UNCOVERING MECHANISMS OF CORONAL MAGNETISM VIA ADVANCED 3D MODELING OF FLARES AND ACTIVE REGIONS

Gregory Fleishman[1], Dale Gary[1], Gelu Nita[1], David Alexander[2], Markus Aschwanden[3], Tim Bastian[4], Hugh Hudson[5], Gordon Hurford[5], Eduard Kontar[6], Dana Longcope[7], Zoran Mikic[8], Marc DeRosa[3], James Ryan[9], Stephen White[10]

[1] NJIT, [2] Rice University, [3] LMSAL, [4] NRAO, [5] University of California, Berkeley, [6] University of Glasgow, [7] Montana State University, [8] PSI, [9] University of New Hampshire, [10] AFRL/RVBXS

ABSTRACT

The coming decade will see the routine use of solar data of unprecedented spatial and spectral resolution, time cadence, and completeness. To capitalize on the new (or soon to be available) facilities such as SDO, ATST and FASR, and the challenges they present in the visualization and synthesis of multi-wavelength datasets, we propose that realistic, sophisticated, 3D active region and flare modeling is timely and critical, and will be a forefront of coronal studies over the coming decade. To make such modeling a reality, a broad, concerted effort is needed to capture the wealth of information resulting from the data, develop a synergistic modeling effort, and generate the necessary visualization, interpretation and model-data comparison tools to accurately extract the key physics.

1. INTRODUCTION

Solar activity, although energetically driven by subphotospheric processes, depends critically on *coronal magnetism*, which, broadly speaking, includes magnetic field generation, morphology/topology, evolution, and transformation into kinetic, thermal, and nonthermal energies in the corona. While reliable direct diagnostic information has been lacking, during the next decade the situation must drastically change if we are to fully take advantage of the large wealth of high resolution data and modeling that is currently, or soon to be, available. New space- and ground-based solar optical telescopes are already capable of precise measurements of the photospheric magnetic field with sub-arcsecond angular resolution and high temporal resolution. Being combined with modern extrapolation algorithms, these data offer important clues on the coronal magnetic field structure and evolution.

Owing to their finite angular resolution, sensitivity, observational errors, and theoretical limitations, those extrapolations are not unique, so the extrapolations require independent verification. An opportunity for quantitative verification through radio coronal magnetography will be available during the coming decade when the new generation of high-resolution solar-dedicated radio instruments, including the expanded Owens Valley Solar Array (OVSA), upgraded Siberian Solar Radio Telescope (SSRT), and Frequency Agile Solar Radiotelescope (FASR), will become operational. There has also been progress made in obtaining the coronal magnetic field of active regions from advanced Stokes Polarimetry of infra red lines from the HAO CoMP instrument (Tomczyk et al. 2008). Microwave radiation from flares is produced by the gyrosynchrotron mechanism as accelerated fast electrons gyrate in the coronal magnetic field. It has recently been demonstrated using ideal (simulated) microwave data, that the coronal magnetic field can, in principle, be reliably recovered from the radio data on the flare dynamical timescale, along with the key parameters of the thermal plasma and accelerated electrons. The ability to detect the magnetic field and its changes on the dynamic time scales is a critically needed element to uncover fundamental physics driving solar flares, eruption, and activity.

2. MODELING COMPONENTS

Comprehensive modeling must include two closely related flows of effort: (i) *direct 3D modeling* based on our theoretical knowledge and constrained by available observations, which adopt some realistic physics and geometry and predict/calculate observables, and (ii) *robust diagnostics tools*, which achieve the complementary goal by starting from observables in order to quantify the geometry and physical processes.

Two major approaches are available to build the diagnostic tools: *true inversions*, which explicitly solve the inverse problem, and *forward fitting*, i.e., finding a number of free parameters of a physically motivated model of the system from fitting the model to observations. These diagnostics tools, being developed, will provide us with an array of the relevant coronal and flare physical parameters through a detailed sophisticated analysis of the data: e.g., radio imaging spectroscopy data for coronal plasma, accelerated electron, and field conditions and X-ray data for flare dynamics and energetics. We concentrate, here, on the solar flare modeling on dynamic time scales (down to ~ 1 s or so); as a byproduct, most of the model components, described below, will also be applicable to the active region modeling, see also `http://lws-trt.gsfc.nasa.gov/trt_sc20063dar.htm`

Direct Modeling.

Very few fully 3-dimensional models of solar flares have been attempted up to the present time. Available models (Preka-Papadema & Alissandrakis 1992; Kucera et al. 1993; Bastian et al. 1998; Tzatzakis et al. 2008; Simões & Costa 2006; Fleishman et al. 2009; Simões & Costa 2010) have used simplified, generic magnetic geometries such as a dipole loop. In order to make contact with observational data, the next generation of models should employ realistic geometries from extrapolations or long-time-evolution MHD simulations based on vector photospheric measurements of the magnetic and velocity fields. As an example of complex concerted efforts leading eventually to the relevant 3D modeling, we itemize below a number of required major (but not all-inclusive) steps needed to develop realistic, interactive, and adjustable 3D models of solar flares.

Elements of direct flare modeling to be covered:

1. **A model of the pre-flare coronal plasma.**

   The magnetic field, density, temperature and elemental abundance of the pre-flare plasma is essential for modeling the subsequent solar flare. The basis of the magnetic field model would typically be a non-linear force free extrapolation from a photospheric or chromospheric vector magnetogram. The expected situation is for a low-beta hydrostatic equilibrium plasma to exist within this magnetic structure. The density and temperature structure would be set by heating determined either by an accepted form (Schrijver et al. 2006; Lundquist et al. 2008) or through comparison to EUV images. Alternatively a time-dependent, slowly-evolving simulation could be used to supply the pre-flare conditions.

2. **The energy release and flaring site.**

   According to current understanding, the rapid magnetic energy release powering a solar flare results form fast magnetic reconnection. Where in the magnetic field this process will occur, how much energy it will release and into which forms the energy will be converted will be the subject of active research over the coming decade. The modeling proposed here will provide critical input and constraints into these investigations. One approach will be to select flare-energized field

lines or flux tubes based on the observed locations of flare signatures, independent of theoretical considerations. Comparing the results of subsequent modeling to observations will then cast light on possible relations between the magnetic environment and reconnection energy release. Alternatively, a model for three-dimensional reconnection could be used to identify the field lines onto which energy is released. Research in recent years has suggested that non-fluid effects may play a critical role in triggering reconnection (see for example, Birn & Priest 2007). It might occur first where the width of the current sheet has decreased to a scale comparable to the ion skin depth, permitting kinetic effects to become effective.

The largest flares tend to be associated with dynamical eruptions called coronal mass ejections (CMEs). The exact relationship between the flare and the CME is still the subject of ongoing research, but it is generally agreed that the magnetic configuration is far from equilibrium at the time of the flare.

3. **Dynamics of the thermal plasma in the flaring loop** (or in the flaring loop system), i.e., prescribing the evolving electron number density, elemental/ion composition, and temperature to each voxel.

The density and temperature may evolve in time as specified by hydrodynamic response to the flare energy release; ideally the loop will be embedded in a global (pre-flare) coronal model (1). At the level of more advanced modeling the inhomogeneous active region atmosphere is specified self-consistently with the magnetic structure, heating sources (including those driven by the flare), and cooling (see, e.g., Mok et al. 2008). In this case (in place of populating the voxels) the magnetic field model is self-consistently coupled with the thermal plasma distribution, so the data cubes describing the thermal plasma distribution must be imported into the flare modeling tool along with the magnetic field data cube.

4. **Populating the loop by evolving fast accelerated electrons**, which eventually must be determined from the time-dependent solutions of the transport equation (for flare modeling; not needed in case of active regions).

The full problem is far from its final solution. The problem includes two major ingredients: particle acceleration and particle transport. Currently, there is no consensus about the main acceleration mechanisms operating in flares, although there are numerous models capable of successfully accounting for some of the observed properties of the accelerated particles. The modeling tools must be capable of accommodating arbitrary outcomes of (either analytical or numerical) external models describing the particle acceleration. Once the accelerator has been set up, the consequent transport mechanism is basically known: it is defined by the magnetic field line structure and thermal plasma, which is known within a given model. An additional but typically unknown important ingredient, which can affect the transport, is wave turbulence capable of angular scattering the particles. The presence and amplitude of such turbulence would follow either from the energy release model (2) or be set empirically using other observational input, such as spectral line widths.

5. **Calculation of the thermal and nonthermal** (HXR, gamma-ray, radio etc.) **emission characteristics** in each voxel and solution of the radiation transfer equations along all selected lines of sight, thus forming data cubes of the emission for the preselected viewing angle.

These tasks, although based on the well understood and well developed theory, are frequently computationally demanding. So specific efforts for minimizing the computation time and fully optimized computing codes are critically needed.

6. **Developing powerful user-friendly visualization tools for the variety of model-derived 3D data cubes.**

   The visualization tools are needed to fully understand the structure and properties of the 3D objects under study. In addition, similar tools are needed to look at the imaging spectroscopy data as the relevant data volumes are often larger than those available from individual context instruments, and require spherical geometry, so that advanced tools are needed for data coalignment, viewing and analysis.

7. **Folding the data cubes through the instrumental response functions for direct comparison with observations.**

Most of the items mentioned represent major sub-projects within the program of the overall 3D modeling effort. The larger effort requires coordination of model standards and compatibility of the model data formats and consistently defined physical assumptions between the component parts, to enable these sub-projects to mesh seamlessly. Ultimately, these simulated models will be analyzed by the forward fitting or inversion tools, early versions of which are already in development (e.g., Fleishman et al. 2009). They are intended for reliably deriving the physical parameters of the emission region. This direct modeling, coupled with the forward fitting or true inversions, is a critically important step for validating the diagnostics tools prior to their application to real observational data.

Forward Fitting Diagnostics.

Robust diagnostics, understood as the determination of physical parameters of a system under study from arrays of observed parameters, is a key outstanding problem in Solar Physics. In some cases, e.g., in the hard X-ray (HXR) range, regularized true inversions can work well (e.g., Kontar et al. 2004). In most cases, however, true inversions fail because of the highly nonlinear nature of the physical systems they are trying to extract information from. In such cases, forward fitting can often be successfully used in place of true inversions. Although we specifically discuss below the forward fitting of the imaging spectroscopy of the microwave data, most of the discussion applies to imaging spectroscopy data in other wavelengths as well.

Assume that we have a sequence of spatially resolved spectra (both intensity and polarization data) from a solar flare (e.g., one spectrum per pixel). Then, we can fit the data to a model spectrum pixel by pixel to derive physical parameters of the source.

This forward fitting includes the following elements.

1. **Identify the model source function based on the radiation mechanism involved.**

   In the case of microwave emission from solar flares the emission mechanism is generally known: it is gyrosynchrotron (GS) emission with a free-free contribution in some cases (e.g., Bastian et al. 1998). Although the corresponding emission and absorption coefficients are known theoretically, the exact GS formulae are very computationally expensive and cannot be used in practice as the forward fitting input. Fortunately, much faster codes giving the same accuracy have recently been developed by Fleishman & Kuznetsov (2010). These codes, being fast, precise, and applicable for a broad range of regimes including anisotropic distributions of fast electrons imply a breakthrough in both 3D direct modeling and the forward fitting, allowing forward fittings of large bodies of data over reasonable time.

2. **Identify the fitting procedure resulting in fast and reliable finding of the true source parameters.**

   The problem is that most of the minimization algorithms often find a *local* minimum of the normalized residual (or of the reduced chi-square), while the ultimate goal of the fitting is to identify the *global* minimum. So far, we have determined that the simplex algorithm is very efficient in finding a local minimum. Then, it needs to be 'shaken' for the simplex solution to overcome any local minima and continue downhill towards the global minimum (a version of the stimulated annealing approach). Further efforts in optimizing the minimization algorithm are still needed especially for more complex cases when the number of the free model parameters is large.

3. **After-fitting inspection of the results.**

   Even when the algorithm performance is very good overall, there is a non-zero probability that the algorithm fails to find the true solution in some pixels. The post-processing must be able to identify and flag/remove those pixels.

4. **Interactive methods (similar to those used for the direct modeling) to deduce changes to model parameters based on observed mismatch.**

This sequential forward fitting must pave the way towards a global fitting in which a global source model is fitted to the whole body of the observational data (a multidimensional data cube containing spectra, light curves, and evolving spatial structure). Ultimately, the above procedures are iterated by quantitative means (to be determined), to adjust the model to match observations. Note that the model is adjusted to simultaneously match all available (multi-wavelength) observations.

3. THEORETICAL INPUT

The outlined modeling efforts require further development of the theory; the following key input is particularly important.

1. **Magnetic field extrapolations, magnetic reconnection, and energy release.**

   The present state of the art, non-linear force-free extrapolation from photospheric vector data, is known to suffer from inadequacies which must be overcome, or at least addressed, if we are to make progress in the coming decade. The photospheric field does not itself satisfy the force-free conditions used to extrapolate it. It must either be somehow modified or replaced entirely with vector field measurements from higher in the atmosphere (Metcalf et al. 1995; De Rosa et al. 2009). There are numerous other sources of information into the coronal magnetic field, such as EUV images (see Malanushenko et al. 2009), radio emission, coronal polarimetry (Lin et al. 2004; Tomczyk et al. 2008) or loop oscillations (Aschwanden et al. 1999; Nakariakov et al. 1999). These data are either indirect (EUV loops or oscillations) or in a form (sparse or integrated) not easily incorporated into the traditional formalism of extrapolation. Nevertheless, they constitute valuable data on the coronal field and should not be discarded entirely. Innovative techniques must be developed for incorporating such data into coronal field models. The modeling effort here proposed will, in the end, provide constraints on the structure of the coronal magnetic field and it would be valuable to be able to incorporate this back into the magnetic model itself.

   The very nature of upward extrapolation is poorly suited to identifying and resolving thin magnetic structure far from the boundary. Such structures, current sheets in particular, are

believed to play an essential role in the rapid energy release powering flares. In order to make genuine progress in understanding flares new coronal models must be developed which are capable of including these structures and their associated free energy.

2. **Turbulence generation, evolution, and parametrization of wave-particle interactions.**

   Turbulence is a highly important (but elusive for direct probing) element of the coronal plasma. It can play a key role in particle acceleration and transport and in the generation of electromagnetic emission. Since it often cannot be measured, the role of the theory here is crucial to provide the necessary relevant input for the modeling.

3. **Particle acceleration and transport including simplified fast solutions.**

   Particle acceleration remains an outstanding problem in solar flares. Any progress in understanding the acceleration mechanisms and how they work in realistic geometries will be exceedingly valuable for the modeling discussed above. The accelerator plays a role of the source function for the particle transport. Although the transport equations are generally known, their numerical solution is computationally demanding; thus, like in case with radiation coefficients, simplified and optimized (but still accurate) solutions are needed.

4. **Radiation processes including emissivity, absorption coefficients, and radiation transfer solutions; including fast codes.**

   Although many radiative processes are well studied, there is a need to optimize the computing codes for speed in many cases (e.g., Fleishman & Kuznetsov 2010). In addition, new emission processes have recently been identified, e.g., diffusive synchrotron radiation (Li & Fleishman 2009), which can give dominant contribution in the very site of the stochastic acceleration. Thus, both new regimes and mechanisms of emission and efficient computing codes must be developed to provide valuable input to the modeling.

4.   EXPECTED RESULTS AND OUTSTANDING QUESTIONS

The modeling effort outlined above would have a broad impact on the field of solar astronomy. Its most immediate results would be in progress toward answering the following questions.

- Determination of the location of the energy release, the means by which magnetic energy is rapidly released, magnetic field reconfigurations, and the mechanisms of particle acceleration.

- Quantitative verification of magnetic field extrapolations, and refinement of extrapolation methods.

- Quantitative understanding of the hydrodynamic response of the atmosphere to energy input.

- Quantitative understanding of accelerated particle distributions, including energy, pitch angle, and relative proportions of thermal/nonthermal partition.

- The role of turbulence and wave-particle interactions on transport of particles and energy.

5. BROADER IMPLICATIONS

The modeling efforts we have outlined can only bring fundamental knowledge about flare/active region physics if used in conjunction with high-resolution modern observations. Key observations of the coronal plasma parameters can only be made by radio instruments that combine high sensitivity, temporal, spatial, and spectral resolution, which are unavailable now. A small part of the required science will be possible soon with the upgraded OVSA instrument (the funding of the upgrade just [10/01/2010] started; anticipated start of the upgraded instrument operation is fall, 2013). However, the full required capability has to await the completion of the full FASR, see Concept Papers submitted by Bastian et al., Gary et al., White et al.

6. CONCLUSIONS

As is clear from this Concept Paper, sophisticated development of three elements will be needed over the coming decade to significantly improve our understanding of the coronal magnetism, turbulence generation, and particle acceleration: (i) direct 3D modeling; (ii) theory; and (iii) iterative methods and tools for analysis of new, high-resolution, observations through forward fitting.

REFERENCES

Aschwanden, M. J., Fletcher, L., Schrijver, C. J., & Alexander, D. 1999, ApJ, 520, 880

Bastian, T. S., Benz, A. O., & Gary, D. E. 1998, ARA&A, 36, 131

Birn, J. & Priest, E. R. 2007, Reconnection of magnetic fields : magnetohydrodynamics and collisionless theory and observations, ed. Birn, J. & Priest, E. R.

De Rosa, M. L., Schrijver, C. J., Barnes, G., Leka, K. D., Lites, B. W., Aschwanden, M. J., Amari, T., Canou, A., McTiernan, J. M., Régnier, S., Thalmann, J. K., Valori, G., Wheatland, M. S., Wiegelmann, T., Cheung, M. C. M., Conlon, P. A., Fuhrmann, M., Inhester, B., & Tadesse, T. 2009, ApJ, 696, 1780

Fleishman, G. D. & Kuznetsov, A. A. 2010, ApJ, 721, 1127

Fleishman, G. D., Nita, G. M., & Gary, D. E. 2009, ApJ, 698, L183

Kontar, E. P., Piana, M., Massone, A. M., Emslie, A. G., & Brown, J. C. 2004, Sol. Phys., 225, 293

Kucera, T. A., Dulk, G. A., Kiplinger, A. L., Winglee, R. M., Bastian, T. S., & Graeter, M. 1993, ApJ, 412, 853

Li, Y. & Fleishman, G. D. 2009, ApJ, 701, L52

Lin, H., Kuhn, J. R., & Coulter, R. 2004, ApJ, 613, L177

Lundquist, L. L., Fisher, G. H., Metcalf, T. R., Leka, K. D., & McTiernan, J. M. 2008, ApJ, 689, 1388

Malanushenko, A., Longcope, D. W., & McKenzie, D. E. 2009, ApJ, 707, 1044

Metcalf, T. R., Jiao, L., McClymont, A. N., Canfield, R. C., & Uitenbroek, H. 1995, 439, 474

Mok, Y., Mikić, Z., Lionello, R., & Linker, J. A. 2008, ApJ, 679, L161

Nakariakov, V. M., Ofman, L., Deluca, E. E., Roberts, B., & Davila, J. M. 1999, Science, 285, 862

Preka-Papadema, P. & Alissandrakis, C. E. 1992, A&A, 257, 307

Schrijver, C. J., De Rosa, M. L., Metcalf, T. R., Liu, Y., McTiernan, J., Régnier, S., Valori, G., Wheatland, M. S., & Wiegelmann, T. 2006, Sol. Phys., 235, 161

Simões, P. J. A. & Costa, J. E. R. 2006, A&A, 453, 729

—. 2010, Sol. Phys., 266, 109

Tomczyk, S., Card, G. L., Darnell, T., Elmore, D. F., Lull, R., Nelson, P. G., Streander, K. V., Burkepile, J., Casini, R., & Judge, P. G. 2008, Sol. Phys., 247, 411

Tzatzakis, V., Nindos, A., & Alissandrakis, C. E. 2008, Sol. Phys., 253, 79