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J. LEACH

A. G. EMSLIE

V. PETROSIAN

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INSTITUTE FOR PLASMA RESEARCH
STANFORD UNIVERSITY, STANFORD, CALIFORNIA

The Interpretation of Hard X-ray Polarization Measurements in Solar Flares

J. Leach,[‡] A. G. Emslie,[†] & V. Petrosian.[‡]

Tramiel *et al.* [1] have recently reported observations of polarization in moderately hard (5 – 20 keV) X-rays occuring in solar flares. In contrast with earlier observations[2–7], these new measurements exhibit low degrees of polarization ($\lesssim 5\%$). In this letter we comment on the significance of these new measurements for models of hard X-ray production in solar flares, in particular on the issue of whether impulsive, solar flare hard X-ray emission is predominantly a thermal[8–10] or a non-thermal[11–14] process. Low polarizations are generally considered to be indicative of a near isotropy of the distribution of bremsstrahlung-producing electrons, a situation which can arise more naturally in thermal models. Here we shall discuss the significance of low hard X-ray polarization measurements for non-thermal models. We shall show that such a low polarization result can in fact occur in non-thermal models, and we shall discuss the ways in which the degree of X-ray polarization is correlated with the parameters of these models.

The characteristics of the hard X-ray emission from solar flares can give important information about the underlying population of energetic electrons and

‡ Institute for Plasma Research and Department of Applied Physics, Stanford University, Stanford, California 94305

† Department of Physics, The University of Alabama in Huntsville, Huntsville, Alabama 35899

hence, indirectly, about the mechanisms by which that electron population is created. It has been clearly demonstrated[15] that we cannot discriminate between the non-thermal and thermal models on the sole basis of the hard X-ray spectral form. General attention, therefore, has been turned to other characteristics of the hard X-ray field, such as its spatial structure, directionality and, most important, its polarization. In the early 1970's, observations of hard X-rays in flares found evidence for large polarizations (up to 40%)[2 - 7,16]. A large polarization implies a non-isotropic distribution for the electrons and therefore favors a non-thermal model over a thermal model. These measurements have been challenged[17], however, and the resulting dispute[18] has not clearly been resolved. The new observations of Tramiel *et al.*[1] are on a more solid observational footing and so should be able to provide a better diagnostic into the nature of the energetic electron population.

For isotropic electron distributions such as are expected on the basis of the thermal models, the polarization of the emitted radiation should, of course, be zero. However, the presence of temperature gradients can lead to slight electron anisotropies and hence to low degrees of polarization[19]. In addition a small polarization can arise from the consideration of those photons which are backscattered by the photosphere[20 - 23].

Early studies with non-thermal models, with[23,27] or without[24 - 27] photospheric albedo effects, were all based upon highly simplified angular distributions for the beam electrons. These early studies all ignored the effects arising from the geometry of the magnetic field and most of them (except Brown[28]) also ignored the Coulomb scattering of the electrons within the target. Hence early non-thermal studies tended to derive somewhat higher polarizations than did studies with thermal models.

The most recent study[29,30] uses a Fokker-Planck treatment to follow the evolution of an electron beam in the solar atmosphere and evaluates the characteristics of the bremsstrahlung hard X-rays produced in such non-thermal models. This technique is a substantial improvement upon the previous theoretical analyses, and the results show that low polarizations can arise naturally in non-thermal models. Here we shall compare some of these recent results with the new observations[1] and then we shall discuss why the calculated X-ray polarizations are lower than one would have expected on the basis of earlier models.

The three parameters by which Leach and Petrosian[29] describe their models are κ ($= d\ln B/ds$, where B is the magnetic field strength and s is the distance along the loop), and δ and α_0, which describe the energy (E) and pitch angle (α) distribution of the injected electrons, viz. $f(E,\alpha) \sim E^{-\delta}\exp(-\alpha^2/\alpha_0^2)$. One of the effects which would normally reduce the polarization of the X-rays and which has not been included in previous theoretical studies is the curvature of the flare magnetic field. Since the orientations of the polarization vectors from different parts of a curved loop will differ, observations with low spatial resolution will measure a degree of polarization which is lower than that derived from smaller (and straighter) portions of the loop. Here, following Leach and Petrosian[29], we shall be using flare loops which are semi-circular. Clearly, more complicated loop geometries could give rise to an even greater reduction in the degree of polarization.

For one of the observed flares[1] (designated as flare 2*I*) we have information about the hard X-ray spectrum (Kane, private communication). This data allows us to select a value for δ, thus leaving us with two free parameters. We therefore compare the observed degree of polarization for this flare with the calculated polarization curves for three models having different values of α_0^2 and κ (Figure 1). There are two observational effects to be considered which would reduce the degree of polarization measured from that which would otherwise be obtained:

(*i*) At these low X-ray energies there may be a significant contribution from an unpolarized thermal background[31]. A clear indication of such contamination would be an increase in the polarization with increasing X-ray energy. There may be some evidence for this in the data[1].

(*ii*) Any variation in the flare characteristics over the relatively long ($\approx$ 2 minutes) integration times of the observations will give rise to a lower observed polarization than would be expected from a typical isolated elementary burst of duration $\approx$ 10 seconds, especially if different elementary bursts are due to the energization of different loops[32].

In addition, there is a substantial error bar on the observation and some uncertainty inherent in the calibration procedure followed[1]. Consequently we cannot set strict limits on the values of the model parameters. However, as we clearly show in figure 1, a low degree of polarization does not necessarily militate against non-thermal models.

The reasons for the polarization estimates of reference 30 being lower than the earlier estimates[23–28] are as follows. As seen in a full Fokker-Planck analysis of the beam dynamics, any injected electron beam becomes increasingly isotropized as it penetrates further down through the solar atmosphere[29]. Since the rate at which the electrons diffuse in pitch angle is comparable to the rate at which they lose energy[33] the bulk of the observed hard X-rays are emitted only after the electron beam has undergone much of this isotropization. Thus the integrated X-ray emission from the whole source will have the character of the emission from a highly broadened electron beam, no matter what the original degree of electron beaming was at injection. A spatially unresolved measurement of the hard X-ray polarization must then give rise to a low value. Certainly, the stronger the initial beaming of the electrons is, the higher will be the X-ray polarization, though we stress that this is no more than a weak effect once the Coulomb collisions have been properly incorporated into the analysis. Calculations from a variety of flare models[30] show that X-ray polarizations of around 25% are the most that can be expected from reasonable model parameters such as those given in Table I, even from a highly beamed (low α_0^2) model with a uniform magnetic field. The effect of any non-uniformity in the magnetic field ($\kappa \neq 0$) is to further reduce the degree of polarization for the highly beamed models.

The parameter δ (the spectral index of the injected electron beam) exercises a strong influence upon the hard X-ray polarization. (This parameter was fixed in our above comparison with the flare of reference [1] by independent observations). The two cross sections for linearly polarized bremsstrahlung production are functions of the photon to electron energy ratio and the two cross sections behave differently as functions of that energy ratio[34]. A flux of "hard" photons, *i.e.* photons each having an energy close to that of the emitting electron, will, in general, be more highly polarized than a flux of "soft" ones (*i.e.* photons each having an energy much less than that of the emitting electron). Injected electrons with a flat energy spectrum (*i.e.* low δ) will give rise to X-rays in which a greater proportion of the photons are soft and, therefore, the X-rays will be less polarized. Conversely, electron distributions which are steep (large δ) produce generally harder photons and thereby result in a more highly polarized emission (*cf.*, for example, figure [3b] in reference 23). As demonstrated in Table I, δ has a very substantial influence upon the observed polarization, and is at least as significant as the degree of electron beaming at injection. This effect has received little attention in the literature to date.

In summary, the observations of low hard X-ray polarization in solar flares[1] are in fact quite consistent with both thermal and non-thermal models of hard X-ray production. Our hope of using polarization data as a discriminant rests upon our being able to observe the coronal component of the emission in isolation, for then any strong beaming of the non-thermal electrons, not yet having been smoothed away by collisions in the thick target, should result in a quite high polarization signature[30], easily in excess of that produced in thermal models[22]. Spatially resolved polarization measurements are not yet possible. However, by looking at flares occuring just past the edge of the solar limb[35], it should be possible to observe the emission from the upper part of the flare loop without that emission being contaminated by the signal from the less polarized component which is formed in the lower parts of the flare loop and is absorbed in the intevening photospheric layers. Unfortunately, by the same token, the emission from this upper part of the loop will generally be no more than a small fraction of the total flare emission, thus presenting problems with statistical noise unless the observed flare is very large. Currently available instruments, such as the one used by Tramiel *et al.* [36], should be capable of observing the coronal signal from the large flares that can be expected to occur during the next solar maximum.

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Table I

The variation of the maximum percentage polarization at 16 keV with δ and α_0^2, for $\kappa = 0.0$

	α_0^2			
δ	∞ †	0.4	0.04	0.01
3	≤ 5	≤ 5	≤ 5	6
4	8	8	11	13
5	10	11	20	21
6	10	16	26	26

† Electrons injected isotropically at the top of the loop

Fig. 1: A comparison between the polarization measured for flare 2I of Tramiel *et al.* [1] and the polarizations calculated for three of the models of Leach and Petrosian [30]. The solid line is for a model with $\alpha_0^2 = 0.4$ and $\kappa = 0.0$, the dashed line is for a model with $\alpha_0^2 = 0.4$ and $\kappa = 1.5 \times 10^{-9}$, and the dotted line is for a model with $\alpha_0^2 = 0.1$ and $\kappa = 1.5 \times 10^{-9}$. $\kappa = 1.5 \times 10^{-9}$ corresponds to a twentyfold increase in the magnetic field strength from the top of the flare coronal loop to the transition region, a distance of $2 \times 10^9 cm$. All three models have a coronal density of $5 \times 10^9 cm^{-3}$. For a flare at disk center the viewing angle would be 0°, for one on the solar limb it would be 90°.

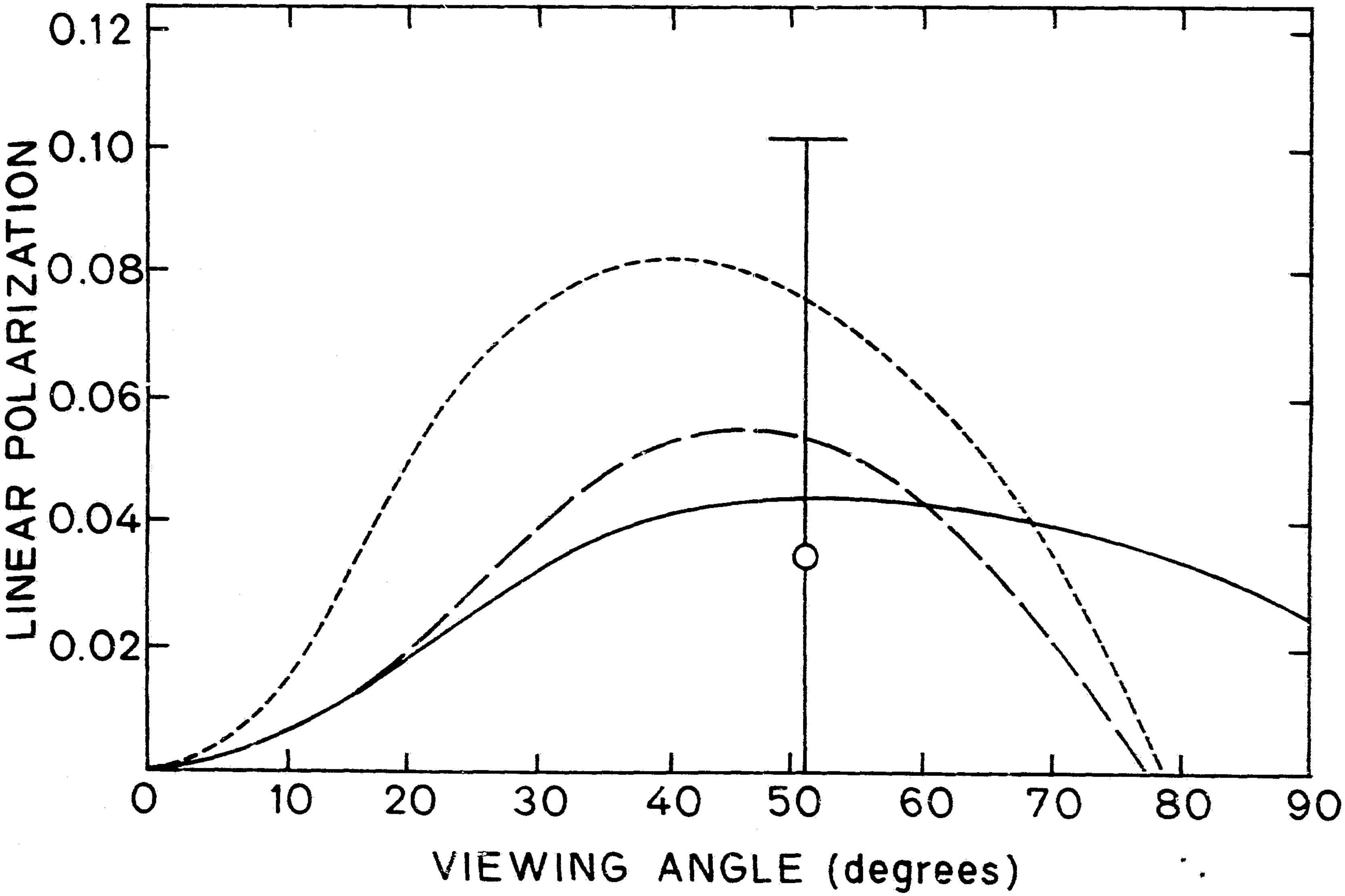
LINEAR POLARIZATION
0.12
0.10
0.08
0.06
0.04
0.02
0
10
20
30
40
50
60
70
80
90
VIEWING ANGLE (degrees)

Figure 1

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