Introduction

B.R. Dennis[1] & A. G. Emslie[2]
[1] *Solar Physics Laboratory, Code 671, NASA Goddard Space Flight Center, Greenbelt, MD 20771* (`brian.r.dennis@nasa.gov`)

[2] *Department of Physics, Oklahoma State University, Stillwater, OK 74078* (`gordon.emslie@okstate.edu`)

STILL NEEDS QUITE A BIT OF WORK, PENDING REVIEW OF OTHER CHAPTERS

1. Historical Perspective

This volume of *Space Science Reviews* contains a comprehensive review of our current understanding of the high energy aspects of solar flares. It is written with the same philosophy as the book on solar flares (Sturrock, 1980b) that grew out of the Skylab workshops. This book is the accumulated wisdom of the many scientists who attended the seven RHESSI science workshops and is intended as a summary of the published literature as of the end of 2007.

Although great progress has been made in understanding the solar flare phenomenon since the *Skylab* report, the basic concepts were well established at that time from the extensive ground-based observations and early space missions. As summarized by Sturrock (1980a), the basic picture of a flare involved the sudden explosive release of the "free" magnetic energy of a current-carrying magnetic field in the corona. During the flare, the energy is released by "somehow" reducing or destroying the currents to convert the field to its lower-energy potential or current-free form. Various energy release mechanisms were considered, including magnetic reconnection, but then, as now, it was recognized that the plasma processes are very complicated and no definitive conclusions could be made on which specific processes were involved.

The acceleration of particles was considered as a primary requirement of any flare model. It was recognized though that there was a serious electron number problem in that the number of electrons required to explain the measured hard X-ray fluxes was a "substantial fraction of the electron content of the corresponding coronal region before the flare." Also, the total power in the 10 − 100 keV electrons (e.g., 2×10^{29} erg s^{-1} in the Aug. 4, 1972 flare) and the total energy contained in these electrons assuming thick-target interactions was known to be an unexpectedly large fraction of the total flare energy (Ramaty et al., 1980). Indeed, Lin & Hudson (1976) had shown that the ∼10 to 100 keV electrons "constitute the bulk of the flare energy," perhaps as high as 10 to 50%.

The thermal or nonthermal origin of the hard X-ray emission was still an ongoing debate in the *Skylab* report. This is still not fully resolved but strong support for the nonthermal electron beam model came with the Yohkoh Hard X-ray Telescope (HXT) images (Sakao, 1994; Sakao et al., 1996) and microwave observations (Kundu et al., 1995). The X-ray images showed the commonality of double footpoint sources and the near simultaneity of their light curves to within a fraction of a second. The stronger X-ray source and the weaker radio source both tend to be located in the weaker magnetic field region, consistent with an electron beam model where magnetic mirroring is significant (Bastian et al., 1998).

The acceleration of ions was also recognized from the gamma-ray observations on OSO-3 (Chupp et al., 1973) and HEAO-1 (Hudson et al., 1978) but their numbers and energy content were not well understood. It required observations made by the Gamma Ray Spectrometer (Forrest et al., 1980) on the *Solar Maximum Mission* in the 1980s to realize that the ions could be accelerated simultaneously with the electrons (Forrest & Chupp, 1983) and that the total energy in ions above 1 MeV/nucleon could be comparable to, or even exceed, the total energy in electrons above 20 keV (Ramaty et al., 1995).

The biggest discrepancy between our current understanding of the flare phenomenon and the Skylab ideas is in the relationship between flares and coronal mass ejections (CMEs). In the Skylab era, CMEs were referred to as coronal transients and it was still questioned if they were "incidental to flares or whether they reveal something fundamental about the energy release process." (Rust et al., 1980). It was not until *The Solar Flare Myth* was exposed by Gosling (1993) that it was realized that CMEs are the major cause of solar effects at the Earth and should be considered as a separate phenomenon independent of flares. This sea-change in our understanding has had far-reaching consequences in the emphasis that has been placed on flare and CME observations. Nevertheless, it is now clear that the largest and fastest CMEs that have the greatest effect on space weather and pose the greatest danger to the nations space assets are mostly (possibly always) associated with large flares of comparable total energy. Indeed, the origins and energy sources of flares and CMEs are so intimately entwined that it is impossible to explain one without understanding the other. Thus, if we are to understand these phenomena and develop predictive capabilities, it is imperative that we still consider them as interrelated phenomena.

2. Review of Flare Models

It was established very early on in flare studies that the source of the energy released in a flare is in current-carrying (i.e., "non-potential") magnetic fields. Not only are flares ubiquitously connected with regions of strong magnetic activity on the Sun (ref.), but an examination of the various candidate sources of energy reveals magnetic energy to be the only plausible contender (Tandberg-Hanssen & Emslie, 1988). Release of the energy stored in the twisted magnetic field configuration proceeds through a process termed *magnetic reconnection*, in which the magnetic field topology is fundamentally changed through breaking and re-tying of field lines. However, what are far less clear, and what to a large extent drives much of flare research, are the geometry of the energy release region, the mechanism that causes the dissipation of the stored energy, and the "trigger" that causes the energy to be released suddenly after many hours or even days of energy buildup without significant dissipation of the energy stored to date.

Sturrock (1980a) has provided a concise, yet thorough, review of the various reconnection scenarios that existed through the end of the 1970s. In fairness, it must be conceded that most of these scenarios are still valid, although many have "fallen out of favor." Perhaps the most significant "casualty" is the model of Gold & Hoyle (1960), which invoked the self-attraction of magnetic loops carrying parallel, or near-parallel, currents, leading to an energy release at their mutual interface. While this laboratory analogy is rather appealing, it unfortunately fails to recognize that it is not currents that attract *per se*, but rather one current interacts with the magnetic field produced by the other. Thus, in the global force-free field appropriate to the low-β solar corona, the current density $\mathbf{J}$ is always nearly parallel to the local magnetic field $\mathbf{B}$, and no $\mathbf{J} \times \mathbf{B}$ force exists. Independent magnetic flux loops therefore have no particular attraction to (or repulsion from) each other, and some external influence (such as a photospheric velocity field; e.g., Heyvaerts et al. (1977)) must be postulated in order to drive them together.

The fundamental reconnection model of Sweet (1969), which invokes reconnection at the interface between two locally potential (i.e., current-free) field lines, has also fallen out of favor somewhat, not so much because of any fundamental inconsistency or flaw, but rather in view of the observations, which show no tendency for the initial energy release to appear at the location suggested by the Sweet geometry. With the availability of concurrent soft and hard X-ray imaging observations, the model that is perhaps most "in vogue" is that of (Tsuneta et al., 1997). This model, suggested by the appearance of hard X-ray sources *above* an underlying system of soft X-ray loops, invokes a reconnection site near the apex of a loop system, which injects energy (e.g., as accelerated particles) into the underlying loops. Although this model does not, unfortunately, account for the vast majority of events, a great deal of effort has been expended in quantitative modeling of such structures. (density of loop-top source, standing shocks in loop legs, etc.)

It was recognized early in the RHESSI workshop series that there was a need to address the physics of magnetic reconnection, and the concomitant acceleration of electrons and ions, *in the context of the observations.* For example, it was recognized early on that "test-particle" approaches to particle acceleration, in which the electric and magnetic fields are *prescribed* and constant in time, do not adequately take into account the fact that the mass, momentum, energy, and electrical current carried by the large number of accelerated particles necessary to account for flare observations must necessarily have a major "feedback" on both the electrodynamic and magnetohydrodynamic environments of the acceleration region. A major emphasis of the "theory team" at the RHESSI workshops was concerned, therefore, with developing acceleration models that explicitly take this "non-test-particle" aspect of the process (Vlahos et al. 2008).

3. Challenges for Simple Acceleration Models

The impulsive phase of a solar flare is characterized, in part, by the emission of a copious flux of hard X-rays (photon energy $\epsilon \gtrsim 10$ keV). It is generally accepted (see however, Section ?? in Kontar et al. 2008) that these hard X-rays are produced by collisional bremsstrahlung (free-free emission) when accelerated electrons encounter ambient protons and heavier ions in the solar atmosphere. The amount of electron energy required to produce these hard X-rays depends on the model used to characterize the interaction of the accelerated electrons with the target. A lower limit is given by a *collisional thick-target* interpretation (Brown, 1971), in which all of the electron energy is absorbed in the target only through Coulomb collisions with ambient particles (primarily electrons). In this interpretation, the ratio of electron power to emitted hard X-ray power is of order 10^5, and this gives an order-of-magnitude estimate for the rate of electron acceleration in the flare. For a large (e.g., GOES X-class) flare, the required rate of acceleration of electrons can exceed 10^{37} s^{-1}, a large number with several interesting consequences (Miller et al., 1997).

First, the number of electrons $\mathcal{N}$ confined in the coronal portion of a flare loop is simply the number density n (cm^{-3}) multiplied by the volume V (cm^3). Inserting typical values $n \sim 10^{11}$ and $V \sim 10^{27}$ gives $\mathcal{N} \sim 10^{38}$, so that the acceleration process would deplete the store of available electrons in some 10 s or so, significantly less than the observed duration of the flare. This simple observation therefore rules out models in which all the electrons to be accelerated are "stored" in a volume prior to the onset of the flare; it instead requires that the acceleration mechanism "recycles" the electrons through the acceleration site(s). Given that electrons in the solar atmosphere have gyroradii of order a centimeter and so are strongly tied to the guiding magnetic field lines, this presents formidable difficulties for current closure of the accelerated electron streams. Although solutions to this problem have been offered (Emslie & Henoux, 1995), they require the synergistic interaction of a large number ($\sim 10^{10}$ or so) separate acceleration regions, and the origin (not to mention stability) of such a system has yet to be adequately explored.

Second, the accelerated electron *number* carries with it an associated *electrical current* of some 10^{18} A (3×10^{27} statamps). In steady-state, such a current, if assumed to propagate unidirectionally in a flux tube of radius 10^9 cm, gives rise, via Ampére's Law, to a magnetic field $B \sim 2 \times 10^8$ Gauss). Not only is such a high magnetic field completely untenable on observational grounds, the associated energy density $B^2/8\pi \sim 10^{15}$ erg cm^{-3}, for a total energy content $\int (B^2/8\pi)\, dV$ of some 10^{42} ergs, some ten orders of magnitude larger than the energy content in a 1000-second duration beam.

Third, a current of this magnitude cannot appear instantaneously. The inductance $\mathcal{L}$ of a structure is of order $\mu_o \times \ell$, where ℓ (m) is the characteristic dimension of the structure. For a solar flare loop, this gives $\mathcal{L} \sim 10$ H. Hence, to initiate a current $I \sim 10^{18}$ A in a time $\tau \sim 10$ s requires a voltage $V \sim \mathcal{L}I/\tau \sim 10^{18}$ V, which is *fourteen* orders of magnitude higher than the typical energy of the accelerated electrons.

Such considerations have led various authors (e.g, Knight & Sturrock (1977); Brown & Bingham (1984); Spicer & Sudan (1984); Larosa & Emslie (1989); van den Oord (1990); Zharkova et al. (1995)) to consider models in which cospatial reverse currents locally neutralize the beam current. However, such models can only produce beam current neutralization in the *propagation* region, and considerable analysis has been performed on the details of the beam/reverse current interaction in this propagation region (van Oss & van den Oord, 1995). However, in the acceleration region itself, return current electrons would have to flow in a direction counter to the applied electromotive force and so cannot neutralize the unacceptably large currents therein. A satisfactory resolution of this issue has yet to be offered, which has led various authors to reject acceleration models featuring large-scale electric fields in favor either of acceleration by very large electric fields in localized current sheets, or stochastic acceleration by MHD and/or plasma waves (Miller, Petrosian).

4. Importance of Hard X-Rays and Gamma-rays as Diagnostics of Accelerated Particles

It is perhaps important to first of all emphasize that the energy released as hard X-rays and gamma-rays is *in and of itself* a negligible component of that released in the flare. The importance of this radiation lies not so much in its energy content *per se*, but rather in the energy in accelerated particles required to produce this diagnostic radiation.

The process of hard X-ray emission is very inefficient. In order to produce a photon by bremsstrahlung (or even by free-bound radiation; see Kontar et al. 2008), an electron must suffer a near-direct collision on an ambient ion. Most electrons rather lose their energy in a large number of small-angle scatterings off ambient electrons, and do not contribute to the bremsstrahlung yield. We may compare the energy emitted through bremsstrahlung to that suffered in Coulomb collisions by comparing the cross-sections for the two processes. The differential cross-section (cm^2 per unit photon energy) for free-free emission of a photon of energy ϵ by an electron of energy E may be, to order-of-magnitude, approximated by the Kramers form

$$\sigma(\epsilon, E) \sim \alpha \frac{r_o^2 mc^2}{\epsilon E}, \tag{1}$$

where $\alpha \simeq 1/137$ is the fine structure constant and $mc^2 = 511$ keV is the electron rest mass. From this it follows that the cross-section (cm^2 keV) for energy loss through bremsstrahlung by an electron of energy E is

$$\sigma_E^B = \int_0^E \epsilon\sigma(\epsilon, E)\, dE \sim \alpha r_o^2 mc^2. \tag{2}$$

By contrast, the cross-section for Coulomb energy loss (cm^2 keV) by an electron of energy E is (Brown 1972; Emslie 1978)

$$\sigma_E^C(\epsilon, E) = \frac{2\pi e^4 \Lambda}{E} \sim \Lambda \frac{r_o^2 (mc^2)^2}{E}, \tag{3}$$

where Λ is the Coulomb logarithm and we have used $r_o = e^2/mc^2$. Taking the ratio

$$\eta = \frac{\sigma_E^B}{\sigma_E^C} \sim \frac{\alpha}{\Lambda} \frac{E}{mc^2} \sim 4 \times 10^{-4} \frac{E}{mc^2} \tag{4}$$

gives the energetic efficiency of the bremsstrahlung process relative to Coulomb collisions. For $E \simeq 20$ keV, $\eta \simeq 1.5 \times 10^{-5}$. For each erg of bremsstrahlung liberated, then, some 10^5 ergs of electrons are needed.

Gamma-rays in solar flares are produced principally by the interaction of accelerated protons and heavier ions with the ambient atmosphere, although electron-ion bremsstrahlung from accelerated electrons can also contribute (Share et al. 2008). Unlike hard X-ray emission, not all gamma-ray emission is prompt – in particular, the capture of neutrons onto ambient protons to create the 2.223 MeV deuterium-formation line can take several minutes because of the need to reduce the momentum of the neutrons to a value where the cross-section for recombination is sufficiently high. The slow speed of the captured neutrons also leads to the extremely small spectral width of the 2.223 MeV line; by contrast, most gamma-ray lines (e.g., the prompt nuclear de-excitation lines of Carbon [6.1 MeV] and Oxygen [4.4 MeV]) exhibit a relatively broad spectral profile, indicative of the energy of the ions that excite them.

RHESSI not only provided gamma-ray spectra with unprecedented spectral resolution (Smith et al., 2003), but also, on a few occasions, *images* of the gamma-ray line emission (in particular, in the 2.223 MeV line; Hurford et al. (2003)). These pioneering observations are discussed in more detail in Share et al. (2008).

Some time after the publication of the *Skylab* volume, study of observations from the *Solar Maximum Mission* Gamma-Ray Spectrometer (GRS) (Share & Murphy, 1995) led solar physicists to realize that the spectra of the accelerated ions could remain steep down to energies $\approx$ 1 MeV, and hence that the *energy content* of accelerated ions in solar flares, as revealed by their gamma-ray emission, could rival that of the accelerated electrons, hitherto thought to dominate the energy budget of accelerated particles. Further study of the relative partitioning of energy between accelerated electrons and ions was carried out by Emslie et al. (2004), who reached similar conclusions. Further discussion of the partitioning of flare energy amongst its constituent parts can be found in this volume (Fletcher et al. 2008).

5. RHESSI Design and Capabilities

RHESSI (Lin et al., 2002) uses nine cooled and segmented germanium detectors to achieve high-resolution X-ray and gamma-ray spectroscopy across the full energy range from 3 to 17 MeV (Smith et al., 2002). The FWHM energy resolution increases from $\sim$1 keV at the lowest energies to $\sim$ 10 keV at the highest. This has proved adequate to detect the iron-line complex at $\sim$ 6.7 keV, measure the steep hard X-ray continuum spectra with accuracies as fine as 1%, and resolve all of the narrow nuclear gamma-ray lines except for the intrinsically narrow neutron-capture line at 2.223 MeV. A bi-grid tungsten collimator over each detector modulates the incident photon flux as the spacecraft rotates at $\sim$ 15 rpm to provide the temporal information needed for the Fourier-transform technique that is used to reconstruct the X-ray and gamma-ray images (Hurford et al., 2002). Imaging is possible at all energies with an angular resolution as fine as ~ 2 arcsec up to ~ 100 keV and ~ 35 arcsec in the gamma-ray range. When the count rates are sufficiently high, images can be be made routinely in the hard X-ray domain with 4-s cadence and in the 2.223 MeV neutron-capture line. The field of view is ~ 1 deg such that a flare can be imaged no matter where on the visible disk it occurs. RHESSI has an effective sensitive area that reaches ~ 60 cm^2 at 100 keV. Two thin aluminum disks can be automatically moved above each detector to attenuate intense soft X-ray fluxes so that RHESSI can handle flares without detector saturation over a very wide dynamic range from microflares with the attenuators removed to the largest X10 flares with both attenuators in place over each detector.

RHESSI was launched on 2002 February 5 and has been in operation almost continuously since that time. As of 2007 July 13 , it has detected over 36,000 hard X-ray flares in the 12 - 25 keV energy range with many more at lower energies. A total of 117 flares reached the 50-100 keV energy range as listed in the online catalog at
http://hesperia.gsfc.nasa.gov/hessidata/dbase/hessi_flare_list.txt
and ~ 10 showed significant gamma-ray line emission.

5.1. OTHER OBSERVATIONS

Many complementary flare, CME, and in situ particles and field observations have been made with other instruments during the RHESSI operational lifetime. Instruments on other spacecraft and at ground-based observatories around the world have been active participants in providing the magnetic, thermal, and dynamic context in which the X-ray and gamma-ray sources are produced. In addition, microwave observations of the gyrosyncrotron emission provide additional information on the accelerated electrons themselves. Coronagraph observations of CMEs, and in situ particle and field measurements in the near-Earth environment, also provide information that can be used to establish the links between these related phenomena and any associated flares.

A partial list of all collaborating space-based observatories with links can be found on the Max Millennium web site at
http://solar.physics.montana.edu/max_millennium/obs/SBO.html
They include ACE, Cluster, Coronas, GOES, HXRS, INTEGRAL, SOHO, TRACE, and WIND. They have provided X-ray, EUV, UV, optical, and in situ particle and field measurements relevant to the many events recorded by RHESSI. A partial list of all collaborating ground-based observatories can be found on the Max Millennium web site at
http://solar.physics.montana.edu/max_millennium/obs/GBO.html.

They have provided optical observations of all types in white light, Hα, and other wavelengths; magnetograms; radiograms; and polarimeters.

Thanks to the daily email messages and the coordinating efforts of the Max Millennium program
(http://solar.physics.montana.edu/max_millennium/),
many collaborative observing campaigns have been conducted to maximize the overlap of the various observatory programs.

6. Outline of The Volume

The current volume consists of a series of articles, each representing the work of several authors. The purpose of each article is to present a review of the pertinent subject matter, linking the results of a variety of published works into a coherent whole, which we hope is useful both for the reader who wishes an overview of contemporary knowledge in the area, and for the experienced researcher to view results in context. Rather than occupy space with detailed developments, each article presents the essential results of already-published literature, particularly in the context of other work, and provides a comprehensive reference list for the reader who seeks more detailed developments or information. Each chapter is indexed, and a composite index appears at the back of this volume.

Chapter 2 (Fletcher et al.) summarizes the overall characteristics of a solar flare, as determined from observations at a variety of wavelength ranges. The inter-relationship of the various observations are discussed, and they are synthesized into a global picture of the flare phenomenon, complete with a discussion on the partition of the energy released in the flare into the various manifestations of flare activity.

Chapter 3 (Holman et al.) focuses on the physics of flare-accelerated electrons, their energy and angular distributions. It is important to note that for the purposes of this article, the electron distribution function $F(E, \mathbf{r}, \Omega)$ (where E is the electron energy, $\mathbf{r}$ a spatial location, and Ω an element of solid angle) is assumed known; the more mathematical determination of $F(E, \mathbf{r}, \Omega)$ from observations of count spectra and images is deferred to Chapter 7 (Kontar et al.)

Chapter 4 (??) discusses the inference and implications of accelerated ion spectra in solar flares.

Chapter 5 (White et al.) discusses various aspects of flares observed in the radio domain, and the relation of these results to those in other articles in this volume.

Chapter 6 (Hannah et al.) discusses properties of flares that are obtained by viewing an ensemble of flare events from a statistical perspective.

Chapter 7 (Kontar et al.) discusses the various methodologies through which the electron distribution function $F(E, \mathbf{r}, \Omega)$ is determined from spectroscopic (and in some cases imaging spectroscopy) observations.

Chapter 8 (Vlahos et al.) summarizes the salient features of flares presented in the other articles, and the impact of these results on theoretical models for energy release, and particle acceleration, propagation, and interaction.

Finally, in Chapter 9 (Lin), the overall results are summarized and prospects for future research offered.

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