Chapter 10

Concluding Remarks

Now it is time to step back and review this work. Here we recapitulate our motivation and highlight our conclusions. We then comment on directions for future investigations.

10.1 Summary and Conclusions

We have carried out an investigation of acceleration and transport of particles in solar flares, and their thermal and nonthermal radiative signatures, using both HXR data analysis and combined Fokker-Planck and hydrodynamic (HD) modeling. This research focuses on solar flares because they provide a unique laboratory for us to understand particle acceleration mechanisms which have far-reaching implications, not only for solar and space physics in particular, but also for astrophysics in general. We summarize here our conclusions and their implications in the context of contemporary flare research as follows.

10.1.1 Hard X-ray Observations

Our observational efforts utilized HXR data obtained by the currently active *RHESSI* mission and focused on spatial, temporal, and spectral variations of the LT and FP emissions.

1. In the stochastic acceleration (SA) model, the LT emission comes directly from the accelerated electrons and the FP emission is produced by escaping electrons. The emissions of the two sources are related and can thus be used to constrain the SA model parameters. We have carried out a preliminary **statistical study** of 29 limb flares, which have minimal projection effects, and obtained the relative spectra and fluxes of the LT and FP sources. As presented in *Chapter 2*, for the LT and FP sources, respectively, we find an average spectral index of $\bar{\gamma}_{\rm LT} = 6.84$ and $\bar{\gamma}_{\rm FP} = 3.35$, with a large difference which could, in principle, be explained by the SA model. However, the spectral indexes (of a given flare and from flare to flare) do not seem to be correlated. This is not expected, but not surprising either because of the complexity of the exact physical processes involved. This statistical study has also led us to identify four flares of special interest for further investigations, each of which presents *evidence* of particular aspects as well as imposes *challenges* for the classical reconnection model of solar flares.

2. In the classical flare model, magnetic reconnection takes place at lower altitudes first and then progresses to higher overlying loops. In this picture, one would expect that the

FPs separate while the LT source moves up with time. However, such a **correlated motion** of the different sources was rarely observed *simultaneously* in the past, although either a rising LT or two separating FP sources have been reported. We have shown in *Chapter 3* an excellent example of such a picture. The 2003 November 03 X3.9 flare, unlike many other complex X-class flares, shows a very simple morphology with a well-defined LT and two FP sources. The almost monotonic upward motion of the LT source and the increase of separation between the two FPs at comparable speeds are exactly what are expected. In addition, we find that the source motions are relatively slower during the more active phases of HXR emission; the emission centroid of the LT source shifts toward higher altitudes with increasing energy; the separation between the LT emission centroids at two different photon energies is anti-correlated with the FP flux. Non-uniformity of the reconnecting magnetic fields could be a possible explanation of these features.

3. Outflow jets of high speed plasmas and associated turbulence, in the classical 2-D picture of magnetic reconnection, is present in opposite directions along the current sheet. Accelerated particles and heated plasmas are expected to be present in both directions as well. During the impulsive phase, we have commonly observed *one* LT source. A **double-coronal-source** structure has only been observed recently by *RHESSI* in a few flares (Sui & Holman, 2003; Sui et al., 2004; Veronig et al., 2006; Li & Gan, 2007) which show an additional, weaker source above the common LT source. Due to the faintness of the additional source, its spectrum has not been studied in these flares. We discovered another yet stronger case of such a double-source morphology in the 2002 April 30 flare, in which the upper source is relatively bright and long-lived, and imaging spectroscopy can be obtained to infer its spectrum and light curve. Another advantage of this event is that the FPs are occulted and thus they do not contaminate the LT emission at high energies. Analysis of this flare has been presented in *Chapter 4*. We find that the two coronal sources, observed over the 6–30 keV range, appear at different altitudes and show energy-dependent structures with the higher energy emission being closer together (also see Sui & Holman, 2003; Sui et al., 2004). Spectral analysis implies that the emission at higher energies in the inner region between the two sources is mainly *nonthermal*, while the emission at lower energies in the outer region is primarily *thermal*. The two sources are both visible for about 12 minutes and have similar light curves and power-law spectra above about 20 keV. These observations suggest that the magnetic reconnection site lies between the two sources. Bi-directional outflows of the released energy in the form of turbulence and/or particles from the reconnection site could be the source of the observed radiation. The spatially resolved thermal emission below about 15 keV, on the other hand, indicates that the lower source has a larger emission measure but a lower temperature than the upper source. This is likely the result of the differences in the magnetic field and plasma density of the two sources. For the lower source, the separation between the centroids of the emission at different energies seems to be anti-correlated with the HXR light curve, which is consistent with our earlier finding mentioned above (see Chapter 3).

4. Magnetic field measurement in a flare region, in general, can provide clues of magnetic reconnection, while HXR data contains useful information of accelerated particles. Both types of observations, if available, can be combined and used to uncover the relationship between particle acceleration and magnetic reconnection development. In *Chapter 5*, we have examined the FP HXR emission together with the associated magnetic field in the

2003 October 29 X10 flare. This event occurred close to the disc center and thus had minimal projection effects for the line-of-sight magnetic field which can be obtained from *SOHO*/MDI. We find that there are two well-defined conjugate FPs showing **unshearing motions**, **various correlations**, **asymmetric characteristics**. (1) The double FPs first move toward and then away from each other, mainly parallel and perpendicular to the magnetic neutral line, respectively. The transition of these two phases of FP *unshearing motions* coincides with the direction reversal of the motion of the LT source, and with the minima of the estimated loop length and LT height. (2) The FPs show temporal *correlations* in HXR flux, spectral index, and magnetic field strength. The HXR flux exponentially correlates with the magnetic field strength which also anti-correlates with the spectral index before the second HXR peak's maximum, suggesting that particle acceleration sensitively depends on the magnetic field strength and/or reconnection rate. (3) *Asymmetries* are observed between the FPs: on average, the eastern FP is 2.2 times brighter in HXR flux and 1.8 times weaker in magnetic field strength, and moves 2.8 times faster away from the neutral line than the western FP; the estimated coronal column density to the eastern FP from the LT source is 1.7 times smaller. The two FPs have marginally different spectral indexes with their mean values of $\langle\gamma\rangle = 3.63 \pm 0.06$ vs. 3.79 ± 0.11. The eastern-to-western FP HXR flux ratio and magnetic field strength ratio are anti-correlated only before the second HXR peak's maximum. Neither magnetic mirroring nor column density *alone* can explain these observations when taken together, but their combination, together with other transport effects (including non-uniform target ionization, relativistic beaming, albedo, and return currents), may play a role.

5. **Chromospheric evaporation** is a consequence of energy deposition by electrons in the lower atmospheres and it is usually observed by blue-shifted line emissions. Such observations, in a sense, are indirect evidence of chromospheric evaporation, because the mass motion is not directly imaged. The superior capabilities of *RHESSI* enabled us to remedy this shortcoming with the observation of the M1.7 flare of 2003 November 13, which shows some unusual spatial evolution and provides direct evidence for chromospheric evaporation. Analysis of this flare is presented in *Chapter 6*. We find that, as expected, the LT source dominates at low energies, while the FP sources dominate the high-energy emission. At intermediate energies, both the LT and FPs may be seen, but during certain intervals emission from the legs of the loop dominates, in contrast to the commonly observed LT and FP emission. The HXR emission tends to rise above the FPs and eventually merge into a single LT source. This evolution starts at low energies and proceeds to higher energies. The spectrum of the resultant LT source becomes more and more dominated by a thermal component with an increasing emission measure as the flare proceeds. The SXRs and HXRs show a Neupert-type behavior. With a nonthermal bremsstrahlung model, the brightness profile along the loop is used to determine the density profile and its evolution, which reveals a gradual increase of the gas density in the loop. These results are evidence for chromospheric evaporation and are consistent with the qualitative features of hydrodynamic simulations of this phenomenon. However, some observed source morphologies, such as the leg emission, and their evolution cannot be accounted for by previous models. This motivated us to carry out the following modeling efforts.

10.1.2 Combined Fokker-Planck and Hydrodynamic Modeling

We have started an investigation of combining our Fokker-Planck $\mathcal{F}lare$ code (Petrosian et al., 2001) with the NRL flux tube HD code (Mariska, Emslie, & Li 1989). The motivation is two-folded, one from the aforementioned new *RHESSI* observations and the other from theoretical demands which we describe as follows.

In solar flares, there are two important processes, one of which is the acceleration and transport of energetic particles, and the other of which is the HD response of the atmosphere heated via the particle energy deposition. The two processes are coupled together and can affect each other in a circular way. Variations of the acceleration rate and thus the spectrum of particles, for example, can alter the electron heating rate and thus affect the HD evolution. The chromospheric evaporation, as one form of the atmospheric response, can modify the density and temperature in the loop and possibly in the acceleration region as well. This, in turn, will change the acceleration process. The *circular nature* of the problem requires that the two processes should be studied together in a self-consistent way. However, because of the complexity of the subject, people in the past tended to separate them and focused on one process at a time, while making some simplified, yet not entirely accurate assumptions for the other. As progresses have been made on both sides over the past two decades, we are now in a position ready to break through previous imitations and conduct a combined study of both processes more accurately.

As described in *Chapter 7*, we use the Fokker-Planck code to calculate the electron distribution at each depth along the loop and thus obtain the spatial distribution of the electron energy loss rate (due to Coulomb collisions). Such energy loss is used as the heating function in the HD code and it drives the HD evolution. The updated density distribution is then fed back to the Fokker-Planck code to calculate the new heating rate. In this way, the two codes communicate in real time and keep track of the temporal evolution of the system. The heating rate calculated here is more accurate than the approximate, analytical ones (e.g., Emslie 1978) used in previous models. We also use more realistic electron spectra obtained from the recent SA model by Petrosian & Liu, S. (2004), which has a smooth transition from the quasi-thermal component at low energies to the nonthermal tail at high energies. Such a spectrum shape is consistent with that inferred from observed X-ray spectra, which can usually be fitted with a thermal plus power-law model. The previous models (e.g., Fisher et al., 1985a; Mariska et al., 1989), however, assumed a power-law spectrum with a low-energy cutoff (say 15 keV), thus essentially eliminating low-energy electrons from the distribution.

We now summarize our results from this newly combined Fokker-Planck and HD simulation. (1) One of the main findings is that inclusion of the more realistic electron spectrum from the SA model affects the spatial distribution of energy deposition and thus influences the HD evolution. The low-energy electrons in the quasi-thermal portion of the distribution produce more heating in the corona than the previous models (Mariska et al., 1989) which have more heating in the chromosphere. Because the radiative loss function has its peak in the upper chromosphere, direct chromospheric heating results in a significant portion of the energy being radiated away and less energy left available to evaporate the plasma. Therefore, our new model generally drives chromospheric evaporation more efficiently than previous models. (2) Another finding is that variations of the acceleration rate are actually coupled with variations of the escape time $T_{\rm esc}$ and both factors can modify the escaping electron spectrum and thus the resulting HD response. In general, a higher acceleration rate produces a harder electron spectrum but smaller escaping electron flux, because stronger turbulence scatters particles more and traps them longer in the acceleration region. These two factors combine to produce less coronal heating and relatively more chromospheric heating. Therefore, for the same reason mentioned above, this results in comparably weaker chromospheric evaporation for a harder electron spectrum.

From the same simulations, we have checked the empirical Neupert effect, as presented in *Chapter 8*. Here we use more rigorous calculations of the energy contents and thermal and nonthermal X-ray radiation than previous works, e.g., by Veronig et al. (2005). We find that a correlation of the SXR derivative and the HXR flux indeed exists. A better linear correlation is found between the SXR derivative and the more physically related thermal energy variation rate. We point out that a simple *linear* correlation between the SXR derivative and the HXR flux is not expected, due to the many nonlinear processes involved.

As an extension of our studies on the flare impulsive phase, we have also carried out a simulation of the decay phase (*Chapter 9*). The motivation here is to test the effects of heating and suppression of conduction, presumably produced by turbulence (at a lower level during the decay phase), in the presence of HD flows. Our result confirms our earlier conclusion (Jiang et al., 2006) that suppression of conduction and/or heating is required to produce the observed low energy decay rate and the compact LT source seen in SXRs. The new conclusions include that plasma flows and waves can carry energy away from the hot LT region, and thus counteract the effects of heating and suppression of conduction. Therefore, an even larger factor of suppression would be required to explain the SXR observations.

10.2 Future Work

Now it is time to take a look into the future. As progress was made in this work, we realized that many aspects of this research can be improved and we briefly discuss several important ones as follows.

1. Time-dependent Transport Code: The current particle transport code finds a steady state solution, while time-dependent solutions can be obtained with the particle acceleration and HD codes. One can upgrade the transport code to a time-dependent version and then the combined codes can make time advances in a more self-consistent manner. The upgrade can be done based on the time-dependent code of Hamilton, Lu, & Petrosian (1990). Once a fully time-dependent version is available, we can drop the constraints set by the current assumption of semi-time-dependent approach in which the heating rate is a function of column depth. These constraints include: (1) the loop must be uniform, i.e., no magnetic convergence or divergence; (2) synchrotron loss and diffusion must be neglected.

2. Warm-target Coulomb Collisions in the Transport Code: The current transport code assumes a cold ambient plasma, whose electron thermal velocities are negligibly small compared with those of the accelerated high-energy electrons. This is true for the chromospheric materials, as well as for the coronal plasma during the early stage of a flare. However, as the flare proceeds and as the chromospheric evaporation takes place, the plasma in the flaring loop is significantly heated and the thermal energy of the ambient electrons could be comparable to the kinetic energy of the accelerated electrons, particularly those in the low-energy portion of the spectrum. A modification to the Coulomb loss rate by taking into account the thermal energy of the background electrons is thus needed (e.g., Miller et al., 1996; Benz, 2002; Emslie, 2003). This has been done in the acceleration code, but has not yet been implemented into the transport code due to some technical difficulties. As an intermediate fix to this problem, one can stop the Fokker-Planck calculation once the energy of the beaming electrons degrades to the level of the thermal energy of background electrons. This is equivalent to the argument that such beaming electrons leave the nonthermal particle population and merge into the thermal background.

3. Angle-dependent Radiation Code: At present, the bremsstrahlung radiation is calculated using an angle-averaged cross-section for simplicity. A fully angle-dependent radiation code is available (McTiernan, 1989), but has not been implemented in the code yet. This would be included in the future development plan.

4. Momentum Deposition of Accelerated Particles: In the current model, momentum exchange between the accelerated particles and the background particles is not included in the HD equations. That is, the only contribution from the particles is the heating rate term in the energy equation. This is a valid approximation for electrons because of their small mass compared with that of the background protons. However, for accelerated protons (although less important in population than electrons), their momentum loss to the background plasma could be a significant portion of the system's momentum budget. This momentum, in addition to that produced by electron beam heating and the resulting overpressure, could be responsible for flaring seismic waves observed by helioseismological techniques (Kosovichev & Zharkova 1998). One of our future improvement would include the moment exchange term in the HD equation and we hope to combine this with the proton acceleration model (Petrosian & Liu, 2004).

5. Asymmetric Loops: The current HD model assumes a symmetric loop geometry and only calculates the evolution of one half of the loop. In reality, an asymmetric (to various extents) loop geometry is more general, which is indicated by commonly observed asymmetric HXR FP emissions (see *Chapter 5*). In such a configuration, on the side of the loop with a weaker magnetic field, the smaller convergence of the magnetic field results in a larger loss cone; this would allow more electrons to precipitate to the chromosphere, producing more heating and probably a stronger chromospheric evaporation upflow as well as a higher coronal density. However, such effects are counteracted by the larger cross-sectional area of the loop on this side and the energy deposited by electrons in a unit area may not be quite different from that on the other side. Another effect of an asymmetric loop geometry is that the evaporation upflow will not be symmetrically reflected at the loop apex and rather a stronger flow (higher velocity or density) on the one side will push a weaker flow on the other. The exact hydrodynamics will depend on the outcome of the interplay of such many factors and processes. A future direction would thus be to include the full loop in the combined HD and Fokker-Planck simulation. The NRL HD code is capable of a full-loop calculation, but the main challenge may come from making the acceleration and transport code work simultaneously in this manner and from setting proper boundary conditions. The simulation results can be checked against available HXR observations, particularly of those flares showing asymmetric FP emissions.

6. Auroras on (Extrasolar) Planets are produced by energetic particles bombarding and heating the planetary atmosphere, giving rise to emission in EUV and other wavelengths. These particles are accelerated as a result of interactions between the solar (stellar) wind and the planetary magnetosphere at the magnetopause or in the magnetotail. Auroras have been observed on magnetized solar-system planets, including the Earth, Jupiter, and Saturn. A number of Jupiter-like planets have recently been detected around giant stars. We (Liu, W. & Airapetian, 2008) argued that the massive winds from the hosting giants can produce strong and detectable auroral emission on those planets, despite their remote distances. We proposed to apply our combined Fokker-Planck and hydrodynamic code to an investigation of auroral processes in an evaporation scenario caused by injection of energetic electrons into the outer atmospheres of an extrasolar planet. Refinements to the existing solar-flare oriented code will be made to accommodate different physical conditions, such as collisional losses in a background plasma of various chemical compositions and ionizations. The model will be able to predict expected fluxes in UV continuum and emission lines, and new observations that can be used to search for evaporating planets around stars with high mass-loss rates.