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INTERSTELLAR PHOTOELECTRIC ABSORPTION CROSS SECTIONS, 0.03–10 keV

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ABSTRACT

An effective absorption cross section per hydrogen atom has been calculated as a function of energy in the 0.03–10 keV range using the most recent atomic cross section and cosmic abundance data. Coefficients of a piecewise polynomial fit to the numerical results are given to allow convenient application in automated calculations.

Subject headings: interstellar: grains — interstellar: matter — opacities — X-rays: general

I. INTRODUCTION

Accurate estimates of interstellar absorption are necessary for the analysis and interpretation of almost all astronomical soft X-ray observations. The recent publication of a "state of the art" compilation of X-ray absorption cross sections by Henke *et al.* (1982*a*) and a review of solar abundance data by Anders and Ebihara (1982) provide an opportunity to reduce considerably the uncertainties in interstellar cross-section values. The current standard is the 1970 compilation of Brown and Gould. Although various improvements have been suggested in the meantime (Fireman 1974; Cruddace *et al.* 1974; Ride and Walker 1977), they have not generally been applied. The new atomic cross sections and relative abundances are substantially different in many cases, iron and several less important medium-weight elements have been added, and L-shell absorption is now included for all elements considered. These changes make the resulting cross section larger than Brown and Gould's at most energies and smaller at some, but rather surprisingly the difference never exceeds 30% below the iron K-edge. A major qualitative change is the introduction of the iron L-edge at 0.71 keV, which as pointed out by Ride and Walker (1977) should be one of the most readily observable interstellar X-ray features.

Compton scattering adds significantly to the photoelectric cross section above 4 keV and dominates above 10 keV, but it is seldom of practical importance in the interstellar medium since the entire galactic disk is optically thin at these energies.

II. ATOMIC CROSS SECTIONS AND COSMIC ABUNDANCES

The best measurements of atomic absorption cross sections are in good agreement with current calculated values, at least for elements up through iron and nickel (Henke *et al.* 1982*a*, and references therein). Accurate experimental data are available to verify this for all the abundant elements except hydrogen, for which there is no doubt about the calculations. All atomic cross sections are taken from Henke *et al.* (1982*a*, *b*) and should have errors much less than the uncertainties in the corresponding relative abundances.

Direct astronomical abundance measurements have rather large uncertainties. On the other hand, the accuracy of meteoritic abundances has increased remarkably in recent years and is thought to be better than 10% for almost all elements (Anders and Ebihara 1982). A good case can be made that these C1 chondrite values accurately reflect the local cosmic abundances at the time of formation of the Sun, and they do agree with astronomical determinations within the larger uncertainties of the latter.

Unfortunately, the few elemental abundances which cannot be determined from meteorites include several of the most important for interstellar X-ray absorption: H, He, C, N, O, Ne, and Ar. Hydrogen is not a serious problem, since the meteoritic abundance scale can be normalized to hydrogen by an average over several of the best determined solar abundances. This procedure seems accurate to better than a few percent. Anders and Ebihara adopt abundances for carbon, nitrogen, and oxygen which are a compromise between the values of Ross and Aller (1976) and those of Lambert (1978), which are 10% higher than Ross and Aller's for C and N and 17% higher for O. Their value for argon is based on interpolation between other elements using nucleogenic calculations by Cameron (1982). Neon has the most uncertain abundance of the abundant elements. The value used is a compromise between the best estimate from nebulae and hot stars and the 60% higher abundance implied by the Ne/Ar ratio observed in the solar wind.

Helium is the only element for which we have not used the abundance adopted by Anders and Ebihara. There is some evidence that the helium abundance may vary in different parts of the galaxy, but 10% seems closer to the local interstellar value than the 8% they adopted for the Sun (Peimbert and Torres-Peimbert 1977).

It is interesting to note that using the cosmic abundance from Allen (1973) for any element instead of that of Anders and Ebihara would change the total interstellar cross section by less than 5% at any energy below the iron K-edge. Using Allen's helium abundance instead of the higher one we have adopted would decrease the effective cross section by 10% at 0.2 keV.

Enrichment of the heavier elements since formation of the Sun was considered by Ride and Walker (1977). Talbot (1974) estimates an increase by a factor of about 1.12 for all elements above helium, but since the uncertainties are at least as large as the effect (Audouze and Tinsley 1976), we have chosen not to include this correction. The effect of such enrichment can readily be estimated by increasing by 12% the difference between our total effective cross section and that due to hydrogen and helium alone.

Although errors in the net cross section due to abundance uncertainties now seem considerably reduced, we emphasize that these abundances apply to the solar neighborhood, and that there is good evidence for a radial abundance gradient in the Galaxy of about $-16\%\ \mathrm{kpc}^{-1}$ for elements heavier than helium (Shaver *et al.* 1982).

III. DUST GRAINS, MOLECULES, AND IONIZATION STATES

As pointed out by Fireman (1974), condensation of interstellar material into grains will reduce its effective cross section if the grains are optically thick to X-rays. To estimate the importance of this effect, we have followed Ride and Walker (1977) and take the grain thickness as 2.1×10^{18} atoms cm^{-2} (0.3 μm thick, $\rho = 2$ g cm^{-3}). Hydrogen, helium, neon, and argon should have negligible fractions bound in grains. To obtain an approximate upper limit to the magnitude of the effect, all other elements except oxygen were assumed to be entirely in grains. De Boer (1979, 1981) finds oxygen to be depleted by 25% or less even on the heavily reddened paths to ζ Oph and o Per, so we have adopted this value for the fraction in grains.

The net result can be seen in Figure 1, where the effective cross section per hydrogen atom (scaled by E^3) is shown as a solid line for the case with no grains, and as a dotted line when the fraction of each element indicated in Table 1 is condensed into 0.3 μm grains. The effect is very small at low energies, where hydrogen

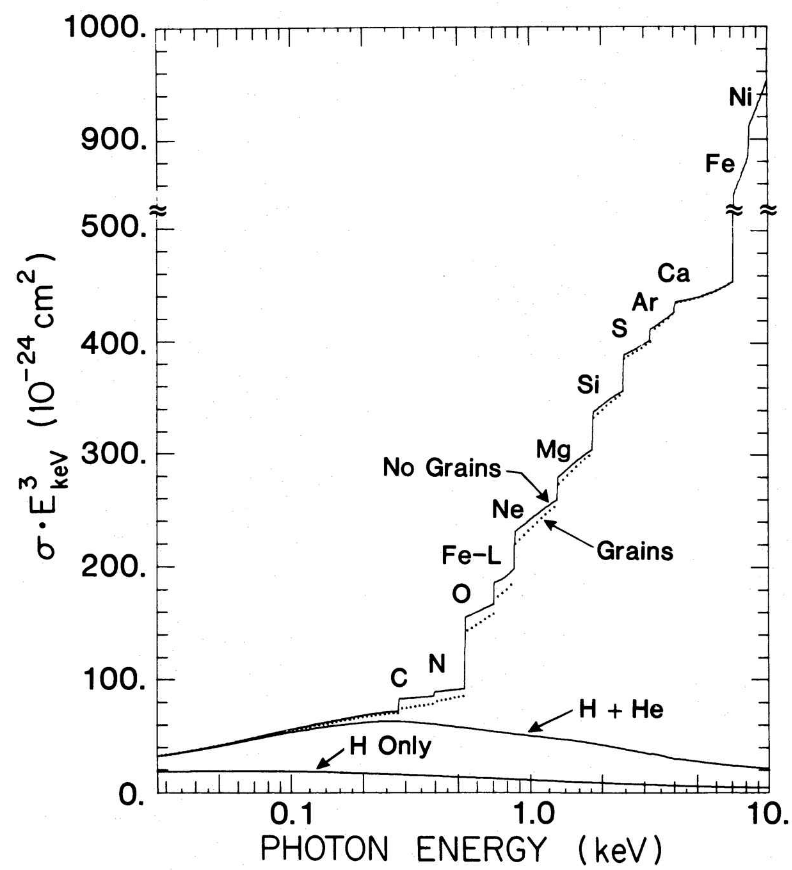

FIG. 1.—Net photoelectric absorption cross section per hydrogen atom as a function of energy, scaled by $(E/1\ \mathrm{keV})^3$ for clarity of presentation. The solid line is for relative abundances given in Table 1, with all elements in the gas phase and in neutral atomic form. The dotted line shows the effect of condensing the fraction of each element indicated in Table 1 into 0.3 μm grains. The contributions of hydrogen and hydrogen plus helium to the total cross section are also shown.

TABLE 1

ELEMENTAL ABUNDANCES

Element	Abundance[a]	Fraction in Grains[b]
H	12.00	0.
He	11.00	0.
C	8.65	1.
N	7.96	1.
O	8.87	0.25
Ne	8.14	0.
Na	6.32	1.
Mg	7.60	1.
Al	6.49	1.
Si	7.57	1.
S	7.28	1.
Cl	5.28	1.
Ar	6.58	0.
Ca	6.35	1.
Cr	5.69	1.
Fe	7.52	1.
Ni	6.26	1.

[a] Log_{10} abundance relative to hydrogen = 12.00. All values except helium are from Anders and Ebihara 1982.

[b] Fraction of atoms of each element assumed depleted from gas phase and condensed into grains of average thickness 2.1×10^{18} atoms cm^{-2} for case shown as dotted line in Fig. 1.

TABLE 2

COEFFICIENTS OF ANALYTIC FIT TO CROSS SECTION

Energy Range (keV)	c_0	c_1	c_2
0.030–0.100[a]	17.3	608.1	−2150.
0.100–0.284	34.6	267.9	−476.1
0.284–0.400	78.1	18.8	4.3
0.400–0.532	71.4	66.8	−51.4
0.532–0.707	95.5	145.8	−61.1
0.707–0.867	308.9	−380.6	294.0
0.867–1.303	120.6	169.3	−47.7
1.303–1.840	141.3	146.8	−31.5
1.840–2.471	202.7	104.7	−17.0
2.471–3.210	342.7	18.7	0.0
3.210–4.038	352.2	18.7	0.0
4.038–7.111	433.9	−2.4	0.75
7.111–8.331	629.0	30.9	0.0
8.331–10.000	701.2	25.2	0.0

NOTE.—Cross section per hydrogen atom = $(c_0 + c_1 E + c_2 E^2)E^{-3} \times 10^{-24}$ cm^2 (E in keV).

[a] Break introduced to allow adequate fit with quadratic: no absorption edge at 0.1 keV.

and helium are responsible for almost all of the absorption, and at high energies, where the grains are transparent. The reduction in cross section is 11% just above the carbon edge at 0.3 keV and drops to less than 4% at 1 keV. Because of the rather small magnitude of the decrease and the lesser depletions present in much of the interstellar medium, we have not included the effects of grains in the fit whose coefficients are given in Table 2.

Inclusion of an atom in a molecule has little effect on the magnitude of its photoelectric cross section at these energies. Even for hydrogen, having half the atoms in molecular form increases the net interstellar cross section by less than 5% at 0.1 keV (Cruddace *et al.* 1974). A more serious effect of significant amounts of molecular hydrogen is that estimates of total gas column density can be much too low, since they are often made using 21 cm or Lyman-α observations of atomic hydrogen.

Single ionization and double ionization of elements heavier than helium have only a small effect on the magnitude of X-ray absorption cross sections. A potentially more noticeable effect is that the absorption-edge energies are shifted by several percent. Ionization of hydrogen obviously reduces its cross section to zero, but the sign of the net effect of partial ionization of hydrogen on calculated absorption depends on whether or not observations of hydrogen were used to estimate the total gas. We have therefore not attempted to include any ionization effects in these cross sections, but one should keep in mind that at least 20% of interstellar hydrogen at high galactic latitudes seems to be ionized (Terzian and Davidson 1976). Cross sections are also reduced significantly by ionization in helium (see Cruddace *et al.* 1974), but a much smaller fraction of interstellar helium is expected to be ionized.

IV. CONCLUSIONS

The effective absorption cross section per hydrogen atom for interstellar material with the relative abundances given in Table 1 is shown in Figure 1. The effects of abundance enhancements, dust grains, molecules, and ionization state are either small or too uncertain to be useful for general applications, and none has been included in the primary model shown in Figure 1. Coefficients for polynomial segments with less than 1% deviation from this model are given in Table 2.

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