THE ULTRAVIOLET SPECTRUM OF A 3B CLASS FLARE OBSERVED WITH SOLSTICE

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ABSTRACT

An observation of the ultraviolet spectrum (1200–1800 Å) during the impulsive phase of a very extended 3B–X3 class solar flare on 1992 February 27 was obtained with the Solar-Stellar Irradiance Comparison Experiment (SOLSTICE). This observation is combined with ground-based Hz, magnetogram, and microwave data as well as hard X-ray measurements from the Ulysses spacecraft. This flare shows a dramatic enhancement of lines formed in the solar transition region. The irradiance (emitted flux density from the entire solar disk) of the resonance lines of C IV and Si IV increased by a factor of 12–13 during the impulsive phase of the flare. These irradiance enhancements are comparable with those measured during stellar flares. By taking into account the emitting flare area we infer that the irradiance (specific intensity) of the flaring plasma was at least a factor of 15,000 brighter than the average solar disk radiance just prior to the event. Assuming the flare site’s initial radiance was that of a typical active region, it then must have brightened by a factor of at least 3400. Such enhancement far exceeds previous published values (e.g., OSO 8, Skylab, and SMM) and indicates that many observations were affected by limited dynamic range. Thus, the SOLSTICE observation may be the first measurement of the true UV enhancement during the impulsive phase of very bright solar flares.

The Si iii multiplet near 1295 Å also shows remarkable enhancement, but other allowed lines of C ii, Si iii (1206 Å), N v, and He ii show more moderate enhancements, the weakest being H i Lyα, the irradiance of which increases only 6%. Some of the differences between the various enhancements are certainly caused by the timing of the observations since the scanning spectrometer observed different spectral features over periods of 4 minutes. Other differences due to line formation processes are being investigated but are consistent with density effects in the line emission coefficients. The inferred Lyα irradiance enhancement is consistent with current post–impulsive phase flare models. However, the formation of the C iv and Si iv lines, formed during the impulsive phase of the flare, remains unknown. During the impulsive phase of the flare the strong transition region lines are systematically redshifted by 50 km s⁻¹.

Subject headings: Sun: flares — Sun: transition region — Sun: UV radiation — Sun: X-rays, gamma rays

1. INTRODUCTION

The sudden energy release during solar flares is accompanied by photon emission over a wide range of the electromagnetic radiation spectrum. Flares have been extensively studied in hard X-rays (HXR), soft X-rays (SXR), ultraviolet, radio, and the visible region of the spectrum. Flare development is usually divided into three phases (some authors describe it with four phases, e.g., Somov 1991): (1) a preflare stage of gradual brightening usually lasting a few minutes; (2) an impulsive (flash) phase lasting less than 5 minutes; and (3) a main phase lasting for some tens of minutes when energy is radiated mainly in soft X-rays. The rate of energy release is often largest during the impulsive phase, where harder radiation is also observed. The impulsive phase of solar flares, as observed in the radio, HXR, extreme ultraviolet (EUV), and the ultraviolet (UV) region of the spectrum has been often reviewed (e.g., Kane et al. 1980 and Canfield et al. 1989). For more recent reviews of flare observations see Tsuneta (1993) and Antonucci (1994).

The impulsive phase is believed to correspond to sudden release of stored magnetic energy into various forms of plasma energy leading to accelerated particles, heating and bulk acceleration of plasma, and enhanced radiation fields. This phase is marked by the occurrence of short-lived bursts of radiation, that are most prominent at HXR, EUV, and some optical and radio wavelengths. The character of the processes occurring during the impulsive and gradual phases differ remarkably. The impulsive phase involves the sudden (in tens of seconds) rise and somewhat slower (in a few minutes) decay of the HXR emission, while the gradual phase shows a slower increase in soft X-rays that coincides with increases in Hz. Usually, the gradual phase peaks well after the impulsive phase has decayed, and may last even for an hour or more.

It has been observed that some UV line emissions, especially those formed in the transition region, track very well the rise and decay of the HXR. Also, it is common that the HXR curve shows several superimposed peaks during the decay of the impulsive phase. Many UV lines not only follow the trend of the HXR but also display corresponding
secondary peaks as well. However, some other emissions do not follow the rise of the impulsive phase, but instead behave as the gradual phase curve. This is the case for some UV lines that do not show the burst structure of the impulsive components (e.g., the Fe xxi coronal line at 1354 Å).

The processes leading to the enhancement of the various types of radiation during flares may be quite different. The hard X-rays are thought to be produced by electron beams that impact the underlying atmosphere. The soft X-rays are thought to originate from thermal electrons resulting from the collisional dissipation of the beam energy and are therefore a by-product of the original beams. In this context the rise of the soft X-rays would correspond to the integral of the hard X-rays emission. This effect is known as the Neupert effect and has been shown to be consistent with available data for most impulsive flares (Dennis & Zarro 1992). Because the UV transition region line emission correlates well with the HXR, the possibility arises that excitation of some lines may be caused by electron beam bombardment. However, as we will show below, this mechanism seems unlikely in our data. This poses an intriguing question on the origin of the large UV line enhancements that are observed during the impulsive phase.

In this work we present an observation of the ultraviolet spectrum (1200–1800 Å) during the impulsive phase of a very extended 3B-X3 class solar flare on 1992 February 27, obtained with the Solar-Stellar Irradiance Comparison Experiment (SOLSTICE). The full disk irradiance of the resonance lines of C iv and Si iv increased by a factor of 12–13 during the impulsive phase of the flare. The observed irradiance enhancement is comparable to those during stellar flares. By taking into account the emitting area, as determined from Hx data, we infer that the radiance (i.e., the emitted intensity) of this flare area was at least a factor of 15,000 greater than that of the average solar disk radiance just prior to the flare event. The enhancement relative to a typical nonflare active region is at least 3400. We compare this result with previous observations and models that in most cases report the enhancements relative to the nonflare active region plasma. We suggest that this may be the first measurement of the true enhancement of UV resonance lines during the impulsive phase of very large solar flares.

The SOLSTICE instrument gives us a unique possibility to observe the Sun "as a flare star" and to relate the observations with results from stellar UV instruments. Using previous published values for the enhancement in the UV emission and placing the Sun at a distance of 5–50 pc, typical of most observed flare stars, its flares would not have been detectable from Earth. Thus, objects classified as flare stars are generally believed to exhibit flares whose radiative emissions are far more energetic than those observed on the Sun. However, the present observation from SOLSTICE indicates that the increase in UV flux during some very large solar flares is comparable to recent stellar flare observations (e.g., Hawley & Pettersen 1991; Bookbinder, Walker & Brown, 1992; Robinson & Carpenter 1996). Therefore, we must consider the possibility that the Sun may sometimes display "flare star" characteristics.

Before proceeding we will make explicit our terminology. "Irradiance" is the total flux density of the radiation from the entire solar disk at 1 AU, in units of mW m⁻² sr⁻¹ (1 mW m⁻² = 1 erg cm⁻² s⁻¹). It is therefore the quantity that, if scaled properly, must be compared with stellar observations. "Radiance" is the specific intensity (mW m⁻² sr⁻¹) of a given resolved feature on the solar disk. We will use the terms "irradiance" and "radiance" hereafter, except where we quote results from previous observations and models.

2. PREVIOUS FLARE OBSERVATIONS

Measurements of the solar spectral energy distribution are usually given in terms of either the spectral radiance at the center of the solar disk or of the spectral irradiance of the whole Sun at 1 AU. Comparing results from spatially resolved observations with full disk observations requires some caution. Both center-to-limb variations and often different spectral resolutions should be accounted for (e.g., Brekke & Kjeldseth-Moe 1994a, 1994b). In this section we summarize some of the previous UV observations of flares that are relevant for our discussion of the SOLSTICE measurements. Most radiance enhancements derived from spatially resolved observations are relative to the nonflare active region and not to the average quiet Sun level. This will be discussed in more detail in § 4.1.

Unresolved full disk observations of flares in the EUV have been previously reported by Hall (1971) using spectra from the AFCRIL instrument on board the OSE 3 satellite. This instrument integrated over the entire solar disk. The total wavelength range of 270–1310 Å was either scanned in 5.44 minutes, or a fixed wavelength mode was selected to observe a single emission line. More than 300 flares of different classes were observed, and enhanced EUV emission was detected in one-third of them. EUV irradiance enhancements of 25%–35% were observed in lines like He ii 304 Å and O vi 1032 Å. Normalizing the irradiances by the fraction of the disk covered by the Hx flare, radiance enhancements of 50–170 were estimated.

UV spectra obtained with the NRL slit spectrograph (SO-82B) on Skylab showed that during flares the specific intensity of chromospheric and transition region lines are greatly enhanced relative to the postflare active region (e.g., Cheng 1978). The SO-82B instrument had no spatial resolution along the slit and the recorded radiance is averaged over the 2" × 60" slit. Allowed lines like S iv and N v showed radiance enhancements close to a factor 100, while inter system lines such as O i 1355.6 Å, Si iii 1892.0 Å, and O v 1218.4 Å showed much less enhancement (typically a factor of 10). The greatest increase in radiance was observed in the weak lines Ni ii 1467.3 Å and P ii 1542.5 Å, which increased by a factor of 600–800 during the flare. In deriving these factors a filling factor of about ½ of the slit was used, as estimated from near simultaneous He ii 256 Å spectroheliograms (with 3"–4" resolution).

Using spectra from SO-82B Cook & Brueckner (1978) measured absolute continuum radiances in the wavelength range 1420–1960 Å in a flare spectrum. They reported a major enhancement of the continuum radiance during the relatively large two-ribbon flare (2B-X1) on 1973 September 7. The integrated 1420–1520 Å (Si i 3P) continuum radiance during the event was approximately 60 times that of the quiet Sun, while the increase in the 1520–1680 Å (Si i 4D) continuum was only 15 times. No significant enhancement was observed at wavelengths longward of the Si i 4D photoionization limit at 1680 Å. The enhancement of the Si i continuum may be caused by the ionization of neutral silicon irradiated by ultraviolet radiation emitted in the transition region (e.g., Machado & Hénoux 1982).

From the CNRS instrument on OSE 8, which has a
2" × 20" slit, Skumanich, Jouchoux, & Castelli (1977) reported the Lyz and Mg II radiiances to increase by factors of 110 and 45, respectively, averaged over the slit. These are consistent with the Skylab observations of Canfield & van Hoosier (1980).

The SMM satellite observed flares simultaneously in hard X-rays and UV. The X-ray observations were obtained with the Hard X-Ray Burst Spectrometer (HXRBS, a full disk X-ray monitor), and the Hard X-Ray Imaging Spectrometer (HXIS), with a spatial resolution of 8" × 8" and a lower energy range. The UV observations were recorded with the Ultraviolet Spectrometer and Polarimeter (UVSP) with a spatial resolution ranging from 3" × 3" to 10" × 10". From these data, the relationship between coronal, transition region, and chromospheric emission during the impulsive phase of solar flares has been discussed by several authors (e.g., Tandberg-Hanssen, Reichman, & Woodgate 1983). For instance, it was shown that the emission increase in the O I line at 1371 Å correlates in temporal and spatial nature with HXR data (e.g., Poland et al. 1982). The UV continuum (1500 Å) formed near the temperature minimum is observed to peak simultaneously with the transition region emission and with the hard X-ray burst. After the initial UV and HXR spikes of the impulsive phase, the soft X-ray flux often continues to rise, reaching a maximum several minutes later and then gradually decaying to the background level.

Compared with the rapid increase in the flux of many transition region lines that follow the impulsive HXR, the light curves of Fe xxi (formed near 10^7 K in coronal ionization equilibrium) often show a more gradual rise and decay with maximum occurring after the UV and HXR peak (e.g., Poland et al. 1982 and Cheng et al. 1985). The time behavior indicates that this high-temperature line tends to correlate with the soft X-ray flux. However, as pointed out by Tandberg-Hanssen et al. (1983), this is not always true, and a variety of impulsive phase behavior has also been observed in the Fe xxi line. Compared to other chromospheric and transition region lines, the emission from Hα seems to have a slower rise, reaching peak radiance at a later stage.

A solar subflare (C3.4) was observed with the GSFC SERTS rocket instrument in 1989. During the initial stage of the flare the radiance enhancements were between a few percent and a factor 17 relative to the nonflare active region. The enhancements were found to increase with increasing temperature of formation above log T = 6.3 K, and to increase with decreasing temperature below log T = 6.0 K (Thomas & Neupert 1995).

Mass motions in solar flares have been extensively studied in the lower chromosphere and in the corona. However, there are relatively few measurements of mass flows in the solar transition region during flares. Bruner & Lites (1979) measured the position and intensity of the C iv 1548 Å line with the University of Colorado spectrometer aboard OGO 8 and found downflows up to 30 km s^{-1}. Cheng (1978) reported redshifts in flare spectra observed with Skylab with downw ard motion near 50 km s^{-1}. Cheng & Tandberg-Hanssen (1986) reported downflows of 30 km s^{-1} in Si iv 1403 Å in a few flares. During the impulsive phase coronal emission lines often show a blueshifted component of emission together with a strong stationary component. From Fe xxi 1354 Å data from UVSP, Mason et al. (1986) reported upflows, reaching velocities of 200 km s^{-1} during the impulsive phase. Using the Bent Crystal Spectrometer on SMM, MacNeice et al. (1985) reported upflows in Ca xix with subsonic velocities between 200–300 km s^{-1}. Based on a survey of 219 flares observed in soft X-ray with Yohkoh, Mariska, Doschek, & Bentley (1993) found the centroid of flare profiles to be blueshifted with an average velocity of 58 km s^{-1} during the early impulsive phase. The blueshifted components reached velocities up to 800 km s^{-1}. Nonthermal motions in flares have also been observed in soft X-ray emission lines (e.g., Doschek 1990; Antonucci & Dodero 1995).

The advent of the International Ultraviolet Explorer (IUE) in 1978 provided evidence of flare activity in dMe and RS CVn stars (e.g., Butler et al. 1987; Doyle, Byrne, & van den Oord 1989; Linsky et al. 1989). Chromospheric and transition region line flux densities (which must be compared with solar irradiances) were observed to increase by factors of 2–20 during flares. It should be noted that, because of IUE’s limited sensitivity and the relative faintness of flare stars as UV sources, the integration times were long (typically 30–60 minutes) compared with solar impulsive flare timescales. Hawley & Pettersen (1991) discussed a flare on AD Leo observed with IUE and reported enhancements by factors 10–50 in lines of C iv, Si iv, N v and He ii (with integration time of 15 minutes).

Considerable improvement in stellar flare observations followed the deployment of the Hubble Space Telescope (HST), in particular from observations with the Goddard High Resolution Spectrograph (GHRS). With this instrument exposure times down to 1 s are possible during flare observations, making detailed studies of the different phases in stellar flares possible. Boekbinder et al. (1992) observed a flare on AD Leo in 1991 May with GHRS that displayed a 1 minute impulsive phase, during which the Si iv flux increased by a factor of 60 for about 15 s. The C iv line increased by a factor of 90 for 25 s, while the He ii (1640 Å) line increased only by a factor of 2, and lower temperature lines, such as C i, showed no significant enhancement. Another interesting result from this observation was the extremely large redshift of the Si iv and C iv lines corresponding to 1800 km s^{-1} downflow. Observations with GHRS of the flare star AU Mic showed enhancement in the Si ii (1206 Å) line of a factor of 6 (Robinson et al. 1992). Linsky et al. (1995) report a flare observation of the faint cool dwarf VB 10 (Gl 752B), and they find that the C iv flux increased by a factor of 30.

3. INSTRUMENT AND OBSERVATIONAL DATA

3.1. The SOLSTICE Instrument

The Solar-Stellar Irradiance Comparison Experiment (SOLSTICE) is one of 10 instruments on the Upper Atmosphere Research Satellite (UARS), which was launched in 1991 September 12. The primary science objective of the SOLSTICE is to accurately measure the solar spectral irradiance in the ultraviolet spectral range, 1200–4200 Å. To achieve this goal, the scanning spectrometer is pointed toward the Sun for approximately 30 minutes during each orbit, and the grating drive slowly scans the full spectral range, integrating during 1 s at each wavelength setting. Actually, the instrument has three independent optical channels, each optimized for a particular range; the “G” channel between 1200 and 1900 Å, the “F” channel between 1700 and 3000 Å, and the “N” channel between

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2800 and 4200 Å. The combined data from the three channels provide a full scan, and the spectral resolution is different for each channel: 1 Å for the G, and 2 Å for the F and N channels. Details of the design and operation of the instrument are given by Rottman, Woods, & Sprain (1993) and Woods, Rottman, & Ucker (1993).

SOLSTICE has the unique capability of observing bright, blue stars with the very same optics and detectors as used for the solar observation. Repeated observations of 20 or 30 stars provide a stable instrument calibration. With the assumption that an individual star should vary by only a small fraction of a percent over time periods of thousands of years and, moreover, that the ensemble average flux from many stars should be an even more stable reference, degradation in the instrument performance is precisely monitored (see Rottman et al. 1993) with a relative long-term accuracy of ±1%. Since all of the observations in this report were obtained over a time period of a day or so, the relative accuracy of the measurements is of only secondary importance and we can safely assume that both the precision and relative accuracy are better than 1% for well-exposed features. The absolute calibration is on the order of or better than 10%, and this is the uncertainty we assign to the irradiance values reported here.

Although the normal spectral scan takes approximately 35 minutes to complete, there is an alternative instrument mode called “quick scan” that completes in about 4 minutes 34 s (4 minutes 22 s to scan and about 12 s to reset). Because of the higher data acquisition rate, measurements from only one channel at a time can be recorded. The normal operation therefore is two “G quick scans,” two “N quick scans,” and then three “F quick scans.” It is entirely fortuitous that the SOLSTICE was in the “G quick scan” mode at the time of the flare reported here. In all respects the data from the “quick scans” are identical to the data from the “normal scans,” with the exception that the integration time is only one tenth as long (0.1 s), resulting in a decreased signal-to-noise ratio of about 3. The statistical uncertainty in the integrated irradiance of the strong emission lines reported here is 2%–4%, and in the weak continuum near 1250 Å the uncertainty increases to about 10%.

The detectors used for all three SOLSTICE channels are pulse counting photomultiplier tubes with count rates typically on the order of a few thousand counts s⁻¹ (cps). The detectors are linear to 10⁵ cps, and appropriate dead-time corrections can be applied to extend the usable limit to 10⁶ cps. In all cases reported here, even the brightest flare emissions, the observed count rates are below 10⁵ cps, well within the linear range.

It is important to note that although the SOLSTICE has a programmable grating drive and can scan in either direction, the normal mode, and the mode used in the “quick scan data” reported here is from long to short wavelength. That is, from roughly 1900 Å to Lyα near 1200 Å.

3.2. Observations

We have used the GOES (Geostationary Operational Environmental Satellite) soft X-ray light curves to search for occurrences of large flares during the operation of the SOLSTICE instrument. The SOLSTICE quick scans obtained close in time with the soft X-ray flares were then inspected for flux enhancements. In most spectra investigated no significant enhancements were found, even if the observations were obtained during a high SXR level. In contrast, a quick scan spectrum obtained in 1992 February 27 did show a surprisingly large enhancement in some of the transition region lines. Figure 1 shows the integrated C iv (1548 Å) irradiance during the quick scans recorded on February 27. The shape of the GOES SXR (1–8 Å) emission (on a relative scale) is also plotted to illustrate the correspondence between the timing of the SXR flux and the SOLSTICE observations. The C iv irradiance shows little variation during the entire day except at the time of the rising soft X-ray emission. The first of the two “G quick scans” considered here began at 09:42:47 UT and finished at 09:47:10 UT, just at the onset of the flare as seen in Figure 1. The second scan began at 09:47:21 UT and continued until 09:51:43 UT. It turns out that this second spectrum was recorded almost precisely during the short impulsive phase of the flare, which could explain the lack of enhancement found in other SOLSTICE spectra. These were obtained either prior to the enhanced soft X-ray flux or after the peak was reached, thus missing the impulsive phase. In Figure 1 we see that the C iv emission is not enhanced at 12:00 UT, while the SXR level is still fairly high. The crucial timing may explain how other SOLSTICE observations usually missed the impulsive phase but still observed during a very high soft X-ray level.

In addition to the SOLSTICE data, we considered observations from a number of other instruments as shown in Table 1. These include ground-based images and microwave observations, as well as SXR measurements from GOES and HXR measurements from Ulysses. All of the

![FIG. 1.—Observed C iv (1548 Å) irradiance during the quick scans recorded on 1992 February 27. The shape of the GOES SXR (1–8 Å) emission (on a relative scale) is also plotted. No significant UV variations were observed during the entire day except at the time of the rising soft X-ray emission. A more detailed timing of the flare observation is given in Fig. 6.

<table>
<thead>
<tr>
<th>Type</th>
<th>Region Frequency</th>
<th>Time Resolution</th>
<th>Source</th>
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<td>3.1–35 GHz</td>
<td>1</td>
<td>IAP Bern</td>
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<tr>
<td>Radio</td>
<td>2.5–2.85 GHz</td>
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<tr>
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observations will be discussed in more detail later. From Hα observations the 1992 February 27 flare was classified 3B with an estimated area of \(928 \times 10^{-6}\) of the apparent solar disk, or \(1.4 \times 10^6\) km\(^2\). The X-ray classification was X3.3 on the GOES 1–8 Å soft X-ray scale with a peak flux of \(3.3 \times 10^{-4}\) W m\(^{-2}\) (Solar Geophysical Data, 571/l). It is somewhat atypical that such a large flare did not reach a larger soft X-ray intensity. The Sun was fairly active on this day, as illustrated by the full disk Hα and Ca II observed from Big Bear Observatory and shown in Figure 2 (Plate 2). The February 27 flare was located in the active region (AR 7070) in the upper part of the marked area. This was close to the disk center (N06 W02); thus, our study is not affected by limb projection effects.

The SOLSTICE spectrum obtained during the 1992 February 27 flare is compared to the normal solar irradiance spectrum in Figure 3 (upper panel) and the strong enhancement of the transition region lines and the “continuum” is clear. For the normal (or nonflare) solar spectrum we have used the daily average spectrum from the previous day (February 26). This spectrum gives the same irradiance level as the individual quick scan data obtained early on Feb-

![Graph showing spectral irradiance](image)

**Fig. 3.**—Upper panel shows a comparison of the spectrum obtained with SOLSTICE during the impulsive phase of the 1992 February 27 flare and a “normal” spectrum recorded the previous day. Lower panel shows the irradiance increase from the flaring region, derived by subtracting the normal spectrum from the spectrum obtained during the impulsive phase, compared to the normal Sun. It demonstrates that the emission in several emission lines from the flaring region is stronger than that from the rest of the solar disk. Note that completing the flare observation takes about 4 minutes, and that time runs from right to left as indicated by the arrow.
Fig. 2.—Full disk Hα (left) and Ca II (right) observed from Big Bear Observatory 1992 February 27 at 18:40:27 UT and 18:02:05 UT, respectively. The Sun was fairly active ($F_{10.7} = 293$) with several active regions on the visible hemisphere. The flare was located in the active region (AR 7070) in the upper part of the marked area.

Brekke et al. (see 468, 422)
Figure 2. The level of the 10.7 cm radio flux, $F_{10.7} = 239$, also indicates a high activity level, and the C IV irradiance on 1992 February 26 was about 20% higher than the irradiance measured during a low activity level (1995 spring).

The lower panel in Figure 3 represents the flare spectrum derived by subtracting the normal spectrum from the spectrum obtained during the flare. A discussion of the enhancement of various features follows.

3.2.1. Transition Region Lines

Figure 4 shows selected spectral regions in more detail and demonstrates the strong enhancements observed in some transition region lines. Certain properties of the dominant emission features are listed in Table 2, including the integrated flux from Gaussian fits to the lines both during the flare and for the normal Sun. The resonance lines from C IV and S IV show the largest irradiance enhancement, an increase by a factor 12–13 during the impulsive phase. The N V lines at 1240 Å increase only by a factor of 3. The latter may seem surprising since the term levels involved and formation processes are similar to those of C IV. However, we note that the N V lines were obtained about 2 minutes after the C IV lines were registered. We will show in a later section the N V lines probably show less enhancement because they were obtained at the end of the impulsive phase, while C IV was recorded during the peak of this phase.

The irradiance changes for Si III depend strongly on the multiplet to which the emission lines belong. Four of the six transitions in the $3p^2 3P \rightarrow 3s^3 3P^o$ multiplet, at 1294.55, 1296.73 and the blended 1298.95 + 1298.89 Å components, show irradiance enhancements of a factor or 13 or so during

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Fig. 4—Comparison of the flare spectrum (solid lines) and a normal Sun spectrum (dashed lines) in selected wavelength regions. We point out the large enhancement observed in lines such as C IV, Si IV, and Si III, while L is shows modest enhancement. Some of the differences between the various enhancements may be caused by the timing of the observations.
the flare (derived using peak irradiances). The other two transitions at 1301.15 and 1303.32 Å may also show such enhancements, but they are largely blended with the much stronger resonance lines of O I at 1302 and 1304 Å, and so we cannot determine the irradiance of the nonflaring plasma from the data. The flare spectrum is, as far as we can determine, consistent with the expected line intensity ratios on the basis of calculations of the relative intensities of the 3p^2 3P → 3s3p^2 3P multiplet (we used atomic data from Dufson et al. 1983 and Dufson & Kingston 1989). The measured irradiance of the 3s3p^2 3P → 3s^2 1S line at 1206.5 Å, in contrast, was enhanced by a factor of 5 or so, and the intersystem line 3s3p^3P^0 → 3s^2 1S0 at 1892.0 Å increased in irradiance by less than 10%.

The timing of our observations must also affect these ratios since the scanning spectrometer observed different spectral features with up to 4 minutes time difference. However, the different behavior of all the transition region lines is at least qualitatively consistent with the picture that the electron density is substantially higher in the UV emitting flare plasma than in the average nonflaring solar disk plasmas. Thus, in the regimes of density appropriate to the Sun, the intersystem lines (such as Si iii 1892.0 Å) increase only marginally (4%), owing partially to the density dependence of the line's emission coefficient, scaling with N_e^2 for N_e ≪ N_ee = 5 × 10^{10} cm^{-3}, and with N_e^4 for N_e > N_ee, where N_ee is the “critical electron density” for the upper level (3s3p^3P^0). The resonance lines of Be- and Mg-like ions (e.g., Si iii 1206.0 Å) scale as N_e^2, and the resonance lines of the Li-like (N v, C iv) and Na-like ions (Si iv) increase with N_e^{2+α}, where α is small positive numbers ≪ 1, determined by density effects in the ionization balance (Vernazza & Raymond 1979; Keenan & Doyle 1992). The emitted power of lines excited from a metastable level (e.g., Si iii 3p^2 3P → 3s3p^3P near 1300 Å), scale as N_e^{2+β} where β is a small positive number that can approach unity close to the same critical density N_ee as above, and approaches zero or becomes slightly negative above this density. All of these effects can be seen by examining, for example, the dependence of emitted power at constant emission measure, listed by Keenan & Doyle (1992).

In principle, lines of the 3p^2 3P → 3s3p^3P multiplet, near 1300 Å, can be used as diagnostics of electron density. Unfortunately, no density determination is possible using the Si iii lines in this multiplet alone, since density-sensitive ratios involve the blended 1301.15 and 1303.32 Å lines. The ratios of 1206.0 Å to 1298.9 Å and/or 1892.0 Å might also be used, but we prefer not to do this owing to the fact that these ratios are also strongly dependent on electron temperature T_e. Without a determination of T_e, these ratios are therefore ambiguous. We do not trust statistical equilibrium calculations in the flaring plasma, or even in the nonflaring quiet Sun plasmas (Judge et al. 1995), and therefore we decide not to use this to estimate the electron temperature.

3.2.2. Coronal Lines

The Fe xxii coronal line at 1354 Å has previously been observed during flares by UVSP (e.g., Poland et al. 1982) and HRTS (Brueckner 1981). No significant emission from the Fe xxii line at 1354 Å was detected in the SOLSTICE spectrum during the impulsive phase. This line has been observed to show a more gradual rise (e.g., Poland et al. 1982), peaking up to several minutes later than the transition region lines. This may explain why we do not observe any Fe xxii emission in the SOLSTICE flare spectrum.

3.2.3. H Lyα Line

In Lyα the irradiance increased by only 6%, which is the smallest increase of the strong lines we observe. Nevertheless, the large intensity of this line makes even this moderate enhancement energetically important for the emitting plasma. Comparing the total energy integrated over the disk observed from the flare in Lyα with that from the two C iv lines, we estimate the Lyα to be about 4 times larger (see Table 2). This can be compared to the preflare values, where Lyα is about 48 times stronger than the combined emission from C iv. The relative weakness of the Lyα may
be related to the fact that this line was observed at the very end of the UV impulsive phase as discussed in §4.2.

Considering the Lyα line profile, the strongest relative enhancement occurs in the Lyα wings, and the blue wing increases somewhat more than the red wing. Thus, in this flare we do not observe any evidence of charge exchange between hydrogen atoms and proton beams that would produce a red wing enhancement (e.g., Fang, Feautrier, & Henoux 1995). However, we also note that the blue wing may be affected by several unresolved weak emission lines.

3.2.4. UV Continuum

With the available spectral resolution of 1 Å it is difficult to isolate the continuum radiation between the large number of emission lines in the short-wavelength range of the spectrum, and likewise absorption lines at longer wavelengths. The observed flare spectra, however, suggest that the continuum irradiance increased by almost a factor of 2.

As shown in Figure 3 (upper panel), there is less enhancement in the UV radiation at longer wavelengths. This decreasing enhancement with increasing wavelength may be strongly affected by timing of the scans as a function of wavelength. The scan starts at the longest wavelength, and thus time runs toward shorter wavelength, as the impulsive phase advances.

However, the decreasing flare enhancement toward long wavelength is consistent with previous flare observations of the UV continuum (e.g., Cook & Brueckner 1978). We have compared high-resolution spectra of the quiet Sun from the NRL High Resolution Telescope and Spectrograph (HRTS; Brekke 1993), with a flare spectrum obtained with the NRL SO-82B spectrometer reported by Doyle & Cook (1992).

The NRL flare spectrum is from a large two-ribbon flare (2B-X1) on 1973 September 7. The UV continuum radiation during the Skylab flare was enhanced with respect to the quiet Sun (HRTS) by a factor 10–20 at wavelengths shorter than 1680 Å, while the longer wavelengths the flare continuum merges with the quiet Sun spectrum. It should be pointed out that these flare observations were obtained after the soft X-ray maximum, viz., well after the phase we study here.

3.3. Kinematics

Measurements of line shifts during the flare indicate the strongest transition region lines are systematically red-shifted by \( \approx 50 \text{ km s}^{-1} \pm 20 \). This result is comparable to previous findings from \( \text{OSO 8} \) and \( \text{Skylab} \) (e.g., Bruner & Lites 1978; Cheng & Tandberg-Hanssen 1986). No systematic variation of the velocity with temperature of formation has been found in these SOLSTICE data. Although timing of the observations may obscure this relationship, further analysis of these data is warranted to rule out such variations.

4. COMPLEMENTARY OBSERVATIONS OF THE FLARE EVENT

The 1992 February 27 09:51 UT flare was observed in Hα at the Udaipur Solar Observatory in India. It was classified as a “two-ribbon” flare where the two characteristic ribbons of bright Hα emission lie on either side of the neutral line threading the active region as seen in photospheric magnetograms. A time series of Hα images is shown in Figure 5 (Plate 3) together with a magnetogram from the Kitt Peak Observatory, a white light and a soft X-ray image from \( \text{Yohkoh} \). The Hα time series starts at 09:41 UT and ends at 09:56 UT, thus covering the impulsive phase of the flare. The approximate field of view is \( 350' \times 500' \), and the location on the solar disk is illustrated in Figure 2. We have used these data together with magnetograms to place constraints on the topology of the flaring plasma. The Hα at 09:41 UT shows a filament that extends along the neutral line and disappeared shortly afterward as is typical in these flares.

The daily magnetogram from Kitt Peak Observatory was taken at 14:55 UT long after all phases of the flare. According to these data the active region was separated in two areas of opposite polarity, negative (black) to the north, and positive to the south. The location of the Hα flare at 09:48 UT is indicated by the contour plot.

We have also investigated observations from the \( \text{Yohkoh} \) satellite. Unfortunately, \( \text{Yohkoh} \) crossed the South Atlantic Anomalous (SAA) between 09:45:29–10:16:29 UT, almost exactly during the impulsive phase. During this passage the high-voltage supplies for the HXT photomultipliers are reduced and no solar observations are made. Thus, no HXR observations of the impulsive phase were available. In contrast, the SXT instrument operates through the SAA for better continuity of coverage.

The SXT on \( \text{Yohkoh} \) was operating during the impulsive phase but did not go into flare mode until 10:21 UT, resulting in saturated images during the impulsive phase. The first high-resolution partial frame images of the flare came out of saturation about 6 minutes after the SXR maximum (10:01 UT).

The lower panels in Figure 5 (right column) show the white light and SXT images extracted from the full disk \( \text{Yohkoh} \) images. These images were taken prior to the impulsive phase, and the location of the flare relative to the sunspots is established by the white light image. We have also investigated a time series of white light images from \( \text{Yohkoh} \), which showed that the two leftmost sunspots in the group were moving toward each other just before the onset of the flare. Relative motion of sunspots has often been linked to flaring (e.g., Gaizauskas, Harvey, & Proulx 1994). The SXT image outlines the coronal loop structure above the flaring region prior to the flare.

4.1. Spatial Extent of the Flare

From the irradiance observations and the spatial extent of the flare area we can estimate how much the irradiance of the flare region increased above the average quiet Sun level. This number is relevant for comparison with stellar work. It should also be important for design of future solar instruments since the detector in many cases will cover both quiet Sun, plages, and a flare site simultaneously. To compare the measured enhancements with previous spatially resolved flare observations and models it is more appropriate to derive the enhancement relative to the nonflare plage radiance. This requires knowledge of the fractional area covered by plages and enhanced network as well as the contrast between these areas and the quiet Sun.

The spatial extent of the UV emission during the impulsive phase of the February 27 flare is difficult to estimate without spatially resolved UV observations. We have attempted to determine an upper limit of the UV flare kernel's area using the Hα image taken at 09:48 UT near the very beginning of the impulsive phase and a second image taken several minutes after the impulsive phase.
Fig. 5.—Images of the active region AR 7070 obtained from ground and the Yohkoh spacecraft. The left column shows a time series of Hα images from Udaipur Observatory. The right column shows, from top: Magnetogram from Kitt Peak Observatory, white light image from Yohkoh, and a soft X-ray image from Yohkoh. The location of the Hα flare at 09:48 UT is indicated on the other images by the contour plot. The approximate field of view is $350'' \times 500''$, corresponding to the marked area in the full disk images of Fig. 2.

Brekke et al. (see 468, 425)
The flare area of Hα is known to show a much more gradual increase during the impulsive phase compared to HXR and microwave emissions. This area usually reaches maximum several minutes after the peak of the HXR flux (e.g., Wang et al. 1987), which is consistent with the Hα images in Figure 5. The Hα flare area was reported in SGD to be 928 x 10^{-8} solar disk units. This size corresponds to the maximum area that occurs close to the time of the Hα image obtained at 09:56 UT. Our estimate from the Hα images gives a flare area of 800 x 10^{-6} (thus, 0.08% of the solar disk at 09:48 UT).

Previous observations (e.g., Tandberg-Hanssen et al. 1984) showed that the UV flare kernels are situated in areas of enhanced Hα emission located on opposite sides of the polarity inversion line of the longitudinal magnetic field. SMM observations have shown that during the impulsive phase of flares the UV emission originates in small, localized kernels, whose size may be even smaller than the 3" x 3" UVSP pixel (e.g., Cheng, Tandberg-Hanssen, & Orwig 1984). Many of these kernels are present in extended flares, such as the one we study, and their accumulated size is hard to assess. We conclude that the spatial extent of the UV emission during the February 27 flare was certainly less than 0.08% of the visible disk. The actual kernel area is probably between this number and one-tenth of this value based on previous observations (Wuelser 1995). In the following discussion we use the value of 0.08% as a conservative upper limit on the UV flare area.

4.1.1. Absolute Flare Radiance and Radiance Relative to Average Sun

The enhancement $I_f/I_{pf}$ of the flare radiance ($I_f$) relative to the average preflare disk radiance ($I_{pf}$) can be estimated from the following. If $\omega_r$ is the total solid angle of the solar disk, as seen from SOLSTICE, and we assume there are $N$ components on the disk each with radiance $I_i$ and solid angle $\omega_i$, the irradiance can be written

$$S = \sum_{i=1}^{N} \omega_i I_i,$$

where

$$\omega_r = \sum_{i=1}^{N} \omega_i = \frac{\pi R_\odot^2}{d^2}.$$

$R_\odot$ is the solar radius, and $d$ is 1 AU. Before the flare, we can define a mean disk radiance, the preflare radiance $I_{pf}$, such that

$$S_{pf} = \omega_r I_{pf},$$

where $S_{pf}$ is the irradiance before the flare (preflare), and includes both quiet Sun, enhanced network, and plages. To demonstrate the flare’s effect more clearly, we can also write

$$S_{pf} = \omega_r I_0 + \sum_{i=1}^{N} \omega_i I_i,$$

where $\omega_f$ is the solid angle of the eventual flaring area and $I_0$ is its preflare radiance. During the flare we have

$$S_f = \omega_f I_f + \sum_{i=1}^{N} \omega_i I_i,$$

where $I_f$ is the radiance of the flaring area, the only component whose radiance displays appreciable change over the short timescale considered. Combining these expressions, one can show that the measured ratio $R_s$ of the flare to preflare irradiance is given by

$$R_s \equiv \frac{S_f}{S_{pf}} = 1 + \frac{I_f - I_0}{I_{pf}} \frac{\omega_f}{\omega_r},$$

and that the radiance ratio $R_f$ is then

$$R_f \equiv \frac{I_f}{I_{pf}} = \left( R_s - 1 \frac{\omega_f}{\omega_r} \right) \frac{\omega_f}{\omega_r}.$$

In the solar case, $(I_f/I_{pf})(\omega_f/\omega_r) \ll 1$, even for very large flares, and is always positive in any event. Thus, equation (7) can be simplified to

$$R_f \equiv \frac{I_f}{I_{pf}} \approx (R_s - 1) \frac{\omega_f}{\omega_r}.$$

For this particular flare, therefore, $R_f \approx (R_s - 1)$. 2.5 x 10^3. Table 2 lists values of $R_s$ and lower limits of $R_f$ for the different spectral features. The inferred C iv and Si iv radiances are at least factors of 14,500 and 15,300 larger, respectively, than the average solar disk radiance, while the Si iii multiplet at 1295 Å is at least a factor of 14,700 larger. Other allowed lines such as Ca ii, Si iii (1206 Å), N v, and He ii show more moderate enhancements. The radiance from chromospheric lines (e.g., the O i lines at 1300 Å) are only a factor \geq 390 larger. The Lyα line shows only a weak enhancement. However, even this enhancement relative to the average disk radiance is substantial, a factor of \geq 75 (though its value is more uncertain). By comparison, the UV "continuum" radiance is a factor of \geq 1200 larger than the average solar disk radiance for wavelengths shortward of 1550 Å with less enhancement at longer wavelengths.

Finally, in Table 2 we list lower limits to the radiances in the flare, derived from tabulated values for $R_s$, since

$$I_f = \frac{S_{pf} R_f}{\omega_r} = 1.47 \times 10^4 S_{pf} R_f \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}.$$

The derived values of $I_f$ in absolute terms, as listed in Table 2, allow direct comparison with models and other observations. Note that these numbers are all lower limits.

4.1.2. Radiance Relative to Mean Plage Radiance

To compare the observed enhancement with previous results and models it is useful also to derive the radiance enhancement relative to the nonflare plage plasma. This is the number usually reported since most flares occur in active region loops. The enhancement relative to the nonflare plage emission can be derived taking into account the total area of all plages on the disk and the contrast between the plage and quiet region radiance. We can further extend this two-component model to include the fraction of enhanced network covering the solar disk. The following relations can be used to estimate the radiance enhancement ($R_f = I_f/I_f$) relative to the average plage emission taking into account the solid angle, $\omega_p$, of plages and solid angle, $\omega_n$, of enhanced network. It should be noted that the contrast between the plage emission and the quiet Sun can vary significantly between individual active regions. We sum over these different components (see eqs. [1] and [2]) for the preflare conditions,

$$S_{pf} = \omega_q I_q + \omega_n I_n + \omega_p I_p,$$

where

$$\omega_r = \omega_q + \omega_n + \omega_p.$$
and $I$ denotes mean radiance values. We let the reference radiance be the plage emission, $I_p$, and divide equation (10) by $I_p$:

$$\frac{S}{I_p} = \frac{\omega_p}{I_p} + \left( \frac{\omega_q I_q + \omega_u I_u}{I_p} \right).$$

(12)

We define $C_q = I_q/I_p$ and $C_u = I_u/I_p$ as the contrasts of the network radiances relative to the quiet Sun and the plage radiances relative to the quiet Sun. From equations (6) and (12) the enhancement in radiance relative to the plage emission is then

$$R_I = \frac{I_I}{I_p} = \frac{(R_I - 1) (\omega_p C_p + \omega_u C_u + \omega_q)}{\omega_q C_p}.$$  

(13)

The contrast factors $C_p$ and $C_u$ depend strongly on the wavelength of interest, and spatially resolved observations with high spatial resolution are needed to derive these numbers. This would require a detailed study of such data, which is beyond the scope of the present paper. From C IV observations with HRTS (e.g., Sandlin et al. 1986; Brekke 1993) we estimate typical values as $C_p = 20$ and $C_u = 10$. The total plage area was approximately 10% of the solar disk on 1992 February 27 as derived from the Ca II image shown in Figure 2. The corresponding network area was approximately 20% for this period (White 1995). Applying these values to equation (13) we find a C IV radiance enhancement ($R_I$) of approximately 3400 relative to the preflare plage radiance. This is therefore a measure of how much the flare plasma itself brightened from its initial level during this event. Similar values were found for S IV ($R_I \approx 3300$) and Si III ($R_I \approx 4000$), while the enhancement of the N V lines was approximately 550 relative to the preflare plage radiance. These derived enhancements are substantially larger than previous values reported from Skylab and UVSP.

4.2. Time Relationships

The completion of one G-channel scan takes 4.4 minutes. It is therefore necessary to consider the temporal evolution in order to properly evaluate and intercompare the enhancement at each different wavelength. As mentioned earlier, the HXR and UV light curves usually follow each other closely. Unfortunately, there are no HXR data available from either Yohkoh or BATSE during the impulsive phase of this flare. However, the event was observed with the hard X-ray telescope on the Ulysses spacecraft. In the following discussion we also examine other UV proxies and techniques to derive the temporal extent of the impulsive phase. These approaches include the use of the time derivative of the soft X-ray light curve and microwave radio emission. The light curves from different sources are shown in Figure 6 and compared to the timing of the SOLSTICE observation. The top panel of Figure 6 shows two SOLSTICE quick-scan spectra indicating the time when each wavelength was recorded. Thus, the wavelength scale runs from right to left because the grating drive scans from long to shorter wavelengths, as described in § 3.1.

4.2.1. Ulysses Hard X-Ray Data

The Ulysses spacecraft carries the solar X-Ray/Cosmic Gamma-Ray Burst Experiment, which is used for monitoring the solar flare X-ray emission (Hurley et al. 1992). While the spacecraft was near Jupiter, the February 27 flare event was observed and the X-ray light curves are shown in Figure 6b. The distance from the Sun was approximately 5.5 AU and the timings have been corrected for light travel time. The hard X-ray light curve from channel 4 covers the energies 52–83 keV and clearly tracks the flare impulsive phase. The somewhat softer X-ray emission from channel 1 (5–20 keV) peaks a few minutes after the HXR emission.

4.2.2. GOES Soft X-Ray Data

The shape of the HXR (and UV) light curve can be estimated from the time derivative of the SXR light curve (the so-called “Neupert effect”). Recently, Dennis & Zarro (1992) compared the time derivative of the SXR emission curve with the HXR light curve for a large number of flares detected by GOES and HXRBs on SMM. They found that for strong impulsive flares the correlation between the SXR time derivative and HXR is quite good, although the correlation is much weaker for nonimpulsive X and M class flares for which the X-ray emission varies more gradually than in impulsive flares.

From their analysis we examine the hypothesis that we can estimate the shape of the HXR and UV light curve during this impulsive flare. Figure 6c shows the GOES 1–8 A soft X-ray emission time profile plotted with a time resolution of 3 s. The time derivative of the SXR emission is shown on a relative scale in the panel. The general shape of the time derivative matches to the curve from Ulysses, in spite of the considerable scatter after the gain change at 09:48:50 UT. This scatter is caused primarily by the digitization of the GOES data and the magnification of the uncertainties that result from taking the time derivative.

The GOES SXR emission can be used to track the temperature and volumetric emission measure ($I N^2 Q dV$) of the thermal plasma. Using the procedure of Thomas, Starr, & Crannell (1985) we estimate the temperature of the February 27 event to be $\sim 20 \times 10^6$ K and the volumetric emission measure to be $\sim 2 \times 10^{48}$ cm$^{-3}$.

4.2.3. Microwave Observations

Microwave radio emission is known to show similar features as the HXR/UV light curve and can therefore be used to approximate the impulsive phase of the flare. This similarity holds on timescales of a fraction of a second for impulsive flares (e.g., Kane et al. 1983; Cornell et al. 1984). Individual hard X-ray and microwave spikes are generally coincident, although delays of 1–2 s have been observed. There is also a good correlation between the flux levels of the two emissions.

Microwave observations of the flare event were obtained from telescopes in Bern (IAP) and Crimea. The frequencies ranged from 2.4–35 GHz and a selection of the observations are displayed in Figure 6d. We point out the good correlation with the Ulysses HXR observations as well as the GOES time derivative. We also note that, compared to the lower frequencies, the higher frequencies show steeper impulsive phase and somewhat earlier peak flux. This may be explained assuming that the high frequencies were caused by electron beams propagating in high-density material (and in high magnetic field regions). The low frequencies usually originate higher in the corona (at low density and low field) and do not agree as well with the UV light curve. The emphasis with Figure 6 is to demonstrate that lines like C IV and Si IV were fortuitously observed during the maximum impulsive phase (Fig. 6e). Lines at shorter wavelengths (e.g., Si II, Lyz, and N V) were obtained later in the decaying part of the impulsive phase.
Fig. 6.—(a) SOLSTICE flare spectrum and preflare spectrum are plotted on a timescale. Thus, wavelengths now run from right to left as indicated by the arrow. The timing of individual emission features are compared with light curves of SXR, HXR, and microwave observations. (b) hard X-ray observed from Ulysses; (c) soft X-ray emission from GOES and its corresponding time derivative; (d) microwave emission observed from IAP Bern and Crimea; (e) the ratio of the SOLSTICE flare data to the normal Sun emission. Clearly, some emission features were obtained during the most intense impulsive phase, while others were recorded later during a lower hard X-ray level. Because of Doppler shifts in the flare spectrum the ratios plotted in (e) are somewhat larger than the line peak flux ratios listed in Table 2.
This particular flare event was also observed by the 2.3–4.2 GHz radiotelescopograph and by the 3 GHz high time resolution radiotelescopograph at Ondrejov Observatory. A detailed analysis of this observation was reported by Karlický & Odstrcil (1994). The 2.3–4.2 GHz radio emission started at 09:47:20 UT and ended at 09:52:10 UT. The 11.8 and 35 GHz radio emission peaked at 09:49:37 and 09:49:20 UT, respectively. The radio observations showed several repeated peaks after the strong impulsive phase (see Fig. 6). Also fast-drift bursts with positive frequency drift were observed and probably indicate propagation of beams into increasing depth regions. These beams may produce increased UV emission by collisional excitation, as we discuss later.

5. COMPARISON WITH PREDICTIONS OF EXISTING FLARE MODELS

Several models of flaring plasma have appeared in the literature (e.g., Hawley & Fisher 1994, and references therein). In this section we ask to what extent these models may or may not explain our observations. Some models have included an impulsive phase as well as a later (decaying) phase.

5.1. Impulsive Phase

The impulsive phase involves complicated dynamical processes in which plasma turbulence may play an important role, large electric fields can be expected, and time variation of the particle acceleration may also be important. This phase lasts up to several minutes, which is a short time compared with some timescales for ionization and recombination. Thus, the spectrum emitted during this phase is very hard to model. Therefore, we cannot expect to make sensible comparisons of models with the C iv and Si iv line radiiances that we believe are characteristic of the impulsive phase. Existing impulsive phase models are based on the evolution of an initial semi-empirical unperturbed plage model that is suddenly heated by Coulomb collisions between the background electrons and an impinging electron beam. These models are usually extremely simplified. They may explain the hard X-rays, but they do not attempt to explain the UV lines. In these models, the basic parameters are the flux and spectrum of the impinging electrons.

The usual adopted energy spectrum is a power-law distribution, \( F \propto E^\alpha \), that is truncated below a cutoff energy, \( E_{\text{cutoff}} \). Thus, these models have two free parameters that can be adjusted to fit the hard X-ray spectrum. Typical values are \( \alpha \sim 4 \) and \( E_{\text{cutoff}} \sim 30 \text{ keV} \).

The impulsive models do not seem to show sufficient increases of the transition region densities to explain our inferred radiances. An alternative explanation to the emission in the impulsive flare models is that this may originate in heated chromospheric layers that have not yet expanded (see Fig. 2 of Hawley & Fisher 1994). According to these models a layer of the chromosphere above mass column \( 3 \times 10^{-4} \text{ g cm}^{-2} \) is heated to temperatures below, but close to, \( 10^5 \text{ K} \). This layer only shows moderate electron density enhancement, but has a large extent and can produce substantial emission in lines such as C iv and Si iv. The detailed modeling of these emissions is complicated by the nonequilibrium ionization due to the fast temporal evolution and must be calculated together with the hydrodynamics of the plasma. This is beyond the scope of the present paper.

Another explanation for the strength of the C iv and Si iv lines might be the direct excitation of the ions by the electrons in the beam and would relate to the beam flux rather than to the beam density. Such a direct effect may also affect the ionization and again careful calculations are required. As a quick evaluation, we adopt an electron beam energy flux in this large flare of \( 10^{10} \text{ ergs cm}^{-2} \text{ s}^{-1} \) (e.g., Hawley & Fisher 1994) and a typical electron energy of 10 keV. This beam would have an electron flux of \( 6 \times 10^{17} \text{ cm}^{-2} \text{ s}^{-1} \) and produce a direct collisional excitation rate of about 1.0 s\(^{-1} \), using a cross section of \( 1.7 \times 10^{-18} \text{ cm}^2 \), derived from the high-energy (Bethe) limit and a multiplet \( g \)-value of 0.59 from the NIST online database. These can be compared with the thermal electron collisional excitation rate of \( 5400 \text{ s}^{-1} \) for a plasma with an electron density of \( 10^{14} \text{ cm}^{-3} \) and temperature of \( 10^5 \text{ K} \), using a Maxwellian-averaged multiplet collision strength of 10 (McWhirter 1994). Thus, direct beam excitation can probably produce no more than a negligible enhancement of C iv emission.

5.2. Gradual Phase

The gradual phase models are simpler to compute because they assume that the gas is in a steady state (i.e., explicit time derivative terms are negligible in the energy and momentum equations) and electrons are thermalized. Existing models give sufficient details so that line intensities can be computed. In most cases the atmospheric structure is determined semi-empirically and the match between certain computed and observed intensities and line profiles is good. The later observations of Lyz and N v might correspond to the early times of this phase.

The models by Canfield, Putter, & Richiazi (1981), are oversimplified because they assume a chromosphere with constant temperature and density, nevertheless they provide a reference point for the Lyz intensities in flares. These authors estimate the temperature of formation of Lyz at about 12,000 K, and the electron density in the range \( 10^{11}–10^{12} \text{ cm}^{-3} \). Such models are early attempts to explain the Skylab (SO-82B) observations of Lyz in flares reported by Canfield & van Hoosier (1980). The maximum radiance observed by these authors, during a large flare, was about \( 4 \times 10^6 \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \), but they indicate that the data do not correspond to the brightest locations of the large flare they observed. The data reported by Skumanich et al. (1977) agree well with values in this range. In comparison, the inferred Lyz radiance of the 1992 February 27 flare is \( 1.1 \times 10^7 \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \).

Models by Machado et al. (1980, hereafter MAVN), Mauas, Machado, & Avrett (1990), and more recently ones by Hawley & Fisher (1994) are more elaborate. All of these models are given in sufficient detail so that spectra can be computed. They include an active electron beam (i.e., the beam has not yet turned off), and a high pressure at the top of the chromosphere and transition region. As modeled, this phase likely corresponds to the lines and continua observed late in our scan (e.g., Lyz at 09:51:32 UT and N v at 09:51:22 UT).

The results for Lyz from models F1 and F2, from MAVN, are shown in Figure 7 and are compared, for reference, with the standard quiet Sun Model C (Fontenla, Avrett, & Loeser 1993). The models F1 and F2 represent faint and bright flares, respectively. From these calculations the integrated radiances are 5.5 \( \times 10^6 \) and 3.8 \( \times 10^7 \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \) for F1 and F2 in the band 1210–1220 Å. These radiances are about 60 and 400 times larger than the quiet Sun standard value (9 \( \times 10^4 \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \)) and
are roughly compatible with the observations presented here. Converting the radiances to irradiances and using the flare area estimated from the Hα data we obtain an expected increase of Lyα irradiance of 0.37 and 2.6 mW m⁻², respectively, in the same wavelength band (compared with about 6 mW m⁻², that is the total solar flux from the standard model). Thus, the F1 and F2 models predict solar irradiance increases of 5% and 40%, which are comparable with the increase of 10% observed by SOLSTICE.

6. DISCUSSION

The SOLSTICE observations presented in this paper suggest that solar flares have much higher UV irradiances and radiances for the flaring plasma than was previously thought. However, the observed irradiance enhancements are similar to stellar observations of flares. The question arises of whether the 1992 February 27 event was an abnormal flare or just a typical large solar flare? In the latter case, why have no other observations ever recorded such enhancements?

The Skylab mission took place during a period of low flare activity. Also, for several reasons Skylab did not obtain data with good temporal coverage during the impulsive phase of flares. Most flare observations with the SO-82B spectrograph were, in fact, obtained during the decaying phase and did not include the impulsive phase. The large enhancements observed with SOLSTICE would also have been difficult to record using photographic plates because of their limited dynamical range.

The UVSP instrument on board SMM observed a large number of flares, but usually relatively small ones. To protect the detectors, if the count rate in any exposure (usually 0.064 s) grew above 10⁶ s⁻¹, the detectors were turned off for the entire orbit. This operating procedure was later changed to turn off the high voltage only for the duration of the current experiment (Gurman 1995) and provided data on the decay of flare events. However, Fontenla et al. (1994) showed a C-class flare where the C iv radiance increased by a factor of 200 above the preflare level in 10 s just before the instrument was shut off. Also, during an M2 flare, the C iv radiance increased by a factor 500 above the preflare level before the shutoff at about 60% of the maximum hard X-ray intensity (Woodgate et al. 1981). We conclude that, because of detector limitations, previous UV instruments were not able to record such large radiance enhancements as seen by SOLSTICE. Most reported enhancements during large solar flares relate to either early in the impulsive phase or the decaying phase. Therefore, estimates of enhancements derived from previous UV observations are probably not valid for the flare impulsive phase.

Based on observations at different wavelengths the 1992 February 27 event was most probably a typical large solar flare. A number of even larger and more energetic flares occurred in 1991 and 1992 (e.g., Kane et al. 1995). If this is the case, this observation has important implications for future instruments. Many instrument detectors will cover the quiet Sun, plage areas, and flare sites simultaneously. Thus, a large dynamical range will be necessary to cover the very large enhancements between the quiet Sun level and the flare emission as observed by SOLSTICE.

We also conclude that our SOLSTICE observation of the February 27 flare is in general agreement with recent stellar flare observations (e.g., Bookbinder et al. 1992; Robinson & Carpenter 1996). Robinson & Carpenter (1996) presented observations of the dMe flare star YZ CMi obtained with the Goddard High Resolution Spectrograph aboard the Hubble Space Telescope. The Si iv (λ1393, 1401) lines increased most, while N v (λ1239, 1243), O v (λ1371), and Lyα showed much less enhancement. This trend is similar to the SOLSTICE observations and indicates that the Sun produces events with energetics similar to those of flare stars. It also supports our assertion that this could be the first measurement of the true UV enhancement during the impulsive phase of a large solar flare.

The flare we have studied also appears normal in that the Lyα emission shows an enhancement compatible with previous solar flare observations. This observation corresponds to the end of the very impulsive phase as shown by the HXR and microwave burst in Figure 6, at the time when the particle beams heated the top of the chromosphere after transversing the transition region. This increase is not inconsistent with existing equilibrium flare models of MAVN, Mauas et al. (1990), and Hawley & Fisher (1994). However, we should point out again that some of the differences between enhancements of different lines may be caused by the observation's timing since the scanning spectrometer observed different spectral features with up to 4 minutes time difference.

The enhancement of the He II Balmer alpha at 1640 Å, observed at 09:48:57 UT, may be partially due to the enhanced illumination from layers above the chromosphere. It has been shown by Wahlström & Carlsson (1994) that in the quiet Sun this line has an important chromospheric contribution due to the coronal illumination. However, as a word of caution we note that at our spectral resolution it is hard to separate the He II from the Fe II component nearby, and that if electron densities are high enough the effects of irradiation can be less important.

In summary, the enhancement of the chromospheric lines, and Lyα, are within the range predicted by standard flare models of the postimpulsive phases when quasi-equilibrium has been established. Detailed modeling of these lines in selected flares may be worth pursuing in order to improve diagnostics of the late stages of the flare process.
However, the transition region line emissions that SOLSTICE observed in the impulsive phase are much stronger than those derived from simple arguments. The accurate modeling of these emissions during the early impulsive phase is complicated because of departures from ionization equilibrium due to velocity (or rather compression), and time-derivative terms, and perhaps even some metastable level populations.

The main challenge for models of the impulsive plasma is to account for the enormous, sudden increases in the observed transition-region radiiances. Such increases are hard to explain by usual thermal electron collisional excitation in a 100,000 K plasma because they require too large an increase of the electron and ion densities (about 100 times greater than are present in existing models). Speculative scenarios include (1) that some transition region emissions increase by heating of portions of the chromosphere just before they are evaporated to coronal temperatures, and (2) that an increase of the thermal electron density is caused by the thermalization of electrons from the beam, in which case the electrons would become stopped in the transition region and excite C iv and similar ions before becoming ionized. These speculations have not been fully studied for most flare observations, and after careful considerations they may not apply to this flare.

7. FUTURE FLARE OBSERVATIONS

At present SOLSTICE, and SUSIM (Brueckner et al. 1993), which also measures the solar irradiance, are the only UV instruments capable of observing such large flux enhancements as presented in this paper. Comprehensive amounts of solar observations in the UV are expected from the spectrometers on the SOHO spacecraft launched in 1995 December. Unfortunately, the UV spectrometers on SOHO are not designed for flare observations.

The Solar Ultraviolet Measurements of Emitted Radiation (SUMER) and Coronal Diagnostic Spectrometer (CDS) spectrometers, on board the SOHO spacecraft, will observe the EUV–UV wavelength range from approximately 155 to 1600 Å with high spatial resolution. The detectors on these instruments were designed primarily to observe quiet Sun intensity levels and will not work properly at very large intensities. TRACE is a NASA Small Explorer mission approved for launch in 1997. The instrument will collect images of solar plasma at temperatures from 10^4 to 10^6 K, with 1" spatial resolution (5 times better than Yokoh) and excellent temporal resolution and continuum. Interference filters isolate different UV bands, including C iv lines at 1550 Å, while multilayers are used for the EUV bands. TRACE will be operated in coordination with SOHO and is expected to handle strong enhancements (Golub 1995). This will make the TRACE instrument very useful for future flare studies.

In the near future we plan to operate the SOLSTICE instrument in modes that will observe the impulsive phase of flares. This will be accomplished by either using the quick scan mode or by setting the grating at a selected wavelength/emission line. In the latter case a light curve of that emission line will be recorded. It is also possible to scan over a small wavelength range (e.g., to record the entire Lyα line profile) to achieve high temporal resolution. There is roughly 0.3 Å per grating step, so with an integration time of 1 s the entire Lyα line profile can be captured in 12 s. There is also a possibility to scan with steps every 0.125 s (8 s^{-1}) to increase the temporal resolution. SOLSTICE must maintain its primary observation mode to provide the community with a daily spectrum of the solar irradiance. Thus, we will only use the instrument in this “flare” mode for about half the available observing time. Still, the SOLSTICE instrument, in combination with other instruments, could significantly increase our knowledge about the impulsive phase of flares, especially as we proceed into the next solar maximum period.

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