THE SOLAR ALBEDO OF HARD X-RAY FLARES

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Abstract. The calculations of Compton backscattering from the solar surface of flare X-rays performed by Tomblin (1972) are extended to higher energies. It is shown that the effect is even more pronounced in the 40 keV region and that it can lead to substantial corrections to the observed X-ray spectra.

1. Introduction

In a recent paper by Tomblin (1972) analytic calculations are presented of Compton backscattering of flare X-rays from the solar surface. As he points out, the X-ray flux seen at the earth is a combination of the reflected and direct X-rays and corrections must be applied both to the line and the continuum spectra to obtain the true production spectrum at the flare site.

The additional flux seen at the Earth at a given energy, expressed as a fraction of the flux which arrives directly, is seen to be a function of the heliocentric angle from the center of the disk to the flare site (h), and depends strongly on the energy.

At 17 keV, the highest energy considered by Tomblin, the fractional scattered flux is about 40% for a flare at the center of the disk and the fraction is still increasing with energy. At this energy the effects of multiple Compton scattering are becoming important; Tomblin computed up to the fourth order of scattering and estimated the contribution of higher order scattering at less than about 20%.

In this short note we communicate the results of a Monte Carlo calculation of the solar albedo which extends Tomblin's calculation to 300 keV, setting no limit on the scattering order.

2. Calculation

The flare was assumed to be a point isotropic source of X-rays located 7000 km above the scattering surface which was taken to be infinitely thin. Abundances were taken as those given in Brown and Gould (1970) for the interstellar medium, adding in Ni as 4.8×10^{-6} H. Two calculations were performed assuming Fe/H ratios of 10^{-4} and 10^{-5} (Tomblin takes the ratio as 1.4×10^{-5}). Except for the addition of Ni and the Fe abundances, the above conditions are those assumed by Tomblin and so the two calculations can be compared at 15 keV where the energy intervals overlap.

The calculation proceeds on the following lines. (1) An initial photon energy is selected at random between 15 keV and 10 MeV from a power law distribution (E^{-3} photons keV^{-1}). (2) An initial polarization direction is chosen, and the program follows the polarization through a routine for random selection of the scattering angles for polarized radiation (Santangelo, 1972). (3) The initial direction is chosen and the local zenith angle at the point of entry into the photosphere is calculated. At this point the program assumes a flat atmosphere and the photon history procedes until either the photon escapes from the atmosphere or is lost by reaching an energy below 15 keV or by being absorbed photoelectrically. The distance travelled by the photon in the scattering region is assumed to be small compared with the distance from the flare site. 10^5 histories of photons between 15 keV and 10 MeV were followed this way for each iron abundance. Then the calculations were repeated with ten times as many photons above 70 keV where the statistical significance of the results would have been too poor otherwise.

When a photon escapes from the surface its final direction and polarization are translated into a system of coordinates centered on the flare (the z-axis being the vector from the Sun's center to the flare), and, taking advantage of the cylindrical symmetry of the problem, the photons are collected into equal intervals of solid angle. The assumption implicit in this latter is the neglect of parallax.

It is also clear from the symmetry of the problem that the reflected radiation will be partially linearly polarized along a line perpendicular to the projected radius vector of the flare on the solar disk. The polarization is, of course, zero for h equal to zero. The percent polarization for a given h also results from the calculation but is of too poor a statistical significance to be reported here.

3. Results

An E^{-3} photon spectrum was assumed. This spectrum was chosen as a compromise among those actually observed for impulsive events but it must be kept in mind that the results will in general depend on the spectrum.

Experience with a calculation of the diffuse celestial X-ray albedo from the Earth's atmosphere (Horstman and Horstman-Moretti, 1971) suggests that a harder spectrum will have a higher percentage reflected in the peak region. Changing the spectral index in the latter case from 2 to 2.5 changed the percent reflected from 42% to 32% near the reflection peak and from 15% to 12% in the energy interval 15 to 300 keV. The dependence of the solar albedo on the spectral shape will be reported at a later time.

In Figure 1 the ratio of the reflected to the directly arriving flux is shown as a function of energy. As can be seen the points fall somewhat above those of Tomblin. The difference is due to the fact that we assumed 10^{-5} for the Fe/H ratio and he used a slightly larger value, 1.4×10^{-5}. The importance of this factor can be seen from Figure 2, where we compare the results for the average albedo for two different iron abundances, 10^{-4} and 10^{-5}.

Figure 3 demonstrates that the albedo as a function of heliocentric angle is roughly independent of the energy considered, at least up to 100–120 keV. There is, though, a suggestion in Figure 1 that at higher energies the slope of the spectrum depends on the angle. Figure 4 shows for the two assumed Fe concentrations the form of the reflected spectrum as a function of energy. All of the reflected photons were used to give a curve with good statistical significance.

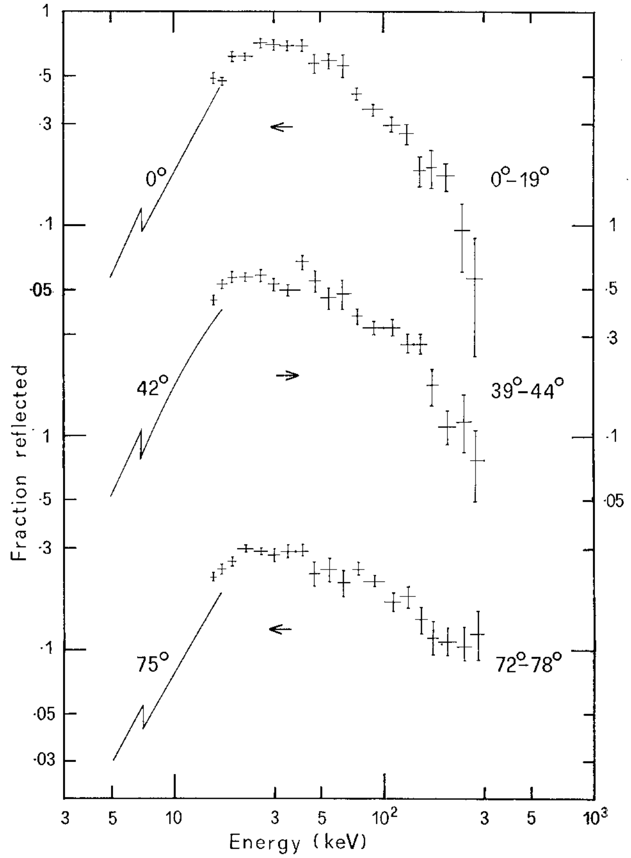

Fig. 1. Percent reflection of energy expressed as a fraction of the flux which arrives directly at the Earth, taking the ratio Fe/H as 10^{-5}. The solid lines are from Tomblin (1972) for an iron ratio of 1.4×10^{-5}. Graphs are shown for three different heliocentric positions of the flare.

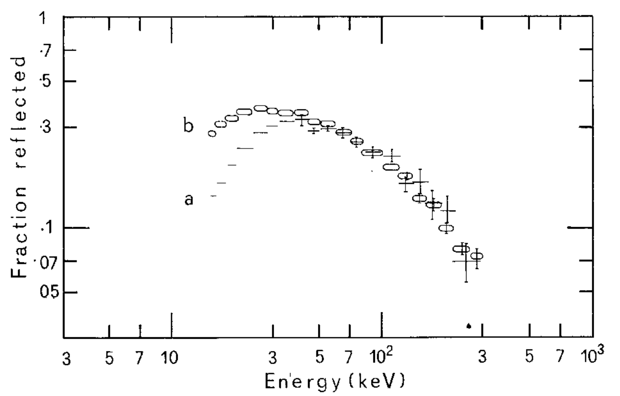

Fig. 2. Ratio of the reflected flux to the direct flux, averaged over all heliocentric angles. Two different Fe/H values were used. The ovals refer to Fe/H$=10^{-5}$ and the crosses to 10^{-4}.

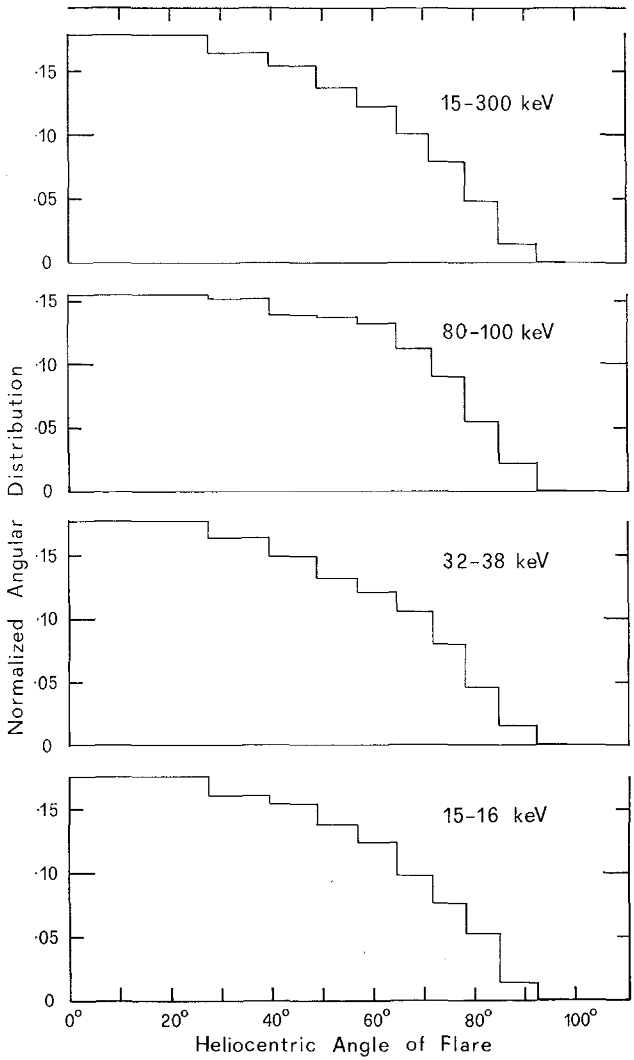

Fig. 3. Ratio of reflected flux to direct flux as a function of heliocentric angle from the center of the disk to the flare site, for different energy intervals.

4. Discussion

As can be seen in Figures 1 and 2 the peak of the reflection efficiency falls in the interval 20–40 keV for Fe/H equal to 10^{-5} and in the interval 30–50 keV for the Fe/H ratio equal to 10^{-4}. When this is multiplied by the E^{-3} spectrum to obtain the scattered photon flux seen at the Earth, the peak flux occurs below our lowest energy. The photon spectrum seen at the Earth will have both its form and its intensity modified by the presence of this scattered flux. Below the peak reflection efficiency the spectrum observed will appear harder and above the peak it will appear softer. For the worst

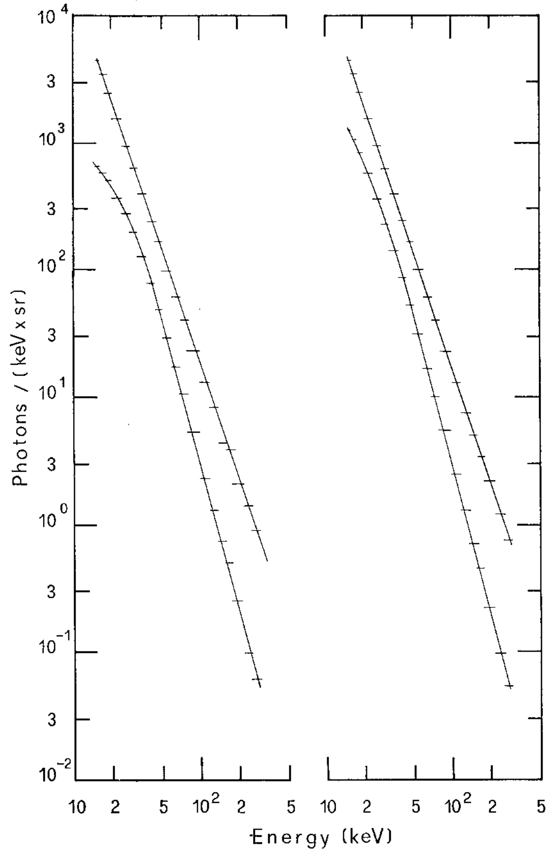

Fig. 4. Average reflected spectra for the two different iron concentrations: at left Fe/H is 10^{-4} and at right it is 10^{-5}. For comparison the emitted photon spectrum is also shown.

case, with the Fe/H ratio at 10^{-5} and the flare centered on the solar disk, the spectral index would be about 2.65 and 3.25 below and above the scattering peak instead of the 3 of the production spectrum at the flare site, and the flux at 30 keV would be 1.7 times that of the directly arriving photons.

The effect would be intensified if the flare produced X-rays anisotropically. In this case it could happen that the direct path from the flare to the Earth occurs where the flux is low, while the scattered flux would still be large, given that the solar surface subtends a large solid angle at the flare and would be likely to contain the directions in which the production spectrum is peaked. These same remarks are applicable with equal force to some of the sources in X-ray astronomy.

Observations of these effects would have considerable importance since the albedo depends critically on the iron abundance and on the presence or absence of anisotropy in the X-ray production. The present effects should also be considered when studying the longitudinal distribution of X-ray flares on the solar disk (see, for example, Pintér (1969) and Ohki (1969)).

References

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