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Thermal X-Ray Emission with Intense 6.7-keV Iron Line from the Galactic Ridge

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Abstract

An intense emission feature attributed to iron has been discovered in the unresolved excess emission along the galactic ridge. The mean line energy is 6.71 ± 0.04 keV, which indicates emission from iron of helium-like ions. The observed spectra are in good agreement with that predicted from a model of thermal bremsstrahlung from an optically thin plasma. The temperature is found to vary from region to region in the range of $kT=5$–10 keV. The observed intensity distribution is consistent with a disk-shaped emission region with a scale height of 100–300 pc and a radius of 10 kpc. The average luminosity per unit surface area is estimated to be $(2.4\text{–}2.8)\times10^{29}$ erg s^{-1} pc^{-2}, giving a total luminosity of roughly 10^{38} erg s^{-1} for the whole disk. This excess emission is considered to be of discrete origin. Within the constraints imposed by the observational results, possible classes of sources are discussed, including white dwarf binaries, RS CVn's, emission nebulae as well as unidentified supernova remnants.

Key words: Galaxy; Supernova remnants; X-ray sources.

1. Introduction

The diffuse X-ray background above 2 keV at high galactic latitude is constant in intensity and spectrum. Because of its isotropy, this component has been considered to be of extragalactic origin. The spectrum can be very well expressed by a thermal bremsstrahlung spectrum in the range 2–50 keV with kT of about 40 keV (Marshall et al. 1980). In addition, the presence of an excess emission above the isotropic background was noted near the galactic plane by previous observations (Cooke et al. 1969; Hudson et al. 1971; Bleach et al. 1972; Warwick et al. 1980; Protheroe et al. 1980). The most extensive observation of the excess emission thus far was carried out by the HEAO-1 satellite. Iwan et al. (1982) reported the presence of a galactic diffuse component with a scale height of several kiloparsecs. Worrall et al. (1982) found another unresolved component from the galactic ridge with a half-thickness of 240 pc. These components were found to be much softer than the diffuse extragalactic background. They considered that the observed emission is most likely of a low-luminosity discrete source origin. Recently, Koyama (1984) has confirmed the excess emission from the galactic ridge by the Tenma satellite. Warwick et al. (1985) have also reported the diffuse excess emission from the inner galactic disk with a better spatial resolution by the EXOSAT satellite. Information on the spectrum is crucial for the identification of the origin of the emission from the galactic ridge. We conducted a series of observations along the galactic plane from the X-ray satellite Tenma and obtained good-quality spectra of the excess galactic component. In this paper, we report on the results of these observations, which invariably reveal an intense iron emission line.

2. Observations

We carried out observations of selected source-free regions along the galactic ridge with the gas scintillation proportional counters (GSPC) on board the Tenma. Details of the Tenma satellite, the GSPCs, and their performance are given in separate papers (Tanaka et al. 1984; Koyama et al. 1984). The observations were performed with two sets of four GSPCs: SPC-A and SPC-B. However, the present analysis is limited to the data obtained with SPC-A. One counter of SPC-B became noisy during the course of the observations, and the data from the three remaining counters are yet to be analyzed. The total effective area of SPC-A is 320 cm^2 and the field of view is a circle of 3°.1 (FWHM). The observed regions are shown in figure 1 in the galactic coordinate system and also in table 1. The cataloged X-ray sources and radio supernova remnants (SNR) are also given in the figure. These regions were selected so as to exclude any cataloged X-ray sources above 2-m Crab intensity and any identified supernova remnants from the full field of view. The observed regions mostly lie between 280° and 335° of galactic longitude and within $\pm 5°$ of the galactic equator. A few other outside regions near the general anticenter were also observed. A typical observation time for each position was roughly 10^4 s.

3. Results

The observed fluxes in most of the selected positions indeed show a significant excess above those at high galactic latitudes. Exceptions were found in the general anticenter region, in which no significant excess was observed. The spectra of the excess emission in the individual directions observed were obtained by subtracting the background spectrum from a source-free region off the galactic plane ($|b|>20°$). This background spectrum consists of two components: diffuse extragalactic background and intrinsic background. In neither component, significant structure near

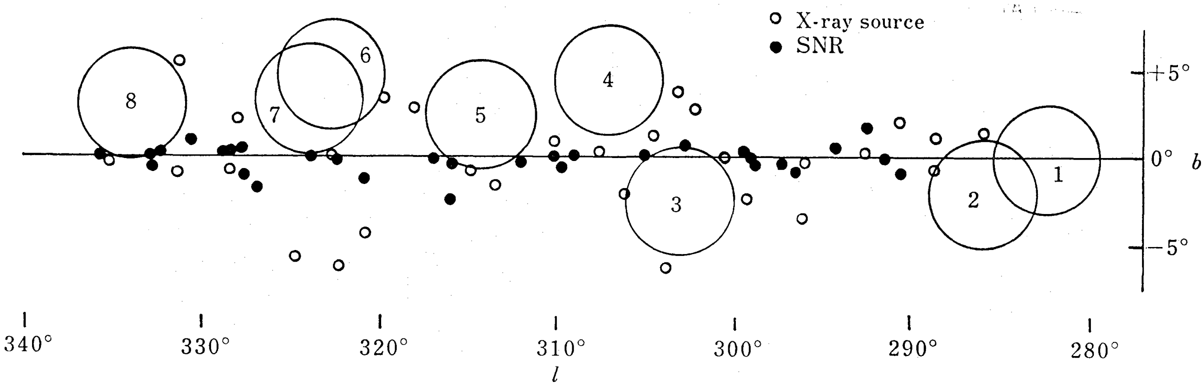

Fig. 1. Observed positions near the galactic ridge, indicated by the full field of view of the detector (large open circles). Cataloged X-ray sources (Forman et al. 1978; Wood et al. 1984) with intensity greater than 2 m Crab and radio supernova remnants (Clark and Caswell 1976) are given by small open circles and closed circles, respectively.

Table 1. Best-fit parameters for a model of thermal bremsstrahlung from an optically thin plasma.

Position No.	(l, b)	Normalization† A (photons s^{-1} keV^{-1})	Temperature kT (keV)	N_H (10^{22} cm^{-2})
1	(281°8, −0°2)	4.4±0.9	7.3±1.1	<1
2	(285.3, −2.1)	7.1±1.1	5.6±0.6	<1
3	(302.6, −2.4)	4.4±0.7	9.3±1.3	<1
4	(306.6, +4.3)	5.9±1.7	5.1±0.9	<1
5	(313.8, +2.3)	5.1±0.9	9.1±1.3	1±1
6	(322.2, +4.6)	2.9±0.8	6.0±1.1	<1
7	(323.4, +3.3)	4.0±0.8	9.4±1.6	<1
8	(333.4, +3.0)	5.4±0.8	10.3±1.3	2±1

Position No.	Line energy E_0 (keV)	Line flux† I_0 (photons s^{-1})	Equivalent width (keV)	Reduced χ^2 (28 degrees of freedom)
1	6.51±0.11	0.10±0.08	0.47±0.15	1.7
2	6.76±0.08	0.12±0.13	0.60±0.13	1.6
3	6.68±0.09	0.13±0.03	0.45±0.12	1.2
4	6.69±0.12	0.10±0.03	0.68±0.23	1.0
5	6.75±0.07	0.19±0.04	0.59±0.12	1.1
6	6.76±0.15	0.05±0.02	0.52±0.22	1.3
7	6.81±0.11	0.12±0.04	0.48±0.14	0.9
8	6.70±0.07	0.18±0.04	0.45±0.09	1.9

Errors quoted are 90% confidence limits.

† For an effective area of 320 cm^2 and 3°1 field of view (FWHM).

the energy of the iron emission line (6–7 keV) was present. The interstellar absorption of the diffuse extragalactic component was taken into account using the interstellar gas model by Baker and Burton (1975).

The observed pulse-height spectra after the subtraction of the background are shown in figure 2. One immediately notices that a pronounced emission line at about

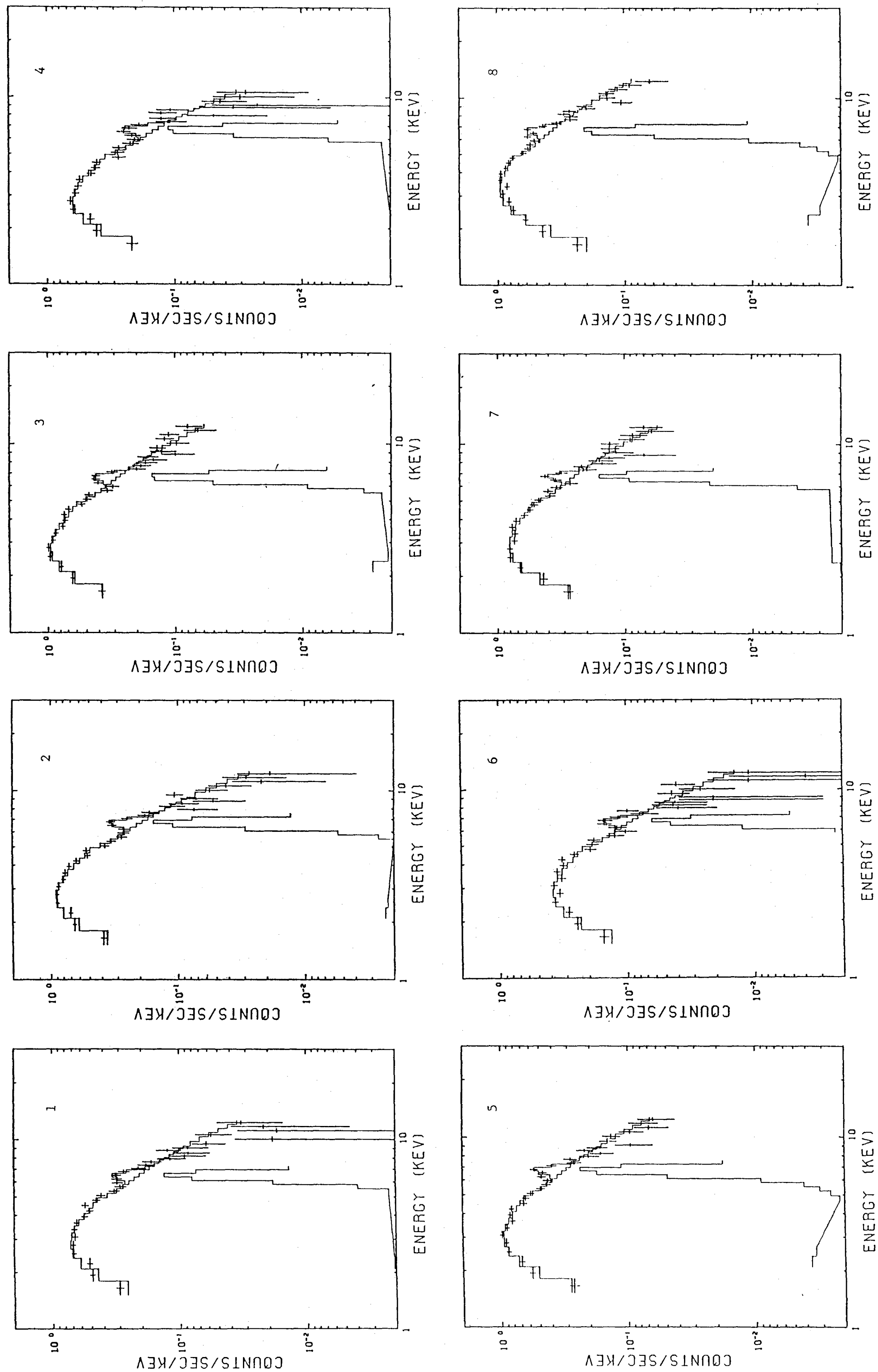

Fig. 2. Pulse-height spectra of the galactic excess emission from each position near the galactic ridge (see figure 1). The solid lines are the best-fit thermal bremsstrahlung model with a narrow line, convolved with the detector response.

6.7 keV is present in every spectrum. The line energy at 6.7 keV corresponds to that of the iron K-line from helium-like ions. Each of the observed spectra was compared with three different model spectra assumed for the continuum: (1) thermal bremsstrahlung spectrum for an optically thin plasma, (2) power-law spectrum, and (3) blackbody spectrum. Each model involves five parameters: temperature (or power index), absorption column density, normalization factor, narrow line energy, and line intensity.

The most satisfactory fit was obtained with a thin thermal bremsstrahlung model for the continuum. The power-law model gave systematically larger values of χ^2 than those in the case of thermal bremsstrahlung model, and turned out to be unacceptable in several spectra for which statistics were relatively good. In all cases, the blackbody model was unacceptable. It is, therefore, most likely that the observed excess emission is thermal emission from a thin hot plasma. The best-fit parameters are summarized in table 1. Here, the model function is given as

$$f(E)=\exp[-\sigma(E)N_{\mathrm{H}}]\{Ag(E)\exp(-E/kT)(1/E)+I_0(1/\sqrt{2\pi}\,\Gamma)\times\exp[-(E-E_0)^2/2\Gamma^2]\}\ \text{photons s}^{-1}\,\text{keV}^{-1}\,.$$

where, $g(E)$ is the Gaunt factor and the line width Γ is fixed at 0.03 keV.

An important fact is that the plasma temperature varies significantly from place to place in the range of kT between 5 and 10 keV. The energy of the iron line is consistent with 6.7 keV except for one case (position 1), in which 6.7 keV is marginally outside the 90% confidence limit. Since one exception out of 8 cases is expected statistically, we can conclude that the observed lines are all at the same energy with the weighted mean of 6.71 ± 0.04 keV. The equivalent widths of the line are 400 to 700 eV.

For further examination of the spectral detail, we added all the observed spectra of individual positions as shown in figure 3a. This composite spectrum was then fitted to a model spectrum. The model continuum this time is the weighted mean of those best-fit thermal bremsstrahlung spectra which were previously determined for the individual positions. With this fit, the profile of the iron line can be studied in more detail. No significant broadening of the line is observed. The upper limit of the line width is determined to be 600 eV (FWHM, 90% confidence). As regards the continuum, a deviation is found below 3 keV. This discrepancy is also noticed in some of the individual spectra and probably due to the emission lines of silicon and sulfur, at about 1.9 keV and 2.5 keV from helium or hydrogen-like ions, respectively. In fact, the inclusion of these lines gives a satisfactory fit as is demonstrated in figure 3b, though the best-fit intensities of these lines are found to be significantly greater than expected from the temperatures determined with the cosmic abundance. Intensities of the silicon and sulfur lines larger than expected can be understood, if the plasma consists of components with various temperatures lying on the line of sight or if the plasma is in a nonionization equilibrium stage (Hayakawa 1985, private communication).

We estimate the galactic latitude distribution of the excess component in the longitude range $l=300°$–$340°$, since the observed positions are relatively dense in this

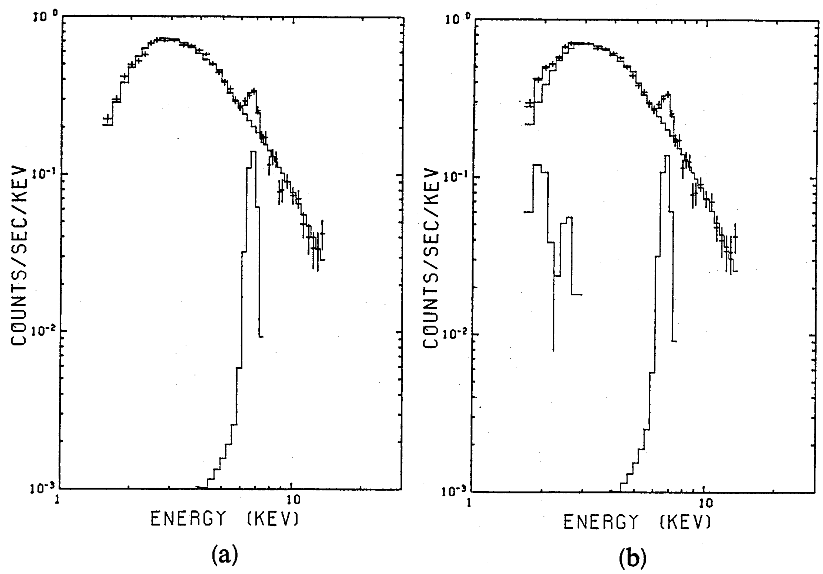

Fig. 3. (a) Composite spectrum from the galactic ridge. The solid line is the best-fit curve with an iron line (see the text). (b) Same as figure 3a. The solid line is the best-fit curve with silicon, sulfur, and iron lines (see the text).

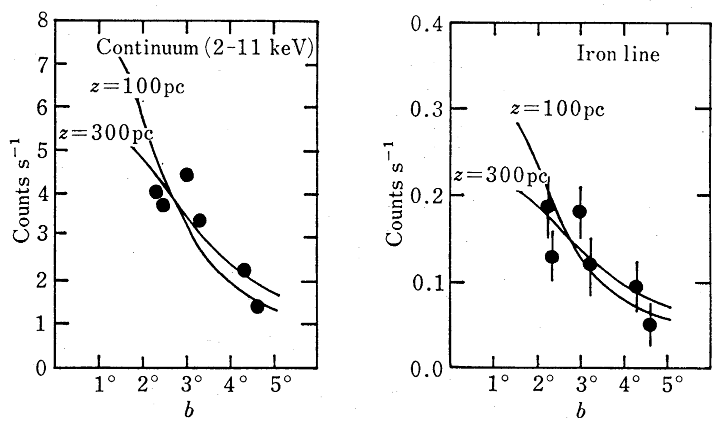

Fig. 4a. Galactic latitude distributions for the continuum emission (2–11 keV) and iron line intensities in the galactic longitude range 300°–340°. Positions Nos. 3–8 of table 1 are included. The solid curves show the model distribution (see the text) convolved with the collimator response.

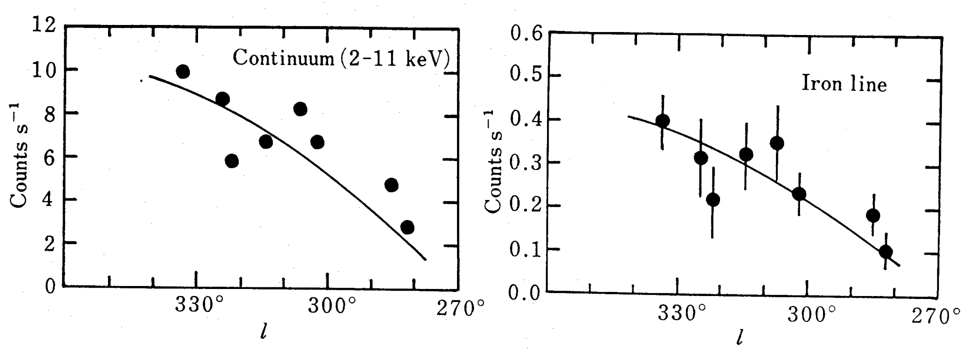

Fig. 4b. Galactic longitude distributions for the continuum emission (2–11 keV) and iron line intensities on the galactic plane. Measured intensities have been extrapolated, by using the latitude dependence with $z=200$ pc, to give the values at $b=0°$. The solid curves represent the model distribution with $R=10$ kpc (see the text).

longitude range. The observed intensities of the continuum and the iron line are separately plotted in figure 4a as functions of the angular distance of the detector field center from the galactic plane. We shall adopt the model in which the excess emission comes from a disk of radius R with its axis at the galactic center, and the volume emissivity is constant as a function of radial distance, but varies with the vertical distance from the midplane with exponential scale height z. The distance to the galactic center is assumed to be 10 kpc. The curves shown in figure 4a are those calculated for $R=$ 10 kpc, taking into account the collimator response. Since our field of view is approximately 3° (FWHM) wide, the present observation is not very sensitive to the scale height. The measured galactic latitude distribution is consistent with a scale height in the range 100–300 pc.

Figure 4b shows the galactic longitude distributions of the observed fluxes of the continuum and the iron line, in which each observed flux is converted to a value for $b=0°$ by using the galactic latitude dependence for a scale height 200 pc. This correction includes an uncertainty of a factor of two for the allowed scale-height range 100–300 pc. The figure also shows the expected galactic longitude dependence for $R=10$ kpc, which is in fair agreement with the distribution of the observed points. Then, for $R=10$ kpc and $z=200$ pc, we find the on-plane ($b=0°$) flux in the longitude range $l=300°$–$340°$ to be 8×10^{-8} erg cm^{-2} s^{-1} sr^{-1}. This gives an average volume emissivity $L_V=6.5\times10^{26}$ erg pc^{-3} s^{-1} on the galactic plane ($b=0°$) and a mean square density $\langle n^2\rangle=2\times10^{-6}$ cm^{-6} using the emissivity by Raymond et al. (1976). The uncertainty is about a factor of two, mostly coming from the uncertainty of scale height. Instead of volume emissivity, the emissivity per unit surface area ($2zL_V$) of the disk can be estimated with a smaller uncertainty. The result is $(2.4$–$2.8)\times10^{29}$ erg s^{-1} pc^{-2}, nearly independent of the scale height assumed. Then, the total luminosity of this excess emission integrated over the whole disk of 10 kpc radius becomes roughly 1×10^{38} erg s^{-1}. Note, however, that local irregularities of emission which may probably exist are neglected in the above estimation.

4. Discussion

There is no doubt that the excess emission which we observed along the galactic ridge is the same as the one previously reported by Worrall et al. (1982). The present observations provide good-quality spectra of this excess emission for the first time. A pronounced iron line is detected in every observed direction, and the underlying continuum is best explained by a thin thermal bremsstrahlung spectrum. The iron line is found at 6.7 keV, indicating the emission from helium-like ions. This high degree of ionization of iron and the measured equivalent width are consistent with the interpretation that the excess component is a thermal radiation from an optically thin plasma. The plasma temperature varies from place to place in the range of $kT=$ 5–10 keV. Worrall et al. (1982) estimated the temperature for the thermal emission to be within 3–8 keV, which is generally consistent with the present result.

Based on a uniform disk model with a constant scale height, we estimate that the emission region extends to roughly 10 kpc from the galactic center. In fact, we covered only one side of the longitude range with respect to the galactic center ($l=280°$–$335°$).

Worrall et al. (1982) excluded the region within 50° longitude on both sides of the galactic center. Yet, their result shows that the excess emission falls off towards 90° longitude also in the other half of the galactic plane, which is consistent with an effective disk radius of 10 kpc. The emission region does not seem to extend substantially further, because no significant excess above the isotropic diffuse background was observed in the general anticenter region. Worrall et al. (1982) estimated a half thickness to be about 240 pc for a uniform slab model. The present result allows a scale height in the range between 100 and 300 pc, which is consistent with their value. The result is rather insensitive to the assumption of either an exponential scale height or a uniform slab. It is yet uncertain whether or not the scale height of the emission is larger than those of gas and stars in the Galaxy.

What is the origin of this diffuse emission? First, we will discuss a possibility of a tenuous plasma of several times 10^7 K uniformly extended over the galactic scale. Apart from the question of how to produce such an extended plasma, the plasma would have too high a pressure to be a stable existence within the galactic plane. The estimated volume emissivity implies the pressure (p/k) to be $2\,nT=10^5$ (cm^{-3} K) as compared to 2000 (cm^{-3} K) for the neutral interstellar gas. Moreover, the thermal velocity substantially exceeds the escape velocity from the galactic plane.

The excess emission is probably an integrated effect of unresolved discrete sources. In this case, the estimated volume emissivity gives a relation between the space density of the discrete sources n (pc^{-3}) and the average source luminosity $\langle L \rangle$ (erg s^{-1}) as shown in figure 5. Worrall and Marshall (1983) carried out an analysis of serendipitous sources seen during the observations of the galactic plane by the Einstein Observatory and concluded that the major contributors to the galactic ridge emission were low-luminosity X-ray sources including RS CVn's and cataclysmic variables (CV). A more extensive survey was conducted by Hertz and Grindlay (1984). Excluding extragalactic sources and coronal sources, they concluded that there remain noncoronal galactic sources which give a luminosity per unit surface area $2nz\langle L \rangle$ of 8×10^{28} erg $\mathrm{s}^{-1}\,\mathrm{pc}^{-2}$ for a uniform disk-like distribution. They considered that these noncoronal sources are probably accreting white dwarfs including CV's. This value is smaller by a factor of three than that obtained from the present observations. In addition, RS CVn stars also contribute to the galactic emission as much as these noncoronal sources. Therefore, in view of the uncertainties in their estimation and ours, it is possible, at least from the luminosity budget, that these noncoronal sources as well as RS CVn's are the main contributors to the excess emission from the galactic ridge.

The proper candidate, however, must have a thin thermal spectrum with an appropriate iron emission line at 6.7 keV. The neutron-star binary sources with luminosities of 10^{36}–10^{38} erg s^{-1} are excluded, not only because most of them are individually resolved but also because few of them exhibit an iron line with so large an equivalent width as presently observed. As regards the accreting white dwarf sources and RS CVn's, the information on the average spectra in the 2–10-keV range, in particular on the iron line, is still very meager. This leaves the possibility for further discussion.

Another constraint against these low-luminosity sources of 10^{30}–10^{32}-erg s^{-1} range comes from the important fact that the observed temperature of the excess emission varies from direction to direction. This places an upper limit to the number of sources

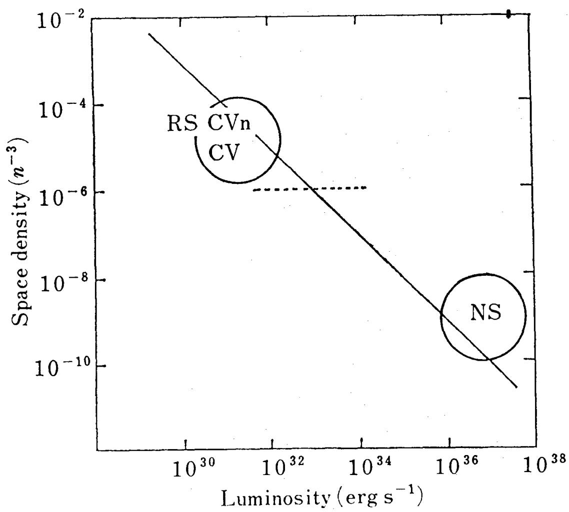

Fig. 5. The relation of average luminosity ($\langle L \rangle$) and space density (n) for the discrete sources as an origin of excess emission on the galactic ridge is given by the solid line. The dotted line is the upper limit to the space density for which the number of discrete sources in the detector field of view does not exceed one thousand. The circles plotted indicate different classes of X-ray sources: RS CVn stars (RS CVn), cataclysmic variables (CV), and neutron-star binaries (NS) (Hertz and Grindlay 1984).

in a field of view. A simple statistical study shows that, if the temperature kT of individual sources is assumed to be distributed uniformly between 2 and 10 keV, the number of sources in a field of view should be substantially less than one thousand; otherwise the flux-weighted mean temperature would not vary significantly. From figure 5, this gives a lower limit to the source luminosity to be about 10^{33} erg s^{-1}. Therefore, most of CV's and RS CVn's are outside of this luminosity range. The white dwarf binaries recently discovered in globular clusters by Hertz and Grindlay (1983) lie in this luminosity range. However, the broad occurrence of such sources in the galactic plane is yet uncertain.

Some nebulae in star formation regions such as the Orion Nebula (Agrawal et al. 1985) and ρ Oph (Koyama 1985) and η Car (Becker et al. 1976) are known to emit thermal emission of the right order of temperature with strong iron lines. Their luminosities are around 10^{33} erg s^{-1}. However, it is not clear whether or not such luminous thermal X-ray emission is common in the other star formation regions.

On the other hand, the observed spectrum of the excess emission is quite reminiscent of young supernova remnants. Remnants of interest here are those with temperature kT greater than 2 keV. There are about 150 radio supernova remnants known in our Galaxy (Clark and Caswell 1976), and about 1/5 of them have been detected in X-ray (see, e.g., van den Bergh 1982). Among those observed, however, the number of remnants with kT greater than 2 keV is relatively small. Besides, only a few remnants which escaped radio detection have been serendipitously discovered from the Einstein Observatory (Markert et al. 1981). Could there be many more young supernova remnants which remain undetected?

The probability of serendipitous detection of an X-ray supernova remnant will primarily be determined by its surface brightness. For the Einstein Observatory, the threshold surface brightness for positive detection of a supernova remnant should be on the order of 10^{-13} erg cm^{-2} s^{-1} arcmin^{-2}. Assuming the total energy of a supernova to be 10^{51} erg, we can make an order of magnitude estimate of the condition for such a remnant to escape detection. For a remnant before it cools down below 2 keV, the surface brightness will be lower than the above threshold, if the ambient gas density at the location of the supernova is smaller than 0.1 hydrogen atoms cm^{-3}. The radio surface brightness of such a supernova remnant can also be estimated semi-empirically (Milne 1979; Tomisaka et al. 1980), which turns out to be less than 10^{-20} Wm^{-2} Hz^{-1} sr^{-1} at 1 GHz. This is near the detection limits of radio supernova remnant surveys on the galactic ridge (e.g., Milne 1979; Koyama et al. 1985).

Such a supernova remnant in a tenuous environment as discussed above will remain in the temperature range 2–10 keV with a luminosity around 10^{35} erg s^{-1} for a period of nearly 10^4 yr. Thus, the observed flux of the excess emission can be explained, if one supernova explosion occurs every 10 yr. This rate of occurrence is certainly higher than the generally accepted values, however. The details of this discussion on the hypothesis of undetected supernova remnants and its consequences will be presented separately (Koyama et al. 1985).

In conclusion, a pronounced iron emission line at 6.7 keV was detected for the first time in every position along the galactic ridge, and the associated continuum of the unresolved excess emission was best explained by thin thermal bremsstrahlung. This result implies that the excess emission is due to hot plasmas of several times 10^7 K. As regards the origin of the excess emission, RS CVn's and accreting white dwarfs could possibly satisfy the required volume emissivity. However, their average spectrum above a few keV is yet quite uncertain. In addition, an accumulation of contributions from a large number of such low-luminosity sources would not produce the observed variation of temperature from place to place. As another possibility, supernova remnants within tenuous interstellar medium would account for the flux and spectrum of the excess emission, if the occurrence rate were as high as one in ten years.

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