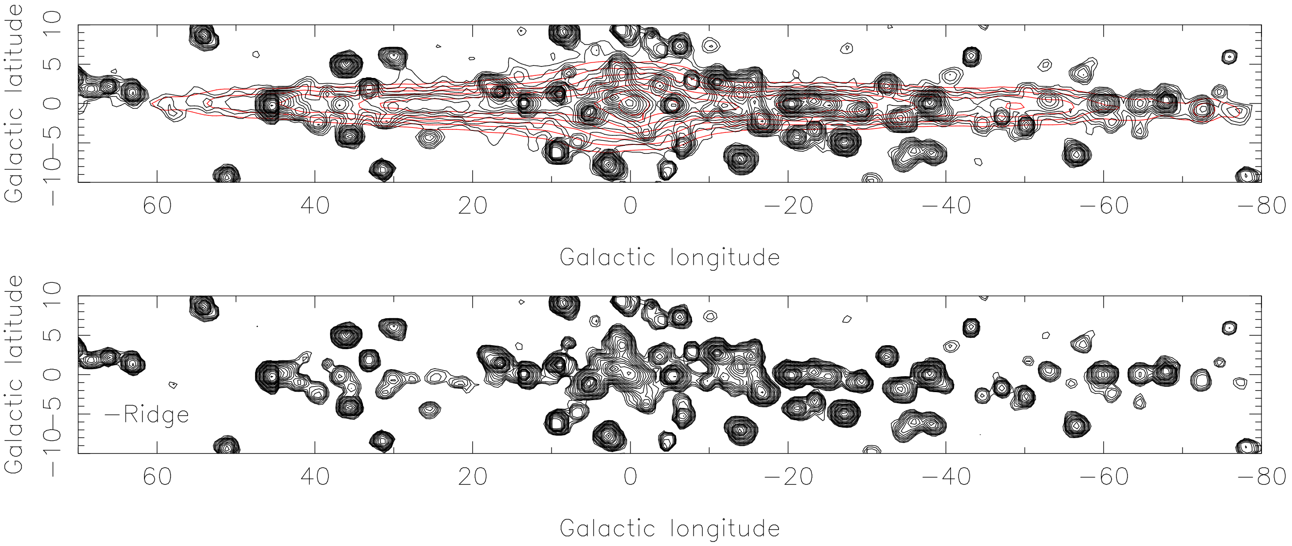

Figure 4. Top panel: RXTE/PCA map of the sky around the Galactic plane in the 3–20 keV band. The red contours show the COBE/DIRBE near-infrared map (3.5 μm) rescaled by a factor $I_{3-20\mathrm{keV}}(10^{-11}$ erg s^{-1} cm^{-2} deg$^{-2})/I_{3.5\mu\mathrm{m}}(MJy/sr)=0.26\pm0.05$ and convolved with the PCA collimator response. The contour levels are logarithmically spaced with a factor of 1.4, with the lowest contour corresponding to an X-ray intensity of 10^{-11} erg s^{-1} cm^{-2} deg^{-2}. Lower panel: the same RXTE/PCA map with subtracted rescaled near-infrared map. Contour levels are the same as for the upper panel.

3. GALACTIC RIDGE X-RAY EMISSION AS A SUPERPOSITION OF POINT SOURCES

In the previous sections we have presented evidences that the GRXE volume emissivity traces the Galactic stellar density and estimated the ridge X-ray emissivity (3–20 keV) per unit stellar mass as $L_{\mathrm{x}}/M \sim (3.5 \pm 0.5) \times 10^{27}$ erg s^{-1} $M_{\odot}^{-1}$. It is interesting to compare this number with the cumulative X-ray emissivity of the known classes of X-ray sources.

We recently used the RXTE slew survey [26] of the sky at high Galactic latitude to construct an X-ray (3–20 keV) luminosity function of nearby ($\sim$ 1 kpc) sources, covering a broad range in luminosity from coronally active stellar binaries to white dwarf binaries [27] (see. Fig.5). Based on this luminosity function, it is straightforward to estimate the contribution of point sources to the GRXE measured by RXTE in the same spectral band.

The total 3-20 keV emissivity of local Galactic X-ray sources per unit stellar mass $L_{\mathrm{x,local}}/M = (5.3 \pm 1.5) \times 10^{27}$ erg s^{-1} $M_{\odot}^{-1}$ or $(6.2 \pm 1.5) \times 10^{27}$ erg s^{-1} $M_{\odot}^{-1}$, if the contribution of young coronal stars is excluded or included, respectively [27]. The bulk of the local X-ray emissivity is produced by coronally active late-type binaries and cataclysmic variables. These classes of sources represent relatively old stellar populations, so their number density is expected to closely trace the overall stellar density in the Galaxy. On the other hand, the relative fraction of young stellar objects is expected to vary strongly from one Galactic region to another, so their locally estimated emissivity may not represent the Galaxy well as a whole. We find that the local X-ray emissivity, excluding the (small) contribution of young coronal stars, agrees within the uncertainties with the GRXE emissivity, $(3.5\pm0.5)\times10^{27}$ erg s$^{-1}M_{\odot}^{-1}$, found in this paper. This suggests that the bulk of the GRXE may be composed of weak X-ray sources of known classes, mostly coronally active binaries and cataclysmic variables.

If the GRXE is indeed superposed on known populations of X-ray sources, then its energy spectrum must be a sum of the spectra of these sources. In Fig. 6 we compare the measured spectrum of the GRXE with typical spectra of those classes of sources that are expected to contribute significantly to the GRXE. Also a composite spectrum is shown, which is a weighted sum of the individual spectra. The weights describing the fractional contributions of different types of sources were fixed at the values determined by [27] for X-ray sources in the Solar neighborhood, namely intermediate polars : polars : dwarf novae : coronally active binaries – 1:0.2:0.6:2.0. As can be seen in Fig. 6, the composite spectrum turns out to be very similar to the GRXE spectrum.

4. CONCLUSIONS

- We have shown that the 3–20 keV map of the GRXE closely follows the near-infrared brightness distribution of the Galaxy and thus the cumulative X-ray emissivity of the Galaxy in back-

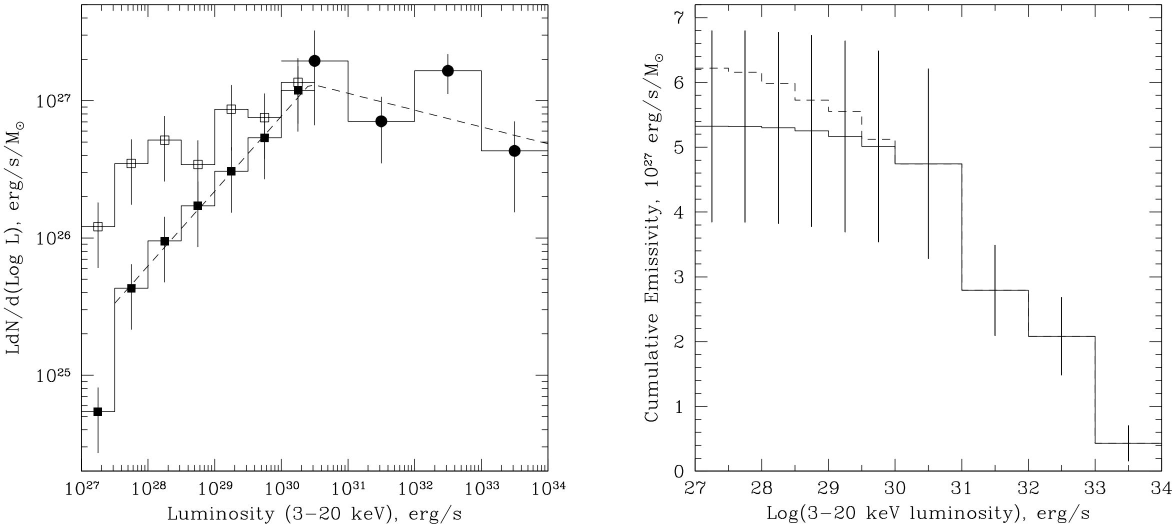

Figure 5. Differential luminosity distribution of 3–20 keV emissivity per unit stellar mass of coronally active stars and CVs. The luminosity function derived from the RXTE all sky survey is shown by filled circles, and the luminosity function derived from the ROSAT all sky survey (RASS) is shown by open squares for all stars and by filled squares for active binaries only. The errors shown for the RASS data points take into account an assumed 50% uncertainty of conversion from the original 0.1–2.4 keV band in addition to statistical errors. The dashed line shows the broken power-law fit to the combined XLF of ABs and CVs (see [27]). Note that in order to explain the "background" emission of the Galaxy one need to have approximately 3.5×10^{27} erg $s^{-1}/M_\odot$.

ground emission is proportional to the stellar density everywhere in the Galaxy.

- Comparison of the GRXE luminosity-per-unit stellar mass with the cumulative emissivity of X-ray sources in the Solar neighborhood suggests that the bulk of the GRXE is very likely superposed of emission from weak Galactic X-ray sources, mostly cataclysmic variables and coronally active binaries.
- The GRXE energy spectrum in the 3–100 keV range can be explained as a composition of spectra of different X-ray-source classes weighted in accordance with their relative contributions to the local X-ray emissivity.

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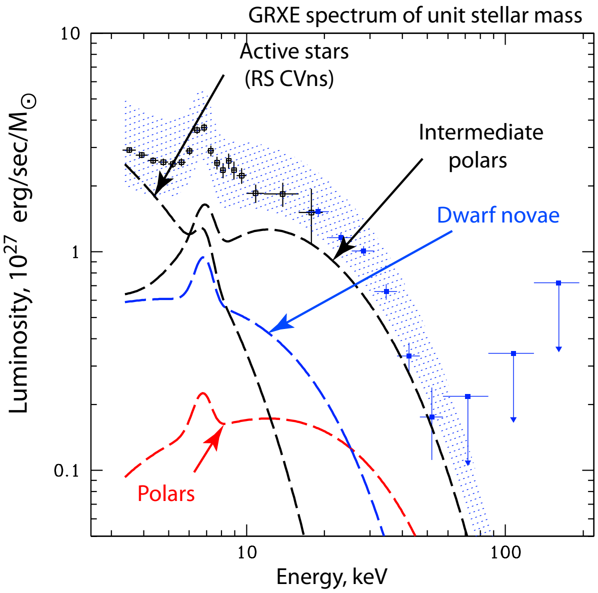

Figure 6. GRXE broad-band spectrum (points) and spectra of its main contributors (dashed lines). The points in the 3–20 keV band are taken from analysis of the RXTE/PCA data, points in energy band 17-200 keV are taken from analysis of the ridge emission by Krivonos et al. (this volume). Normalization of of spectra of main contributors to the ridge emission are calculated from luminosity function of weak X-ray sources in the Solar environment. The shaded region shows a sum of these spectra reflecting uncertainties in the individual spectra and their relative weights.

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