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X-ray Absorption and Optical Extinction in Interstellar Space

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Summary. X-ray and optical observations of five identified galactic X-ray sources, provide an empirical relation between X-ray absorption and optical extinction in interstellar space. The density ratio ϱ of gas to dust in the line of sight of these sources is evaluated. Attributing the low energy cutoffs observed in the spectra of several galactic X-ray sources to interstellar absorption, the reddening of their optical counterparts is estimated.

Key words: X-ray sources – optical identification – interstellar matter

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I. Introduction

There is evidence that selective extinction produced by interstellar dust at optical wavelengths is not negligible in searching for the counterparts of several Galactic X-ray sources.

For instance, no optical object appears within the error box of the radio source associated with Cyg X 3, while an infrared source has been recently detected therein (Becklin *et al.*, 1972). Also in the case of GX 3+1 (Rodgers, 1972) and GX 17+2 (Tarenghi and Reina, 1972) the objects observed in the vicinity of the sources are likely to be field stars, rather than their optical counterparts.

In order to yield some quantitative estimates of the relevance of the absorption effects produced by dust, an empirical relation between X-ray photoelectric absorption and optical extinction is proposed. Spectral observations of several Galactic X-ray sources provide then an evaluation of the reddening of their optical counterparts and this is employed to indicate the wavelength bands in which the optical counterparts may be observable.

II. Absorption Effects in Interstellar Space

Low energy cutoffs observed in the spectra of the majority of the Galactic X-ray sources are probably due to photoelectric absorption in interstellar space (Seward *et al.*, 1972). The transmission factor for this effect reads:

$$T(E)=\exp(-N_{\mathrm{H}}\,\sigma_{\mathrm{eff}}(E))\,, \tag{1}$$

where N_{H} is the columnar density of hydrogen atoms between the observer and the source, and $\sigma_{\mathrm{eff}}(E)$ is the effective photoabsorption cross section, which takes into account the composition of interstellar matter, and, at energies of the order of 1 keV, depends mainly on the abundance of heavy atoms. The composition quoted by Brown and Gould (1971) and the cross section given by them are assumed in the following.

The best fit to the observed spectrum of a law of the form $\Phi(E)=f(E)\,T(E)$, where $T(E)$ is the transmission factor (1) and $f(E)$ is generally chosen among an exponential, power or black body spectral law, provides the value of the columnar density N_{H}.

While at X-ray frequencies the opacity of interstellar matter is independent of its state of aggregation, in the optical range only dust grains produce relevant absorption effects. The number of dust particles associated with a columnar density of interstellar hydrogen N_{H} is

$$N_{\mathrm{gr}}=\frac{m_p}{m_{\mathrm{gr}}}\,\frac{N_{\mathrm{H}}}{\varrho}\,, \tag{2}$$

where m_p is the proton mass, m_{gr} the mean mass of dust grains, and ϱ is the ratio of the gas to dust atom densities. The optical depth for extinction is

$$\tau_{\mathrm{ext}}(\lambda)=\pi a^2\,Q_{\mathrm{ext}}(\lambda)\,N_{\mathrm{gr}}\,, \tag{3}$$

where a is the mean radius of the grains and $Q_{\mathrm{ext}}(\lambda)$ is the ratio of the effective cross section to the geometrical cross section πa^2 of the grains. The visual extinction expressed in magnitudes reads $A_v=1.086\,\tau_{\mathrm{ext}}(0.55\,\mu)$ and it is proportional to N_{H}, since by mean of Eqs. (2), (3) one obtains:

$$\frac{A_v}{N_{\mathrm{H}}}=K_v=1.086\,\pi a^2\,Q_{\mathrm{ext}}\,\frac{m_p}{m_{\mathrm{gr}}}\,\frac{1}{\varrho}\,. \tag{4}$$

Table 1. Spectral features of five identified X-ray sources

Source	Hydrogen columnar density $\times 10^{-20}$ at/cm^2	Ref.	Visual extinction A_v (magnitudes)	Ref.	$K_v = A_v/N_H$ $\times 10^{22}$ cm^2	Association ratio ϱ
GCX	640 ± 60	[1]	29.25 ± 1.25	[2]	4.6 ± 0.6	190 ± 25
SCO X 1	30 ± 10	[3, 9, 10]	0.7	[4]	2.3 ± 0.7	380 ± 110
CRAB NEBULA	20 ± 10	[5, 9]	1.5	[6]	7.5 ± 3.7	120 ± 60
CYG X 1	16 ± 4	[7]	3.3	[8]	20.6 ± 5	43 ± 10
CAS A	100 ± 60	[5]	7.5	[6]	7.5 ± 5	120 ± 80

1. Kellogg *et al.* (1972).
2. Spinrad *et al.* (1971).
3. Rappaport *et al.* (1969).
4. Neugebauer *et al.* (1969).
5. Gorenstein *et al.* (1970).
6. Shklowsky (1968).
7. Gursky *et al.* (1971).
8. Kristian *et al.* (1971).
9. Seward *et al.* (1972).
10. Bunner *et al.* (1972).

Table 2. The selective extinction ratio $K(\lambda) = A(\lambda)/N_H$

Johnson[a]) magnitudes	$\lambda_{\text{eff}}(\mu)$	$A(\lambda)/A_v$	$K(\lambda) = A(\lambda)/N_H$ $\times 10^{22}$ cm^2 [b])
U	0.35	1.560	7.80
B	0.44	1.328	6.65
V	0.55	1.000	5.40
R	0.65	0.738	4.00
I	0.8	0.463	2.50
J	1.25	0.245	1.30
K	2.20	0.088	0.47
L	3.4	0.045	0.24
M	5.0	0.033	0.18
N	10.2	0.013	0.07
O	22.0	0.010	0.05

[a]) Johnson (1966).

[b]) The values listed in this column have been normalized to $K(0.55\,\mu) = \bar{K}_v = 5.4 \times 10^{-22}$ cm^2 obtained averaging the values in Table 1.

Table 3. Lilley results on the association between gas and dust

Galactic latitude	$N_H/N_{gr} \times 10^{-12}$	$K_v = A_v/N_H \times 10^{22}$ cm^2 [a])
120°	3.58	17
130°	2.46	25
140°	3.60	17
150°	2.38	26
160°	8.30	7.5
170°	9.00	6.8
180°	3.90	16
190°	10.16	6
200°	17.24	3.5

[a]) The ratios K_v are provided by $K_v = 1.086\,\pi a^2 Q_{\text{ext}}(0.55\,\mu)\, N_{gr}/N_H$ where N_{gr}/N_H are those obtained by Lilley. For consistency the values $a \simeq 3 \times 10^{-5}$ cm and $Q_{\text{ext}}(0.55\,\mu) \approx 2$ used by Lilley, have been adopted.

For five identified X-ray sources, whose optical and X-ray spectra have been extensively observed, both the columnar density N_H and the visual extinction A_v are available (Table 1). The ratio of these quantities provides directly the value of the parameter K_v. Neglecting Cyg X 1 which lies in a peculiar region, and averaging the other four values in Table 1, Eq. (4) finally becomes:

$$A_v = 5.4 \times 10^{-22}\, N_H \quad \text{(Magnitudes)} \tag{5}$$

where N_H is expressed in atoms/cm^2. Taking into account the wavelength dependence of the selective extinction, one can derive the extinction $A(\lambda)$ at every wavelength λ by means of the coefficients $K(\lambda) = A(\lambda)/N_H$ listed in Table 2.

In order to check Eq. (5), it is relevant to compare it with the values of the ratio of the total Galactic extinction A_v to the columnar density N_H provided by 21 cm radio observation. Table 3 shows the value of the ratio K_v obtained in this way in several directions at $b = -15°$ (Lilley, 1955). Both the range and the mean value of K in Table 3 are in agreement with those obtained from X-ray absorption (see Table 1).

The value of K_v provides an estimate of the ratio of gas to dust atom densities, if a model of dust grains is assumed. In order to compare the results with those in previous literature one can assume the van de Hulst grains mean parameters $a \simeq 3 \times 10^{-5}$ cm, $Q(0.55\,\mu) \simeq 2$, $m_{gr} \simeq 1.1 \times 10^{-13}$ gr (Lilley, 1955). This yields

$$\varrho \simeq 8.8 \times 10^{-20} \frac{1}{K_v} \tag{6}$$

and the value of ϱ in the line of sight of the source for which K_v has been determined are shown in Table 1.

The mean value $\bar{\varrho} \simeq 160$ obtained here agrees with the previous estimates $\bar{\varrho} \simeq 100$ (Kaplan, 1970).

The abnormally low value of ϱ in Cygnus region, obtained also by Ampel and Iwanizweska (1962), may be ascribed to the presence in the line of sight of the Cygnus Rift Nebula which is very rich in dust.

III. On the Reddening of the Optical Counterparts of Galactic X-ray Sources

The arguments developed in Section II may be relevant in the search for the counterparts of Galactic X-ray sources, because the empirical relation (5) leads to an

Table 4. Extinction expected in the optical counterparts of some X-ray sources

Source	Spectrum[a)] C(W/m^2 Hz)	Spectrum[a)] kT(keV)	Hydrogen columnar density N_H $\times 10^{-20}$ at/cm^2	Ref.	Optical extinction A_v magnitude
a) Nearby sources ($N_H < 10^{22}$ at/cm^2)					
GX 9+9	6.0×10^{-30}	>11.0	<48	[3]	$<$ 2.6
SER 1	7.4×10^{-30}	4.3	30 ± 10	[2]	1.6
CEN X 5	4.0×10^{-30}	3.6	115 ± 95	[2]	6.1
GX 327+4.5	1.4×10^{-28}	6.1	79	[1]	4.2
GX 333−5	5.0×10^{-30}	6.1	3 ± 2	[2]	0.16
GX 340+6	2.1×10^{-29}	10.4	35	[1]	1.8
GX 343−2	2.7×10^{-30}	5.5	50 ± 30	[2]	2.6
GX 346−5	3.0×10^{-30}	8.2	15 ± 10	[2]	0.8
GX 349+2	5.0×10^{-29}	5.8	100 ± 25	[2, 1]	5.3
GX 357+2.5	1.0×10^{-29}	4.8	35	[1]	1.8
GX 357−5	3.4×10^{-30}	4.0	9 ± 6	[2]	0.4
b) Faraway sources ($N_H > 10^{22}$ at/cm^2)					
GX 5−1	3.0×10^{-29}	4−5	280 ± 50	[3, 2]	15.0
GX 13+1	2.0×10^{-29}	2.5−6	270 ± 70	[2–4]	14.5
GX 17+2	2.8×10^{-29}	2.1−4.4	270 ± 70	[1, 2, 4, 5]	14.5
GX 321−0.5	2.7×10^{-29}	3.7	290 ± 70	[1, 2]	15.5
GX 337+0	9.4×10^{-29}	3	710	[1]	38.0
GX 340+0	5.5×10^{-29}	3.8−6.1	700 ± 300	[1, 2]	36.0
c) Selfabsorbed sources (N_H variable in time)					
GX 3+1	5.0×10^{-29}	2.4−12	$\begin{cases} 60 \pm 30 \\ 250 \end{cases}$	[1, 2]	$<$ 3.2
GX 9+1	5.0×10^{-29}	3.6−8	$\begin{cases} 50 \\ 200 \end{cases}$	[1–4]	$<$ 2.7
CEN X 3	2.7×10^{-30}	13−15.7	$\begin{cases} 60 \pm 20 \\ 1000 \end{cases}$	[6, 2]	$<$ 3.2
CYG X 3	3.8×10^{-30}	12	$\begin{cases} 500 \\ 300-2000 \end{cases}$	[4, 7]	<16.2

[a)] A spectral shape of the tipe $f(E) = C \exp(-E/kT)$ has been assumed. A conversion factor $1\,\mathrm{keV/cm^2\,s\,keV} = 6.7 \times 10^{-30}\,\mathrm{W/m^2\,Hz}$ has been used.

1. Cruddace *et al.* (1972).
2. Seward *et al.* (1972).
3. Rappaport *et al.* (1969).
4. Gorenstein *et al.* (1967).
5. Tananbaum *et al.* (1971).
6. Schreier *et al.* (1972).
7. Parignault *et al.* (1972).

estimate of the extinction $A(\lambda)$ of the counterparts of the sources for which the columnar density N_H has been determined from the observation of a low energy cutoff.

At present spectral X-ray data are available only for the brightest sources, but even for these objects they are not sensitive enough to determine independently both the intrinsic spectral shape and the amount of interstellar absorption. Therefore the derived columnar densities N_H depend on the adopted model for the spectra of the X-ray sources (Gursky, 1972b). In order to ensure uniformity in the following discussion, Table 4 lists the values of N_H which have been derived by several authors assuming an exponential spectral shape for 22 unidentified sources, in the hypothesis that the low energy cutoffs are entirely due to photoelectric absorption in interstellar space.

For several sources the value of N_H is steady in spite of the temporal variability of the source both in intensity and temperature. This is a circumstantial evidence of the interstellar nature of the cutoff. In these cases the visual extinction A_v has been obtained by means of Eq. (5) and the mean observed N_H.

In a few cases, for instance CYG X 3, CEN X 3, GX 3 + 1, GX 9 + 1, there is evidence of temporal variability of the cutoff, which may be due to selfabsorption taking place in or near the sources and whence the lowest observed value of N_H has been used to obtain an upper limit to the visual extinction A_v of their counterparts.

It has been pointed out (Seward *et al.*, 1972) that, neglecting the sources with variable cutoff, the columnar density is a good distance indicator, suggesting that there are two classes of sources, namely nearby sources, with $N_H < 10^{22}$ at/cm^2 and distances less than 5 kpc, and faraway sources which are clustered around the Galactic Centre. Following this classification, we shall discuss the problem of the optical identification separately for these two classes.

a) Nearby Sources

The low values ($A_v < 6^m$) of the extinction of these objects, reported in Table 4a, indicate that their identification at optical wavelengths may be possible. This is however only a necessary condition, because the apparent intensity of their counterparts depends also on the intrinsic brightness in the optical range. For instance, if the overall spectrum of a source is a black body, it will be too faint for observations even for $A_v = 0$.

In the case that the emission is due to thermal bremsstrahlung from a optically thin hot gas, the spectrum would be flat at optical wavelengths, as happens for SCO X 1. Table 4 lists the values of the flux C of every source in the spectral region $\nu \ll kT/h$. The corresponding visual magnitudes range from $V \simeq 13^m$ to $V \simeq 18^m$. Taking into account the effects of extinction, we note that for $A_v > 2^m$, the intrinsic spectral shape is strongly modified, removing the characteristic blue appearance which has been often useful in picking out a small number of possible candidates to the identification (see e.g. SCO X 1, and Cyg X 2). For example, if $C = 10^{-29}$ W/m^2 Hz ($V \simeq 16\overset{m}{.}1$) and $A_v = 4^m$, the counterpart will appear at $U = 21.9$, $B = 21.9$, $V = 20.1$, $R = 19.3$, $I = 17.8$, $J = 16.5$, and it is brighter at longer wavelengths. This leads to the conclusion that the search for the counterparts of these sources must be extended to $\lambda > 0.6\,\mu$.

If one of those sources belongs to a binary system with a bright primary star (Burbidge, 1972) it would be certainly observable. The distance of these sources being less than 5 kpc, a B supergiant would be at $V \simeq 7\overset{m}{.}5$, and since $A_v < 6^m$, it would appear brighter than $V = 13^m$. A search for bright SAO catalogued stars in the error boxes of several X-ray sources has been made by Gursky (1972a). While there are no stars brighter than $V = 12^m$ in the vicinity of Cen X 5, GX 349 + 2, GX 343 − 2, GX 9 + 9, SER X 1, in the case of GX 333 − 5 (2 U 1637–53) a star of F8 spectral type has been found at $V = 9\overset{m}{.}7$.

b) Far Away Sources

The sources which seem to be clustered around the Galactic Centre are listed in Table 4b. Since the optical extinction is $A_v > 14^m$, the counterparts of these objects are likely to be unobservable at optical wavelengths. This may be immediately realized discussing the most favorable case for the identification in which a source belongs to a binary system with a bright primary star. For example, we can assume that the primary is a B I type supergiant, with absolute magnitude $M_v = -6^m$. At a distance of 10 kpc and with a visual extinction $A_v = 14^m$, it could be too faint for observations at $\lambda \leqq 0.66\,\mu$. It is interesting to examine this case at wavelengths longer than 1 µ where interstellar dust is less opaque. For high temperature stars the spectral shape at these wavelengths can be approximated to the Rayleigh Jeans law $F \div \nu^2$. Assuming a rough dependence on $1/\lambda$ of the extinction cross section, a maximum in the spectrum would appear at

$$\lambda_{\max} \simeq 0.25\, A_v$$

where A_v is expressed in magnitudes and $\lambda_{\max}$ in µ. The reddened spectrum of the B I primary considered above would present a maximum at 3.5 µ, at a flux density around 2.5×10^{-28} W/m^2 Hz, which is well above the minimum flux actually detectable. It seems, then, that the only hope of identifying the sources of this class is to search for counterparts at near infrared wavelengths.

For example a near infrared object has been detected by Becklin *et al.* (1972) within the error box of Cyg X 3, which at 0.65 and 0.55 µ is a "white field" (Braes and Miley, 1972).

IV. Conclusions

The main result of the previous discussion is that from spectral observations of Galactic X-ray sources it is possible to evaluate the reddening of their optical counterparts. Present uncertainties in the determination of the columnar densities N_H limit the validity of the application to single sources of the method outlined here. However the general classification of the X-ray sources on the basis of the observed columnar density N_H, indicates the frequency range at which to search for candidates to the identification. In particular the counterparts of the nearby sources should appear brighter on the colors R, I, while the search for the counterparts of the far away sources ($N_H > 10^{22}$ at/cm^2) should be extended to wavelengths longer than 1 µ.

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