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ABSORPTION OF CRAB NEBULA X-RAYS

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ABSTRACT

The X-ray spectrum of the Crab Nebula closely follows a power law, $I = 9E^{-2.0}$ photons cm^{-2} s^{-1} keV^{-1} for photon energies above 1.5 keV. From 0.2 to 1.5 keV, interstellar absorption strongly attenuates the source spectrum. The equivalent hydrogen density to the Crab is (0.55 ± 0.10) cm^{-3}, in disagreement with the 21-cm absorption value of 0.26 cm^{-3} (a distance of 2 kpc is assumed). The additional X-ray absorption is not expected from the filaments in the Crab Nebula, but could be due to invisible diffuse matter in the nebula. An alternative explanation is possible if interstellar grains contain a significant amount of matter from supernovae. The X-ray spectrum allows us to place the following upper limits on the average volume densities of elements with X-ray absorption edges in the 0.5–1.5-keV range: oxygen $<1.5 \times 10^{-3}$ cm^{-3}, neon $<2.5 \times 10^{-4}$ cm^{-3}, silicon $<3 \times 10^{-4}$ cm^{-3}, and magnesium $<1.3 \times 10^{-4}$ cm^{-3}.

I. INTRODUCTION

Interstellar absorption of soft X-rays may have now been observed for several objects (Rappaport, Bradt, and Mayer 1969). The Crab Nebula (Tau XR-1), as Rappaport *et al.* have pointed out, is an object uniquely suited to such measurement, for it is one of the few X-ray sources that is not significantly variable, it has a well-defined power-law spectrum increasing sharply to low energies, and the source distance is known (Trimble 1968). The sharp increase to low energies is very important, for it allows the Crab to be detected to quite low energies even in the presence of strong absorption. Rappaport *et al.* (1969) were able to set an upper limit of 0.5 H atoms cm^{-3} for the interstellar density between us and the Crab Nebula, as well as upper limits on the densities of several individual atomic species. Radio observations of the 21-cm line in absorption give a density of 0.26 cm^{-3}, if a kinetic temperature of 100° K is assumed for the gas (Clark 1965). Grader *et al.* (1970) reported attenuation of the X-ray flux from the Crab and concluded that there is an average of 0.3 H atoms cm^{-3} between the Earth and the Crab, in approximate agreement with the radio measurements. However, we have already reported briefly (Fritz *et al.* 1971) an observation of the Crab Nebula indicating higher absorption amounting to 0.55 ± 0.10 atoms cm^{-3}. We discuss here the details of that observation.

II. EXPERIMENTAL DETAILS

X-ray detectors on board an Aerobee rocket launched at 22:30 M.S.T. on 1969 March 13, at White Sands Missile Range were pointed for 40 seconds at the Crab Nebula. An on-board camera took photographs showing that the pointing was within a degree of the Crab for the entire 40-s period. Then a 40-s scan was executed in the galactic plane near the Crab. The data obtained during this scan were essentially uniform at all energies over the four (10° full width at half-maximum) angular resolution elements of Galaxy observed; the total 40-s spectrum obtained on this scan was subtracted from the Crab observation.

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The detectors were two proportional counters filled with 800 mm of a 10 percent methane, 90 percent argon gas mixture. One detector had an effective area of 325 cm^2 and a Mylar window 3.8 μ thick, and the other had a 235 cm^2 area and a Teflon window 3.2 μ thick.

III. FITTING THE DATA

Theoretical spectra have been folded through the instrument resolution and efficiency as described by Meekins *et al.* (1969), taking escape radiation into account. The spectra shown in figure 1 are

$$I = 9.2E^{-2.0}e^{-\sigma_E N D} \text{ photons } (\text{cm}^2 \text{ s keV})^{-1}\,, \tag{1}$$

where the distance D was taken as $2000 \times 3 \times 10^{18}$ cm, and N is the density of hydrogen atoms cm^{-3} (labeled values on the curves in fig. 1). We have used the values of Brown and Gould (1970) for the effective interstellar absorption cross-section, σ_E.

Above 2.5 keV, where interstellar absorption is negligible, the fit to the data is seen to be quite good except for a slight difference between the two counters. For comparison, Gorenstein, Kellogg, and Gursky (1970) obtained $9.0E^{-(2.0\pm0.1)}$, and Acton *et al.* (1970) obtained $8.5E^{-2.0}$. In view of the uncertainties in the measurement, we concluded that, unlike many other X-ray sources, the Crab shows no sign of X-ray variability aside from the X-ray pulsar (Fritz *et al.* 1971). The uncertainty in the intensity at 1 keV is about ± 10 percent, and the spectral index appears to be -2.0 ± 0.2 (see below).

The data shown in figure 1 suggest that the density of hydrogen between us and the Crab Nebula is (0.55 ± 0.10) cm^{-3}. In making this statement, we place heavy emphasis on the measurement at 18 Å (0.68 keV). The peak in the pulse-height spectrum due to the Teflon transmission window at 0.68 keV (and below) is somewhat displaced from its expected pulse height. The galactic background (of about 50 percent) that has been subtracted has the Teflon peak at the proper pulse height. The shift in pulse height between the Crab and the Galaxy background is probably produced by temperature effects in the electronics, for the rocket heats up as it rises through the atmosphere, and only some time later does this heat diffuse in from the skin to the electronic modules. Such a temperature shift in the electronics has been duplicated in the laboratory. However, the shift in energy between the two subtracted spectra does not significantly affect the integral under the peak in the resulting difference spectrum.

The data from the Teflon-window counter include a point above the frame of the figure; this point has been accidentally deleted from the other figures. It apparently lies a significant amount above its neighbors, but this is certainly a spurious effect, for the counter resolution is about 1.5 keV at this energy. There was some instrumental scatter of the pulse-height spectra due to uneven widths of the channels in the pulse-height analysis. This effect was largely removed by calibrating the electronic system before flight; the one odd channel on the Teflon counter probably just represents an incomplete removal of the effect.

The Mylar counter did not provide a useful measurement at 44 Å (second-from-lowest energy channel in fig. 1), presumably because of the high interstellar absorption; this is consistent with the data of Rappaport *et al.* (1969). The next two channels toward higher energy fall slightly above the expected curve, but this increase is surely spurious. The curve that best fits the Mylar counter data is 0.6 cm^{-3}, but the value 0.55 cm^{-3} from the Teflon peak is more precise.

Before accepting the value 0.55 cm^{-3}, we may ask what possible effect a variation in the Crab spectral index could have. This question is examined in figure 2, where in addition to the -2.0 index curve with 0.55 cm^{-3}, we have also plotted

$$I = 6.7E^{-1.8}e^{-0.4\sigma_E D} \tag{2}$$

and

$$I = 12.8E^{-2.2}e^{-0.7\sigma_E D}\,. \tag{3}$$

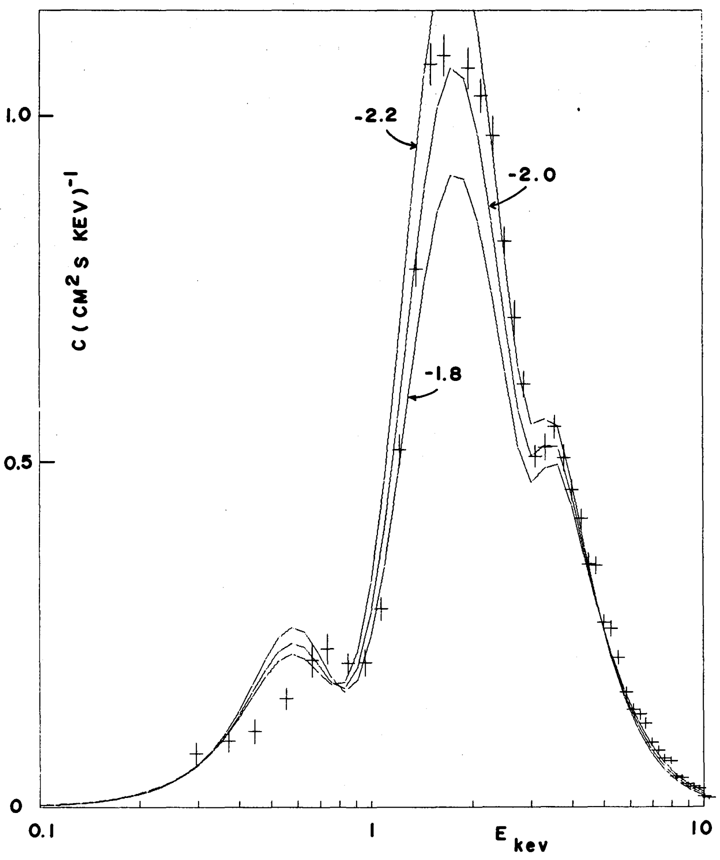

FIG. 2

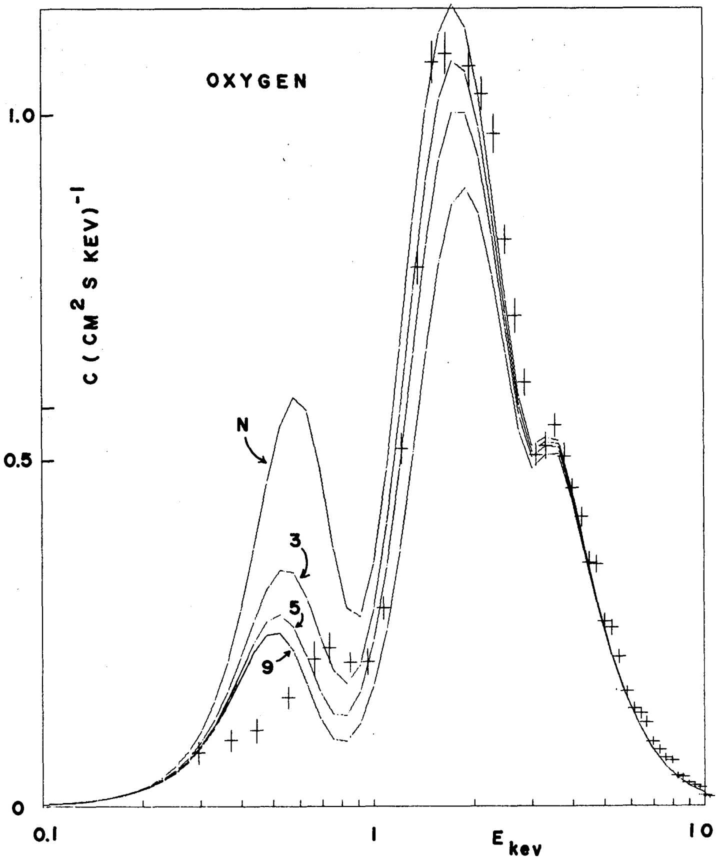

FIG. 3

FIG. 2.—Attempts to fit the Crab Nebula data (Teflon counter) with spectra having slopes different from −2.0. The slope −2.2 curve is normalized at 5 keV, and 0.7 cm^{-3} interstellar absorption is assumed (to produce a fit at 0.7 keV); the slope −1.8 curve is similarly normalized, and 0.4 cm^{-3} is used. Neither curve fits acceptably. Therefore, the slope (spectral index) must be −2.0 ± 0.1.

FIG. 3.—An attempt to reconcile the line-of-sight hydrogen density, determined by 21-cm absorption, with the present determination. We assume that the 21-cm measurement is correct and provide the increased X-ray absorption through addition of more oxygen (3, 5, and 9 times "N" normal abundance).

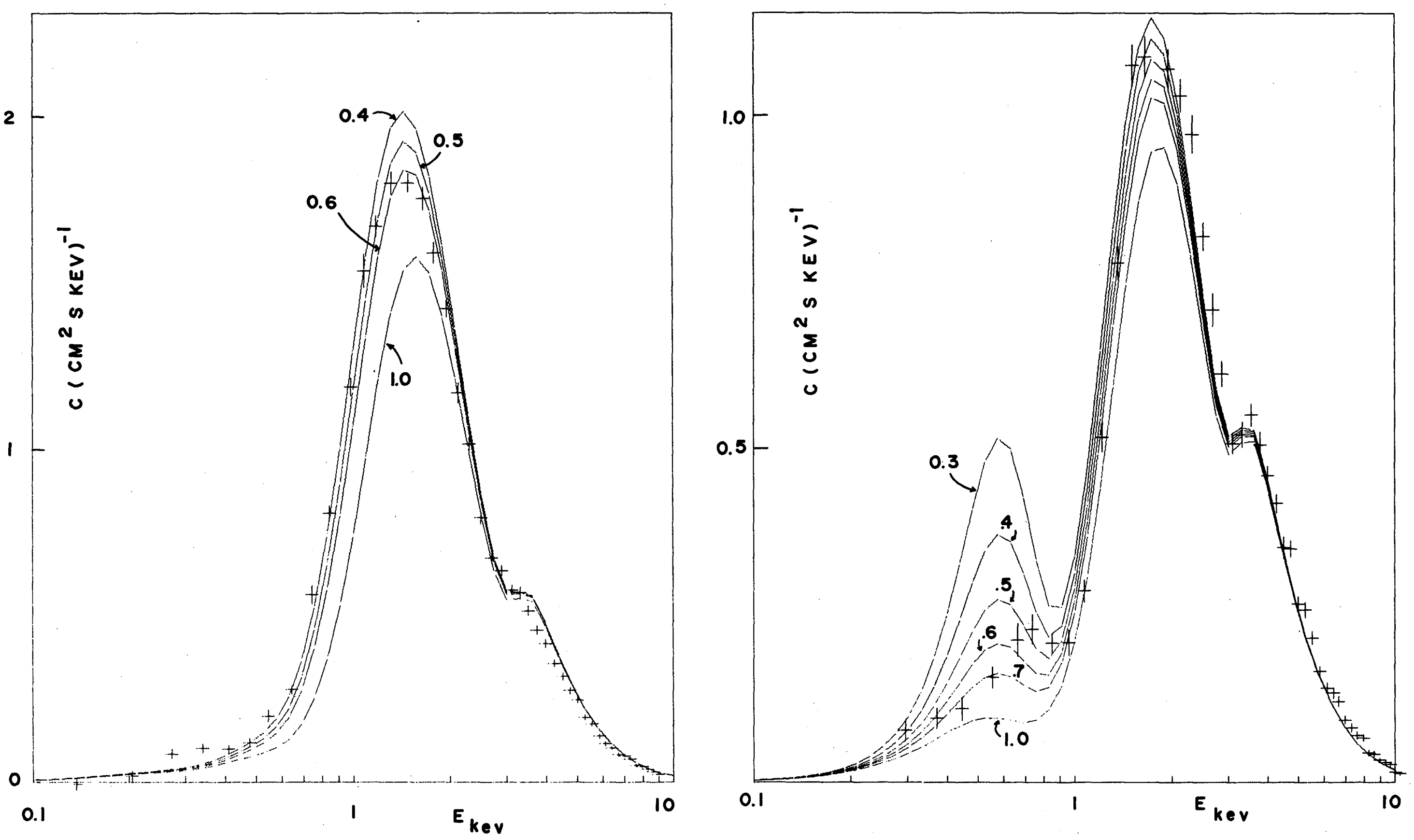

FIG. 1.—Observed X-ray spectra of the Crab Nebula, fitted with a power law ($9.2E^{-2.0}$) spectrum and variable amounts of interstellar absorption. The curves are labeled with the assumed density of interstellar hydrogen atoms cm^{-3}, with a distance of 2000 pc assumed for the Crab. The best fit is obtained with a density of 0.55 ± 0.10 hydrogen atoms cm^{-3}. The Teflon counter (*right*) has a transmission window near 0.7 keV. No flux is observed in the Mylar counter (*left*) at its 0.28-keV transmission window.

That is, we have taken the extremes in index (-1.8 and -2.2) permitted by the observations of others, normalized to our data at 5 keV, and introduced sufficient interstellar absorption (0.4 and 0.7 cm^{-3}, respectively) to preserve the fit at the Teflon peak. The result shown in figure 2 is that neither of the two extreme curves provides an acceptable fit to the data at 2 keV. We can therefore conclude that our present data require both $n = 0.55 \pm 0.10$ equivalent hydrogen atoms cm^{-3} and index $= -2.0 \pm 0.1$ over 0.7–8 keV.

IV. DISCUSSION

The interstellar density of 0.55 cm^{-3} that we have deduced is substantially higher than that obtained by measurement of 21-cm absorption (Clark 1965), 0.26 cm^{-3}. The kinetic temperature of the gas enters directly into the latter measurement; Clark used 100° K, which is the value determined from 21-cm emission at the galactic anticenter. (The temperature or, within limits, the degree of ionization of the interstellar gas does not affect the X-ray measurement, which is an important virtue of the method.) If a kinetic temperature of 200° K applied to the interstellar clouds causing the 21-cm absorption, the two methods would be reconciled. However, a temperature for the 21-cm absorbing clouds that is *higher* than that responsible for the 21-cm emission is not acceptable, for the hydrogen would be observed in emission and the higher temperature would be noted. In a reverse phenomenon, Carruthers (1969) has obtained *lower* hydrogen densities by Lα absorption in θ Ori than are indicated by the 21-cm absorption there. He argued that the 21-cm absorbing clouds are actually cooler than 100° K. If his argument applies generally, then our discrepancy in the density between us and the Crab is even greater than the factor 2 above.

It would seem possible that the explanation for the discrepancy lies in an abnormally large interstellar oxygen abundance. This is an attractive possibility because the absorption of X-rays is actually predominantly by oxygen (hydrogen itself fortunately contributes relatively little to absorption above 25 eV; otherwise the state of ionization of the interstellar gas would indeed be important in determining the effective X-ray absorption). Also, Stone and Morton (1967) found an indication that in the direction of Scorpius, oxygen may be 7 to 70 times above so-called cosmic abundance. This was based on measurement of the equivalent width of the interstellar O I absorption line at 1302 Å. However, the hypothesis that our result is due to a larger interstellar oxygen abundance is not tenable. In figure 3 we have attempted to fit our Teflon-counter data by assuming an interstellar hydrogen density of only 0.26 cm^{-3} in the line of sight between us and the Crab (as indicated by the 21-cm absorption observation) and by increasing the oxygen abundance from normal (per Brown and Gould 1970), marked "N" in the figure, to 3, 5, or 9 times normal. It is not possible, it appears, to fit our data in this way. The oxygen density must be increased 9 times to get a fit at the Teflon peak, and then the fit is bad at 2 keV as well as near 0.8 keV. The reason that the spectrum is at all sensitive to oxygen absorption as opposed to that of hydrogen or helium is that the 0.68-keV window at the fluorine edge extends, with somewhat lower transmission, to well below the oxygen edge. (The transmission at the oxygen edge is 0.05 compared with 0.2 at 0.68 keV.) Thus, in figure 3, when the oxygen density is strongly increased, the mean energy of the radiation of the 0.68-keV peak goes to lower energies.

Not only does this analysis exclude an overabundance of oxygen as the explanation for our data, it also strongly suggests that the interstellar abundance of oxygen is in fact quite normal. It is certainly not more than 3 times normal. The observation of Rappaport *et al.* (1969) had already excluded a density that great or as high as that suggested by Stone and Morton (1967). Our statement is based on the poor fit resulting from assuming an oxygen density 3 times normal, and then adjusting the total density (equivalent hydrogen density) for best fit. This fit is not shown in a figure, but the best match at 18 Å is obtained for 0.4 H atoms cm^{-3} and the fit is then not acceptable at 2 keV. On the other hand, the oxygen density could be *less* than normal and we would not be able to ascertain from our data that this was the case. For example (again not illustrated), a perfectly good fit to the Teflon data is obtained if we assume no interstellar oxygen at all, and an overall density apart from this corresponding to 1.1 H atoms cm^{-3}. Our limit, then, is that the average oxygen abundance is less than 1.5×10^{-3} cm^{-3} in the direction of the Crab. Rappaport *et al.* (1969) obtained the same limit because their upper limit on the total density (0.5 cm^{-3}) is, it appears, the actual value.

We cannot distinguish with our measurement among interstellar absorption caused by hydrogen, helium, carbon, and nitrogen (a positive 44 Å measurement would yield the helium density between us and the Crab). We can, however, observe the effects of elements having their edges at a higher energy than 0.68 keV. If the edge is at too high an energy, however, the total X-ray absorption is small and the test is insensitive. As a result, only neon, silicon, and magnesium are candidates for examination. As the absorption is believed to be predominantly by oxygen, and we wish to vary only one unknown parameter at a time, we hold all the elements at normal abundance and we then raise the neon, silicon, or magnesium abundances until the fit to our data is impossibly poor. This sets an upper limit on the abundance of that element.

In figure 4 the result is shown for neon. It appears that a density of 5 times normal cosmic abundance, i.e., an atom density of 2.5×10^{-4} cm^{-3}, can be excluded. By "normal cosmic abundance" we mean the value used by Brown and Gould (1970), who summarized the difficult radio and optical determinations of the interstellar neon abundance. The present X-ray measurement is independent of the state of ionization of neon and supports the value advocated by Peimbert and Costero (1969) and by Gillett and Stein (1969). The value used by Bell and Kingston (1967), which is a factor 5 higher, can therefore probably be excluded. Rappaport *et al.* (1969) obtained an X-ray upper limit for the neon density of 6×10^{-4} cm^{-3}, and hence could not distinguish between the two alternatives.

In figure 5, the result for silicon forbids 20 times cosmic density, i.e., 3×10^{-4} cm^{-3}, and for magnesium excludes 10 times cosmic density, or 1.3×10^{-4} cm^{-3}.

Finally, let us return to the question of the disagreement between the radio (21-cm absorption) and the present X-ray measurements for the interstellar density between us and the Crab. The 21-cm observation applies to interstellar material, as shown by the radial velocities of the radio lines. Could part of the X-ray absorption, on the other hand, be occurring in the nebula itself? The Crab Nebula consists of an expanding shell of dense gaseous filaments, surrounding an amorphous presumably low-density region in which the X-rays are generated. The X-rays must pass through the shell of filaments in order to reach the observer. These filaments, however, block only a fraction of the area of the shell, and X-rays would escape freely elsewhere. The hydrogen in the filaments is probably mostly (but not all) ionized. Electron densities in the bright filaments are about 10^3 cm^{-3}. Taking 2×10^3 cm^{-3} for the total density of hydrogen, and 0.05 pc for the diameter of a filament, we obtain 3×10^{20} cm^{-2} for the number of hydrogen atoms across one filament, compared with 1.6×10^{21} cm^{-2} for the interstellar space between us and the Crab, according to the 21-cm measurement. The material in the filaments thus does not appear to be sufficient to account for the additional X-ray absorption, even if the nebular helium abundance is somewhat higher than cosmic (Woltjer 1957).

On the other hand, sufficient absorption could be obtained in the nebula if about 1 $M_{\odot}$ of carbon (or a mixture of elements of similar atomic weight) were contained within the X-ray–generating region. This would amount to about 4 atoms cm^{-3} uniformly distributed throughout a sphere of 1 arc minute radius.

If the interstellar helium abundance were higher than is generally believed (Popper *et al.* 1970), it could reconcile the X-ray and radio measures. Unfortunately, since oxygen dominates the X-ray absorption, a full factor of 6 increase in helium abundance would be required. Such a helium abundance appears to be highly unlikely.

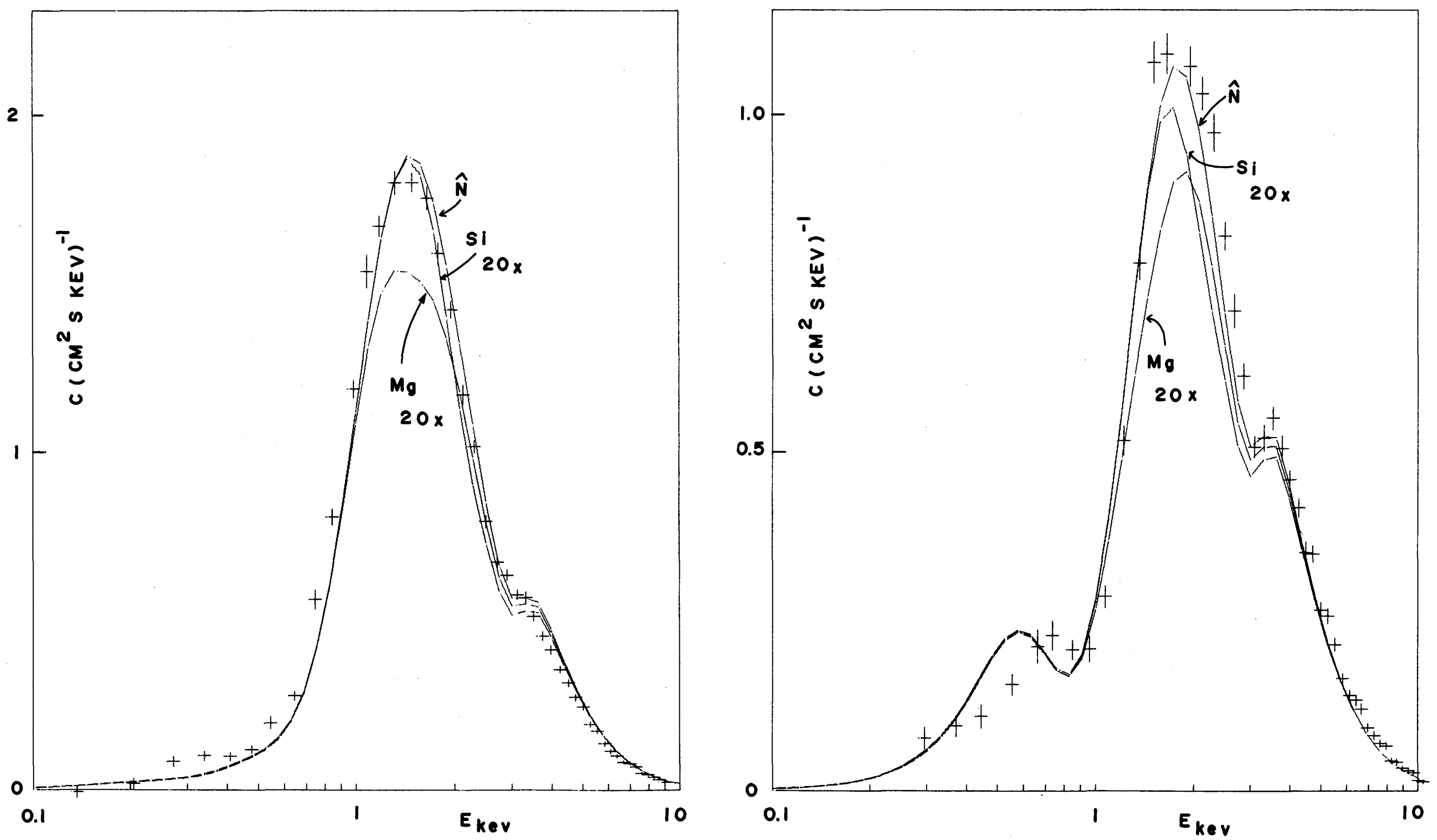

FIG. 5.—The same argument used in fig. 4 excludes interstellar silicon abundances 20 times normal cosmic abundance, and magnesium 10 times normal.

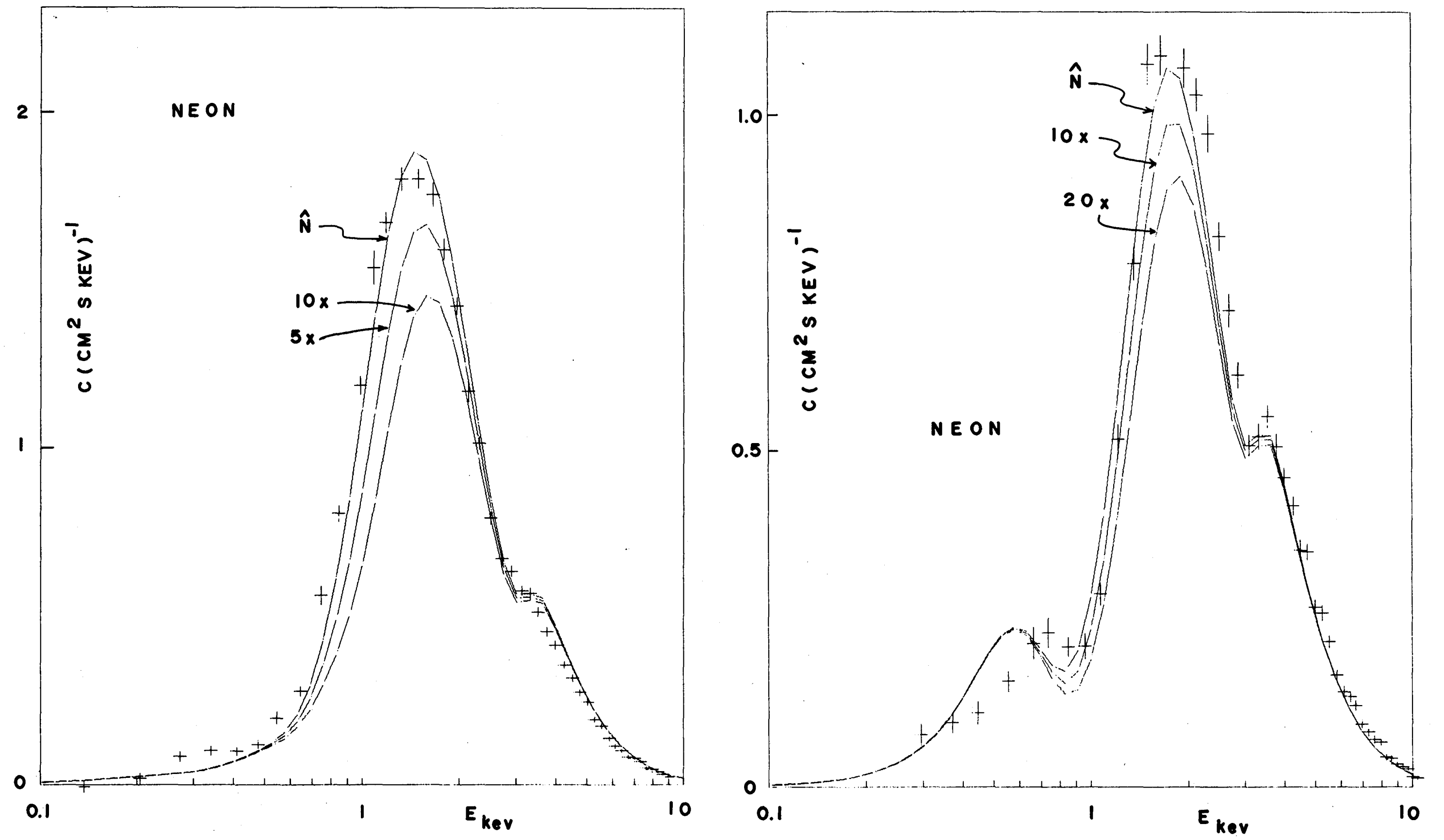

FIG. 4.—The neon X-ray absorption edge lies above the fluorine-edge energy of the Teflon-window detector. Thus varying the interstellar neon abundance does not affect the fit below the fluorine edge. The poor fit at 1.5 keV excludes an interstellar neon density 5 times that used by Brown and Gould.

We discussed (Fritz *et al.* 1971) the possibility of additional X-ray absorption by interstellar grains. Since interstellar absorption due to a cosmic mixture of elements had already been taken into account, the grains would have to contain an excess of one or more elements relative to the assumed cosmic abundances. Grains containing predominantly oxygen, magnesium, aluminum, silicon, or iron cannot entirely produce the necessary X-ray absorption because we do not observe the effect of their K or L X-ray absorption edges that fall within our detector bandwidth. Graphite grains containing $\sim$10 times cosmic abundance of carbon, presumably ejected from supernovae, provide the most likely explanation of the excess absorption if it is due to interstellar grains.

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