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INFRARED STUDIES OF X-RAY SOURCES

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Abstract. A detailed study of the infrared radiation from galactic X-ray sources indicates that the galactic bulge sources and X-ray binary sources have different infrared emission characteristics. The galactic bulge sources seem to show a power law dependence between the X-ray flux and the infrared flux emitted by the X-ray source. The results presented suggests that the infrared radiation in the galactic bulge sources is dominated by free-free radiation and, in the case of eclipsing binary sources, the black-body emission from the early-type companion star contributes significantly to the infrared radiation.

1. Introduction

The infrared investigations offer a specific advantage for studying X-ray sources which are mostly located in the crowded and obscured regions of the Galaxy. This evidently follows from the fact that the interstellar extinction is insignificant at infrared wavelengths compared to visible and several X-ray sources have been detected to have their counterparts emitting infrared radiation. The infrared survey of the galactic X-ray sources by Glass (1979) showed that the approximate ratio of infrared luminosity to X-ray luminosity lies between 6×10^{-3} and 5×10^{-2}. The infrared excess in some of the X-ray sources has been interpreted in terms of the free-free radiation.

Gnedin *et al.* (1981) proposed that infrared radiation from X-ray sources could arise from the neighbourhood of a compact object like a neutron star. It is suggested that the infrared radiation in some X-ray sources can be due to a coherent proton cyclotron process which operates near the surface of a magnetised neutron star accreting matter from its close companion. In fact the infrared bursts detected from the direction of Rapid Burster Liller-I/MXB 1730–335 (Kulkarni *et al.*, 1979; Jones *et al.*, 1980) was attributed to the electron cyclotron maser instability operating above the poles of a neutron star at distances of a few tens of neutron star radii (Apparao and Chitre, 1980). It is suggested that the infrared bursts are associated with type-I X-ray bursts. However, the concurrence of the simultaneity of infrared and X-ray bursts and the association of infrared bursts with type-I X-ray bursts needs further investigation (Sato *et al.*, 1980; Lewin *et al.*, 1980).

From a comprehensive analysis of X-ray bursters and the galactic bulge sources, Lewin and Joss (1981) conclusively showed that the class of bright bulge X-ray sources distinguish themselves from massive X-ray binary sources and indicate a significant difference in the ratio of X-ray luminosity to optical luminosity. It is suggested that the

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galactic bulge sources are collapsed objects of roughly solar mass, probably neutron stars in most cases, which are accreting matter from low-mass stellar companions. The bulge sources and burst sources can be neutron stars in low-mass, close-binary stellar systems.

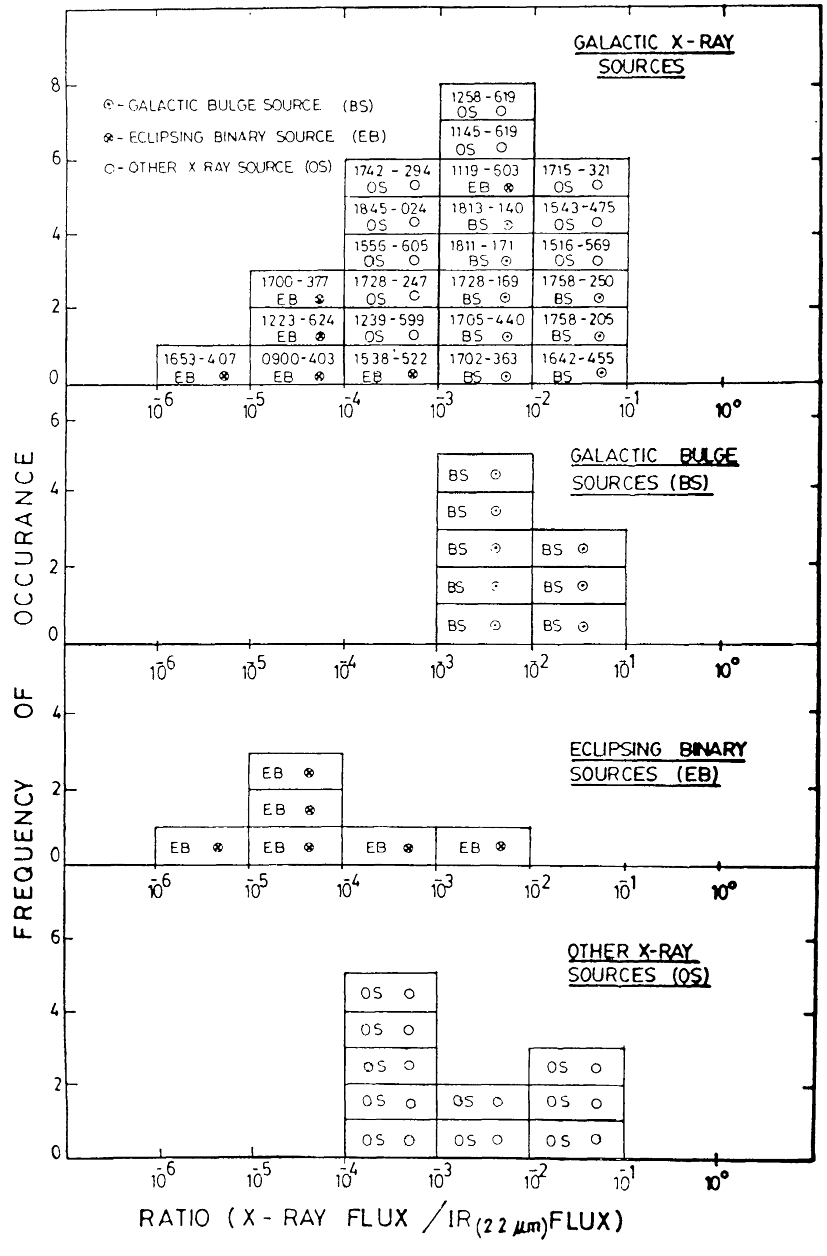

Fig. 1. The frequency distribution of the ratio of the X-ray flux to the infrared flux for the galactic X-ray sources is shown in this figure. The frequency distribution of the ratio for Galactic Bulge Sources (BS) ⊙, Eclipsing Binary Sources (EB) ⊗, and other X-ray Sources (OS) ○ are also shown in the same figure.

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We have made an attempt in this paper to evolve a better picture of various emission mechanisms which are operative in the galactic X-ray sources. A comparative study of the infrared flux and X-ray flux from bulge sources, eclipsing binary sources and otherX-ray sources has been made and the results are presented and discussed in the following sections.

2. Data Analysis

A sample consisting of nearly 24 galactic X-ray sources for which the infrared and X-ray flux measurements are available in the literature have been selected for our analysis. The infrared flux in the 1 μm to 5 μm, *J*, *H*, *K*, and *L*, near infrared bands are derived from the measurements reported by Glass (1979). The X-ray flux in the 2–11 keV energy region has been obtained from the MIT X-ray catalogue published by Bradt *et al.* (1978). The selected X-ray sources have been classified into three categories:

(a) Galactic bulge X-ray sources (BS).
(b) Eclipsing binary X-ray sources (EB).
(c) Other X-ray sources consisting of X-ray pulsators, bursters, transients, etc. (OS).

Using the X-ray and infrared flux measurements, the ratio of X-ray flux to infrared flux and the spectral exponent (α) have been determined individually for each of the X-ray sources. The ratio of X-ray flux to infrared flux and the spectral exponent derived for the X-ray sources are plotted in the form of a histogram and shown in Figures 1 and 4. From the individual values, the average values of X-ray flux, infrared flux, the corresponding ratio, and the average spectral exponent have been estimated separately for the three above mentioned a, b, and c categories of X-ray sources. We have also derived the correlation coefficient for each category of the X-ray sources. The average flux values estimated and the correlation coefficient for the three categories of X-ray sources, i.e., bulge sources, eclipsing binary sources, and other sources are displayed in Table I.

3. The Results and Discussions

It is quite evident from the Figure 1 that the ratio of X-ray flux to infrared flux plotted for the X-ray sources shows a large dispersion in the ratio varying from 10^{-6} to 10^{-1}. However, it may be noted from the figure that the ratio plotted for bulge sources and eclipsing binary sources clearly indicates a polarization in the ratio of X-ray flux to infrared flux. The bulge sources indicates a larger ratio ranging between 10^{-3} to 10^{-1}, where as eclipsing binary sources have a smaller ratio ranging between 10^{-6} to 10^{-2}. The average ratio computed in Table I clearly projects that the average ratio for bulge sources is around 3.8×10^{-3} and for eclipsing binary sources it is around 4.8×10^{-5} and the difference in the ratio is a factor of ~80 for these two classes of X-ray sources.

The observational data summarised in Table I clearly points out to a very important fact that in case of bulge sources the average X-ray flux is a factor of 5.7 higher than that of eclipsing binary sources and the average infrared flux for eclipsing binary sources

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TABLE I

Gives a summary of the computed average values of the fluxes and other parameters of the galactic bulge X-ray sources, eclipsing binary sources, and other X-ray sources along with the errors

Category	Type of X-ray sources	No. of sources	X-ray flux (Micro–Jansky)	Infrared flux (Jansky)	Ratio X-ray flux/ infrared flux	Spectral exponent (α)	Correlation coefficient
1	Galactic bulge X-ray sources	8	750 ± 134	$(2.0 \pm 0.9) \times 10^{-1}$	3.8×10^{-3}	− 1.1 ± 0.2	0.36
2	Eclipsing binary X-ray sources	6	131 ± 37	(2.7 ± 0.8)	4.8×10^{-5}	− 2.9 ± 0.2	0.005
3	Other X-ray sources	10	886 ± 335	$(1.8 \pm 0.4) \times 10^{-1}$	5.0×10^{-3}	− 1.4 ± 0.2	0.30

is a factor of 13 higher than that of bulge sources. The simple fact that there is a significant difference in the X-ray and infrared flux emitted by bulge sources and eclipsing binary sources is responsible for the polarization of the ratio to a factor of 80 in the two classes of X-ray sources.

The results presented above suggest that:

(a) The infrared flux and the X-ray flux in bulge sources and eclipsing binary sources are differently related; and

(b) The mechanism which produces infrared radiation in the bulge sources is different from that of eclipsing binary sources.

These suggestions have been further investigated by examining the relation between infrared flux, the X-ray flux and spectral exponent (α) for bulge sources and eclipsing binary sources.

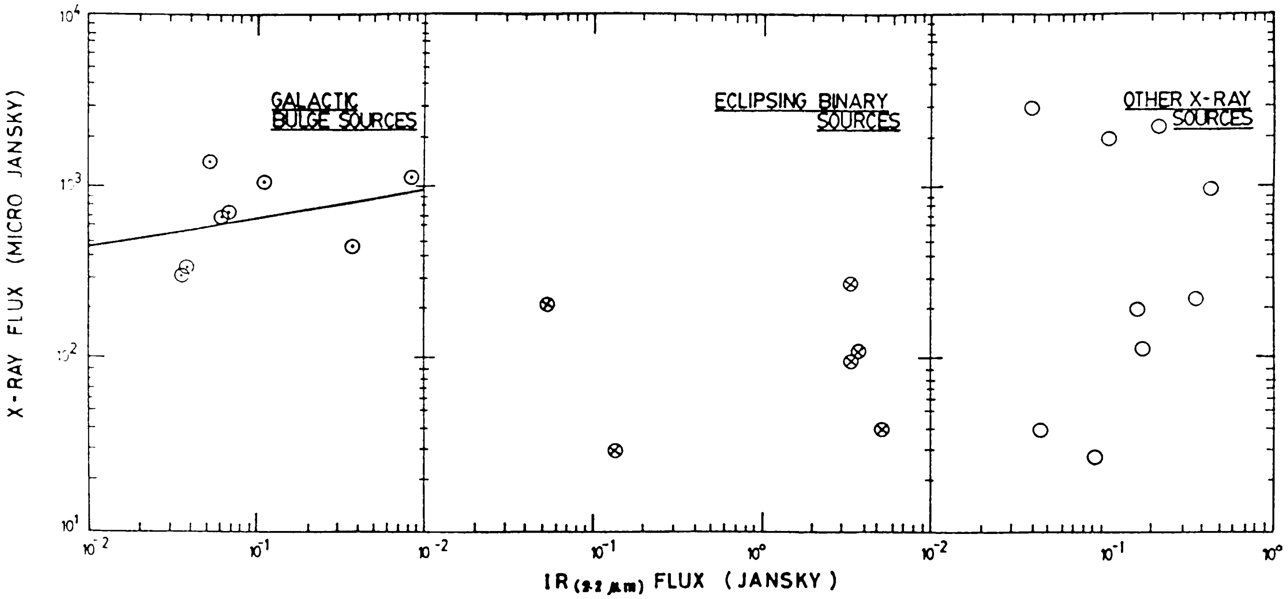

Fig. 2. Shows a graph of X-ray flux plotted against the infrared flux for galactic bulge sources ⊙, eclipsing binary sources ⊗, and other X-ray sources ○.

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In order to establish a relation between X-ray flux and IR flux in X-ray sources, the X-ray flux is plotted against infrared flux in a logarithmic scale for the three categories of X-ray sources and shown in Figure 2. A closer examination of the figure brings out the simple fact that for bulge sources the X-ray flux and infrared flux are better related when compared to that of eclipsing binary sources and other X-ray sources.

These observations can be further supplemented by comparing the correlation coefficients between the three categories of X-ray sources given in Table I. The correlation coefficient derived for bulge sources shows a value around 0.36 where as the correlation coefficient for eclipsing binary sources being very poor is ~ 0.005. Even though we find that for bulge sources, the correlation between X-ray and infrared flux is not very good due to poor statistics, the galactic bulge sources definitely indicates a better correlation between X-ray flux and infrared flux in comparison with eclipsing binary sources.

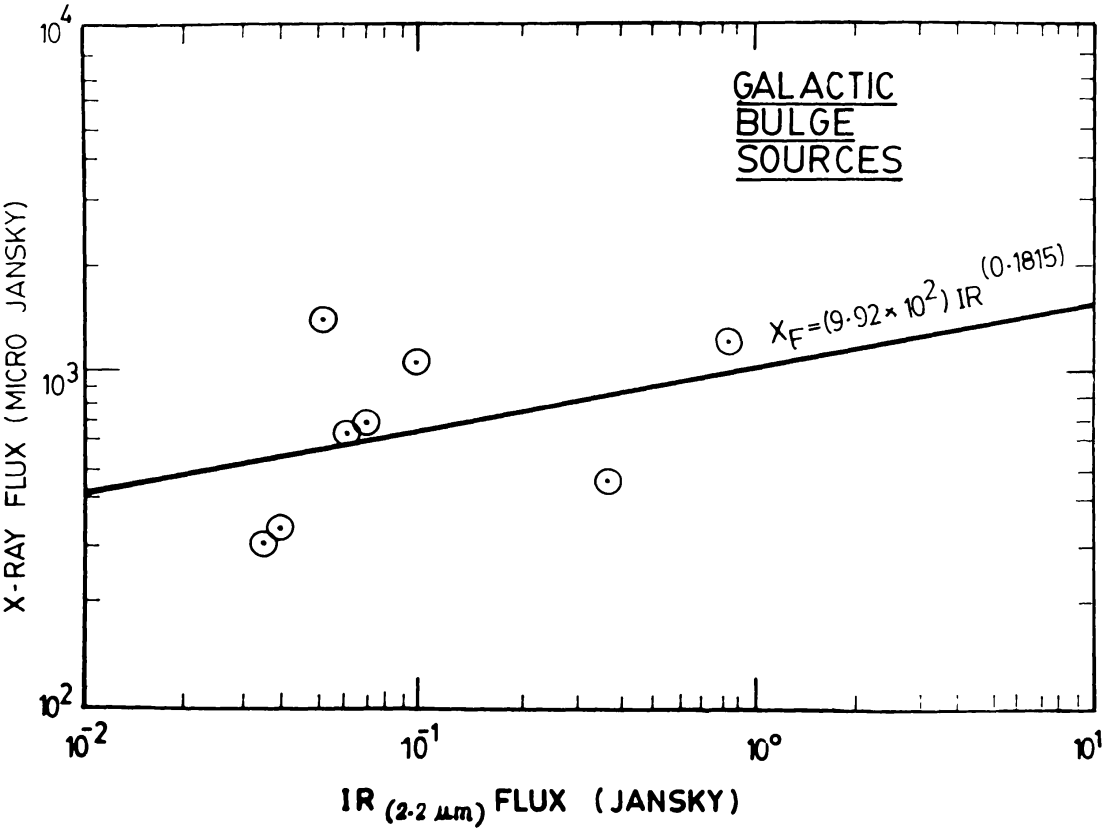

Fig. 3. Shows the linear relation between the X-ray flux and the infrared flux for the galactic bulge sources. The equation of the best-fit-line is indicated in the same figure.

We have made an attempt to obtain a simple empirical relation between the X-ray flux and infrared flux for the galactic bulge sources. The best fit line for the bulge sources is shown in Figure 3. The exponential relation derived from the equation of the best fit line can be given by an expression of the form

$$\text{X-ray flux} = (9.93 \pm 0.2) \times 10^2\ \text{IR flux}(0.18 \pm 0.19)\,.$$

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The large errors in the exponent is attributed to the poor statistics and the small sample of data available for this analysis.

It is seen from the earlier discussions that the average infrared flux emitted from eclipsing binary sources is a factor of 13 higher than that of bulge sources. This is in accordance with the fact that the eclipsing binary sources selected for analysis are associated with bright early type companion stars. It is quite possible that the infrared radiation directly coming from the companion star is contributing to the infrared flux

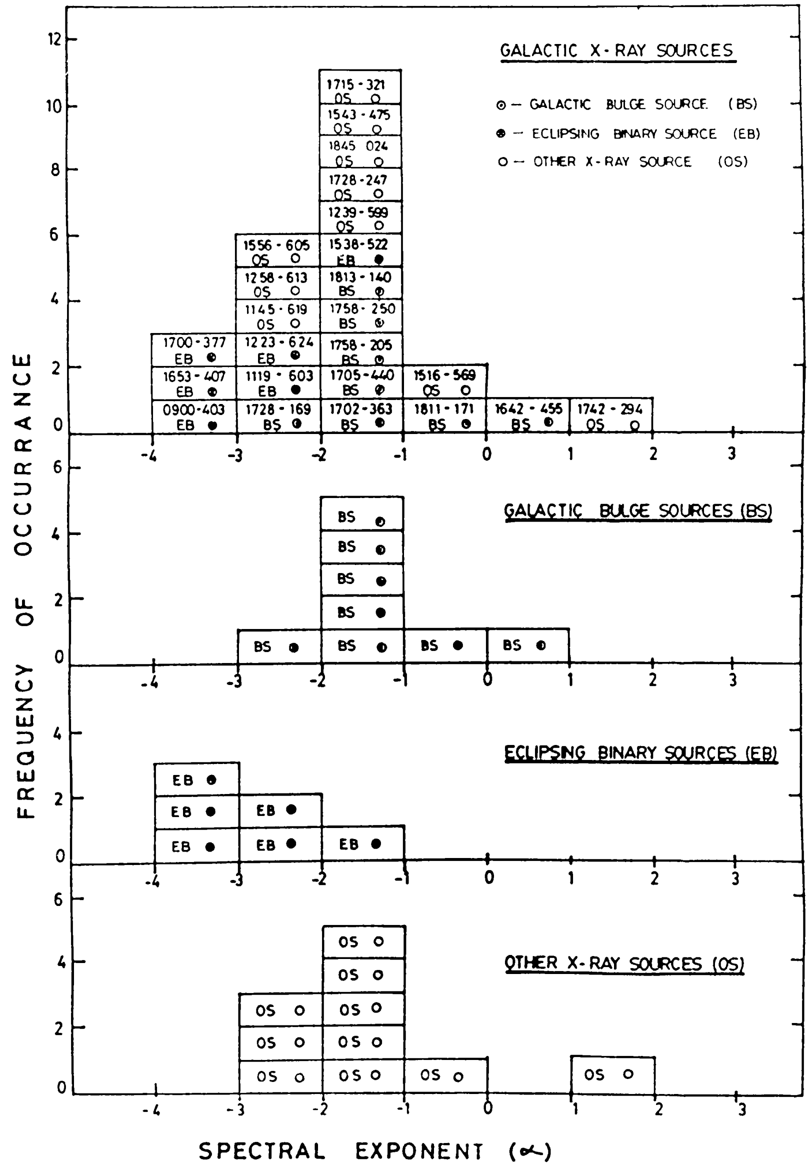

Fig. 4. The frequency distribution of the spectral exponent (α) derived from near infrared fluxes for the galactic X-ray sources is shown in this figure. The frequency distribution of spectral exponent for the Galactic Bulge Sources (BS) ⊙, Eclipsing Binary Sources (EB) ⊗, and for Other X-ray Sources (OS) ○ are also shown in the same figure.

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observed in the eclipsing binary sources where as in case of bulge sources the situation is not exactly similar. The star-like counterparts of bulge sources are detected to be faint ($M_v \approx +2$) in contrast to the luminous eclipsing binary sources. One can suppose that in bulge sources, the infrared radiation to originate mostly from the accretion disc and contribution to the infrared flux from the companion star is not very significant.

This hypothesis has been verified by examining the near infrared spectrum of X-ray sources.

The spectral exponent (α) derived from the infrared measurements for the X-ray sources are shown in Figure 4. The distribution of spectral exponent (α) for the three categories of X-ray sources are shown separately in the same figure. The average spectral exponent derived from the individual values are given in Table I. In spite of the poor statistics, it is striking to see in the figure that the spectral exponent (α) for bulge sources peaks around -1 to -2, where as the spectral exponent (α) for eclipsing binary sources peaks around -3 to -4. Furthermore, it is noted from Table I that the average spectral exponent (α) for bulge sources is around ~ -1.1 and for eclipsing binary sources it is around is ~ -2.9. The observations on spectral exponent conclusively show that the spectral exponent for bulge sources are different from that of eclipsing binary sources.

It is well known that in the Rayleigh–Jeans portion of the black-body curve, the energy distribution shows a -3 power law dependence on wavelength. The spectral exponent computed for eclipsing binary sources does indicate that the infrared radiation from eclipsing binary sources follows black-body emission mechanism.

Similarly we find that for free-free emission process the energy dependence shows a -1 power law dependence on wavelength. The spectral exponent (α) for bulge sources do indicate that the infrared radiation from bulge sources is essentially produced by the free-free emission mechanism. Such a conclusion is in agreement with the observations made by Glass (1979).

4. Conclusions

From the results and discussions presented above we can draw the following conclusions:

(1) The infrared radiation emitted by the galactic bulge sources is significantly different from that of eclipsing binary sources.

(2) The relation between X-ray flux and the infrared flux emitted by the galactic bulge sources show a simple power-law dependence.

(3) The near infrared spectrum of eclipsing binary sources follows a black-body type of emission and for galactic bulge sources the free-free radiation seem to be the most probable mechanism for infrared emission.

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