5.4.4 The Post-Flare Phase

A new phase of flare activity, namely a late, high-altitude, coronal phase, was first identified in SMM data for May 21/22 by Svestka et al. (1982a). Other similar events from SMM were reported by Lantos et al. (1982) and Svestka et al. (1982b and c), and in retrospect some of the large-scale structures observed by Webb and Kundu (1978) probably fall in this category.

Based upon HXIS observations, Svestka (private communication) has estimated that the total energy content of the post-flare arch structures in the 21 May event was between $1.5 \times 10^{39}$ and $4.7 \times 10^{39}$ ergs; the total energy in the analogous structure of the November 6 event was $1.2 \times 10^{31}$ ergs. In both cases, the estimated energies are comparable to the energies of other major flare components. It is necessary in a complete picture of flare energetics to understand the relationship between these manifestations and those of the more well-known flare phases. It is premature, based upon the limited number of events — not all of which may be of the same type — to draw general conclusions yet.

5.4.5 Phenomena in the Distant Corona

Coronal transients, coronal mass ejections, interplanetary shock waves, and the like have an uncertain but important place in flare energetics. These phenomena can be observed by coronagraphs and by meter-wave radio telescopes, as well as by in situ techniques at larger distances from the Sun. The Skylab coronagraph observations provided the earliest comprehensive views of coronal transients (Rust et al., 1980), and observations have continued both in space (SMM and P78-1) and on the ground (notably with the Mauna Loa K-coronameter).

The relationship of these coronal phenomena with classical Hz “chromospheric flares,” or with the high-energy flare events, remains problematical. There is no doubt that major flares often produce major coronal transients, but we have to guard against inferring a causal relationship: the BFS may confuse the picture (Kahler 1982). Indeed the suggested existence of “forerunner” coronal transients (Jackson and Hildner 1978) could imply that the coronal phenomena cause the flare rather than the other way round, and this is consistent with some theoretical views. The relationships are obscured by two major factors: there are only limited quantitative observations in the key inner corona, and in the outer corona there is confusion and uncertainty in the assignment of a given event to a given flare because of overlapping in time. Finally, it is known that coronal transients, especially with low speeds, may arise without the occurrence of a flare (Wagner, 1984). These events tend to fall in the “eruptive prominence” classification.

The energetics analysis of coronal phenomena has not advanced appreciably since the Skylab Workshop treatment (Webb et al., 1980). Among the prime flares studied by the energetics team in this chapter, only one (June 29) had C/P observations. However, even this limb flare was not satisfactory for quantitative energetics analysis because it could not properly be compared with the disk flares in the remainder of our list.

5.5 CHARACTERIZATION OF TOTAL FLARE ENERGY

H.S. Hudson

5.5.1 Statement of the Problem

5.5.1.1 Introduction

The total energy released by a solar flare has a certain distribution in form as well as a certain pattern of flow among the several forms, as described above. As data have grown more comprehensive, the definition of this distribution has improved; classical assessments are found in the works of Ellison (1963), Brueck (1967), Smith and Smith (1963), and Smith and Gottlieb (1975). Most recently the Skylab flare workshop (Sturrock 1980) addressed this question in two surveys of a single well-observed flare on 1973 September 5. These surveys dealt with the radiant energy (Canfield et al., 1980) and the mechanical energy (Webb et al., 1980), and their results have become the definitive data on flare energetics despite acknowledged gaps in coverage and in theoretical understanding.

This section aims at updating our knowledge of this fundamental matter. Unfortunately, there are still limitations in data coverage, as described in detail below. In some areas, notably the X-ray and gamma-ray ranges, there have been striking improvements, as reported above. We summarize the improvements here and take the further step of attempting to fill in the gaps in coverage to estimate the total radiant energy. One purpose for doing this is to permit a comparison of the observed or estimated total with the upper limits derived from the precise total-irradiance monitor (the Active Cavity Radiometer Irradiance Monitor-ACRIM) on SMM.

5.5.1.2 Availability of Data

What are the key limitations in the data set available to us? The foregoing discussions have naturally emphasized the observed forms and have relied on theoretical considerations to bridge the gaps. Where are the largest gaps? We discuss these items briefly here and present recommendations for future observations in Section 5.6.

The most important omissions from the data set fall into two major areas: the radiant energy in optical and EUV wavelengths, and coronal observations of all types. The brightness of the quiet Sun makes the optical wavelengths

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particularly important, since an undetectably small optical continuum (for example) could rival the energy in wavelength ranges for which flares produce greater contrast. The Sacramento Peak observations from the white-light flare patrol show that continuum emission is not the rarity once thought (Neidig and Cliver 1984), and the line emission spectrum may contain even more energy. Even where spectrographic observations exist, these usually have covered only a fraction of the flare area or time profile, so that no definitive knowledge of the distributions even in a statistical sense now exists.

At EUV and XUV wavelengths a similar lack of coverage is striking; even though SMM carried an EUV instrument, its observations were extremely limited in coverage by a lack of imaging capability and appropriate telemetry bandwidth. SMM did not carry an XUV instrument, and so this vital wavelength range was totally omitted from consideration either from the diagnostic or the energetic point of view. Finally, considerable flare energy could appear at infrared wavelengths, but because of the simplicity of the emission mechanisms (H and H-free-free and free-bound continua should dominate), the omission of direct observations is less important than that of the optical and EUV-XUV ranges.

The optical and EUV-XUV data provide us with our best knowledge of the magnetic field distribution. Although vector-magnetograph observations began in a systematic way during the past solar maximum (Hagyard 1984), data that are extensive, precise, and sensitive enough to characterize the field adequately do not exist. As a result, we have only rough knowledge of the system of currents flowing in and around a flaring active region.

More serious omissions occurred in the area of coronal observations. The existing coronal observations have neither the sensitivity nor the diagnostic capability to contribute effectively to determining the key physical conditions in the corona. This is an enormous loss, because the coronal aspects of solar flares (at least in some cases, such as that of the well-documented Skylab flare of 1973 September 5) may dominate the total energy. In addition, the white-light coronagraph on board the SMM provided observations of only one of the well-observed prime flares chosen for detailed study here.

Because of these problems in availability of coronal data, this report does not address the non-radiant energy of a solar flare. This problem is reserved for a future solar maximum.

5.5.2 Techniques for Estimating Radiant Energy

5.5.2.1 Direct Observation

The radiant energy would ideally be determined from a full knowledge of the specific intensity as a function of wavelength, position, and time. Unfortunately, we must deal with integrals or small samples of this abstract function. Since our goal is to define the integral radiant energy in broad wavelength bands, fully detailed spectral information is important only for diagnostic purposes. At the highest energies, the coverage from broad-band soft and hard X-ray and gamma-ray detectors adequately describes the total flare radiation. The very large contrast of flare radiation at these wavelengths makes background subtraction, even for the disk-integrated radiation, relatively simple.

5.5.2.2 Differential Emission Measure (DEM)

Although observations are rarely available for wavelengths longer than about 20 Å, there is generally sufficient diagnostic information to characterize a DEM, as described in Section 5.3.2.1. With such a tool one can turn to a tabulation of the characteristic radiations for a plasma of the proper temperatures and, with assumptions about plasma conditions (abundances and state of equilibrium), estimate the total theoretical luminosities. Cox and Tucker (1969) provided one of the first systematic tabulations of characteristic plasma radiations.

The DEM approach works well enough for the present application at temperatures above a few million Kelvin, and this technique provides a much better characterization of the X-ray emission from flares than was previously possible. Unfortunately, the missing wavelength ranges contain emission lines necessary to define the temperature domain from a few million Kelvin down through the transition region, and so this domain requires an extrapolation to obtain complete coverage.

5.5.2.3 Scaling

For the lowest temperatures, including those responsible for the dominant optical-EUV-XUV radiations, the DEM approach cannot work in principle because the fundamental assumption of this technique, i.e., that the strong resonance lines (and possibly the continuum) are optically thin, is incorrect. For these wavelengths, the only possible route to obtaining energy estimates is through scaling from a well-observed representative wavelength such as Hα. Unfortunately, even the Hα line seldom is observed with simultaneous line profile and imaging data, so that it cannot be used as a reference; furthermore, no detailed studies of the errors induced by the scaling approach exist. Is the rest of the Balmer series inferable from the Hα line alone? Is the line-to-continuum ratio approximately a constant from flare to flare, or across the space or time profiles of a given flare? Is the scaling approach adequate for regions of different morphological class — for example “broad line” and “narrow line” regions — separately? The answers to these questions do not exist at present and will require the accumulation of a more complete data base.
5.5.3 Determination of Radiant Energies

5.5.3.1 Measured Energies of Different Components

For each of the prime flares, Table 5.5.1 gives the total radiant energies derived from the data in different energy or wavelength ranges. These observations do not cover the entire spectrum, as discussed in detail above. The table entries cannot be simply summed because of overlap, for example between the 0.5-4 Å and the 1-8 Å GOES broad-band soft X-ray entries. Suitable optical data were only available for a single flare (1980 November 5). By “suitable” we mean observations of Hα with sufficient spatial, temporal, and spectral coverage to permit a rough estimate of the excess radiation. Such data come either from the Multi-Slit Spectrograph (see Section 5.2) or else from Sacramento Peak CCD observations (e.g., Gunkel et al., 1984), and unfortunately such observations are presently available only infrequently.

The purpose of Table 5.5.1 is to enable us to make intercomparisons among these observable components for these and other solar flares, and to allow us to make comparisons with other, possibly related, phenomena such as stellar flares.

5.5.3.2 Estimates of Total Radiant Energy

With these component radiant energies and the methods described above, we have made estimates of the broad components of total flare energy. These are given in Table 5.5.2, as measured by the three techniques: the direct estimations give the energy above 25 keV; the DEM analysis gives the soft X-ray energy, essentially 1 – 25 keV; and the scaling method gives the optical-EUV-XUV component. The typical uncertainties of these components are, respectively, 50%, 20%, and a factor of 10. For the direct estimates, the uncertainty comes from the photometric accuracy of the X-ray and gamma-ray detectors at higher energies; for the integrated energy above 25 keV this accuracy is dominated by the lack of spectral resolution in the determination of steep spectral distributions. In the soft X-ray region, we have a good check on the accuracy of the DEM approach from the broad-band soft X-ray photometry from GOES data. As noted in Section 5.3, the DEM in the $10^6$ to $25 \times 10^6$K range tends to

**Table 5.5.1 Component Radiant Energies (in ergs)**

<table>
<thead>
<tr>
<th>Date in 1980</th>
<th>Apr 8 03:07</th>
<th>May 21 21:05</th>
<th>Jun 29 18:26</th>
<th>Aug 31 12:52</th>
<th>Nov 5 22:35</th>
</tr>
</thead>
<tbody>
<tr>
<td>SXR Peak Time (UT)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&gt; 1 MeV*</td>
<td>—</td>
<td>$&lt;1 \times 10^{23}$</td>
<td>—</td>
<td>$&lt;1 \times 10^{23}$</td>
<td>$&lt;3 \times 10^{22}$</td>
</tr>
<tr>
<td>&gt; 300 keV†</td>
<td>$&lt;8 \times 10^{21}$</td>
<td>$3 \times 10^{22}$</td>
<td>$&lt;8 \times 10^{21}$</td>
<td>$2 \times 10^{22}$</td>
<td>$8 \times 10^{22}$</td>
</tr>
<tr>
<td>&gt; 25 keV</td>
<td>$1.5 \times 10^{24}$</td>
<td>$1.1 \times 10^{25}$</td>
<td>$1.1 \times 10^{24}$</td>
<td>$1.2 \times 10^{24}$</td>
<td>2.8 $\times 10^{24}$</td>
</tr>
<tr>
<td>0.5 – 4 Å</td>
<td>$1.7 \times 10^{28}$</td>
<td>$9 \times 10^{28}$</td>
<td>—</td>
<td>—</td>
<td>$1.3 \times 10^{28}$</td>
</tr>
<tr>
<td>1 – 8 Å</td>
<td>$1.9 \times 10^{28}$</td>
<td>$6 \times 10^{29}$</td>
<td>$1.0 \times 10^{28}$</td>
<td>—</td>
<td>$8 \times 10^{28}$</td>
</tr>
<tr>
<td>Hα</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>$2.3 \times 10^{29}$</td>
</tr>
</tbody>
</table>

*2σ upper limits based on nuclear gamma-ray line component, only.
†2σ upper limits and values from positive detections based on power-law fits to the observed continuum between 300 keV and 1 MeV, integrated to infinity.

**Table 5.5.2 Total Energies (in ergs) of Component Radiations**

<table>
<thead>
<tr>
<th>Date 1980</th>
<th>SXR Peak Time (UT)</th>
<th>T $&gt;2 \times 10^6$K</th>
<th>Soft X-ray T $&gt;5 \times 10^6$K</th>
<th>T $&gt;10^7$K Scaled T $&lt;2 \times 10^6$K Hard X-rays $&gt;25$keV</th>
<th>Hα</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 Apr 03:07</td>
<td>—</td>
<td>—</td>
<td>$1.1 \times 10^{30}$</td>
<td>—</td>
<td>$1.5 \times 10^{24}$</td>
</tr>
<tr>
<td>21 May 21:05</td>
<td>—</td>
<td>$5.8 \times 10^{30}$</td>
<td>$2.6 \times 10^{30}$</td>
<td>—</td>
<td>$1.1 \times 10^{25}$</td>
</tr>
<tr>
<td>29 Jun 18:04</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>$5.4 \times 10^{22}$</td>
</tr>
<tr>
<td>31 Aug 12:49</td>
<td>$7.4 \times 10^{28}$</td>
<td>—</td>
<td>$3.8 \times 10^{29}$</td>
<td>—</td>
<td>$1.1 \times 10^{24}$</td>
</tr>
<tr>
<td>12:52</td>
<td>$7.6 \times 10^{29}$</td>
<td>—</td>
<td>$4.5 \times 10^{27}$</td>
<td>—</td>
<td>$6 \times 10^{23}$</td>
</tr>
<tr>
<td>5 Nov 22:28</td>
<td>—</td>
<td>$1.3 \times 10^{29}$</td>
<td>$5.1 \times 10^{28}$</td>
<td>—</td>
<td>$3.3 \times 10^{23}$</td>
</tr>
<tr>
<td>22:35</td>
<td>—</td>
<td>$4.0 \times 10^{29}$</td>
<td>$2.9 \times 10^{28}$</td>
<td>$1.8 \times 10^{10}$</td>
<td>$2.3 \times 10^{24}$</td>
</tr>
</tbody>
</table>

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show a bimodal distribution, with one "low-temperature" peak in the vicinity of normal active-region temperatures and one "high-temperature peak" above 10^7 K. Since these are distinctly resolved, we have made separate entries for them. In the rest of the spectrum, there are insufficient data to estimate the uncertainties, and the result has little significance.

5.5.4 Comparison with Total-Irradiance Upper Limits

The radiant energies estimated in Table 5.5.2 could in principle be observed by using ACRIM. A preliminary search for flare effects in the ACRIM data was carried out by Hudson and Willson (1983), with the result that only upper limits could be established. Similar limits appear in Table 5.5.3 for the prime flares discussed above. These limits consist of comparisons between the SMM orbit containing the soft X-ray flare maximum and adjacent orbits; the data themselves appear in Figure 5.5.1. In no case was a significant excess detected. The table expresses the results in terms of 5σ upper limits on total radiant power and energy over the one-orbit interval indicated. Hudson and Willson (1983) give further details on the treatment of data.

Table 5.5.3 Comparison of ACRIM Upper Limits with Total Radiant Energy

<table>
<thead>
<tr>
<th>Date</th>
<th>Time interval (UT)</th>
<th>Power limit (10^{38} ergs s^{-1})</th>
<th>Energy limit (10^{32} ergs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apr 8</td>
<td>02:29 - 03:24</td>
<td>3.2</td>
<td>5.0</td>
</tr>
<tr>
<td>May 21</td>
<td>20:48 - 21:47</td>
<td>2.7</td>
<td>4.4</td>
</tr>
<tr>
<td>Jun 29</td>
<td>18:04 - 19:03</td>
<td>2.1</td>
<td>3.4</td>
</tr>
<tr>
<td>Aug 31</td>
<td>12:34 - 13:31</td>
<td>1.8</td>
<td>3.0</td>
</tr>
<tr>
<td>Nov 11</td>
<td>22:06 - 23:03</td>
<td>2.1</td>
<td>3.4</td>
</tr>
</tbody>
</table>

5.5.5 Conclusions

The estimates of total radiant energy in the prime flares lie well below the ACRIM upper limits. This is consistent with our knowledge of the energy distribution in solar flares. Insufficient data exist for us to be very firm about this conclusion, however, and major energetic components could exist undetected, especially in the EUV-XUV and optical bands. In addition, the radiant energy cannot quantitatively be compared at this time with non-radiant terms because of even larger uncertainties in the latter.

![Figure 5.5.1 Radiant energy measured with ACRIM for 2 hours before and 6 hours after the prime flares listed in Table 5.5.3.](image-url)
5.6 CONCLUSIONS

H.S. Hudson

5.6.1 Introduction

In this chapter we have tried to carry out a detailed accounting of the energy of a solar flare, intending that a clear view of the sources, sinks, and conditions for transport of energy would allow us to obtain a unique insight into the physics of flares. This tool was applied to several “key questions” stated in the introduction to this chapter, and in this section we give the responses to these questions as they appeared to follow from the energetics analysis. Unfortunately, the tool was generally not sharp enough — there are many key data missing from the observations — and the responses to the key questions are in some cases not definitive. As a result we have added a further section below, giving our suggestions for further observations needed to fill in the gaps and to give authoritative answers to the questions at some time in the future.

5.6.2 Responses to Key Questions

5.6.2.1 How Do We Characterize the Impulsive and Gradual Phases?

The classical definition of the impulsive phase depends on the presence of spiky (timescales of < 10 s) hard X-ray bursts (Kane 1969). The presence of this emission correlates well with the occurrence of microwave bursts whose spiky time profile, high polarization, and spectral maximum establish gyrosynchrotron radiation from energetic electrons as the emission mechanism. The microwaves thus serve as an effective substitute for the hard X-rays in defining the time of the impulsive burst.

The microwave spectrum also has an equivalent to the gradual phase, namely the “post-burst increase.” The source of the post-burst increase is identified with the thermal soft X-ray source (Hudson and Ohki 1972). It is clear that this definitely “thermal” region — thermal in the sense of a Maxwellian, although optically thin, plasma — must coexist with the energetic electrons of the impulsive phase. A physically meaningful definition of the gradual phase therefore requires that the two phases overlap. We have therefore adopted this convention in describing flare energetics.

5.6.2.2 Do all Flares Have an Impulsive Phase?

The answer to this question is a qualified “yes,” as judged from the correlation established between hard and soft X-ray occurrence shown in Figure 5.4.1 and 5.4.2. All of the flares considered fall near the correlation line with a scatter of ~0.5 (rms) in the logarithm. At the faint end, flares for which we have only upper limits on hard X-rays may appear to be purely thermal or gradual, but the absence of hard X-rays appears to be no more than a threshold effect within the bounds of the observed correlation.

One should note that a full answer to this question depends on knowing what defines a solar flare. Many flare-like effects appear in different environments, ranging from the photosphere to the middle corona, and extreme cases may exist that have not been selected as data for the correlation plot. It is quite clear that the Hinotori “B” and “C” flare classifications (see Section 5.1.5) represent distinctly different physical phenomena, for which there are different values for the hard/soft ratio.

5.6.2.3 What is the Total Energy Content of the Flare in the Impulsive Phase?

This question is discussed in detail in Section 5.2 and 5B.

5.6.2.4 What is the Relative Importance of the Thermal and Non-thermal Components of the Impulsive Phase of the Flare?

The thermal components of a flare often display a distribution of temperatures. In the later gradual phase, this distribution usually has relaxed into the bimodal emission-measure distribution described above, with peaks at about $3 \times 10^6$ and $15 \times 10^6$K. At earlier times, higher temperatures are best seen in data with high spectral resolution (Lin et al., 1981). During the impulsive phase itself, the hard X-ray spectrum in the 20 to 100 keV range is often well represented by an isothermal, free-free emission spectrum. The same data may be equally well represented by a power law or by a broken power law. The distinction between thermal and non-thermal radiations therefore becomes quite fuzzy if based on the spectrum alone. The inclusion of the microwave data does not help very much, since the key low-frequency emission (i.e., the microwaves produced by the same electron population responsible for the hard X-rays) is optically thick to self-absorption and cannot yield physical parameters inside the source in a model-independent manner. On this basis, the present data alone are not sufficient to provide an unambiguous answer to this question.

One may go beyond the hard X-ray and microwave spectra to clarify the distinction between thermal and non-thermal distributions. Additional evidence from observations include time correlations with other emission such as EUV or white light, correlation with definitely non-thermal processes such as ion acceleration as represented by gamma-radiation; to this we may add insight gained from theoretical knowledge. This need to resort to secondary characteristics has historically resulted in enormous confusion and controversy, and it would be fair to state that at present this controversy continues unabated. The SMM observations and data obtained from other sources do not permit us to present a clear consensus answer to this question. The most likely scenario, however, is given in Section 5.5 of this chapter. The chief
result of this scenario is an answer to the key question under consideration, namely that non-thermal electrons accelerated during the impulsive phase have a dominant energetic role and that the thermal sources of soft X-rays are only one of several subordinate effects produced by this inherently non-thermal energy release.

5.6.2.5 How does the Gradual-Phase Energy Compare with the Impulsive-Phase Energy?

The answer to this question is model-dependent because of the ambiguity of the thermal/non-thermal question. We therefore give two answers in Table 5.6.1 based on the thermal \([E_{th}(>10^6K)]\) and non-thermal \([W(>25keV)]\) impulsive energies and the gradual thermal energies \([E_{th}(>10^7K)]\) given in Table 5.2.7.

From Table 5.6.1 one can see that in the thermal case, the impulsive phase tends to be relatively unimportant and the main flare energy release occurs gradually throughout the duration of the flare. In the non-thermal case, it is possible that the impulsive phase contains a large fraction of the total flare energy.

Table 5.6.1 Ratio of Impulsive to Gradual Energies

<table>
<thead>
<tr>
<th>Date</th>
<th>Time (UT)</th>
<th>Thermal Ratio</th>
<th>Non-thermal Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apr 8</td>
<td>03:07</td>
<td>0.25</td>
<td>3.4</td>
</tr>
<tr>
<td>May 21</td>
<td>21:05</td>
<td>0.13</td>
<td>1.5</td>
</tr>
<tr>
<td>Jun 19</td>
<td>18:04</td>
<td>—</td>
<td>2.9</td>
</tr>
<tr>
<td></td>
<td>18:26</td>
<td>1.6</td>
<td>1.1</td>
</tr>
<tr>
<td>Aug 31</td>
<td>12:49</td>
<td>3.0</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>12:52</td>
<td>—</td>
<td>2.5</td>
</tr>
<tr>
<td>Nov 5</td>
<td>22:28</td>
<td>0.0805</td>
<td>-4</td>
</tr>
<tr>
<td></td>
<td>22.35</td>
<td>0.46</td>
<td>1.2</td>
</tr>
</tbody>
</table>

The “Thermal Ratio” is given by \(E_{th}(>10^6K)/E_{th}(>10^7K)\) from Table 5.2.7.

The “Non-Thermal Ratio” is given by \(W(>25keV)/E_{th}(>10^7K)\) from Table 5.2.7.

5.6.2.6 What are the Dominant Cooling Mechanisms at Different Stages of the Gradual Phase?

The answer to this question depends crucially on the presence of unresolved fine structure in the soft X-ray sources. Decreasing the fluxtube diameter while holding the length and emission measure fixed requires higher densities, thus enhancing the radiative cooling rate. SMM has provided diagnostic evidence for small filling factors, but the observations are not comprehensive enough, nor at high enough spatial resolution, to permit this question to be answered in a model-independent fashion.

5.6.2.7 Do all the Post-Flare Loops Need Continual Energy Input?

In large, two-ribbon flares such as the 1980 May 21 flare, the reduction of the radiative cooling time due to filamentary fine structure would worsen the discrepancy between the observed long cooling time and the predicted shorter time. Thus the SMM data confirm the need for continued energy input in the late phases of such flares, as reported in the Skylab workshop for the classical loop-prominence systems of the gradual phases of such flares. For compact flares, the observational situation is still vague.

The post-gradual phase phenomena found high in the corona after some major flares have an uncertain energetic link with the flare proper. At the other extreme, the “forerunner” of a coronal mass ejection sometimes appears to precede the associated flare. In both of these cases, there are simply insufficient data to understand the direction of energy transport or the forms of energy storage. These phenomena are energetically significant, however, and since they are remote from the flare it would be reasonable to assume that their energy sources are different.

5.6.2.8 Are There Extended, Late, Flare-Associated Sources in the Corona?

Yes, but there is no systematic knowledge of their relationship to the flares because of the lack of observations. They are energetically important.

5.6.3 Worthwhile Observations in the Future

The key questions addressed above are not sophisticated ones, and yet the present data have not proven capable of answering them all unambiguously. We can identify several reasons for this: first, the diagnostic capability of the available techniques is neither great enough nor fully executed in data of moderate resolution, such as those provided by the SMM observations. Second, the emphasis on diagnostic data has resulted in a lack of attention to basic data designed to define the energetics. Third, coronal observations have made insufficient technical progress and certainly have not provided an adequate data base. As a result, our knowledge of the physics of the lower corona above active regions is inadequate to define a correct conceptual model of flare evolution. Finally, the ground-based observatories have only begun to provide data that are sufficiently comprehensive to define morphology and energetics quantitatively. There is
much room for improvement in ground-based observations at optical wavelengths.

As is evident from the ambivalent answers to some of the key questions, the information presently available does not distinguish between thermal and/or non-thermal models of solar flares. To address that fundamental issue, observations are required with sufficient spatial and temporal resolution to distinguish between large thermal plasma volumes, on the one-hand, and beams of energetic electrons which stream through comparably large volumes at speeds of one third or more the speed of light, on the other. These observations must be obtained in the appropriate spectral range to characterize mildly relativistic electrons, from several tens to several hundreds of keV.

Part of the resolution of these problems will come from the high resolution facilities planned for space in the future: the Solar Optical Telescope, the Pinhole/Occultor Facility, and other instruments leading up to the full-fledged Advanced Solar Observatory. However, it is a strong recommendation of this group that there be, in the next solar maximum, a renewed effort to obtain substantially improved ground-based observations at both optical and radio wavelengths.

5.6.4 Final Statement

This chapter has described our approach to understanding flare physics through analysis of the energy transport and storage in flares. Such an approach can only succeed if accurate, comprehensive data exist and can be understood in the context of a correct model for the flare phenomenon. Neither of these requirements has been met, and so the exercise has to be considered a failure. The introduction to this chapter describes the energy storage and flow in terms of the diagrams shown in Figure 5.1.1 and Figure 5.1.2. It would be safe to bet that not one single entry in these diagrams is presently known to better than an order of magnitude. Nevertheless, we feel that the attempt has been worth the effort, since by failing at this basic level to understand solar flares, we bring into question all more sophisticated channels of analysis.

Despite pessimism about our present state of knowledge, there is little doubt that remarkable progress has been made. We expect that a future exercise along these lines, hopefully during the forthcoming solar maximum, will be considerably more successful.

APPENDIX 5A. FLARES CHOSEN FOR THE ENERGETICS STUDY

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5A.0 Introduction

In this appendix we present brief descriptions of the flares which were chosen for the energetics study. A listing of the dates, times, locations, and classifications of these flares is given in Section 5.1 with the rationale for choosing this particular group of flares. More detailed discussions of these flares can be found in Sections 5.2 and 5.3.

5A.1 1980 April 8 at 03:04 UT


This flare occurred in Hale region 16747 (Boulder no. 2372), which had been very active in the preceding days. The region was characterized by two large sunspots of opposite polarity, separated by a small, isolated bipolar area in a delta configuration. The longitudinal magnetic field is shown in Figure 5A.1, which also illustrates how the region changed during the preceding days. The isolated pole moved quite rapidly toward the leading sunspot in the days before April 8, leaving the magnetic neutral line highly deformed, with the transverse component of the field showing high magnetic shear.

The light curve for this flare is shown in Figure 5A.2, which illustrates the behavior of X-rays at 26-53 keV (HXRBS) and at 3.9 keV (BCS Ca XIX). Note that the hard X-ray flux observed before 03:03 UT is believed to originate from a different active region on the west limb, since no increase at that time was observed with the BCS or HXIS in their restricted fields of view. The relatively simple time profiles mask an extremely complex flare with a hierarchy of extended magnetic loop structures which became energized at different times and which had substantial temperature structure. Within the loops there appears to be a continuous evolution of the volumes confining the plasma, coupled with significant mass motions during the first few minutes of the impulsive phase. In fact, the maximum upflow of 310 km s\(^{-1}\) was observed around 03:04 UT, before the sharp increase in hard X-rays. The peak turbulent velocity was 120 km s\(^{-1}\). One question we need to address is whether it is important to the flare energetics to consider the detailed morphology or whether it is adequate to analyze simply the full-flare light curves.

The spatial evolution of the flare as imaged in 11.5 to 16 keV X-rays is presented in Figure 5A.3 from the onset

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