The stereoscopic observations of solar flare hard X-ray source in the high corona

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Abstract

The hard X-ray burst observed on 1984 February 16 (0900 UT) by the 5 keV–3.2 MeV X-ray spectrometry aboard the ICE/ISEE 3 spacecraft was associated with a flare which occurred ~40° behind the west limb of the Sun. The X-ray source directly associated with the flare was partially occupied by the photosphere from the view of the ICE instrument. The occultation height above the solar limb was ~1.6 x 10^5 km, a height much larger than that observed in previous stereoscopic measurements. The occultation height for the GOES soft X-ray (0.5–8 Å) monitor, which also observed the flare, was ~2.1 x 10^5 km. The flare was in full view of the 100 keV–2 MeV gamma-ray burst detector on the PVO spacecraft which was located at that time ~16° behind the west limb of the Sun. The X-ray sources observed by the ICE and GOES instruments are identified as the unocculted coronal parts of the primary X-ray source associated with the flare. A comparison of the occulted and unocculted photon spectra shows the following: (1) The sources of the impulsive hard X-ray (≥25 keV) and impulsive soft X-ray (2–5 keV) emissions in this flare extended to coronal altitudes ≥2 x 10^5 km above the photosphere. (2) At ~100 keV, the ratio of the coronal source brightness to the total source brightness was ~10^{-3} during the impulsive phase and ~10^{-2} during the gradual hard X-ray burst. (3) During the impulsive phase, the low energy cutoff of the nonthermal electron spectrum seemed to be ≤5 keV, indicating that the total energy carried by these electrons was much larger than that normally estimated on the basis of most solar flare models. (4) The sources of the gradual hard X-ray burst and gradual soft X-ray burst were almost completely occulted, indicating that the bright parts of these sources were located at heights <2 x 10^5 km above the photosphere. (5) During the impulsive phase, the average rate of injection of electrons >5 keV was ~6 x 10^{36} electrons s^{-1}, the total number injected being ~10^{39}. The rate of energy injection and the total injected energy were ~10^{38} ergs s^{-1} and ~10^{31} ergs, respectively. (6) The volume of the impulsive hard X-ray source in the corona is estimated to be ≥10^{10} cm^3 with an average density of ≤10^9 ions cm^{-3}, indicating a large diffuse hard X-ray source in the corona.

Subject headings: Sun: corona — Sun: flares — Sun: X-rays, gamma rays

1. Introduction

An important characteristic of energetic solar flares is the acceleration of particles from a few keV to relativistic energies. Acceleration of electrons is of particular interest because, during the impulsive phase of a flare, they seem to carry a substantial fraction of the total released energy (Kane 1974; Lin & Hudson 1976) and also provide a mode of rapid energy transport to the sources of different impulsive emissions such as EUV (Kane & Donnelly 1971; Donnelly & Kane 1978) and white light (Hudson 1972; Svestka 1976; Neidig 1983; Kane et al. 1985). Characteristics of the energetic electrons at the Sun can be studied through observations of the bremsstrahlung X-rays produced by these electrons as they interact with the ambient solar atmosphere. Observations of hard X-ray sources made with high spatial, spectral, and temporal resolution are therefore essential for understanding the acceleration and propagation of electrons in solar flares.

The imaging and stereoscopic observations of solar flare hard X-ray sources made with instruments aboard the SMM (Solar Maximum Mission), Hinotori, ICE/ISEE 3 (International Cometary Explorer, formerly ISEE 3), and PVO (Pioneer Venus Orbiter) have been reviewed by Kane (1987). The stereoscopic observations indicate that the impulsive hard X-ray source extends from the chromosphere to the corona, the brightness of the source decreasing rapidly with increase in height above the photosphere (Kane et al. 1982; Kane 1983). The SMM observations of relatively small impulsive flares indicate that the hard X-ray emission originates in a double source presumably at the footpoints of a magnetic loop (Duijveman, Hoyng, & Machado 1982). On the other hand, the Hinotori observations favor a single source structure for the impulsive hard X-rays, although a double source cannot be completely ruled out because of the modest spatial resolution of the Hinotori hard X-ray telescope (Tsuneta 1987).

In the past, the maximum height above which the impulsive hard X-ray source was clearly identified was 3 x 10^5 km (Kane & Donnelly 1971; Frost & Dennis 1971; Hudson 1978; Kane 1983). A fortunate set of circumstances has permitted the stereoscopic observations of a behind-the-limb solar flare on 1984 February 16 (0912 UT) in which an impulsive hard X-ray source seemed to extend into the corona to heights ≥2 x 10^5 km above the photosphere. We present here the X-ray observations of that flare and their implications with regard to our understanding of the energetic electrons in solar flares. Here we will be concerned primarily with the observed characteristics of the coronal X-ray source and its evolution during the flare.
TABLE 1
NEAR-EARTH OBSERVATIONS OF THE 1984 FEBRUARY 16 FLARE

<table>
<thead>
<tr>
<th>Emission</th>
<th>Data Source</th>
<th>Energy/Wavelength Range</th>
<th>Begin Time (UT)</th>
<th>Maximum Time (UT)</th>
<th>Peak Flux</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soft X-rays</td>
<td>GOES</td>
<td>0.5–8 Å</td>
<td>0858:30</td>
<td>0859:54</td>
<td>$3 \times 10^{-4}$ ergs cm$^{-2}$ s$^{-1}$</td>
</tr>
<tr>
<td>Hard X-rays</td>
<td>ICE</td>
<td>$&gt;25$ keV</td>
<td>0858:18</td>
<td>0859:18</td>
<td>1.7 photons cm$^{-2}$ s$^{-1}$ keV$^{-1}$</td>
</tr>
<tr>
<td>Radio</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Microwave</td>
<td>Bern</td>
<td>5.2 GHz</td>
<td>0858:30</td>
<td>0859:18</td>
<td>19 sfu</td>
</tr>
<tr>
<td>DCIM</td>
<td>Weissenau</td>
<td>8.4 GHz</td>
<td>0858:00</td>
<td>0859:42</td>
<td>25 sfu</td>
</tr>
<tr>
<td>Type III (Harm)</td>
<td>Weissenau</td>
<td>Metric</td>
<td>0858:24</td>
<td>0900:42*</td>
<td>Intensity 3</td>
</tr>
<tr>
<td>Type IV</td>
<td>Weissenau</td>
<td>Metric</td>
<td>0900:24</td>
<td>0916:00*</td>
<td>Intensity 3</td>
</tr>
<tr>
<td>Energetic particles</td>
<td>ICE</td>
<td>$\Delta E &gt; 1$ MeV</td>
<td>0904</td>
<td>0930</td>
<td></td>
</tr>
<tr>
<td>Protons</td>
<td>GOES</td>
<td>$&gt;100$ MeV</td>
<td>0915</td>
<td>0935</td>
<td>280 protons cm$^{-2}$ s$^{-1}$ sr$^{-1}$</td>
</tr>
<tr>
<td>Neutron monitor</td>
<td>Goose Bay</td>
<td>GeV</td>
<td>0905</td>
<td>0914:30</td>
<td>98% above background</td>
</tr>
</tbody>
</table>

* End time of burst.

Details regarding the possible models of the X-ray source and their limitations will be the subject of a separate paper (McTiernan & Kane 1992).

2. GENERAL CHARACTERISTICS OF THE FLARE

The solar flare on 1984 February 16 (0900 UT) produced a variety of intense emissions characteristic of a major flare. Principal characteristics of the flare-associated emissions are summarized in Table 1. Absence of any optical brightening on the visible solar disk and the passing of the flare-producing active region 4408 over the west limb of the Sun on February 13 has placed the most probable location of the February 16 (0900 UT) flare at about 40° behind the west limb. The observational evidence strongly supports this deduced location of the flare (Kane & Urbarz 1986; Coffey 1987). For example, a weak impulsive microwave burst was observed with the onset at about 0858:30 UT and maximum at about 0859:18 UT. Figure 1 shows the instantaneous microwave spectrum observed by the Learmonth instrument at three different times near the burst maximum (based on Cliver, Gentile, & Wells 1987). It can be seen that the peak in the microwave spectrum occurred at an unusually low frequency ($<1$ GHz). This is consistent with the low-altitude part of the microwave source being occulted by the photosphere from the view from Earth.

Intense type III and type IV radio bursts were observed with onset at about 0858:24 UT, the type III bursts extending into the decimetric range. An intense type II radio burst with harmonic structure started at 0900:24 UT near the end of the type III bursts. The flare produced energetic particles with energies up to several GeV. The highest energy particles were detected by the ground-level neutron monitors beginning at about 0905 UT. Lower energy particles were detected by instruments aboard spacecraft such as ICE. Details of these and other observations can be found in the NOAA Solar Geophysical Activity Report on this flare (Coffey & Allen 1987).

3. X-RAY AND LOW-ENERGY GAMMA-RAY OBSERVATIONS

The observations reported here were made with the X-ray and low-energy gamma-ray spectrometers aboard the ICE (International Cometary Explorer, formerly ISEE 3) spacecraft, the gamma-ray burst detector on the PVO (Pioneer Venus Orbiter) spacecraft, and the soft X-ray detectors aboard NOAA's GOES satellite. Characteristics of the ICE and PVO instruments, their intercalibration, and procedures for fitting photon spectra to the observed count rates have been described earlier (Kane et al. 1982, 1988a, b). The ICE instrument covers the photon energy range 5 keV–3.2 MeV with two detectors, a proportional counter for 5–14 keV X-rays (six channels) and a NaI(Tl) scintillator for 26 keV–3.2 MeV.
The PVO instrument consists of two identical CsI(Na) scintillators, each covering 100 keV–2 MeV photons (four channels). Both ICE and PVO scintillators also monitor the flux of penetrating charged particles (one channel) detected by the plastic anticoincidence shield.

The averaging time for the real time data obtained with the two instruments depends on the spacecraft telemetry rate. At the time of the present observations, the time required for a complete spectral readout was 4 and 8 s for ICE and PVO, respectively. In 1984 the ICE spacecraft was in a heliocentric orbit on the way to rendezvous with the incoming comet Giacobini Zinner in 1985 September. The PVO spacecraft was orbiting Venus. The times of observations and the photon fluxes observed by ICE and PVO are normalized to Earth’s distance from the Sun.

The instrument aboard the geostationary satellite GOES has been described by Donnelly, Grubb, & Cowley (1977). The instrument consists of two simple ion chambers covering two broad X-ray wavelength bands 0.5–4 Å and 1–8 Å, respectively. The basic data averaging time is 3 s.

For a correlative analysis of the observations made with the three instruments, it was considered desirable that the averaging time for the three data sets be comparable. Therefore, unless stated otherwise, the data averaging times used for most of the analysis presented here are 8, 8, and 9 s for ICE, PVO, and GOES, respectively.

3.1. Locations of the Spacecraft Relative to the Flare

The 1984 February 16 (0912 UT) flare most probably occurred in the region AR4408 which rotated off the visible solar disk early on February 13. The February 16 flare was located about 40° behind the west limb of the Sun. The observational evidence strongly supports this deduced location of the flare (Kane & Urban 1986; Coffey & Allen 1987). The locations of the PVO, ICE, and GOES spacecraft at the time of the flare are shown in Figure 2. The flare was in full view of PVO which was located about 16° behind the west limb of the Sun. On the other hand the ICE and GOES spacecraft were located about 4° and 0° west of the Sun-Earth line, respectively. The view of these spacecraft was therefore partially occulted by the photosphere. The minimum height above which the flare source could be clearly observed by the ICE and GOES instruments was about $1.6 \times 10^5$ and $2.2 \times 10^5$ km, respectively. An uncertainty of 5° in the location of the flare corresponds to an uncertainty of $\sim 7 \times 10^4$ in the deduced occultation height.

3.2. Time-Rate Profiles

Figure 3 shows the time-rate profiles of the X-ray emission observed by the ICE, PVO, and GOES instruments. PVO recorded an intense burst of 100 keV–2 MeV photons beginning at about 0857:25 UT and lasting for more than 7 minutes. There were two broad maxima, a large maximum between 0857 and 0901 UT followed by a second much smaller maximum between 0901 and 0905 UT. We identify the impulsive phase of this flare with the first maximum. It can be clearly seen in all photon energy channels from soft X-rays to 2 MeV. The occurrence of impulsive microwave burst and metric type III radio bursts during the 0857–0901 UT supports the identification of that period as impulsive phase based on the hard...
X-ray observations (Kane 1974). The onset of an intense type II radio burst at 0900:24 UT suggests that the second maximum (at about 0902:30 UT) in the PVO hard X-ray time profile could be ascribed to a gradual hard X-ray burst associated with a second phase of particle acceleration in a flare. The time 0901 UT is therefore identified as the onset time of the gradual hard X-ray burst. It is important to note, however, that some of the distinctive characteristics of a gradual hard X-ray burst, such as a photon spectrum substantially harder than that for the impulsive hard X-ray burst, are not evident in this flare.

The energetic photon emission observed by PVO consisted of many fluctuations superposed on a gradually varying component. On the other hand, the hard X-ray emission observed by ICE is relatively smooth. Also, as discussed in detail later, the photon flux at ICE is weak, being about $10^{-3}$ times the expected flux. The soft X-ray flux observed by GOES is also very weak (NOAA class C) for a large flare indicated by the intense flux of high energy photons detected by PVO. Moreover, the soft X-ray emission is detectable only during the impulsive phase. The gradual soft X-ray emission, which usually develops a relatively large peak few minutes after the impulsive phase (and to which the NOAA classification usually refers to), is not detected by GOES in this flare.

Energetic solar particles escaping from the Sun began to arrive at the PVO, ICE, and GOES locations at about 0904:30 UT (see Fig. 4). The gradual increase in the counting rates of all the three instruments after 0904:30 UT is therefore mainly due to the increase in the detector background caused by the energetic solar particles escaping into the interplanetary space.

### 3.3. Rise and Decay Characteristics

In case of the PVO, the relatively broad maxima and frequent fluctuations in the count rates make it difficult to obtain unique parameters for the time variation. The analysis is further complicated by the fact that the valley (minimum) between the two maxima is not sufficiently deep so that the impulsive and gradual X-ray components contributing to the two maxima could be completely separated. This is particularly true of the 1–2 MeV photon channel where the second count rate maximum is barely detected. The apparently very slow decay of the impulsive component in the 500 keV–1 MeV and 1–2 MeV channels is probably caused by the increasing flux of the gradual component. The onset of the type II radio burst at 0900:24 UT also suggests the beginning of the second phase of particle acceleration (and gradual hard X-ray burst) before the end of the impulsive phase.

Unlike the PVO data, the ICE and GOES count rates show only a single well-defined maximum during the impulsive phase (Fig. 3). The rise and decay time characteristics of the ICE and GOES counting rates (Fig. 5) will therefore be empha-
3.3.1. Initial Rise of the Impulsive Emission

Figure 6 shows an expanded plot of the initial rising part of the ICE time-rate profile for 26–43 keV X-rays. The rates shown are the excess above the background rate. The onset time for PVO is also shown for reference. It can be seen that the observed onset for the ICE rates is delayed with respect to the onset for PVO by about 42 s. In order to determine if this apparent delay could be due to the smaller increase at ICE compared to that at PVO, a plot of the ICE rate multiplied by $10^3$ is also shown. Note that it is possible that the apparent delay is caused by the smaller increase in the counting rate at ICE compared to that at PVO.

3.3.2. Decay of the Impulsive Emission

A plot of the excess (above the background) count rates of the ICE and GOES X-ray channels during the flare has already been presented in Figure 5. The energy dependence of the $e$-folding decay times for the time interval 0900–0901 UT are shown as a function of X-ray energy $E$ in Figure 7. The decay time for both the soft and hard X-ray emissions decreases with increase in the photon energy $E$, being about 8 minutes for 1 keV X-rays, about 2.5 minutes for 5 keV X-rays, and about 1 minute for 60 keV X-rays. The general decrease in decay time with increase in X-ray energy is consistent with the decay characteristics of simple impulsive 10–100 keV X-ray bursts associated with flares on the disk (Kane & Anderson 1970). However, the decay time (minutes) observed in the present flare is much larger than that (seconds) for simple on-the-disk X-ray flares.

For the 100–500 keV photons detected by PVO, the decay time is about 25 s. The decay time for 1–2 MeV photons is about 75 s indicating a possible increase in the decay time with increase in photon energy. However, as discussed earlier, it is more likely that the slower decay at high photon energies is caused by the increase in the gradual hard X-ray component before a substantial decay of the impulsive component.

3.4. Photon Energy Spectra

Single or double power laws are often found to be consistent with the observed spectral shape of the hard X-ray emission in solar flares (cf. Kane & Anderson 1970; Kane, Frost, & Donnelly 1979). At energies < 10 keV, however, the X-ray spectrum from disk flares is often predominantly thermal.
The PVO instrument covers the 100 keV–2 MeV energy range in four relatively broad channels. The PVO observations were, therefore, fitted to a single power-law spectrum of the form

$$\frac{dJ}{dE} = KE^{-\gamma} \text{photons (cm}^2 \text{s keV)}^{-1} \quad (3.1)$$

Since the ICE instrument covers the 5 keV–3.2 MeV energy range in 18 channels, it was possible to investigate whether thermal or power-law spectra fitted the observations better. The ICE observations were, therefore, fitted to three different types of spectra: (1) double power-law, (2) thermal + power-law, and (3) double thermal.

The double power-law spectrum had the form

$$\frac{dJ}{dE} = \begin{cases} K_1 E^{-\gamma_1} & \text{for } E < E_b \\ K_2 E^{-\gamma_2} & \text{for } E > E_b \end{cases} \text{photons (cm}^2 \text{s keV)}^{-1} \quad (3.2)$$

where $K_1$, $\gamma_1$, $\gamma_2$, $E_b$ are free parameters and $K_2 = K_1 E_b^{\gamma_1}$.

In the case of the “thermal + power-law” spectral fit, thermal photon spectrum (Culhane & Acton 1970) corresponding to a temperature $T$ and emission measure $\xi_m = n_e^2 V$, where $n_e$ is the electron density in a volume $V$ occupied by the X-ray source, was added to a power-law photon spectrum $KE^{-\gamma}$. The break-point energy $E_b$ is defined as the photon energy for which the photon fluxes due to the power law and thermal spectra were equal. $\gamma$, $T$, $\xi_m$, and $E_b$ were treated as free parameters.

The “double thermal” spectral fit assumed two thermal spectra with temperatures and emission measures $T_1$, $\xi_{m1}$ and $T_2$, $\xi_{m2}$, respectively. The energy, at which the photon fluxes implied by the two spectra were equal, was defined as the break-point energy $E_b$. $T_1$, $T_2$, $\xi_{m1}$, and $E_b$ were treated as free parameters.

The estimated uncertainty in the spectral indices $\gamma_1$, $\gamma_2$, and $\gamma$ is about 0.1, 0.1, and 0.2, respectively. The uncertainty in the break-point energy $E_b$ is about 1 keV. The uncertainty in the temperatures $T_1$, $T_2$, and $T$ is estimated to be about $1 \times 10^6$ K.

3.4.1. Impulsive Phase

Figure 8 shows the average photon energy spectra observed by ICE and PVO during the principal part of the impulsive phase (0857–0901 UT). Although the ICE count rates averaged over 8 s (Fig. 3) do not show a maximum in the >78 keV X-ray channels, the 232 s average data near impulsive phase maximum show significant excess counts above the background in ICE channels up to 200 keV (Fig. 8). The observations are fitted to the three types of spectra described above. The ICE data are most consistent with a double power-law X-ray spectrum $\gamma_1 = 4.5$, $\gamma_2 = 3.8$, and $E_b = 10$ keV. For PVO, the spectral index $\gamma = 3.3$, which is harder by about 0.5 than the spectral index $\gamma_2$ for ICE at high energies. Thus, around 100 keV, the photon emission from the total source seems to have a harder spectrum than that from the partially occulted source. Also, for 100 keV X-rays, the flux observed by ICE is less than the flux observed by PVO by a factor of about 10^3.

In order to obtain an estimate of the low-energy (1–5 keV) part of the impulsive phase photon spectrum, we show in Figure 9 and Table 2 the photon fluxes measured by GOES and the double power-law fit for the ICE data. It should be pointed out that if GOES and ICE are observing X-ray sources partially occulted by the photosphere, the corresponding occultation heights above the photosphere are different for the two instruments: $1.6 \times 10^5$ km for ICE and $2.2 \times 10^5$ km for GOES.

Two types of spectra were fitted to the counting rates of the two channels of the GOES instrument, a thermal fit based on the computations by Thomas, Starr, & Crammel (1985) and a power-law fit based on the basic response of the GOES detectors (Donnelly et al. 1977). The power-law fit ($3.5 \times 10^6 E^{-0.5}$) is shown in Figure 9. It can be seen that the GOES observations at 2 keV are in very good agreement with the extrapolation of the ICE spectrum down to 2 keV. At 4 keV, however, the flux at GOES is less than the flux implied by ICE by a factor of about 3. In case of the thermal fit, the temperature and emission measure are found to be about $6 \times 10^6$ K and $6 \times 10^{47}$ cm^{-3}, respectively. The 4 keV X-ray flux deduced...
### Table 2

**Partially Occulted and Unocculted X-Ray Spectra:**

**1984 February 16 Flare**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Impulsive</th>
<th>Gradual</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time (UT)/average time (s)</td>
<td>0859:28/232</td>
<td>0902:22/128</td>
</tr>
<tr>
<td>Unocculted X-rays (PVO):</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Occultation height $h_{\text{occ}}$ (km)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Energy range $E_{\text{min}}$-$E_{\text{max}}$ (keV)</td>
<td>100–2000</td>
<td>100–2000</td>
</tr>
<tr>
<td>Power-law spectrum:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\gamma$</td>
<td>3.3</td>
<td>3.1</td>
</tr>
<tr>
<td>$K$</td>
<td>$1.2 \times 10^7$</td>
<td>$1.6 \times 10^6$</td>
</tr>
<tr>
<td>Partially occulted hard X-rays (ICE):</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Occultation height $h_{\text{occ}}$ (km)</td>
<td>$1.6 \times 10^2$</td>
<td>$1.6 \times 10^3$</td>
</tr>
<tr>
<td>Energy range $E_{\text{min}}$-$E_{\text{max}}$ (keV)</td>
<td>5–200</td>
<td>5–200</td>
</tr>
<tr>
<td>Double power-law spectrum:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\gamma_1$</td>
<td>4.5</td>
<td>53</td>
</tr>
<tr>
<td>$K_1$</td>
<td>$7.2 \times 10^5$</td>
<td>$1.7 \times 10^6$</td>
</tr>
<tr>
<td>$\gamma_2$</td>
<td>3.8</td>
<td>2.6</td>
</tr>
<tr>
<td>$K_2$</td>
<td>$1.3 \times 10^4$</td>
<td>$4.7 \times 10^2$</td>
</tr>
<tr>
<td>$E_b$ (keV)</td>
<td>10.2</td>
<td>19.9</td>
</tr>
<tr>
<td>Partially occulted soft X-rays (GOES):</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Occultation height $h_{\text{occ}}$ (km)</td>
<td>$2.1 \times 10^3$</td>
<td>$2.1 \times 10^3$</td>
</tr>
<tr>
<td>Energy range $E_{\text{min}}$-$E_{\text{max}}$ (keV)</td>
<td>1–5</td>
<td>1–5</td>
</tr>
<tr>
<td>Power-law spectrum:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\gamma$</td>
<td>6.5</td>
<td>7.4</td>
</tr>
<tr>
<td>$K$</td>
<td>$3.5 \times 10^6$</td>
<td>$5.9 \times 10^6$</td>
</tr>
<tr>
<td>Thermal spectrum:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$T$ (K)</td>
<td>$6.3 \times 10^6$</td>
<td>$4.9 \times 10^6$</td>
</tr>
<tr>
<td>$\epsilon_{\text{eq}}$ (cm$^{-3}$)</td>
<td>$5.6 \times 10^{17}$</td>
<td>$1.1 \times 10^{17}$</td>
</tr>
</tbody>
</table>

From GOES is found to be less than the extrapolated ICE spectrum by a factor of about 6. Thus the agreement between GOES and ICE is somewhat better with a power-law spectral fit for GOES than with a thermal fit.

#### 3.4.2. Gradual Hard X-Ray Burst

Figure 10 shows the average photon energy spectrum observed by ICE and PVO during the principal part of the gradual hard X-ray burst (0901–0903 UT). Again, a single power-law spectrum has been fitted to the PVO observations and three different types of spectra have been fitted to the ICE observations. The double power law gives the best fit to the X-ray spectrum observed by ICE with $\gamma_1 = 5.3$, $\gamma_2 = 2.6$, and $E_b = 20$ keV. For PVO, the spectral index $\gamma = 3.1$, which is softer by about 0.5 than the spectral index $\gamma_2$ for ICE at high energies. Thus, around 100 keV, the photon spectrum from the total source is softer than that from the partially occulted source. Moreover, at 100 keV, the photon flux at ICE is smaller than the flux at PVO by a factor of about 200.
In Figure 11 the GOES observations are compared with the double power-law fit to the ICE data shown in Figure 9. As in the case of the impulsive phase, both power-law and thermal spectra were fitted to the GOES data. The power-law fit \( (5.9 \times 10^6 E^{-7.4}) \) is shown in Figure 11. It can be seen that the 2 keV X-ray flux deduced from GOES is in good agreement with the ICE spectrum extrapolated to 2 keV. However, at 4 keV, the flux observed by GOES is less than that implied by ICE by a factor of about 4. The thermal fit gives \( T = 5 \times 10^6 \text{ K} \) and \( \xi_m = 1 \times 10^{47} \text{ cm}^{-3} \). The corresponding 4 keV X-ray flux at GOES is less than that implied by ICE by a factor of 10.

### 3.4.3. Comparison of the Impulsive and Gradual Hard X-Ray Bursts

The shape of the average photon energy spectra observed by ICE and PVO in the impulsive and gradual hard X-ray bursts are basically similar. Both are consistent with double power law for ICE and single power law for PVO. However, a detailed comparison shows that there are several major differences:

1. Whereas the ratio of PVO flux to ICE flux at 100 keV is about 10\(^3\) in the impulsive burst, the corresponding ratio in the gradual burst is \( \geq 10^4 \).
2. Whereas the ICE spectrum around 100 keV is softer than the PVO spectrum during the impulsive burst, the corresponding ICE spectrum is harder than the PVO spectrum during the gradual burst.
3. Since the GOES instrument has only two rather wide energy channels, it is not possible to determine which of the two spectral types, power-law or thermal, fit the GOES observations better. When compared with ICE observations, the power-law fit seems to give better agreement between the two sets of measurements in both impulsive and gradual bursts.
4. The 2 keV X-ray flux, deduced from the power-law fit to the GOES observations in the impulsive and gradual bursts, is in good agreement with an extrapolation of the corresponding ICE spectrum down to 2 keV. However, at 4 keV, the flux deduced from GOES is less than the extrapolated ICE spectrum by a factor of 3–4.

### 3.4.4. Detailed Time Variation of the Photon Spectrum

Figure 12 presents some details of the time variation of the photon spectra observed by the ICE and GOES instruments. The indices \( \gamma_1 \) and \( \gamma_2 \) for the double power-law fit to the ICE data and the temperature \( T \) and emission measure \( \xi_m \) obtained from a thermal fit to the GOES data are shown as a function of time. Excess rate of the 26–43 keV X-ray channel on ICE is also shown for comparison. All the parameters are based on data averaged over 16 s for ICE and 15 s for GOES. Note that the scale for the spectral exponents is reversed, i.e., the value of the exponent decreases as the data point moves toward increasing Y-axis. This was done for ease in comparing with the variation in temperature which increased as the data point moves toward increasing Y-axis.

From Figure 12 it can be seen that the temporal evolution of the photon spectrum for X-rays \( \geq 20 \text{ keV} \) was completely opposite to that for photons \( < 10 \text{ keV} \). The spectral hardness \( (\gamma_1) \) of 6–10 keV photons and the temperature \( T \) deduced...
from 0.5–8 Å X-rays reached their maxima respectively about 30 and 40 s after the maximum of 26–43 keV channel count rate. After the maximum, both parameters decreased with increasing time, the spectral hardness decreasing more rapidly than the temperature. On the other hand, the spectral hardness $(-\gamma)$ for photons >20 keV decreased from the burst onset, reaching its minimum about 40 s after the burst maximum, and then increased systematically as the X-ray flux decreased. Variation in the emission measure was relatively small. It reached a broad minimum around the time of the temperature maximum and then gradually increased during the decay of the burst.

It is important to note that the ICE and GOES spectra presented in Figure 12 show, in general, the development of a single burst well correlated with the impulsive phase. Gradual hardening with time of the >20 keV spectrum during the decay of the burst is the only indication that a gradual hard X-ray burst may be in progress.

4. SUMMARY OF OBSERVATIONS

The time-rate profiles and photon spectra recorded by PVO, ICE, and GOES have provided vital information about the sources of three distinct types of X-ray emissions in solar flares, viz., impulsive hard X-ray emission, gradual hard X-ray emission, and gradual soft X-ray emission. In addition, these observations have provided important parameters for the impulsive soft X-ray emission about which very little is known at the present time. The principal findings are as follows:

1. In contrast to the large intensity of the energetic photon burst recorded by PVO, the bursts recorded by ICE and GOES are very weak. At the ICE the emission could be clearly observed only at X-ray energies <200 keV. The soft X-ray (0.5–8 Å) burst recorded by GOES is only of NOAA class C compared to a burst of class X expected from such an energetic flare.

2. The impulsive phase X-ray emission was observed by all the three instruments. There is an apparent delay in the onset of the burst at ICE and GOES compared to the onset at PVO. However, this apparent delay could have been caused by the fact that the early part of the X-ray burst, as observed from the locations of ICE and GOES, was not intense enough to be detected by these two instruments.

3. The time-rate profiles of ICE and GOES are relatively smooth. This is particularly significant for ICE measurements of X-rays >25 keV which usually show substantial intensity structure in the X-ray flux from impulsive flares on the solar disk.

4. During the impulsive phase, the decay time for the X-ray emission observed by GOES and ICE decreases with increase in photon energy, being ~8, 2.5, and 1 minutes for 2, 5, and 60 keV X-rays, respectively. For the 150, 250, 750, and 1500 keV photons detected by PVO, the decay time is ~25, 28, 35, and 75 s, respectively, indicating a possible increase in the decay time with increase in photon energy. However, it is possible that the slower decay at high photon energies is caused by the increase in the gradual hard X-ray component before a substantial decay of the impulsive component.

5. A large gradual soft X-ray burst, which is often associated with a hard X-ray/gamma-ray flare of this magnitude, was not even detectable with the GOES instrument.

6. For 100 keV photons, the flux at ICE is smaller than the flux at PVO by a factor of about $10^3$ during the impulsive hard X-ray burst and by a factor of about $10^2$ during the gradual hard X-ray burst.

7. The 5–200 keV photon spectrum at ICE is consistent with a double power law during the impulsive as well as gradual hard X-ray bursts. The PVO spectrum is consistent with a single power law during both bursts.

8. Whereas the ICE spectrum around 100 keV is softer than the PVO spectrum during the impulsive hard X-ray burst, the corresponding ICE spectrum is harder than the PVO spectrum during the gradual hard X-ray burst.

9. The 2 keV X-ray flux, deduced from the power-law fit to the GOES observations in the impulsive and gradual hard X-ray bursts, is in good agreement with an extrapolation of the corresponding ICE spectrum down to 2 keV. However, at 4 keV, the flux deduced from GOES is less than the extrapolated ICE spectrum by a factor of 3 to 4.

5. HEIGHT DEPENDENCE OF THE X-RAY SOURCE BRIGHTNESS

The observed partial occultation of the three types of X-ray sources in the 1989 February 16 flare has provided new information about the height dependence of the brightness of these sources:

5.1. Impulsive Hard X-Ray Source

The impulsive hard X-ray source in this flare extended to height $\approx 1.6 \times 10^4$ km above the photosphere, the brightness at these heights being $\sim 10^{-3}$ of the total brightness of the source. The intense part of the source was occulted from the view of ICE. This is consistent with the height dependence deduced earlier from the stereoscopic observations of several partially occulted flares (Kane et al. 1982; Kane 1987).

5.2. Gradual Hard X-Ray Source

Gradual hard X-ray emission detected by the ICE instrument was very weak. The ICE observations are consistent with detection of no significant gradual hard X-ray emission. Hence the effective height of the intense part of the gradual hard X-ray source in this flare was $< 1.6 \times 10^4$ km above the photosphere. This is consistent with the height $4 \times 10^4$ km of the gradual hard X-ray source in the 1981 May 13 flare observed by the Hard X-Ray Telescope on Hinotori (Tsuneta et al. 1984).

5.3. Impulsive Soft X-Ray Source

The source of impulsive soft X-ray emission in this flare was also found to extend to heights $\approx 2 \times 10^4$ km above the photosphere. Since PVO and/or ICE instruments did not measure the X-ray spectrum down to 2 keV, it is not possible to determine how much (if any) of the impulsive soft X-ray source was occulted from the view of the GOES instrument. In view of the very small increase in the observed soft X-ray flux, it seems very likely that the effective height of the intense part of the impulsive soft X-ray source was $< 2 \times 10^4$ km.

5.4. Gradual Soft X-Ray Source

The gradual soft X-ray source was completely occulted from the view of GOES. The gradual soft X-ray source was, therefore, located at heights $< 2 \times 10^3$ km above the photosphere. This is consistent with the stereoscopic observations of the partially occulted flare on 1978 October 5 where the gradual soft X-ray source was found to be located at heights $< 2.5 \times 10^3$ km above the photosphere (Kane 1987).

6. ORIGIN OF THE WEAK IMPULSIVE X-RAY EMISSION

Identification of the origin of the weak impulsive X-ray emission detected by ICE and GOES depends on assumptions.
regarding the large-scale magnetic field structure in the vicinity of the flare and its relationship to the electron acceleration/injection region. We consider below three basic explanations of this X-ray source: (1) coronal part of the primary X-ray source, (2) behind-the-limb secondary X-ray source, and (3) on-the-disk secondary X-ray source.

If the magnetic field structure is assumed to be relatively compact except for the essentially open field lines along which accelerated electrons are injected, the X-ray source will extend from the chromosphere to the high corona. The impulsive emission observed by ICE and GOES can then be attributed to the coronal part of the primary impulsive X-ray source. Such an interpretation is consistent with the observations of intense type III radio bursts simultaneously with the impulsive X-ray and microwave bursts. The type III radio bursts are excited by energetic electrons escaping through the corona.

An explanation in terms of an extended primary X-ray source could be valid also if the accelerated electrons are injected into a large closed magnetic loop oriented in the north-south direction. In this case, impulsive X-rays will be emitted by most of the loop, the X-ray brightness decreasing with height above the chromosphere. Because of the north-south orientation of the loop, the lower part of the X-ray source will be occulted from the view of ICE and GOES.

As the X-rays emitted by the primary X-ray source pass outward through the corona, they will undergo scattering. Those photons which are scattered above the occultation height and move in appropriate direction (toward Earth) will be detected by ICE and GOES. Calculations show that the brightness of the scattering source relative to the primary source will be about $10^{-8}$, which is much smaller than the relative brightness of the observed source ($10^{-2}$).

If the magnetic field in the flare region were connected to a distant region on the visible disk through a giant east-west magnetic arch of length $>0.75$ solar radii, some (if not many) of the accelerated electrons would conceivably propagate along such a magnetic arch and produce a secondary X-ray flare at the distant footpoint. Such a large magnetic arch has been invoked in the past to explain long lasting soft X-ray emission sources in the corona (Svestka et al. 1982). A smaller arch has been assumed in the explanation of weak gamma-ray emission from a behind-the-limb flare (Forrest & Vestrand 1991).

If the magnetic arch (very large magnetic loop) is symmetric and the primary X-ray source is located at the footpoint $F_p$, behind the limb, the footpoint $F_{p2}$ on the disk will give rise to a second X-ray source on the disk nearly equal in brightness to the primary source. This has not been observed.

If the magnetic arch is asymmetric so that most electrons mirror back toward the footpoint $F_{p1}$, only a small fraction would precipitate toward the footpoint $F_{p2}$. The X-ray emission from the secondary source at $F_{p2}$ would therefore be much weaker than that from the primary source at $F_{p1}$. The energetic electrons responsible for the second X-ray flare at $F_{p2}$ are also expected to give rise to an Hz flare and normal ($I_{\text{max}} \sim 10$ Ghz) impulsive microwave burst consistent with the on-the-disk (observed) impulsive hard X-ray burst. Neither an Hz flare nor a microwave burst has been reported.

If the magnetic arch is symmetric but not well connected to the region of electron acceleration, very few of the energetic electrons are injected into the arch. The secondary X-ray sources at both footpoints of the arch are therefore weak. The intense primary X-ray source is independent of the arch and may consist of compact X-ray sources at the footpoints of a small magnetic loop located behind the limb. The secondary X-ray burst is expected to be accompanied by an Hz flare and normal microwave burst. None have been reported.

Injection of electrons into the large arch may result from an across-the-field drift of the electrons from the small primary loop to the arch. This could result in a delay of the onset of the X-ray emission from the arch compared to that from the primary loop. A delay has been observed, although it could be also attributed to the limited sensitivity of the instruments.

The assumption of a large magnetic arch, either symmetric or asymmetric, requires a very special geometry for the magnetic field and the electron injection process. In addition, other conditions must also be satisfied. For example, the ambient conditions near the on-the-disk footpoint $F_{p2}$ and its location are required to be such that observed X-rays will be produced without any significant Hz or microwave emission that could be detected from Earth.

In addition to the acceleration of particles in the vicinity of the flare region, particles in locations away from the flare may also be accelerated by the shock and/or other disturbances associated with the flare. Such an “acceleration at a distance” is in fact sometimes invoked to explain the prompt arrival of solar flare particles at Earth from flares located far away from the optimum flare location (~60° west) for rapid transit of accelerated particles to Earth along the spiral interplanetary magnetic field lines connecting the Sun to Earth.

It may be argued, for example, that the impulsive hard X-ray source observed by the ICE instrument was produced by electrons accelerated near or in front of the solar limb by a shock propagating outward from the flare. The X-ray emission from such a secondary source will be delayed with respect to the primary impulsive X-ray emission, the total delay being determined by two factors: (1) time interval (~1 minute) between the onset of the impulsive phase and the onset of the shock (indicated by the onset of the type II radio burst); and (2) transit time (~10 minutes) required for the shock, travelling at a speed of $\sim 10^7$ km s$^{-1}$, to reach the secondary X-ray source region. The observed delay of $\sim 42$ s is much smaller than either of these two time delays. It is, therefore, unlikely that the X-ray emission observed by ICE was produced near or in front of the solar limb by energetic electrons resulting from “acceleration at a distance.”

In the following discussion we assume that the source of the impulsive X-ray emission observed by the ICE and GOES instruments was located behind the west limb in the corona above the flare. We identify the observed X-ray source to be the coronal part of the primary X-ray source.

7. MODELS OF IMPULSIVE HARD-RAY SOURCES

Stereoscopic observations of hard X-ray sources at heights $>3 \times 10^4$ km have shown in the past (Kane et al. 1982; Kane 1983; Brown et al. 1983) that in impulsive solar flares the hard X-ray source extends from the chromosphere to the low corona, the brightness of the source decreasing with increase in altitude. The present observations show that this property of the impulsive hard X-ray sources continues to hold even in the high corona at heights $h \sim 2 \times 10^5$ km. Moreover, the low-energy part (2–10 keV) of the impulsive X-ray spectrum, which is often not observable in on-the-disk flares because of the relatively intense simultaneous thermal emission from the gradual soft X-ray source, has been observed in the high
corona and is found to be consistent with the extrapolation of the non-thermal spectrum.

The gradual hard X-ray source and the thermal (gradual) soft X-ray source could not be detected presumably because they were confined to altitudes <2 x 10^5 km. These observational results for the thermal (gradual) soft X-ray source are in agreement with similar stereoscopic observations of the behind-the-limb flare on 1978 October 5 for which the occultation height was much lower (2.5 x 10^4 km) (Kane 1983). The photon spectra in the two events were very similar. A gradual soft X-ray source located at heights <2.5 x 10^4 km is therefore consistent with the observations of both the flares.

7.1. Simple Thick Target Model

In the simple thick target model (Arnoldy, Kane, & Winckler 1968; Brown 1972; Hudson 1972) energetic electrons accelerated in the corona propagate downward toward the photosphere and produce X-rays through thick target bremsstrahlung. The height distribution of the hard X-ray emission from a nonrelativistic electron beam moving vertically (radially) and having a single power law spectrum (AE^2 electron s^{-1}keV^{-1}) has been computed by Brown & McClymont (1975). The bremsstrahlung emission is assumed to be isotropic. The ICE/ISEE 3 hard X-ray observations indicate that the electron injection spectrum is more complex and is probably more like a double power law of the form

\[ F(E_e) = \begin{cases} A_1 E_e^{-\delta_1} & \text{for } E_e \leq E_{eb} \\ A_2 E_e^{-\delta_2} & \text{for } E_e \geq E_{eb} \end{cases} \quad (7.1) \]

where \( A_1, \delta_1, \delta_2, E_{eb} \) are spectral parameters and \( A_2 = A_1 E_{eb}^{\delta_2 - \delta_1} \).

There are two important characteristics of the simple thick target model, with isotropic electron distribution everywhere:

1. The X-ray source has no directivity. This seems to be consistent with the stereoscopic observations of 100 keV-1 MeV flares with view angles between 0° and 65° (Kane et al. 1988a), but not consistent with the center-to-limb variation of the occurrence frequency of flares with significant photon emission at energies >300 keV and >10 MeV (Vestrand et al. 1987; Rieger et al. 1984).

2. Also, there is essentially a one-to-one correlation between the emissions from the chromospheric and coronal X-ray sources. It cannot, therefore, explain the relatively smooth time-intensity profile for the coronal source while the chromospheric source seems to have considerable temporal structure.

7.2. Partial Precipitation Model

It seems unlikely that all the accelerated electrons promptly precipitate into the chromosphere. Some of the energetic electrons may be confined to the corona for a short but significant time interval. The partial precipitation model (Kane 1974; Melrose & Brown 1976), which is a modified thick target model, takes this possibility into account. In the generic model of this type, energetic electrons are injected into a magnetic trap in a low-density region (corona). Depending on the initial pitch angle distribution and scattering processes, some of the electrons escape from the trap and precipitate into the chromosphere. The resulting thick target bremsstrahlung emission is, in general, anisotropic. The transport of electrons from the injection region to the thick target X-ray source has been studied by several workers (Bai & Ramaty 1978; Petrosian 1985; Langer & Petrosian 1977; Vilmer, Kane, & Trotter 1982). Recently McTiernan & Petrosian (1990a, b) have performed extensive calculations in the X-ray emission from a magnetic loop in which energetic electrons are injected continuously. McTiernan, Kane, & Loran (1991) have examined that model to determine if it can explain the stereoscopic hard X-ray observations of the 1984 February 16 flare. We present below some of the findings from these calculations. A more general discussion of the stereoscopic observations of partially occulted flares and their implications regarding models of hard X-ray sources in solar flares will be presented in a separate paper (McTiernan & Kane 1992).

The basic model consists of a “thin” semicircular magnetic loop with a cross-sectional diameter much smaller than the length of the loop. The loop extends from the photosphere to the corona. For a point \( P \) located at a height \( h \) above the photosphere, let \( s(h) \) be the distance of \( P \) along the loop measured from the top of the loop (\( s = 0 \)). The column depth \( N(s) \) of \( P \) is given by

\[ N(s) = \int n(s)ds \quad (7.2) \]

where \( n(s) \) is the ambient ion density at \( s \).

The magnetic field inside the loop is assumed to be due to a dipole. Convergence of the field is characterized by the mirror ratio \( b \) given by

\[ b = B_{max}/B_0 \quad (7.3) \]

where \( B_0 \) and \( B_{max} \) are the field strengths at the top of the loop and in the transition region, respectively.

Let energetic electrons with a power-law spectrum (~\( E^{-\delta} \)) and Gaussian pitch angle distribution [\( -\exp(-x^2/\alpha_0^2) \)] be injected at the top of the loop. Here \( E_0, \alpha, \text{ and } \alpha_0 \) are the initial electron kinetic energy, pitch angle, and FWHM of the pitch angle distribution respectively. The electron distribution \( F_0 \) at the top of the loop is given by

\[ F_0(E_0, \alpha) = AE_0^{-\delta} \exp(-x^2/\alpha_0^2) \quad \text{electrons s}^{-1} \text{keV}^{-1} \text{rad}^{-1}. \quad (7.4) \]

As the electrons propagate to lower altitudes (\( s > 0 \)), they undergo an increasing number of collisions with ions. The resulting energy loss, scattering and mirroring modify their distribution to \( F(E_0, \alpha, F_0) \) which depends on the distance \( s \) from the top of the loop, the initial distribution given by equation (7.4), and the mirror ratio \( b \) given by equation (7.3). The energetic electrons produce bremsstrahlung X-rays throughout the loop, the brightness and directivity of the X-ray source varying with the position along the loop. The best-fitting parameters are obtained by applying the model to observations and minimizing \( \chi^2 \). The best-fit parameters for the hard X-ray source model are determined by minimizing \( \chi^2 \) given by

\[ \chi^2 = \Sigma \{ [j_{\text{obs}}(E_i) - j_{\text{model}}(E_i)]^2 / \sigma_i^2 \}, \quad (7.5) \]

where \( j_{\text{obs}}(E_i) \) and \( j_{\text{model}}(E_i) \) are, respectively, the observed and predicted photon fluxes for the X-ray energy channel \( i \) with effective energy \( E_i \), and \( \sigma_i \) is the uncertainty in the observed flux. The procedure adopted is as follows. Since a converging magnetic geometry counters, to some extent, the beaming of electrons, we start by choosing \( \alpha_0^2 \) and \( b \). For each choice of \( (\alpha_0^2, b) \), the electron spectrum parameters (\( \delta, A \)) are deduced by minimizing \( \chi^2_{\text{model}} \) for the unocculted X-ray spectrum predicted by the model and the spectrum observed by the unocculted
spacecraft PVO. The X-ray spectrum of the partially occulted flare observed by ICE is then used to deduce the visible column depth \( N_{vis} \) that minimizes the \( \chi^2 \text{occ} \). The parameters deduced so far are then used as a starting point to minimize the sum \( [\chi^2 \text{unocc} + \chi^2 \text{occ}] \) of the \( \chi^2 \) for the two instruments.

The X-ray flux as observed by a spacecraft instrument depends on the visible column depth \( N_{vis} \), given by equation (7.2), and the four parameters of the loop model, viz., \( A, \delta, \sigma_0, \) and \( b \). In a two-spacecraft stereoscopic observation, where one spacecraft observes the whole (unocculted) X-ray flare and the other spacecraft observes only a part of the X-ray flare above a certain occultation height \( h_{occ} \), only four parameters can be observed, viz., the photon spectrum \( (KE^{-\gamma}) \) observed by the two instruments. Although the occultation height is known, the column depth is not measured because the height dependence of the ambient ion density is not known. It is therefore not possible to determine uniquely all the five parameters of the model X-ray source. The deduced electron spectrum also depends on whether the X-ray emission, especially at high energies, is assumed to be anisotropic or isotropic. The deduced best-fit parameters given below are therefore intended to be estimates suitable only for describing the basic morphology of the impulsive and gradual X-ray sources in solar flares.

8. ELECTRONS IN THE IMPULSIVE HARD X-RAY SOURCE

The results obtained from the partial precipitation model for the impulsive phase of the 1984 February 16 flare are summarized in Table 3. They are based on the observed hard X-ray spectra presented earlier in Figure 9 and Table 2. The cases of anisotropic and isotropic emission are considered separately.

### 8.1. Anisotropic X-Ray Source

For an assumed mirror ratio \( b = 2.5 \) and the injection of electrons at the top of the loop in a relatively narrow beam \( (\sigma_0^2 = 0.04) \), the best-fit double power-law spectrum (eq. [7.1]) is found to have the following parameters:

\[
\delta_1 = 4.0, \quad \delta_2 = 2.5, \quad A_1 = 4.0 \times 10^{39}, \quad A_2 = 5.6 \times 10^{37},
\]

\( E_{eb} = 21 \text{ keV} \).

The visible column depth for ICE is \( N_{vis} = 4.0 \times 10^{18} \text{ ions cm}^{-2} \). A comparison of the observed X-ray spectra with the bremsstrahlung X-ray spectra computed from the above best-fit parameters is shown in Figure 13. It can be seen that the computed X-ray spectra are in good agreement with the observations.

For electrons with energy \( E_e > 21 \text{ keV} \), the average rate of injection is \( 3.9 \times 10^{35} \text{ electrons s}^{-1} \), which corresponds to an average rate of injected energy \( 3.9 \times 10^{28} \text{ ergs s}^{-1} \) over a period of 232 s. For electrons with energy \( > 6 \text{ keV} \), the average injection rates are \( 6.4 \times 10^{36} \text{ electrons s}^{-1} \) and \( 1.2 \times 10^{29} \) ergs.

### TABLE 3

<table>
<thead>
<tr>
<th>Electron Energy (keV)</th>
<th>Anisotropic X-Ray Emission</th>
<th>Isotropic X-Ray Emission</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
<td>2-6</td>
<td>6-21</td>
</tr>
<tr>
<td>Power-law spectrum (electrons s(^{-1}) keV(^{-1}))</td>
<td>( \delta )</td>
<td>5.8</td>
</tr>
<tr>
<td>( A )</td>
<td>1.1E + 41</td>
<td>4.0E + 39</td>
</tr>
<tr>
<td>Number rate (electrons s(^{-1}))</td>
<td>8.2E + 38</td>
<td>6.0E + 36</td>
</tr>
<tr>
<td>Energy rate (ergs s(^{-1}))</td>
<td>3.3E + 30</td>
<td>8.2E + 28</td>
</tr>
<tr>
<td>Total number (electrons)</td>
<td>3.8E + 30</td>
<td>1.4E + 39</td>
</tr>
<tr>
<td>Total energy (ergs)</td>
<td>7.6E + 32</td>
<td>1.9E + 31</td>
</tr>
<tr>
<td>Relevant spacecraft</td>
<td>GOES</td>
<td>ICE</td>
</tr>
<tr>
<td>Column depth (ions cm(^{-2}))</td>
<td>5.0E + 17</td>
<td>4.0E + 18</td>
</tr>
</tbody>
</table>

* Electron injection at the top of a magnetic loop (see text for details).
* Isotropic electron distribution at all heights; segmented electron spectra shown as examples (see text for details).
In the soft X-ray source without causing a large increase in its temperature and the consequent thermal X-ray emission, thus violating the assumption of a cold ambient plasma.

It should be pointed out that the "segmented" electron spectra (Table 3) computed from the isotropic model do not match exactly at the common edge (200 keV) of the two higher energy intervals. This could be an indication of either the inadequacy of the isotropic model to explain the observations or the uncertainties in the simplified simulation of an isotropic X-ray source. Since a self-consistent nonthermal model of the isotropic X-ray source is not available at the present time, it is not possible to rule out completely the isotropic model.


As stated earlier, the GOES observations cover the soft X-ray range in only two broad wavelength bands. It is therefore not possible to determine whether the observed impulsive emission is thermal or nonthermal. Hence, we will consider here both interpretations and their implications.

9.1. Nonthermal Model

In a nonthermal model, the ambient plasma is cold \((T < 2 \times 10^6 \, \text{K})\) so that thermal X-ray emission is negligible at energies \(\gtrsim 2 \, \text{keV}\). A power-law fit to the GOES observations (Fig. 9 and Table 2) indicates an X-ray spectrum much steeper \((\gamma = 6.5)\) than the spectrum observed by ICE above 5 keV. The corresponding injection spectrum for 2–6 keV electrons is given by \(1.1 \times 10^{14} E_{\text{e}}^{-5.8} \, \text{electrons s}^{-1} \text{keV}^{-1}\) and the column depth for the GOES occultation height is found to be \(5.0 \times 10^{17} \, \text{ions cm}^{-2}\) (Table 3). A comparison of the computed and observed X-ray fluxes is shown in Figure 13.

The rates of injection for the number and energy of \(\gtrsim 2 \, \text{keV}\) electrons due to this additional electron component are \(8.2 \times 10^{38} \, \text{electrons s}^{-1}\) and \(3.3 \times 10^{39} \, \text{ergs s}^{-1}\), respectively. The total number of injected electrons is \(1.9 \times 10^{41}\) and the total energy deposited is \(7.6 \times 10^{32} \, \text{ergs}\). As we find in the next section, it is difficult to maintain this rate of energy dissipation in the soft X-ray source without causing a large increase in its temperature and the consequent thermal X-ray emission, thus violating the assumption of a cold ambient plasma.

9.2. Thermal Model

If the impulsive soft X-ray source is thermal, we find the temperature \(T \sim 6 \times 10^6 \, \text{K}\) and the emission measure \(\zeta_m = N_e n_i V = 6 \times 10^{47} \, \text{cm}^{-3}\) (Table 2). For an average density \(n_i = 8 \times 10^8 \, \text{cm}^{-3}\), the total number of hot electrons is \(N_e V \sim 10^{39}\). For \(N_e \lesssim n_i\) this gives the volume \(V \gtrsim 10^{30} \, \text{cm}^3\).

10. Size of the Impulsive X-ray Source in the Corona

10.1. X-Ray Source at Height \(\gtrsim 1.6 \times 10^5 \, \text{km}\)

For the 1984 February 16 flare, the occultation heights for the ICE and GOES spacecraft were \(1.6 \times 10^5\) and \(2.1 \times 10^5\) km, respectively. Thus the radial length of the region R visible to the ICE instrument (which includes the region visible to...
The cross-sectional area \( A_\text{c} \) of this thermal source can be deduced above for height \( >1.6 \times 10^5 \) km. The effective thermal conductivity \( K_\text{T} \) for hydrogen in the corona is given by (Spitzer 1956)

\[
K_\text{T} = \epsilon \delta_T K_L = 4.67 \times 10^{-12} \epsilon \delta_T T^{2.5} \ln \lambda^{-1} \text{cal (s deg cm)}^{-1} \text{ergs (s deg cm)}^{-1}
\]

where \( \epsilon = 0.4, \delta_T = 0.25, \) and \( \ln \lambda = 20. \) Thus \( K_\text{T} = 10^{-6} T^{2.5} \text{ergs (s deg cm)}^{-1} \) and

\[
Q_T = 10^{-6} A_\text{c} T^{2.5} \Delta T = 10^{-6} A_\text{c} T^{3.5} / L \text{ ergs s}^{-1}.
\]

Hence, if \( \eta(E) < \eta(E) \), we must have the cross-sectional area

\[
A_\text{c} > 10^6 L \eta(E) T^{-3.5} > 10^{-8} \eta(E) \text{cm}^2.
\]

A low-energy cutoff \( E_{\text{c}} \) = 2 keV implies \( \eta(>2 \text{ keV}) = 3.4 \times 10^3 \text{ ergs s}^{-1} \) and hence \( A_\text{c} > 3 \times 10^{22} \text{ cm}^2 \), an area larger than the visible solar disk! Therefore the X-ray source is unlikely to be nonthermal for X-rays down to 2 keV. However, if the low-energy cutoff is \( E_{\text{c}} = 6 \text{ keV} \), we find \( \eta(>6 \text{ keV}) = 1.2 \times 10^9 \text{ ergs s}^{-1} \) and hence \( A_\text{c} > 10^{21} \text{ cm}^2 \) which is large but plausible. Thus, a source which is nonthermal for X-rays > 5 keV and thermal for X-rays < 5 keV is consistent with the observations. The volume of the nonthermal source is given by \( V = A_\text{c} L \approx 5 \times 10^{30} \text{ cm}^3 \).

10.2. X-Ray Source at Height \( >2.1 \times 10^5 \) km

As discussed above, the impulsive soft X-ray (1–5 keV) source in the corona is probably thermal with temperature \( T = 6 \times 10^8 \text{ K} \) and emission measure \( \xi_{\text{em}} = 6 \times 10^{52} \text{ cm}^{-3} \). The cross-sectional area \( A_\text{c} \) of this thermal source can be deduced from the emission measure \( \xi_{\text{em}} \), ambient density \( n_\text{a} \), and visible column depth \( N_{\text{vis}} \) obtained for GOES:

\[
\xi_{\text{em}} / N_{\text{vis}} = n_{\text{a}}^2 V / n_\text{a} L = n_\text{a} A_\text{c} \text{ ions cm}^{-2}
\]

(10.4)

or

\[
A_\text{c} = \xi_{\text{em}} / (n_{\text{a}}^2 n_\text{a}) \text{ cm}^2.
\]

(10.5)

For GOES observations, \( N_{\text{vis}} = 5.0 \times 10^{17} \text{ ions cm}^{-2} \) (Table 2) and the average ion density is expected to be less than that deduced above for height \( >1.6 \times 10^5 \text{ km} \), i.e., \( n_\text{a} < n_\text{a}(\text{ICE}) < 8 \times 10^8 \text{ cm}^{-3} \). Hence we get the cross-sectional area \( A_\text{c} > 1.5 \times 10^{21} \text{ cm}^2 \) and volume \( V = \xi_{\text{em}} / n_\text{a}^2 > 10^{30} \text{ cm}^3 \).

11. Electrons in the Gradual Hard X-Ray Source

In Table 4 we summarize the characteristics of the energetic electrons injected during the gradual hard X-ray burst. These characteristics are based on the photon spectra presented earlier in Table 2. Electron spectra have been computed for both anisotropic and isotropic X-ray emission models.

11.1. Anisotropic X-Ray Source

The basic procedure used to deduce the electron spectrum is the same as the one used for the impulsive phase (Table 3). The anisotropic emission model assumes the mirror ratio for the magnetic field to be \( b = 2.5 \) and the injection of accelerated electrons to be at the top of the loop in a narrow beam (\( \alpha_0 = 0.4 \)). For electrons with energy > 10 keV, the best-fit double power-law spectrum (eq. [2]) is found to have the following parameters:

\[
\delta_1 = 5.3, \quad \delta_2 = 2.4, \quad A_1 = 5.6 \times 10^{40}, \quad A_2 = 5.6 \times 10^{36}, \quad E_{\text{ob}} = 24 \text{ keV}.
\]

A single power law for the 2–10 keV electron spectrum is given by \( 3.2 \times 10^{41} E^{-0.6} \text{ electrons s}^{-1} \text{ keV}^{-1} \). The visible column depth for ICE and GOES is \( N_{\text{vis}} = 4.0 \times 10^{18} \) and \( 1.3 \times 10^{16} \) ions cm\(^{-2} \), respectively.

11.2. Isotropic X-Ray Source

The electron spectrum for the isotropic X-ray emission model has been deduced as in the case of the impulsive phase (Table 3). The results are presented in Table 4. The nonthermal (power-law) electron spectrum is segmented in four energy intervals, viz., 2–8, 8–50, 50–200, and > 200 keV. The number and energy requirements for > 200 keV electrons are, in general, smaller for the isotropic model than those for the anisotropic model. In the soft X-ray region, thermal spectrum has been fitted to the GOES observations. The temperature and emission measure are obtained by \( T = 4.9 \times 10^8 \text{ K} \) and \( \xi_{\text{em}} = 1.1 \times 10^{34} \text{ cm}^{-3} \) (Table 2). The temperatures for the times of the impulsive and gradual hard X-ray bursts are comparable. However, the emission measure for the gradual burst is smaller than that for the impulsive burst by about a factor of 5.

11.3. Limitations of the Analysis

It is important to note that during the gradual hard X-ray burst recorded by VSO, the count rates of the ICE and GOES instruments continued to decrease as they did after the impulsive burst maximum. Thus there is no clear indication that the ICE and GOES instruments detected any X-ray emission associated with the gradual hard X-ray burst. Hence, either most of the gradual hard X-ray source was occulted by the photosphere from the viewpoint of ICE and GOES instruments or its brightness was very low for X-rays with energy < 100 keV. Since the gradual hard X-ray source in a flare is known to produce flux of 20–100 keV photons which is comparable to the flux during the impulsive phase (Frost & Dennis 1971; Hoyng, Brown, & Van Beek 1976; Vilmer et al. 1982), it is more likely that most of the brightest part of the gradual hard X-ray source in the 1984 February 16 flare was located below 1.6 \times 10^5 \text{ km}. It is, therefore, not possible to determine unambiguously the characteristics of the coronal part of the gradual hard X-ray source in this flare. Hence among the electron spectra presented in Table 4, only those based on the unocculted VSO observations \( (E > 200 \text{ keV}) \) can be considered as representative of a gradual hard X-ray burst.

12. Conclusions

The VSO, ICE, and GOES observations of the energetic flare on 1984 February 16 (0900 UT) have provided a unique opportunity to study the vertical structure of the impulsive and gradual hard X-ray sources and the characteristics of the

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### Table 4
Nonthermal Electrons—Gradual Phase—1984 February 16 Flare

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Anisotropic X-Ray Emission(^a)</th>
<th>Total</th>
<th>Isotropic X-Ray Emission(^b)</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2-10</td>
<td>10-24</td>
<td>&gt; 24</td>
<td>&gt; 2 keV</td>
</tr>
<tr>
<td>Power-law spectrum (electrons s(^{-1}) keV(^{-1})):&lt;br&gt;(\delta)</td>
<td>6.0</td>
<td>5.3</td>
<td>2.4</td>
<td>6.5</td>
</tr>
<tr>
<td></td>
<td>3.2E+41</td>
<td>5.6E+40</td>
<td>5.6E+36</td>
<td>2.0E+41</td>
</tr>
<tr>
<td>Number rate (electrons s(^{-1}))</td>
<td>2.0E+39</td>
<td>6.4E+35</td>
<td>4.7E+34</td>
<td>2.0E+39</td>
</tr>
<tr>
<td>Energy rate (ergs s(^{-1}))</td>
<td>8.0E+30</td>
<td>1.3E+28</td>
<td>6.3E+27</td>
<td>8.0E+30</td>
</tr>
<tr>
<td>Total number (electrons)</td>
<td>2.6E+41</td>
<td>8.2E+37</td>
<td>6.0E+36</td>
<td>2.6E+41</td>
</tr>
<tr>
<td>Total energy (ergs)</td>
<td>1.0E+33</td>
<td>1.6E+30</td>
<td>8.0E+29</td>
<td>1.0E+33</td>
</tr>
<tr>
<td>Relevant spacecraft</td>
<td>GOES</td>
<td>ICE</td>
<td>ICE</td>
<td>GOES</td>
</tr>
<tr>
<td>Column depth (ions cm(^{-2}))</td>
<td>1.3E+16</td>
<td>4.0E+18</td>
<td>4.0E+18</td>
<td>3.2E+18</td>
</tr>
</tbody>
</table>

\(^a\) Electron injection at the top of a magnetic loop (see text for details).

\(^b\) Isotropic electron distribution at all heights; segmented electron spectra shown as examples (see text for details).
impulsive soft X-ray emission. Although PVO could observe the entire flare X-ray source, the part of the X-ray source below the occultation heights of 1.6 \times 10^5 and 2 \times 10^5 km was not visible to ICE and GOES, respectively. The X-ray source observed by the ICE and GOES instruments could be either (1) the unocculted coronal part of the primary X-ray source associated with the flare, or (2) a secondary X-ray source (located on the visible solar disk) excited by some of the accelerated electrons propagating along a large (1 R_\odot) magnetic loop connecting the behind-the-limb flare to a region on the visible solar disk. Although neither of these two possibilities can be completely ruled out, the absence of any correlated optical brightening and/or a typical impulsive microwave burst on the visible solar disk suggests that only the primary X-ray source existed in this flare.

The average photon spectra observed by these three instruments during the impulsive and gradual hard X-ray bursts are summarized in Table 2. A comparison of these unocculted and partially occulted spectra shows the following.

1. The sources of the impulsive hard X-ray (>25 keV) and impulsive soft X-ray (2-5 keV) emissions in this flare extended to coronal altitudes \approx 2 \times 10^5 km above the photosphere.

2. At \approx 100 keV, the ratio of the coronal source brightness to the total source brightness was \approx 10^{-3} during the impulsive phase and \approx 10^{-2} during the gradual hard X-ray burst.

3. During the impulsive phase, the low-energy cutoff of the nonthermal electron spectrum seemed to be <5 keV, indicating that the total energy carried by these electrons was much larger than that normally estimated on the basis of most solar flare models.

4. The sources of the gradual hard X-ray burst and gradual soft X-ray burst were almost completely occulted indicating that these sources were located at heights <2 \times 10^5 km above the photosphere.

5. During the impulsive phase, the average rate of injection of electrons >5 keV was \approx 6 \times 10^{36} electrons s^{-1}, the total number injected being \approx 10^{39}. The rate of energy injection and the total injected energy were \approx 10^{39} ergs s^{-1} and \approx 10^{31} ergs, respectively.

6. The volume of the impulsive hard X-ray source in the corona is estimated to be \approx 10^{50} cm^3 with an average density \approx 10^9 ions cm^{-3}. Such a large volume suggests a large diffuse X-ray source in the corona covering several magnetic loops.

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