CHAPTER 3: IMPULSIVE PHASE TRANSPORT

Richard C. Canfield, University of California, San Diego
Francoise Bely-Dubau, Nice Observatory
John C. Brown, University of Glasgow
George A. Dulk, University of Colorado
A. Gordon Emslie, University of Alabama in Huntsville
Shinzo Enome, Nagoya University
Alan H. Gabriel, Rutherford Appleton Laboratory
Mukul R. Kundu, University of Maryland
Donald Melrose, University of Sydney
Donald F. Neidig, Air Force Geophysics Laboratory
K. Ohki, Tokyo Astronomical Observatory
Vahe Petrosian, Stanford University
Arthur Poland, Goddard Space Flight Center
Erich Rieger, Max-Planck-Institut fur Physik und Astrophysik
Katsuo Tanaka, Tokyo Astronomical Observatory
Harold Zirin, California Institute of Technology

3.1 INTRODUCTION

3.1.1 Motivation for Transport Studies

In the astrophysics community, ‘the solar flare problem’ is generally considered to be how to accumulate sufficient magnetic energy in one active region and to subsequently release it on a sufficiently short time scale. Satisfactory solution of the solar flare problem will require at least two achievements by the solar physics community: first, convincing theoretical demonstration that one or more mechanisms of energy storage and release can occur; second, convincing observational demonstration that one (or more) of these theoretical processes actually does occur in the solar atmosphere. The contents of this Chapter essentially relate to the second problem, being largely concerned with how the energy released from magnetic form is transported through the solar atmosphere before escaping in the form of the radiant and mechanical energy signatures which we must interpret.

A central point of general agreement concerning all mechanisms suggested for dissipation of magnetic energy in flares is that the actual sites of reconnection must involve scale lengths well below currently, or forseeably, achievable spatial resolution. Consequently, observational evidence in support of a flare theory is necessarily indirect, in the sense of not involving measurement of plasma parameters in the primary dissipation regions. Such indirect evidence may be of several kinds. Firstly, circumstantial evidence may be obtained by spatial resolution of the geometry, on a larger scale, of the magnetic environment in which the mechanism operates. This may permit distinction between such options as emerging flux models and twisted arch models or between mechanisms driven by currents parallel to the magnetic field, as opposed to perpendicular. Spatial resolution also permits mapping of the paths of flare products. Secondly, temporal evidence can be obtained by use of high time resolution to set limits on instability growth rates, to imply the occurrence of repetitive or multiple dissipation, to indicate the production sequence of the various flare manifestations and, by causality arguments, to set an upper limit to the size of the primary dissipation site. Thirdly, thermodynamic evidence on the nature of primary dissipation is obtainable from the distribution, particularly in the impulsive phase, of the flare energy release over its various modes, i.e. fast particles, conduction etc. For example the Petscheck mechanism releases a major fraction of the magnetic energy directly into bulk mass motion while the tearing mode initially results chiefly in plasma heating and particle acceleration.

Transport of energy away from the primary sites, and its ultimate thermalization, depend not only on the primary mechanism itself but also on the larger-scale structure of the active-region atmosphere in which the transport occurs. Consequently the study of energy transport as a diagnostic of flare mechanisms involves extensive theoretical modeling of the transport processes, as well as observational input, to provide the framework for interpreting the observations. Use of such transport studies to infer properties of the initiating disturbance is essentially an inverse problem, and so carries the danger of indeterminacy through mathematical ill-posedness. For example, the thermal structure of a conductively evolving atmosphere rapidly becomes only very weakly dependent on the heating function which initiated it, and so is a poor signature of this function. In such situations, the best strategy is to utilize jointly as many as possible independent signatures of the process to minimize indeterminacy. It is just such a combination of independent signatures of the flare process (much more compelling when taken together) that the coordinated observational approach of SMM has rendered possible.

In addition to these flare-oriented objectives, of course, the study of flare energy transport has contributions to make to the broader field of transport studies per se, such as in plasma and atomic physics.

3.1.2 Historical Perspective

Energy transport studies have become an increasingly prevalent means of investigating solar flares since around 1970 with the accompanying steady improvement in observational coverage and resolution in space, time, and spectrum, from the start of the Orbiting Solar Observatory (OSO) period onward. By the time of the Skylab Apollo Telescope Mount (ATM), considerable progress had been made toward obtaining the instrumentation needed for acquisition of high resolution data over as wide as possible a variety of
wavelengths from optical to γ-rays. Thus the ATM package achieved spatial resolution of the order of arc seconds in the soft X-ray and ultraviolet ranges together with extensive UV line spectroscopy. Contemporarily though not simultaneously, other satellites (notably ESRO TD1A, OSO-7 and the Intercosmos series) were improving the quality of hard X-ray measurements and extending the spectral range upward in energy resulting in the detection of solar γ-ray lines. Though ATM itself was never designed as a flare mission it nevertheless made major contributions to progress in flare observations, in addition to its pioneering discoveries in relation to solar coronal structures and active regions (cf. Zirker 1977, Orrall 1981). In particular, ATM established the importance of loop structure in the magnetic configuration of many flares, and the compactness of bright XUV flare kernels. In addition, the use of ATM for flare studies (Sturrock 1980) delineated the limitations of such a package for answering some of the key questions concerning flares, and thereby provided important guidelines for the planning of subsequent missions, especially SMM.

The most important obstacles to progress before the launch of SMM were the lack of data of sufficiently high time resolution, the lack of data sufficiently early in (or prior to) the flare, and the lack of data coordination over a wide enough spectral range (Brown and Smith, 1980). Examining ATM in the light of these obstacles, we can see with hindsight that ATM did not respond sufficiently quickly to enable systematic studies of flare onset or impulsive phases. During ATM much information on flare spatial structure was recorded photographically in most characteristically ‘thermal’ wavebands — from optical to soft X-rays — with resulting limitations on time resolution, on simultaneous spectral coverage, and on calibration. Typically ‘non-thermal’ emissions such as hard X-rays, γ-rays, and microwaves were recorded with comparatively low sensitivity, and little or no coordination with the ATM experiments. A typical consequence of these problems was that testing of electron heated models of flare atmospheres involved construction of a spectroscopic model atmosphere from data obtained from a variety of places in a variety of flares, and use of hard X-ray data, devoid of spatial information, from yet different flares.

By contrast, SMM formed a coordinated package of instruments dedicated to study impulsive phase phenomena at high time resolution using pre-planned targets and automated response to flare onset triggers. In addition, the spacecraft carried short wavelength instruments of unprecedented sensitivity and time resolution (the Gamma-Ray Spectrometer, GRS, Forrest et al., 1980, and the Hard X-ray Burst Spectrometer, HXRBS, Orwig et al., 1980) and spatial resolution (the Hard X-ray Imaging Spectrometer, HXIS, van Beek et al., 1980) and the facility for high resolution atomic X-ray line Spectroscopy (the Soft X-ray Polychromator, XRP, Acton et al., 1980), with digital data recording, as well as the Ultraviolet Spectrometer and Polarimeter (UVSP, Woodgate et al., 1980). Furthermore, the package was supported by a wide range of other spaceborne instrumentation and an international network of ground based observations coordinated through the SMY (Svetstka, Rust, and Dryer 1982). Ground support included rapid arc-second resolution in both microwaves, by the VLA, and in spectrally resolved optical lines by the Sac Peak Vacuum Tower. Hard X- and γ-rays were still observed without spatial resolution but with such sensitivity as to permit close temporal correlation with features in the longer wavelength images, as well as γ-ray nuclear abundance spectrometry with some simultaneous millimetric coverage at ultra high time resolution by Itapetinga. On the debit side, SMM was limited in soft X-ray spatial resolution compared to ATM, and in the restricted range of UV spectral coverage, of particular importance in modeling transition-region lines.

A significant contribution to our knowledge of impulsive-phase transport has come about as a result of the post-SMM launch of the Japanese Hinotori spacecraft, whose flare instruments (Solar Gamma-Ray Detector, SGR, Hard X-ray Monitors, HXM and FLM, Imaging X-ray Telescope, SXT, and Soft X-ray Crystal Spectrometer, SOX) are described by Kondo (1982). Early Hinotori results have been described in the Hinotori Symposium on Solar Flares (Takada et al., 1982) and Recent Advances in the Understanding of Solar Flares (Kane et al., 1983); later Hinotori results play an important role in this chapter.

In addition to the observational requirements already mentioned, there is obviously a need for improved theoretical modeling, particularly in the direction of making predictions which would be testable in terms of realizable data (Brown and Smith, 1980). The post-ATM period has indeed seen a major increase in the amount and sophistication of flare modeling work, particularly in respect of relaxation of earlier simplifying assumptions (such as hydrostatic equilibrium and optical thinness) in describing the atmospheric response, and of basic electrodynamic and plasma collective effects on the transport of charged beams.

The perceptive reader will find that many of the questions posed in the Skylab era have been answered in this chapter. Kane et al. (1980), in the impulsive phase chapter of Solar Flares: A Monograph from Skylab Solar Workshop II (Sturrock, 1980), posed three key questions:

1. Is the distribution of energetic electrons thermal or nonthermal?
2. Do the energetic particles (electrons), produced during the impulsive phase, provide the energy for the whole flare?
3. Among the models of the impulsive phase suggested so far, which ones are most consistent with observations?

The answers to these questions are fundamental to our understanding of space plasmas; if the models that are best supported by the observations require particle acceleration efficiencies ≥ 0.1% (Hudson, 1979), a substantial challenge is presented to the solar flare theorist.
Our work answers primarily the first and third questions, while the second motivated the Solar Flare Energetics group. Certainly there are still major gaps in our theoretical understanding of how energy is propagated by electron beams, as well as our observational understanding of spatial, temporal and spectral scales. However, one impulsive phase transport model now stands out above all others: the nonthermal-electron thick-target model, in which the dominant role in the transport of energy on impulsive-phase timescales (usually \(\lesssim\) tens of seconds) is played by beams of electrons, mostly in the deka-keV range, whose velocity distribution function cannot be described by a single-temperature Maxwellian. These electrons are guided along a loop-like magnetic field structure, from an acceleration site in the corona; they heat and cause both thermal and nonthermal emission as they are fully thermalized in the loop plasma, a thick target. The reader should not get the impression that this model describes all flare energy transport, particularly on longer timescales, or that the nonthermal-electron thick-target model passes all the observational or theoretical tests we impose upon it below. Surely there is ample evidence for the impulsive-phase existence of nonthermal particles other than electrons, for example, and for thermal domination of later flare phases. However, our preoccupation with the nonthermal-electron thick-target model in this chapter is testimony to our finding that, of the models available, it does the best job of explaining the wide variety of impulsive-phase observations we have studied.

### 3.1.3 Overview of the Chapter

Some of the most striking recent results have come from observations in the highest energy ranges. Interpretation of SMM \(\gamma\)-ray line data has established the presence of protons (\(E \gtrsim 10\) MeV) in regions of density \(\gtrsim 10^{13}\) cm\(^{-3}\), while the ISEE-3/PVO occultation data demonstrated that electrons of \(E \gtrsim 150\) keV are stopped deep in the chromosphere. Both these results suggest a thick target beam interpretation, in which the radiation is generated in the course of fully stopping the particles, in the lower solar atmosphere. On the other hand, ISEE-3/PVO data surprisingly show very little directivity at 350 keV, contrary to purely collisional transport models of the electron beam. Most notable of all high energy data is the striking demonstration, from limb brightening studies, that directivity is present in the continuum around 10 MeV.

The first-ever images in the deka-keV range (10 – 100 keV) stimulate much of the work of this Chapter. While there remains considerable debate over their implications for theoretical models (in particular beams), the presence in some flares of impulsive hard X-ray footpoints, coincident in time and space with chromospheric emissions, has been clearly established by SMM and Hinotori. Hinotori results have also been used to suggest a provisional classification of hard X-ray flares, of which footpoint events are only one class. Simultaneous microwave data have permitted comparative morphology studies of hard X-rays and microwaves with resulting constraints on the electron and magnetic field distributions. Computations of hard X-ray polarization incorporating the effects of magnetic field curvature show that even the most recent low polarization results from Shuttle experiments are not incompatible with a beam model.

While the greatly improved spatial and temporal resolution and coordination of SMM data in the hard X-ray and EUV further support the view that these radiations have closely related origins, the relationship between the fluxes in these bands remains a theoretical enigma in terms of energy balance.

The inclusion of high resolution X-ray spectroscopy allowed detailed diagnostics of the hot plasma during the onset of the thermal phase, using recent developments in the atomic physics of dielectronic satellite spectra. Line profiles and shifts enabled the determination of turbulent energy content and upward velocities during the impulsive phase, resulting from the chromospheric evaporation process. Observations of X-ray and \(K\alpha\) line excitation, together with data on the soft X-ray plasma as a whole and on the hard X-ray source electrons, have demonstrated that electron beam excitation is not essential to explain the \(K\alpha\) observations, though not precluded by it.

Improved calculations of the production of the nonthermal red shifted \(L\alpha\) line by capture processes on a descending proton beam have placed severe constraints on the flux of such beams and hence on flare models where protons play a central role energetically and in which there has been renewed interest recently.

At the time of ATM, white light flares were still regarded as a rare phenomenon suggestive of an exotic explanation. Studies with improved observational methods have shown that they are in fact of common occurrence. Coordinated temporal, spatial, and spectral information shows that the impulsive phase white light emission is spectrally compatible with a chromospheric origin, and temporally and energetically compatible with a thick-target electron beam as the power supply.

Interpretation of \(H\alpha\) profiles represents a particularly good example of the progress SMM achieved toward the ideals of rapid response, data coordination, and detailed modeling. Full radiative transfer models of the flaring chromosphere have permitted comparison on a pixel by pixel, instant by instant basis of \(H\alpha\) profiles observed at Sacramento Peak with those predicted according to chromospheric evaporation models driven respectively by thick target electron beams (observed by HXIS) and by thermal conduction. Results provide direct evidence in support of electron beam heating in some bright \(H\alpha\) kernels.

Finally, prior to the SMM era decimetric radio waves were considered to be a plasma diagnostic emission of little importance energetically. At this time serious consideration
is being given to their role in heating both the corona (by reabsorption) and the chromosphere (by electron precipitation) in flares where conditions favor the onset of coherent amplification of these radio waves. The full ramifications of this process for flare energy transport are only now beginning to be appreciated.

3.2 IMPULSIVE PHASE OBSERVATIONS AND THEIR INTERPRETATION

3.2.1 Gamma-Ray Emission Above 10 MeV.

Photon emission above 10 MeV during solar flares was observed by the Gamma Ray Spectrometer (GRS) on board SMM. As of February 1984 the highest energy photons detected, energy \( \sim 80 \) MeV, came from an intense flare on June 3, 1982. In this contribution we discuss the timing between hard X-rays and gamma rays and present evidence for directivity of the highly energetic particles that give rise to the emission above 10 MeV.

3.2.1.1 Relative Hard X-ray and Gamma-Ray Timing

As a typical example we show in Figure 3.1 the time history of the flare of June 15, 1982 in different energy bands. The event has a simple time structure consisting mainly of one impulsive burst. The peak of the emission is simultaneous within \( \pm 2 \) sec over more than three decades of energy from 30 keV - 50 MeV. The hard X-ray flux shown in the upper two panels is assumed to originate from electron bremsstrahlung. The emission from 4.1 - 6.4 MeV (the nuclear energy band) is from nuclear lines and from bremsstrahlung of relativistic electrons (Forrest 1983). At energies greater than 10 MeV the gamma rays are expected to be produced by bremsstrahlung of very highly energetic electrons and by the decay of pions (\( \pi^0 \) and \( \pi^+ \)), because the contribution of nuclear lines above 8 MeV is negligible (Crannell, Crannell, and Ramaty, 1979). The relative importance of the two processes for solar flares is discussed by Ramaty et al. (1983) and by Rieger et al. (1983).

Until February 1984, 14 flares were observed with emission above 10 MeV. Their time history has the following general characteristics: They are of short duration (\( \sim 1 \) min) and very impulsive. Rise and fall times are on the order of seconds. They exhibit single or multiple peaks. The peak emissions of the hard X-ray and gamma rays are simultaneous within about \( \pm 6 \) sec. There is no systematic delay of the gamma rays with respect to the X-rays.

Because of the simultaneity of the gamma- and X-rays, the energy loss of the highly energetic particles (electrons and/or ions) has to take place at ambient densities \( > 10^{13} \) cm\(^{-3}\), if we assume a thick target situation (Bai and Ramaty 1976).

![Figure 3.1 Time history of the flare of June 15, 1982 in various energy bands.](image)

3.2.1.2 Directivity of Highly Energetic Particles

The flares with photon emission above 10 MeV are at heliocentric angles of \( > 60^\circ \) (Rieger et al., 1983). This is shown in Figure 3.2, where the location of the flares, known from Hα observations (NOAA: Solar Geophysical Data) is plotted. The arithmetic mean heliocentric angle of all 14 flares is 79°. If the radiation is isotropic the probability for a chance coincidence of such a distribution is \( \sim 2 \times 10^{-7} \). Therefore we conclude, that this "limb brightening" is the result of directivity of the radiation. This directivity must exist also in the primary highly energetic particles, because photons with energies above 10 MeV, if created by electrons (>10 MeV) via bremsstrahlung or by protons (>100 MeV) via pion decay, are emitted preferentially in the direction of the motion of these particles. At this time the most likely interpretation appears to be that the emitting particles are indeed travelling roughly normal to the sun-center direction (J. Cooper and V. Petrosian, private communication), as if they were near their mirroring point, for example.

To study this phenomenon in more detail it would be necessary to make stereoscopic observations with two de-