Coronal scattering as a source of flare-associated polarized hard X-rays

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Abstract. We consider the scattering of flare-associated X-rays above 1 keV at coronal heights, particularly from regions of enhanced density. This includes a discussion of the polarization of the scattered X-rays. Although the scattered radiation would not be bright by comparison with the total hard X-ray flux from a flare, its detectability would be enhanced for events located a few degrees behind the limb for which the dominant "footpoint" hard X-ray sources are occulted. Thus we predict that major flares occurring beyond the solar limb may be detectable via scattering in density enhancements that happen to be visible above the limb, and that such sources may be strongly polarized. Since thin-target bremsstrahlung will generally greatly exceed the scattered thick-target flux in flare loops themselves, these considerations apply only to coronal structures that do not contain significant populations of non-thermal electrons.

Keywords: Corona, flares, X-rays, polarization

1. Introduction

The possibility of observing polarized hard X-ray emission from solar flares has long tempted astrophysicists (Korchak, 1967; Elwert and Haug, 1970; Hénoux, 1975; Bai and Ramaty, 1978). The motivation is that the polarization signature would provide information about the beaming of non-thermal electrons accelerated in the corona during a flare (Brown, 1972). These 10-100 keV electrons, which may carry a dominant fraction of flare energy (Neupert, 1968; Kane and Donnelly, 1971), interact in the chromosphere at the "footpoints" of the coronal magnetic flux tubes in which the acceleration takes place. This signature would give direct knowledge of the pitch-angle distribution of the electrons. A complicating factor would come from the polarized "albedo patch" resulting from the Compton backscatter of a portion of the primary hard X-radiation (Brown et al., 1975; Hénoux, 1975).

In this paper we point out that polarization will also arise by scattering in the corona above the footpoint sources, especially if there are localized density enhancements. Structures such as filaments, flare loops themselves, flare ejecta, spicules, or any ambient coronal material

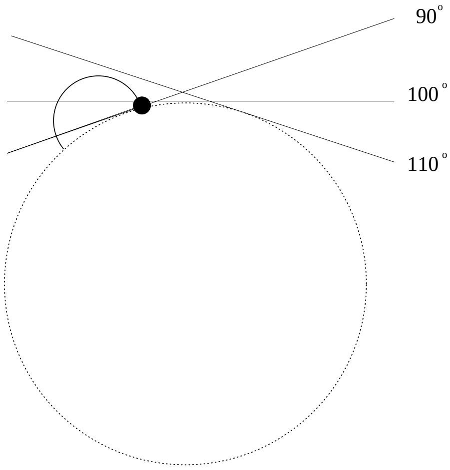

Figure 1. Cartoon showing the geometry (exaggerated) of the solar limb (dotted), a coronal loop, and lines corresponding to occultation at longitudes of 90°, 100°, and 110° respectively for the nearer footpoint (black disk). At 100° the flare loops remains visible; for greater longitudes they would also become occulted.

may serve as scatterers. As described below, these sources will be faint, however. Because present-day hard X-ray imaging is limited in image dynamic range (contrast), faint sources are difficult to detect in the presence of bright (e.g., footpoint) sources. Therefore the best way to isolate secondary polarized sources would be to observe them in a flare for which the footpoint sources were occulted by the solar limb (e.g., Tomczak, 2001). Figure 1 sketches the geometry. Such a case should occur commonly because about 10% of flares occurring in the 0-100° range of central meridian distances will be over-the-limb events. Leach et al. (1985) have already made the suggestion that limb-occulted flares would allow one to study polarization from thin-target bremsstrahlung in the coronal parts of the flare itself. In this paper we discuss the polarized signal arising in coronal features, such as prominences or loops with high density, that are devoid of non-thermal particles. These would not be hard X-ray sources intrinsically, but would appear as sources due to the scattering of X-rays originating from the occulted footpoint sources.

2. Polarization

Typically the footpoint sources in a solar flare occur in a dominant pair, assumed to be the conjugate points of a coronal loop, but they also may spread out along the flare ribbons (Masuda et al., 2001). The coronal loops fill with plasma as the flare develops ("chromospheric evaporation"). Thus such loops themselves could be scattering targets. In addition there may be filament material near a flare site, which could also scatter footpoint photons. In principle a general(spherically symmetric) corona could also contribute, but its low density would make it very faint and the spatially integrated polarization would be diluted because of the distribution of scattering angles.

In general the intensity and plane of polarization of the scattered X-rays will depend upon the relative locations of the footpoints, the observer, and the coronal scattering material. The simplest case consists of a localized coronal feature directly above a footpoint source. In this case the scattering angle is approximately 90°. The flare spectrum falls off rapidly with increasing photon energy, so in practice we are limited to low (non-relativistic) energies. In the Thomson limit, for optically-thin single scattering, we find (e.g., Hénoux, 1975) that

$$J'/J_\circ = N_e(r_e/L)^2 = 7.95 \times 10^{-6} N_{38}/L_9^2, \tag{1}$$

where J' and $J_\circ$ are the scattered and non-occulted intensities, L is a 'mean effective' distance of the scatterer from the footpoint ($L_9 = L/10^9$ cm), r_e the classical radius of the electron, and N_e the total number of electrons in the coronal scattering source ($N_{38} = N/10^{38}$). For a localized coronal feature directly above a footpoint source, L would become the feature height. For a narrow vertical cylinder (e.g flux-tube limb) of area A directly above a footpoint source, the result is

$$J'/J_\circ = Ar_e^2 \int_{L_{min}}^{L_{max}} n_e(z) \frac{dz}{z^2}. \tag{2}$$

If $L_{max} >> L_{min}$ the integral is dominated by small values of z, and if the density scale height is larger than L_{min} we can take the electron density $n_e(z)$ to be approximately constant as n_0 and get

$$J'/J_\circ \approx \frac{An_0 r_e^2}{L_{min}} = \frac{L_{max}}{L_{min}} N_e(r_e/L_{max})^2, \tag{3}$$

which is a factor L_{max}/L_{min} larger than simple application of Equation 1 with $L = L_{max}$ would give. (Note that in our approximation, formally $J'/J_\circ \to \infty$ if $L_{min} \to 0$ because we have assumed a point source; our approximation would need refinement if the source size were of order L_{min}.) The most relevant situation here is that of a point source behind the limb so that L_{min} becomes the occultation height.

The dimensional form of Equation 1 would correspond to a post-flare loop system with volumetric emission measure 10^{49} cm^{-3} and density 10^{11} cm^{-3}, at a height 10^9 cm. An Hα filament of mass 10^{15} g would have $N_{38} \sim$10. From this one can see that the coronal scattering sources are quite faint – roughly speaking, a scattering source corresponding to a GOES class X10 would probably be fainter than GOES class C1!

The kind of occultation an over-the-limb flare experiences depends on its longitude L, as sketched in Figure 1. For $L < 90°$, there will be no occultation; for, $90° < L < 100°$ the flare footpoints would tend to be occulted, and for $100° < L < 110°$, there is a good probability of occulting the entire flare loop system. The Tomczak (2001) study was restricted to the domain 90∼100°, for which the occultation height ($\leq 10^4$ km) would be sufficient to obscure the footpoint sources but not the entire flare loop system. This distinction is important in that that the flare loop system is likely to contain primary hard X-ray sources from the thin-target bremsstrahlung of electrons either coronally trapped or *en route* to the loop footpoints.

An additional scenario would be massive ejecta, which commonly occur in CME-related flares and which consist (in soft X-rays) of moving loops. Except for the single observation of Hudson et al. (2001) we know little about the hard X-ray brightness of such ejecta. This event had an total electron number $N_{38} > 1$.

3. Conclusions

We have discussed the scattering of >1 keV X-rays in the solar corona. The scattering physics is the same as for the K-corona, except that the primary sources would be compact and not extended. In ideal circumstances this would mean a high degree of linear polarization, approaching 100%, with the electric vector parallel to the solar surface, but with a low brightness. The RHESSI Lin et al. (2002) sensitivity to linear polarization (McConnell et al., 2002) will provide our first new opportunity to study this effect, but we note that the RHESSI polarization sensitivity is limited by the design to photon energies >20 keV, where fluxes are much smaller than at lower energies.

Polarization measurements with RHESSI could be easiest for scattering from an over-the-limb flare source. The domain beyond ∼10° might be the most interesting from the point of view of polarization degree. Within the 10° limit one would have an increasing likelihood of competition with direct thin-target bremsstrahlung from flare loops. In either case the scattered source would reveal the presence of the occulted flare. The polarization itself, since it is not intrinsic, would contain no information about electron beaming. However in principle its presence would provide a unique perspective on the coronal density distribution, and would confirm the RHESSI technique for polarization measurement. Because solar spectra are steep and the scattered sources will be faint in any case, observations below the 20 keV lower limit of RHESSI would be important. We suggest that designs for any future polarization measurement try to retain sensitivity at energies below 20 keV.

Acknowledgements

NASA supported this work under NAS 5-98033 (HSH and GJH). JCB acknowledges the support of a PPARC grant. We thank Mark McConnell for helpful comments.

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