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EMPIRICAL RELATION BETWEEN INTERSTELLAR X-RAY ABSORPTION AND OPTICAL EXTINCTION

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ABSTRACT

An empirical relation between interstellar X-ray absorption and optical extinction is derived from the correlation of measurements made on objects of large intrinsic diameter. The result is $A_v = 4.5 \times 10^{-22} N_H$ mag, with the principal error being largely systematic in origin, where N_H represents the column density of interstellar matter in the Brown and Gould model for the X-ray absorption coefficient. Applying this ratio to optically identified compact sources, it is concluded that sources in binary systems showing pronounced X-ray occultations have an intrinsic absorption equivalent to $\sim 10^{22}$ atoms cm^{-2} of interstellar matter and that there are a few compact sources where the absorption seems to be primarily interstellar in origin. The interstellar absorption expected in Cyg X-1 from the extinction of its optical counterpart is much greater than that suggested by X-ray spectra, which may be due to a soft X-ray component greater than that predicted by the power law fitted to higher energy data. A reinterpretation of published spectral parameters of Cyg X-1 in its posttransition phase suggests that the soft component shifted downward in energy during the transition.

The value of A_v/N_H determined from the X-ray measurements is compatible with the Lα results from OAO 2. It is in accord with an interstellar dust-to-mass ratio of $\sim 10^{-2}$.

Subject headings: interstellar extinction — spectra, X-ray — X-rays

I. INTRODUCTION

Comparative studies of optically identified X-ray sources can provide new information on the matter content of the interstellar medium. By now, a sufficient number of X-ray sources with optical counterparts exists for this line of investigation to be pursued seriously. Reina and Tarenghi (1973) have made the first attempt to correlate X-ray absorption and optical extinction measurements. In this paper a similar analysis is carried out, but a larger and more carefully selected body of data is considered.

Simultaneous measurements of interstellar X-ray absorption and optical extinction can be used to determine a value for the ratio of dust to mass in interstellar space. Although the interpretation of the X-ray absorption measurements in terms of interstellar matter is not totally model-independent, it does not depend, as other measurements do, on assumptions of values of temperatures, ionization state, or chemical state of hydrogen. The accuracy of existing X-ray measurements is limited by the rather crude energy resolution of the present generation of instruments. Nevertheless, the correlation of optical extinction with X-ray absorption is quite apparent, and the final result obtained for the ratio of interstellar dust to mass is not qualitatively less precise than determinations based on other kinds of measurements. The limitation in the accuracy may be improved considerably in future instruments, which will have much better energy resolution. In addition to information concerning the interstellar medium, comparative X-ray/optical absorption studies have a mutually beneficial effect in providing a better picture of physical conditions at the source. For example, when the relation between X-ray absorption and optical extinction is known, extinction measurements of the optical counterpart can be used to remove quantitatively the effect of interstellar absorption from the observed spectra of X-ray sources. Thus, the actual source spectrum can be determined, as well as intrinsic absorption in or around the X-ray–emitting region. Conversely, in the case of X-ray–emitting nebulae, such as supernova remnants or clusters of galaxies, a measurement of interstellar X-ray absorption can be used to remove the interstellar component in the reddening and thus potentially refine our knowledge of excitation conditions in nebulae. Finally, since both X-ray absorption and optical extinction are indicators of distance, it is highly desirable to be able to relate the two in a consistent manner as an aid in determining a distance scale for galactic objects.

Section II contains a summary of the measurements of X-ray absorption and optical extinction for several X-ray sources of large intrinsic diameter. The value of A_v/N_H in optical magnitudes per unit column density is derived empirically. The empirical relation is applied to compact X-ray sources in § III to predict the maximum amount of reddening and extinction to be expected in the optical counterparts of typical unidentified pulsating X-ray sources and to calculate representative values for the self-absorption of compact X-ray sources that have been identified. Section IV contains a discussion of the results. Although present results are useful, we can expect a substantial improvement in the precision of X-ray absorption measurements in the foreseeable future, when instruments acquire the energy resolution needed to detect absorption edges of interstellar elements.

II. SUMMARY OF MEASUREMENTS

It is reasonable to expect, on the average, a linear relation between the extinction of light from an object and the integrated column density of heavier elements in the interstellar medium along its direction. This is true because optical extinction is caused by grains that are condensates of heavier elements from the reservoir of matter in interstellar space. Above 0.54 keV, the X-ray absorption process is caused primarily by photoelectric interactions with these same heavier elements. If the percentage of heavier elements in the form of grains were constant, and if the grains had constant extinction properties, it would follow that there should be a simple linear relation between optical extinction and X-ray absorption. The usual description of optical extinction is (e.g., Lilley 1955)

$$A_v = 1.086 N_g Q 4\pi a_g^2 , \qquad (1)$$

where N_g is the number of grains per cm^2 along the line of sight, $4\pi a_g^2$ is the geometric cross section of a single grain, and Q is the extinction efficiency factor. Even if the effective values of a_g and Q do vary locally, their average values may be constant along the large sampling distances to X-ray sources. X-ray opacity is proportional to the total column density of heavier elements of the interstellar medium, almost independent of whether they are in a gaseous or a solid state. If values are assumed for the relative abundances of the heavier elements with respect to hydrogen, the result of an X-ray absorption measurement can be expressed in terms of the single parameter N_H. Since hydrogen itself is not important in the X-ray absorption process above 0.54 keV, the value of N_H determined from X-ray absorption measurements is essentially independent of the ionization state of hydrogen, or whether it is in atomic or molecular form. Therefore, it follows that optical extinction should be correlated to a greater degree with X-ray absorption than with features that depend on the condition of hydrogen, such as 21-cm radiation or Lα absorption. A correct model for the abundance of heavy elements relative to hydrogen is necessary in order to derive a value for A_v/N_H that is numerically correct. The X-ray absorption cross section that has been used most often in the analysis of observations is that of Brown and Gould (1970). Their cross section is the standard in this paper; whenever a result was originally given in some other form, it is converted here to the equivalent of N_H from the Brown and Gould model.

The method of determining N_H from X-ray absorption measurements should be explained. Present instruments have a rather low energy resolution, varying from about 100 percent (FWHM) at 0.28 to about 30 percent at 3 keV. Thus, it has not yet been possible to detect the photoelectric absorption edges of the heavy elements (such as O, Ne, and Mg) directly. A much less precise model-fitting procedure has been used, in which the whole complex of elements is represented by the single parameter N_H. The photoelectric absorption coefficient is characterized by an overall energy dependence of $E^{-8/3}$. If the opacity is one mean free path at energy E, relatively little opacity occurs at twice the energy and a great deal of opacity at half the energy. Therefore, a strong correlation exists between E at unit opacity and the value of N_H determined from fitting the data. For example, if the observed spectrum of a source is deficient in intensity below 0.3 keV, the measured value of N_H is around 2×10^{20} cm^{-2}, and below 1 keV, about 10^{22} cm^{-2}. A multiparameter minimum χ^2 fit is made to the observed data with N_H, and a spectral hardness parameter, such as temperature in a thermal model (or spectral index in a power law), is allowed to vary freely. Therefore, the value of N_H is coupled to that of temperature (or spectral index). Moreover, if the assumed model does not take proper account of all the complexities of the actual spectrum, then N_H will also be in error. Hence, the value of N_H is in virtually every case affected by a systematic error that results from our lack of knowledge of the true spectrum. Yet there is no reason to suspect that there has been an overall tendency to overestimate or underestimate N_H in the present results. So, in considering a number of objects, the net effect of spectral uncertainty in the determination of A_v/N_H may average out to a result that is not systematically distorted.

Inspection of the X-ray absorption coefficient as a function of energy (Brown and Gould 1970; Cruddace *et al.* 1974) reveals that it is dominated by photoelectric absorption by hydrogen and helium below 0.54 keV, the K-edge of oxygen. Above 0.54 keV, photoelectric absorption by heavier elements predominates. If hydrogen or helium is partially or wholly ionized, the absorption cross section will be less than expected below 0.54 keV. Consequently, the value of N_H determined from analysis of broad-band X-ray spectra by the method described above may be less than the actual value. This is likely to occur when values of N_H are less than 10^{21} cm^{-2} or when the opacity is significant only below 0.54 keV. Heavier elements probably have all their K-shell electrons intact, so that the effect of partial ionization on the opacity is not important above 0.54 keV (i.e., for values of N_H exceeding 10^{21} cm^{-2}). Consequently, since the present method of determining N_H may break down below 10^{21} cm^{-2}, it would not be surprising if there were significant deviations from a linear relation between A_v and N_H when the analysis is applied to very soft X-ray sources. Fireman (1974) has pointed out that when heavy elements reside in grains, there is a reduction of the X-ray absorption coefficient compared with a truly gaseous interstellar medium. The maximum correction should occur just above the 0.54-keV absorption edge of oxygen. The grains have typical diameters of 0.1 μ and are composed largely of ice and silicates (see, for example, Field 1974). However, the grain size is considerably smaller than an X-ray absorption mean free path even at 0.54 keV, the most opaque condition. Above 1 keV, loss of absorption due to grains is probably negligible. Therefore, although the condensation of heavy

TABLE 1

X-Ray Absorption and Extinction of Diffuse Sources

Source	N_H	Reference	A_v	Reference
Crab	$(2.4 \pm 1.4) \times 10^{21}$	1	1.6 ± 0.2	2
Cas A	$(4.3 \pm 1.2) \times 10^{21}$	3	4.3 (if R = 3)	4
Tycho	$(10 \pm 5) \times 10^{21}$	5	1.6 ± 0.1	6
Cygnus Loop	$(5.2 \pm 0.3) \times 10^{20}$	7	0.24	8
Vela	$(1.5 \pm 0.2) \times 10^{20}$	7	0.3	9
Puppis	$(3.5 \pm 0.5) \times 10^{21}$	7	2.6	10
GCX	$(64 \pm 6) \times 10^{21}$	11	29.25 ± 1.2	12

References. (1) Summary by Hill *et al.* 1974; (2) Miller 1973; (3) Burginyon *et al.* 1973*b*; (4) Searle 1971; (5) Coleman *et al.* 1973; (6) van den Bergh 1970; (7) Gorenstein *et al.* 1974; (8) Parker 1964; (9) Milne 1968; (10) derived from stars cataloged in Heidelberg publication, Neckel 1967; (11) Kellogg *et al.* 1971; (12) Spinrad *et al.* 1971.

elements into grains results in a finite reduction of the X-ray absorption coefficient of the interstellar medium, the overall effect should be small and probably not worth taking into account at present, given the imprecision of the measurements.

III. OBSERVATIONAL RESULTS

Reina and Tarenghi (1973) have previously reported on the relation between N_H and A_v from a comparison of several cosmic X-ray sources. In the present work, the investigation is restricted to objects of large intrinsic diameter (> 1 pc) in order to be confident that the source is not self-absorbing. Also, a larger number of objects are considered here. The sources include six supernova remnants plus the extended X-ray source at the center of the Galaxy (Kellogg *et al.* 1971). Many of the other galactic X-ray sources (if not all) are characterized by variability in their intensity. This is indicative of compact objects, so there is a good possibility of their being affected by self-absorption. Therefore, they are not included among the list of objects used to determine A_v/N_H for the interstellar medium. They are discussed in the next section, which deals with compact sources.

Several X-ray sources of large intrinsic diameter are listed in Table 1 with measurements of their X-ray absorption and optical reddening. In some cases, notably the Crab Nebula and Pup A, a large discrepancy exists between different observations of the same object. This reflects the difficulty of observing with instruments having low energy resolution. In the case of Pup A, there is a significant difference in N_H between the observations of Burginyon *et al.* (1973*b*) and those of Gorenstein, Harnden, and Tucker (1974). We have chosen the latter somewhat arbitrarily for reasons given in that paper. Hill *et al.* (1974) have averaged a number of absorption measurements to the Crab Nebula. Observations of the Crab that were too late to be included in their summary (Charles, Culhane, and Tuohy 1973; Iyengar, Naranan, and Sreekantan 1974) are consistent with the summary.

The absorption along the line of sight of Cas A and Tycho is poorly determined because of a large uncertainty in their spectral functions. In particular, Coleman *et al.* (1973) find Tycho to have thermal and nonthermal spectral components. Serlemitsos *et al.* (1973) have reported a complex spectrum for Cas A. The spectra of Cas A and Tycho are assumed to be essentially thermal in the region where interstellar absorption takes place. Burginyon *et al.* (1973*a*) obtain $N_H = (4.3 \pm 1.2) \times 10^{21}$ cm^{-2} for a thermal spectrum for Cas A. For Tycho, the results of Coleman *et al.* (1973) imply that $N_H = (1.0 \pm 0.5) \times 10^{22}$ cm^{-2}, depending on the values of the temperature and the strength of the silicon line. For the Cygnus Loop, we take $N_H = (5.2 \pm 0.3) \times 10^{20}$ reported by Gorenstein *et al.* (1974), which is consistent with other observations (Stevens, Riegler, and Garmire 1973; Bleeker *et al.* 1972).

Measurements of reddening are given in the literature for all these objects except Pup A. Assuming the distance to Pup A to be 2 kpc, as reported by Downes

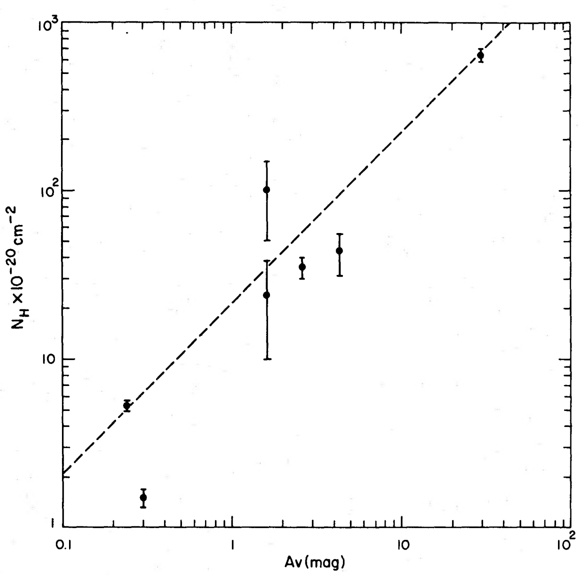

Fig. 1.—N_H versus A_v for identified diffuse X-ray sources shown in Table 1. N_H has been determined by fitting a model spectrum to data from X-ray proportional counters and is characterized by systematic errors not included in the error bars. The dashed line is a linear fit to the data.

(1971), the reddening was estimated from an examination of cataloged values of A_v for stars situated near Pup A (Neckel 1967). By this method, A_v is estimated to be 2.6 mag.

The observational data of Table 1 are shown in Figure 1. A linear least-squares fit to A_v and N_H was made without weighing the measurements of N_H by their quoted statistical error, because systematic errors probably dominate. Formally, the best fit is

$$A_v = (4.5 \pm 0.3) \times 10^{-22} N_H \text{ mag} . \qquad (2)$$

The error does not include the major systematic sources of uncertainty, errors in the intrinsic source spectrum, and variations in the optical extinction properties of the grains. A one-parameter fit does not take into account the possible reduction of X-ray absorption of the interstellar medium below 0.54 keV that would result from ionization of hydrogen and helium. Consequently, the ratio A_v/N_H would tend to be overestimated with respect to the actual value for $N_H < 10^{21}$ cm^{-2}. This may be true of the Vela supernova remnant and the Cygnus Loop, but there is no way to take account of the possibility. The fit of a straight line to the points has a very large chi square, one that would be unacceptable by any strict standard. There is probably no difficulty in explaining the scatter of the individual points from the straight-line fit on the basis of the error in N_H that is attributable to lack of knowledge of the true spectrum.

IV. APPLICATION TO OTHER X-RAY SOURCES

Equation (2) can be applied to the study of other X-ray sources. In particular, for new optical identifications of X-ray sources, it allows the maximum amount of reddening of an acceptable candidate to be determined from the observed value of N_H. If the source is compact and N_H includes a component of intrinsic or circumstellar absorption, the interstellar extinction and reddening of the optical counterpart will, of course, be less than predicted by equation (2). This criterion would be useful in situations where N_H for the X-ray source is well known. Candidates that are too highly reddened can be excluded.

We apply the X-ray/optical relation to the search for optical counterparts of two compact X-ray sources. The X-ray position of GX 17+2 is given to better than $3' \times 3'$ in the 3U catalog of X-ray sources (Giacconi *et al.* 1973). (A proposed radio counterpart has a more precise position [Hjellming and Wade 1971].) The energy at which the opacity is unity (E_a) is about 2 keV, and E_a does not appear to vary (Tananbaum *et al.* 1971). The X-ray absorption implies a column density $N_H = 3 \times 10^{22}$ cm^{-2}. If the X-ray absorption were entirely interstellar, then the extinction of the optical counterpart, according to equation (2), would be 14 mag. The reddening is so severe that the spectral type would probably be unrecognizable and the star would appear essentially as an infrared object. A similar situation exists in the case of Cir X-1, whose position is determined to better than $1' \times 1'$ (Jones *et al.* 1974*b*). E_a varies from 2 to 4 keV. If the minimum value of E_a were interstellar in origin, the intensity of the optical counterpart would again be extinguished by about 14 mag. Jones *et al.* (1974*b*) have pointed out the resemblance of Cir X-1 to Cyg X-1 in its X-ray behavior to within the observing capability of *Uhuru*. If the optical counterpart of Cir X-1 is a B0 supergiant like Cyg X-1 and if the minimum observed X-ray absorption is interstellar in origin, the optical candidate would appear about 11 mag fainter than Cyg X-1 in the visible region (assuming equal distance for the two objects) and severely reddened. Consequently, the optical counterpart of Cir X-1 could be as dim as a 19-mag star in the visible and therefore, like GX 17+2, best detected as an infrared object. However, as discussed below, the possible occultations of Cir X-1 (Jones *et al.* 1974*b*) suggest that intrinsic absorption could be characteristic of this object. In that case, the optical counterpart could be considerably brighter than 19 mag.

Measurements of X-ray absorption and optical extinction are given in Table 2 for a number of X-ray sources and their optical counterparts. The relation $A_v = 3.0E(B-V)$ was assumed for those cases where $E(B-V)$ is reported. For cases in which the X-ray absorption is variable, the minimum value is taken. The excess absorption over the minimum is clearly intrinsic to the source region and thus may be fundamentally different in nature from interstellar absorption. Therefore, it would not be correlated with the extinction of the optical counterpart. Most if not all of these are binary systems in which X-rays are produced by accretion onto a compact object from a main-sequence star emitting most of the visible light. Intrinsic absorption of X-rays is quite possible for compact sources, which is the reason none of these objects was included in Table 1. There is no suggestion of optical extinction having other than an interstellar origin in these cases. Formally, the difference between $(N_H)_x$ as determined from the X-ray observations and $(N_H)_{A_v}$ as determined from A_v through equation (2) is a quantitative measure of intrinsic absorption. Even if it could be determined precisely in a formal way, the difference in N_H would have limited physical meaning, because conditions—e.g., ionization equilibrium or abundances—in or around the source region may well be different from those in the interstellar medium. In a few cases, notably Her X-1 and SMC X-1 (neglecting absorption in the SMC), it is already obvious from their high-galactic-latitude positions that not all their absorption is interstellar. Except for the highly unlikely situation that 21-cm line radiation underestimates the total number of interstellar hydrogen atoms by an order of magnitude, it is apparent from 21-cm surveys (e.g., Tolbert 1971) that there is not enough galactic matter along their directions to account for the X-ray absorption. Because of the uncertainty inherent in the value of A_v/N_H, the numerical value of the difference is uncertain in individual cases. However, general trends can be examined. There is an obvious general tendency for the difference

TABLE 2

N_H FOR COMPACT SOURCES

X-Ray Source/Optical Counterpart	N_H*	Reference	A_v	Reference	N_H†
Sco X-1	$(3 \pm 1) \times 10^{21}$	1, 2	0.7	3	1.5×10^{21}
Cyg X-1/HD 226868	$\{(9 \pm 3) \times 10^{20}$ $(15 \pm 1) \times 10^{20}$	1 6	3.3	4, 5	7×10^{21}
Cyg X-3	5×10^{22}	7	10–20	8	2.2×10^{21}–4.4×10^{22}
Cen X-3	$(6 \pm 2) \times 10^{21}$	1	4.3	9	1.4×10^{22}
Her X-1/HZ Her	1.3×10^{22}	10	0.15	11	2.3×10^{20}
Vel X-1 (3U 0900−40)	4.7×10^{22}	10	2.5	12	5.5×10^{21}
3U 1700−37	3.2×10^{22}	10	1.9	12	4.2×10^{21}
SMC X-1/Sk 160	1.3×10^{22}	10	0.5	13	1.1×10^{21}
Cyg X-2	$(9 \pm 4) \times 10^{20}$	1	1.0‡	14	2.2×10^{21}

* As derived from X-ray observations.

† As determined from the A_v/N_H relation of equation (2).

‡ Not measured, estimated from galactic position of Cyg X-2.

REFERENCES. (1) Seward *et al.* 1972; (2) Bunner *et al.* 1972; (3) Sandage *et al.* 1966; (4) Margon, Bowyer, and Stone 1973; (5) Bregman *et al.* 1973; (6) Kwok Li and Clark 1974; (7) Leach *et al.* 1975; (8) Becklin *et al.* 1972; (9) Krzemiński 1974, Vidal *et al.* 1974; (10) Jones *et al.* 1973; (11) Liller 1974, Gerend 1974; (12) Jones *et al.* 1974*a* (estimated from Fig. 1); (13) Osmer 1974; (14) Giacconi *et al.* 1967.

to be positive for the sources that show pronounced X-ray occultations. In particular, for the high-galactic-latitude sources, such as SMC X-1 and Her X-1, the optical extinction implies interstellar X-ray absorption substantially smaller than 10^{22} cm^{-2}. The value of N_H intrinsic to the source region thus appears to be a few times 10^{22} cm^{-2}. On the other hand, for the sources that do not exhibit pronounced X-ray occultations, such as Sco X-1, Cyg X-1, and Cyg X-2, the internal column density is decidedly smaller than 10^{22} cm^{-2}. This need not have important physical consequences; it could be related merely to the geometry with which the binary systems are viewed. Schreier *et al.* (1972) have suggested that the absence of self-absorption in sources is quite consistent in the accretion-disk model with the nonobservation of occultations of the X-ray source. (Absorption dips detected in Cyg X-1 on a few occasions near zero phase [Sanford 1973; Kwok Li and Clark 1974] are not really typical of the object.) They propose that our line of sight to these sources makes a large angle to the accretion disk, which lies in the plane of the binary system. Thus, their X-rays pass through relatively little absorbing matter. Among the objects listed in Table 2, perhaps Cen X-3 and Cyg X-2 show an amount of X-ray absorption that could be primarily of interstellar origin. Considering the large uncertainty in the extinction of its optical counterpart, this may be also true of Cyg X-3.

Cygnus X-1 appears to have significantly less absorption in its X-ray spectrum than the extinction of HD 226868 would indicate. Therefore, not only does Cyg X-1 not have internal absorption, but evidence exists for soft X-rays in excess of the spectral function that describes it above 2 keV. The evidence for the soft X-ray excess is based on the fact that observers have reported power-law spectra for Cyg X-1 with a spectral index in the number-energy distribution of about -1.5 (Seward *et al.* 1972; Kwok Li and Clark 1974). X-rays above 2 keV determine the value of the spectral index for the most part. With -1.5 as a spectral index, both experiments find values of N_H that are small compared with the $N_H = 7 \times 10^{21}$ predicted from the value found of A_v in equation (2). This discrepancy could be explained if the actual flux below 1 keV before interstellar absorption were considerably higher than predicted by the extrapolation of the -1.5 spectrum to lower energies. Indeed, from the observations of the *Uhuru* satellite, Tananbaum *et al.* (1972) reported the existence of an intense softer component in the spectrum of Cyg X-1 that was detectable in the 2 to 20 keV energy range over and above a power-law spectrum with a spectral index close to -1.5 before the correlated X-ray–radio transition that occurred in 1971. The posttransition observations of *Uhuru* no longer indicated a softer component. However, both Seward *et al.*'s and Kwok Li and Clark's observations of Cyg X-1 occurred after the transition. Their value of N_H is significantly smaller than predicted. This suggests that a soft component in Cyg X-1 persisted following the transition, but that it shifted downward in energy to where it was unimportant above 2 keV.

Optical counterparts of diffuse X-ray sources are another area of study in which the A_v/N_H relation can be usefully applied. The supernova remnant IC 443 and the Perseus cluster of galaxies are two examples of objects for which there is a reasonable expectation of being able to determine N_H from X-ray observations with existing instruments. IC 443 has not yet been shown to be a diffuse object, but it is not unreasonable to interpret the spectral data (Winkler and Clark 1974) as indicative of an extended thermal X-ray source like other older supernova remnants (Gorenstein *et al.* 1974). A measurement of N_H not only would be useful in helping resolve the uncertainty in the distance described by van den Bergh, Marscher, and Terzian (1973), but also would enable optical astronomers to correct for interstellar reddening in their studies of excitation conditions. Analysis of the optical emission-line spectra of supernova remnants requires knowledge of the reddening. Similarly, it should be possible to determine N_H for several X-ray–emitting clusters of galaxies. The determination of the color and intensity of diffuse light from the Perseus cluster and other rich clusters would benefit from prior knowledge of the interstellar reddening.

It does not seem promising to extend this A_v/N_H relation or an alternative one to ultrasoft X-ray sources or to XUV sources, i.e., those that emit primarily below the 284-eV absorption edge of carbon. In this domain, X-ray absorption is dominated by hydrogen and helium. The densities of these two elements are not so directly related to interstellar grains as are the heavy elements that form the raw material from which the grains are condensed. Furthermore, as discussed by Cruddace *et al.* (1974), helium and hydrogen may be entirely or partially ionized in certain volume regions of the Galaxy, thus effectively reducing its ultrasoft X-ray absorptivity. There could be a strong directionality effect in the ionization of hydrogen, particularly within the small volume of our Galaxy from which detectable ultrasoft X-rays can originate.

V. DISCUSSION

The result $N_H/A_v = 2.2 \times 10^{21}$ cm^{-2} mag^{-1} represents a gross average for the Galaxy; taking the usual relation between optical extinction and color excess, $A_v = 3.0E(B-V)$, we obtain $N_H/E(B-V) = 6.6 \times 10^{21}$. This can be compared with the OAO-2 Lα absorption for a number of stars. These measurements are independent of the X-ray absorption measurement because they are a function of the hydrogen column density rather than of heavy elements. Savage and Jenkins (1972) find $N_H/E(B-V) = 5 \times 10^{21}$ cm^{-2} mag^{-1} as the best statistical average from observations of 69 stars with significant scatter from this result. In this report, N_H refers to H I and is thus very sensitive to ionization of hydrogen. In a later paper reporting on a larger collection of stars, Jenkins and Savage (1974) derive $N_H(\text{total})/E(B-V) = 7.5 \times 10^{21}$ cm^{-2} mag^{-1}, where N_H(total) now includes a correction for ionization of hydrogen by the star observed. It is difficult to compare errors for both the present result and the OAO-2 results, for the dominant errors are systematic rather than statistical in origin. Given the existence of these systematic errors, there is certainly no conflict between the present (X-ray) and the OAO-2 (Lα) results in the determination of the ratio of the total mass to color excess. Considering all the uncertainties in the present results and in OAO 2, even poorer agreement would be tolerable. However, agreement between these results and OAO 2 does suggest that there is nothing obviously incorrect with Brown and Gould's description of the X-ray absorption properties of the interstellar medium.

Following Lilley (1955), the present result can be used to estimate the fraction of interstellar mass that is in the form of dust:

$$\frac{\rho_H}{\rho_{\text{dust}}} = \frac{N_H m_H}{N_g \frac{4}{3}\pi a_g{}^3 \rho_g}, \tag{3}$$

where a_g and ρ_g are the radius and density of a typical grain. Combining this with equation (1) results in

$$\frac{\rho_H}{\rho_{\text{dust}}} = \frac{3 \times 1.086 Q m_H}{4 a_g \rho_g} \frac{N_H}{A_v}. \tag{4}$$

By using the same grain model as Lilley did, $Q \approx 2.0$, $\rho_g = 1$ g cm^{-3}, $a_g = 3 \times 10^5$ cm, plus equation (2), the estimate of the mass-to-dust ratio is

$$\rho_H/\rho_{\text{dust}} \approx 200 .$$

Therefore, we conclude from correlated X-ray/optical absorption measurements, as have previous estimates, that on the order of 10^{-2} of the mass of the interstellar medium is in the form of dust.

Detection of specific photoelectric absorption edges of heavy elements with high-resolution instruments will increase the accuracy of correlated X-ray/optical measurements substantially. This capability will allow a determination of the column density of individual heavy elements independent of the source spectrum. Thus, the largest source of systematic error in the present measurements—uncertainty in the intrinsic spectrum of a source—will be removed. With individual elements detectable, there is no need to assume a value of their interstellar abundance relative to hydrogen. Therefore, the results would continue to have a broad range of applicability should variations occur in the interstellar abundances of heavy elements relative to hydrogen. Detection of X-ray absorption edges appears to be within the capability of future rounds of satellite experiments.

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