PROSPECTS FOR SOLAR FLARE X-RAY POLARIMETRY

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Abstract. The history of solar flare X-ray polarimetry is reviewed and it is shown that as yet, there is no experimental evidence for such polarization. The present experimental limits are at the level of a few percent but these results may be biased by a large thermal component at low energies which may decrease the apparent polarization. To avoid this difficulty it will be necessary to make observations at higher energies where thermal emission is less important.

The theoretical estimates of the polarization expected in the solar flare are also reviewed. The best present theoretical estimates are in the range of a few percent and are consistent with the present experimental limits.

In this paper we discuss a new satellite instrument that has sufficient sensitivity at high energies to detect the polarization that is predicted by the present theories. The instrument sensitivity for a moderate (M class) event approaches polarization levels of 1% in each of 7 energy bins spanning the 10 to 100 keV range for integration times as short as 10 s. Comparable results can be obtained for an X class flare in 1 s.

1. Solar Flare X-Ray Polarimetry

The idea that X-ray emission from solar flares might be linearly polarized and that polarization measurements could, therefore, provide a strong flare diagnostic was first discussed by Korchak (1967) and Elwert (1968). Subsequent theoretical investigations (Elwert and Haug, 1970, 1971; Haug, 1972; Brown, 1972; Henoux, 1975; Langer and Petrosian, 1977; Bai and Ramaty, 1978; Emslie and Brown, 1980) have resulted in polarization predictions for a variety of models. There are two extreme classes of models under investigation, termed 'thermal' and 'non-thermal', whose physical difference lies principally in whether the electrons responsible for the bremsstrahlung are part of a relaxed distribution or of a suprathermal tail. Although some form of hybrid model (e.g., Emslie and Vlahos, 1980) is probably appropriate for actual events, the basic components differ significantly in their polarization predictions: the thermal models predict polarizations of at most a few percent, due to either photospheric back-scatter of primary photons (Henoux, 1975), or an anisotropy in the source electron velocity distribution, caused by the presence of a field-aligned thermal conductive flux (Emslie and Brown, 1980). The beamed or linear bremsstrahlung models, on the other hand,

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predict quite high polarizations, of the order of 10% for the spatially integrated radiation field, and even higher than this for the collisionally thin upper portions of the flare loop (Leach, Emslie, and Petrosian, 1985).

The two models also predict different directivities, with the non-thermal models tending to give anisotropic distributions (Elwert and Haug, 1970, 1971), although the intrinsic effect is substantially reduced by photospheric back-scattering (Bai and Ramaty, 1978). Stereoscopic observations by Kane *et al.* (1980) put limits on the anisotropy and tend to favor the thermal models, but are thus far not conclusive. Recent gamma-ray observations from the Solar Maximum Mission Observatory show that above 300 keV more flares are observed at the limb of the solar disk than at the center (Rieger *et al.*, 1983; Vestrand, 1985). Dermer and Ramaty (1985) have shown that this center-to-limb variation may be attributed both to downward-beamed electrons and electron distributions peaked at directions parallel to the surface of the Sun. It is important to recognize that the observations of photon beaming directly imply non-vanishing polarization. The beaming observations that have been made to date are purely statistical in nature. They require one to compare the photon fluxes from different solar flares; since no two flares are the same, this is a very suspect procedure. Polarimetric observations provide direct evidence for electron beaming within a particular flare without recourse to any data from a different flare.

The pioneering observational work in solar X-ray polarimetry was done in a series of satellite experiments by Tindo and his collaborators in the Soviet Union (Tindo *et al.*, 1972a, b; Tindo, Mandel'stam, and Shuryghin, 1973; Tindo, Shuryghin, and Steffen, 1976). Initial results showed high levels of polarization (up to 40%), although of rather low statistical significance, and these were generally interpreted as evidence for strong beaming of the electrons. These results are shown in Figure 1 where they are compared to the theoretical calculations of Bai and Ramaty (1978). The theoretical curve marked 'thermal' in this figure is the polarization expected to arise by X-ray back-scattering in the photosphere when the intrinsic flare radiation is unpolarized (and so presumably thermal in origin). The theoretical curves of Leach and Petrosian that are also shown in Figure 1 are discussed below. The results of the polarimeter flown by the Columbia Astrophysics Laboratory as part of the OSS-1 payload on the Space Shuttle mission STS-3 by contrast showed very low levels of polarization – no more than a few percent. At the same time but independent of the observational work, Leach and Petrosian (1983) showed that the high levels of polarization in the Tindo results were difficult to understand theoretially, since the electron beam is isotropized on an energy loss time-scale – an effect which substantially reduces the expected levels of polarization, although not to zero. Recently Haug, Elwert, and Rausaria (1985) also considered the effect of electron scattering on electron beaming and X-ray polarization. These workers predict higher polarization than Leach and Petrosian, but it is important to note that Haug *et al.* consider only a straight electron path; they do not consider the curvature of the electron path in the flare, an effect which will almost certainly reduce the polarization. In Figure 1 we also compare the results of Tindo, Shuryghin, and Steffen (1976) to the predictions of Leach and Petrosian (1983) (which do not include photospheric back-scatter effects).

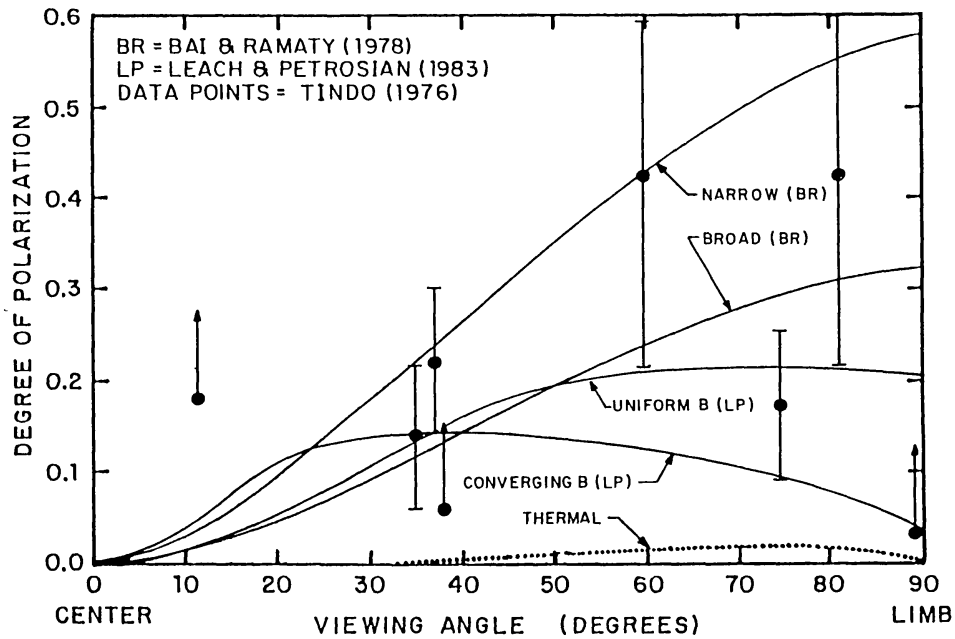

Fig. 1. Comparison of the polarization results of Tindo, Shuryghin, and Steffen (1976) with the theoretical results of Bai and Ramaty (1978) and of Leach and Petrosian (1983). Note that the theoretical curves of Leach and Petrosian are generally below the polarization results of Tindo.

The predictions of Bai and Ramaty (1978) shown in Figure 1 *do* include a photospheric back-scattered component, but they predict a higher intrinsic source polarization due to their approximate treatment of the beam-target interaction. In Figure 2 we compare the STS-3 results to the calculations of both Bai and Ramaty and Leach and Petrosian. These results are considerably below those of Tindo and all of the theoretical results. As noted on Figure 2 one of the STS-3 events was impulsive in nature. A subsequent comparison by Leach, Emslie, and Petrosian (1985) of the (impulsive phase) STS-3 result and the above theoretical treatment shows that the former are consistent with several current models (see Figure 3) and that a factor of ~ 3 improvement in sensitivity is needed to distinguish properly among the possibilities. In addition, there is reason to expect stronger polarization effects at higher energies: although the predicted polarization curves of Leach and Petrosian (1983) are only weakly energy dependent (up to at least 100 keV), there may be a strong admixture of thermal X-rays at the energies seen by the STS-3 instrument (5–20 keV, but predominantly below 10 keV). As Leach, Emslie, and Petrosian (1985) stress, this thermal 'contamination' will tend to reduce the observed polarization, but the effect should decrease sharply with increasing energy (see also Emslie and Vlahos, 1980), so that the need for higher energy observations is clear. Further, in the case where the coronal component can be observed in isolation, such as in a flare whose footprints are just behind the occulting photospheric limb, the predicted polarization is much higher (Leach, Emslie, and Petrosian, 1985). Thus we clearly see that better polarimetric observations are needed, particularly at high energies where thermal effects are unimportant. In the next section we describe a new polarimeter

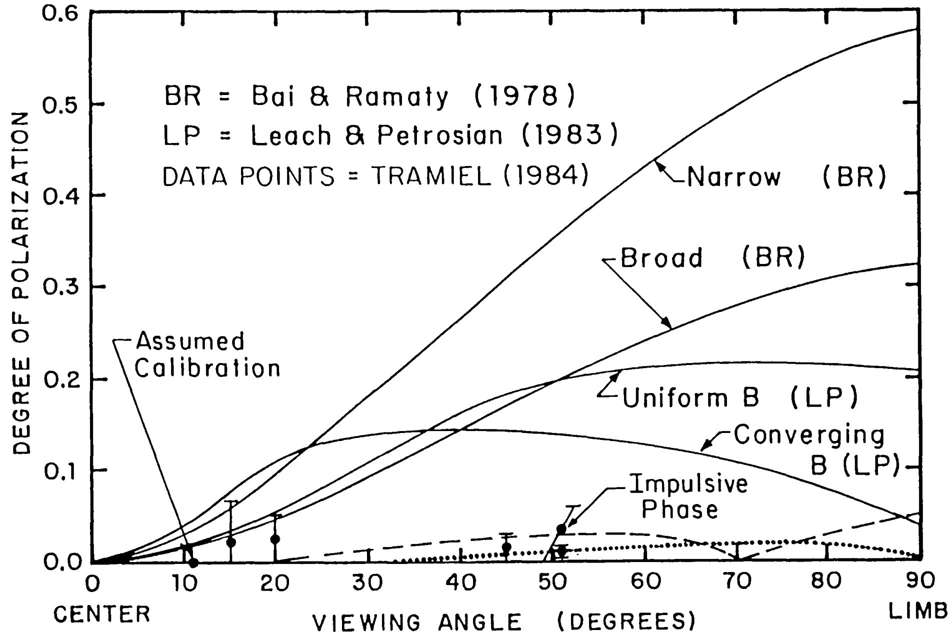

Fig. 2. Comparison of the STS-3 polarization results with the calculation of Bai and Ramaty (1978) and Leach and Petrosian (1983). Note that the STS-3 results are lower than all the theoretical predictions.

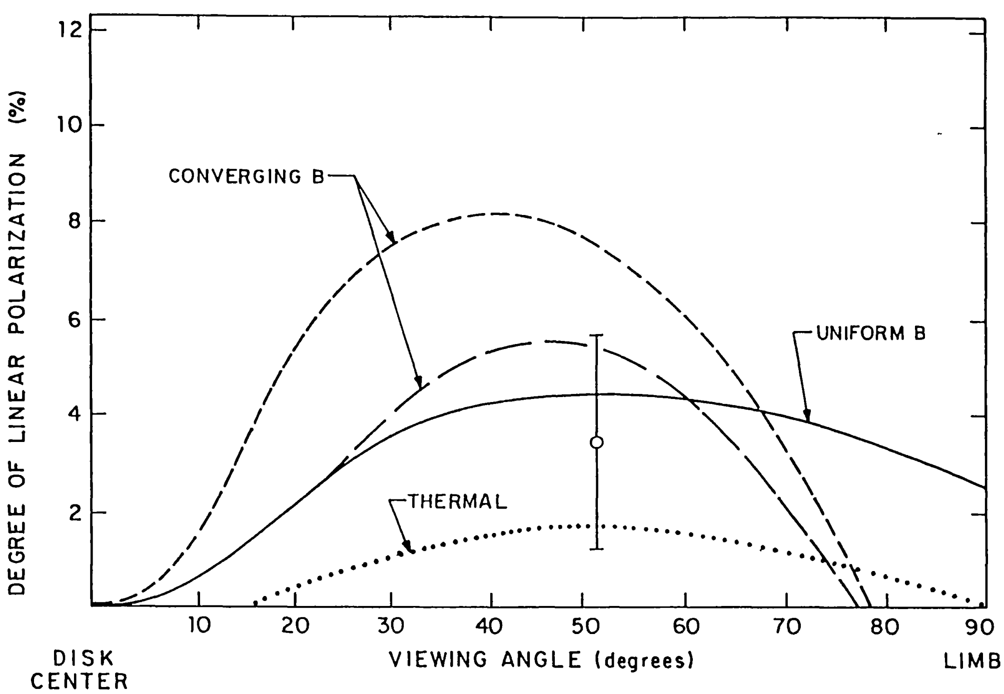

Fig. 3. Comparison of the STS-3 impulsive event polarization result with theoretical predictions of Leach, Emslie, and Petrosian (1985). The reader is referred to the theoretical paper for details of the three different theoretical results that are shown in this figure.

that is designed to answer the outstanding questions regarding electron beaming and scattering in solar flares.

2. An Improved Solar Flare Polarimeter

The previous STS-3 instrument exploited the polarization dependence of Thomson scattering (see Figure 4). The targets (whose dimensions are set by the relevant scattering length) were 12 rectangular blocks of metallic lithium, monitored on two of the four sides by xenon-filled proportional counters; there were thus effectively six targets. The low-energy threshold was set at ~ 5 keV by photoelectric losses in the lithium, the high-energy cutoff by the transparency of the proportional counters at ~ 20 keV. The improved instrument uses plastic scintillator (composed mainly of carbon) in place of the lithium targets, which raises the low-energy threshold to ~ 10 keV. The xenon counters are in turn replaced by sodium iodide detectors; this extends the high-energy response upward to $\gtrsim 100$ keV.

A fundamental improvement in background rejection results from using the carbon target in the form of plastic scintillator. A sufficiently high-energy photon which interacts in the target will give rise to a Compton electron which can be detected by a photo-

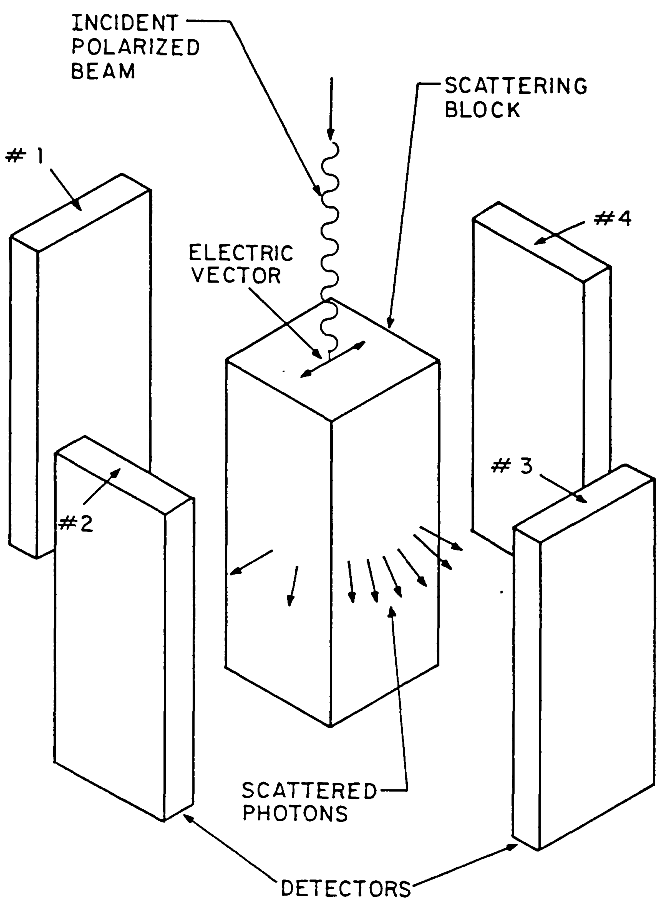

Fig. 4. Scattering polarimeter concept.

multiplier tube which monitors the optical output of the target from below. This can then be used as a trigger for the acceptance of events in the NaI(Tl) detectors. Although the exact value of the Compton threshold (estimated to be ~ 40 keV) is somewhat uncertain, the ultimate performance of the instrument is not very sensitive to the precise value. The reason is that at energies which are low enough for the detection of the Compton electron to be difficult, the source fluxes are high enough that the backround is simply not a problem. (It was not a problem for example in the STS-3 polarimeter.) Conversely, at energies which are sufficiently high that good background rejection is essential (because of the low fluxes), the Compton electron will have enough energy that it will be relatively easy to detect. In fact since both target and detector events will be recorded in flight, the precise value of the Compton threshold can be chosen post-flight to optimize the polarization response.

Because the NaI(Tl) detectors are relatively compact, a large number of target/detector assemblies can be packed into a relatively small space. We further plan to adopt a hexagonal geometry (as opposed to the square geometry used on STS-3); this results in an improved modulation factor, which in turn results in higher sensitivity and reduced vulnerability to systematic effects. Current plans are for an array of 37 targets, each

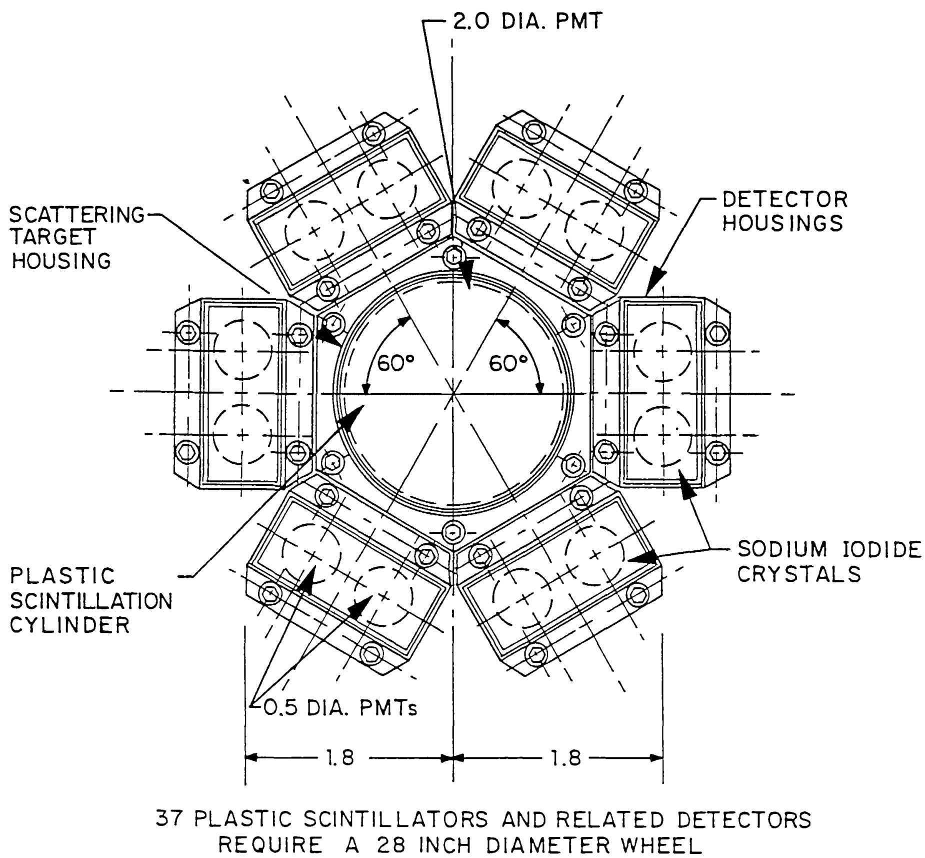

Fig. 5. Basic hexagonal polarimeter configuration. Note that the scattering target consists of an active scintillator which produces a light pulse when a Compton scattering event takes place in the target. The scattered photon is recorded by one of the six NaI(Tl) detectors that surround the target.

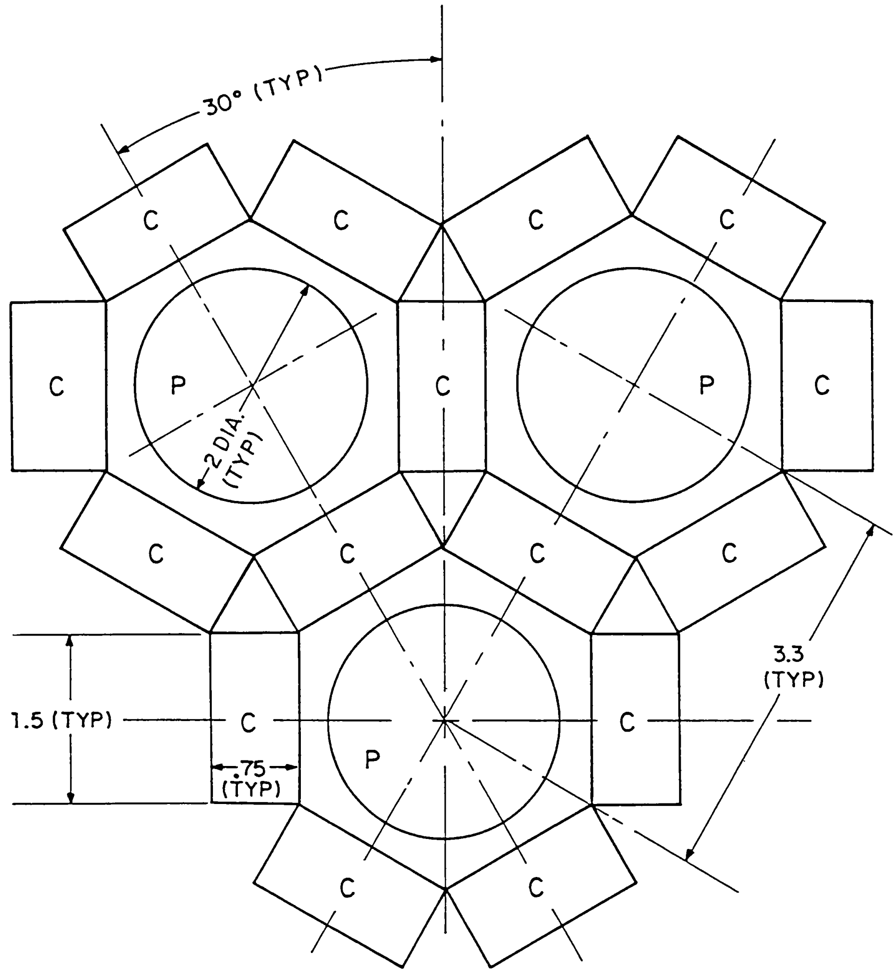

Fig. 6. Assembly of three scintillation targets and surrounding NaI(Tl) detectors.

surrounded by 6 detectors (the latter shared by 2 targets, except on the periphery) (see Figures 5, 6, and 7). Such an array would be 28 in. in diameter. This will increase the sensitivity by a factor of $\sqrt{(37/6)} \approx 2.5$ over the STS-3 instrument in the region where the bandwidths overlap; the high-energy response will be extended upward simultaneously by a factor of 5. The entire polarimeter assembly will be rotated to avoid a large number of possible systematic effects (instrumental polarization). With a static polarimeter it is necessary to compare the counting rates in *different* sodium iodide detectors. Since the sensitivity and spectral responses of such detectors are difficult to monitor, this procedure can lead to false indications of polarization. With a rotating polarimeter one searches for a modulation of the response of each detector. The depth of modulation and phase are simply related to the degree of polarization and the position angle of the polarization vector. By rotating the polarimeter at 20 RPM, only 1.5 s is needed for a determination of the polarization of the incident X-rays. This is clearly desirable for solar flares which vary rapidly in intensity.

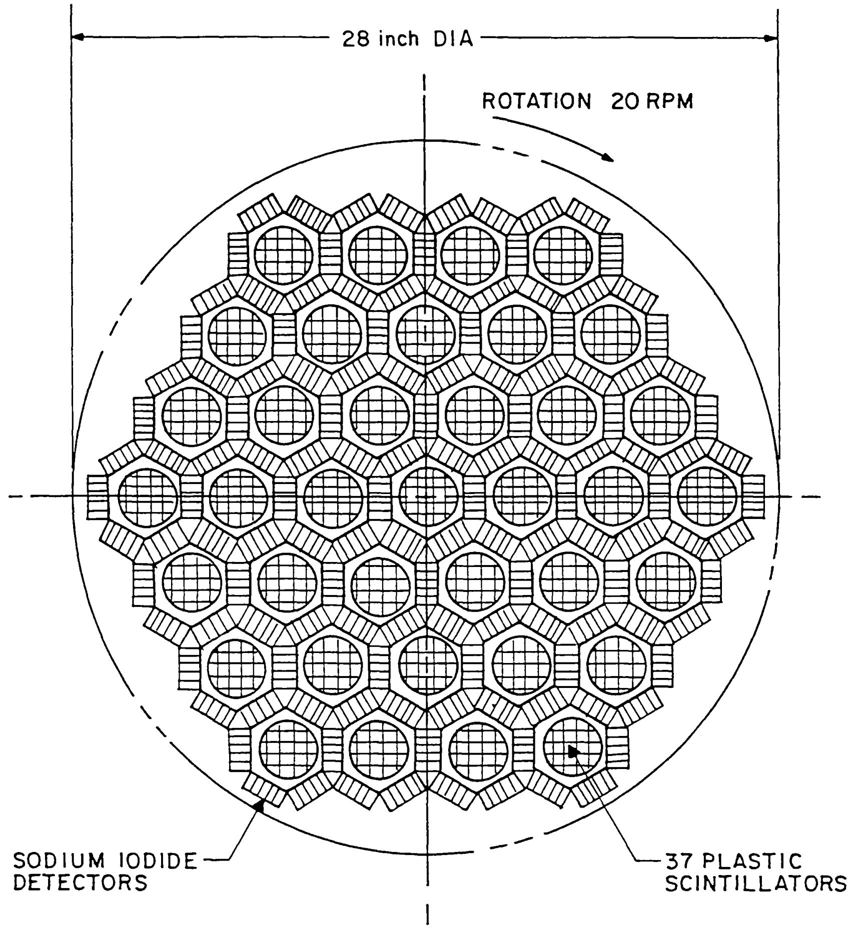

Fig. 7. Complete solar flare polarimeter consisting of 37 scintillator targets and surrounding NaI(Tl) detectors. The entire assembly will be rotated at 20 RPM. This avoids many possible systematic errors that could arise in a static polarimeter in which one must compare the signals in *different* NaI(Tl) detectors. With rotation, polarization manifests itself as a modulation of the signals in each of the NaI(Tl) detectors, the amplitude of modulation is simply related to the degree of polarization and the phase of the modulation to the position angle of the polarization vector.

Preliminary sensitivity calculations for the instrument described above for 5 typical (moderate) flares are shown in Table I; the flare parameters were taken from actual observed events (Lemen, 1981). Assumed integration times are 10 s in each case. Note that sensitivities of a few percent are routinely attained up to ~ 100 keV energies.

3. Conclusion

In this paper we have described a new solar flare X-ray polarimeter that has sufficient sensitivity so that it can be used to detect and measure the polarization that is predicted to arise from beaming in solar flares even when suitable account is taken of electron scattering. In Figure 8 we show the sensitivity of the polarimeter to an M-3 flare in 10 s or for an X-3 flare in 1 s; in both cases we have assumed a spectral photon index of 4.4. Note that the sensitivity is 2% or less at energies up to 50 keV. At these energies

TABLE I

Polarization sensitivities (1σ) predicted for five typical flares (10 s observation time)

Energy range	Polarization
(1) Photon flux at 1 keV = 1.35×10^5 photons cm^{-2} s^{-1} keV^{-1} Spectral index = 3.34 Classification = M2	
10–20 keV	1.25%
20–30 keV	1.70%
30–40 keV	2.69%
40–50 keV	3.89%
50–60 keV	5.40%
60–150 keV	4.25%
(2) Photon flux at 1 keV = 3.60×10^7 photons cm^{-2} s^{-1} keV^{-1} Spectral index = 4.28 Classification = X2	
10–20 keV	0.27%
20–30 keV	0.46%
30–40 keV	0.87%
40–50 keV	1.41%
50–60 keV	2.15%
60–150 keV	2.01%
(3) Photon flux at 1 keV = 2.61×10^7 photons cm^{-2} s^{-1} keV^{-1} Spectral index = 4.66 Classification = M3	
10–20 keV	0.52%
20–30 keV	1.01%
30–40 keV	2.02%
40–50 keV	3.44%
50–60 keV	5.47%
60–150 keV	5.46%
(4) Photon flux at 1 keV = 2.49×10^7 photons cm^{-2} s^{-1} keV^{-1} Spectral index = 4.36 Classification = M3	
10–20 keV	0.36%
20–30 keV	0.63%
30–40 keV	1.20%
40–50 keV	1.97%
50–60 keV	3.03%
60–150 keV	2.87%
(5) Photon flux at 1 keV = 2.30×10^5 photons cm^{-2} s^{-1} keV^{-1} Spectral index = 3.0 Classification = M2	
10–20 keV	0.60%
20–30 keV	0.75%
30–40 keV	1.12%
40–50 keV	1.55%
50–60 keV	2.09%
60–150 keV	1.74%

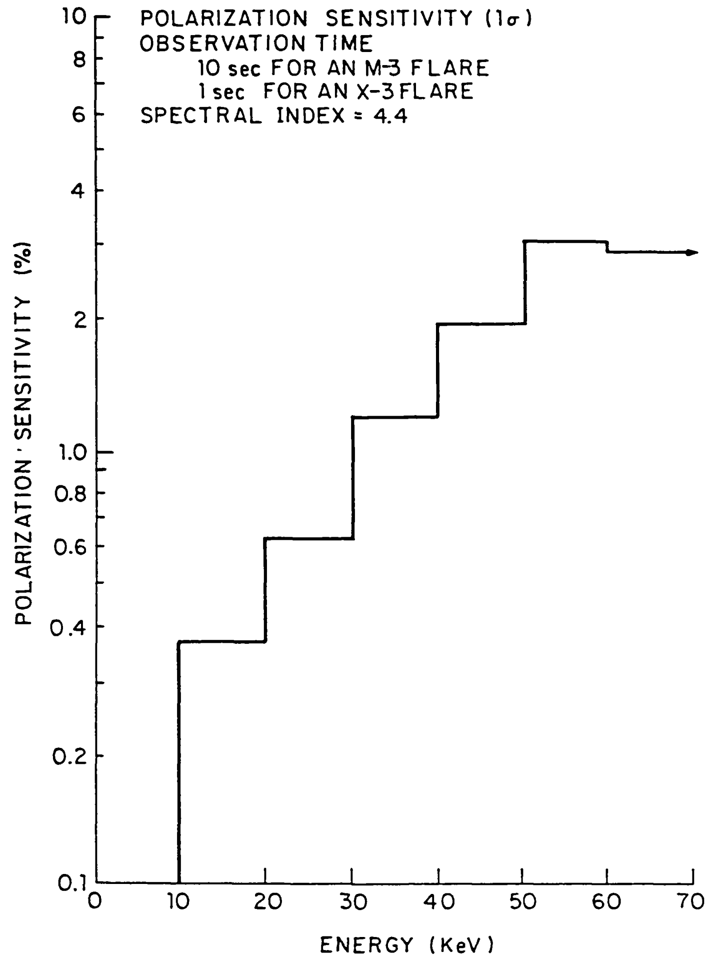

Fig. 8. Sensitivity of the polarimeter to an M-3 flare in 10 s or an X-3 flare in 1 s. In both cases we have assumed a spectral index of 4.4. Note that the highest energy bin extends up to 150 keV.

unpolarized thermal emission from the flare should be unimportant (Emslie and Vlahos, 1980). It is also important to note that the instrument has sufficient sensitivity to detect the polarization expected due to X-ray back-scattering in the photosphere. Since this phenomenon must be present, the polarimeter will certainly yield a positive result. Any deviation of the observed polarization from that due to back-scattering must be attributed to intrinsic flare polarization resulting from electron beaming. Our ability to detect such a deviation will, of course, be limited by the accuracy of the estimate of the polarization that arises from back-scattering. (Back-scatter can *reduce* the intrinsic source polarization if the angles are right.) This polarimeter represents a considerable improvement over the STS-3 instrument, especially at high energies where the contaminating effects of unpolarized thermal radiation are relatively unimportant. The design is based on laboratory tests of individual modules, on detailed computer simulations, and it incorporates the heritage of several successful rocket flights as well as that of the STS-3 experiment. This polarimeter is well matched to the outstanding questions about electron beaming and scattering in solar flares.

Acknowledgements

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