ISSI Team on Coronal Magnetism: Final Report

Coronal magnetism lies at the heart of any understanding of the origins of space weather at the Earth, and of the slower evolution on solar-cycle time scales of its space environment. We are now at a watershed moment: not only are telescopes using infrared, visible, and radio magnetometry obtaining unprecedented observations, but also future large telescopes are under development and construction, ultimately making it feasible to map the 3D magnetic field from photosphere into the corona.

The 2012-2014 ISSI International Team on Coronal Magnetism took a broad approach, considering subjects such as coronal polarimetry at multiple wavelengths, theory and modeling of magnetic energy storage and release, forward and inverse methods of analysis, and the coronal magnetic field throughout the solar cycle. The team met twice, in February 2013 and in March 2014. The meeting agendas, summaries, and presentations are linked to the team web page.

In addition to our original team members, we had several **Young Scientists** attend the meetings:

Don Schmit (Max Planck Institute for Solar System Research) - both meetings
Cooper Downs (Predictive Science Incorporated) - both meetings
Gabriel Dima (University of Hawaii, USA) - second meeting
Sijie Yu (National Astronomical Observatory, China) - second meeting

Moreover, we had interest from the broader community, and welcomed the following **Outside Experts**:

Donald Hassler (Institute d'Astrophysique Spatiale, France) - first meeting
Nour-Edine Raoufi (Johns Hopkins University, USA) - first meeting
Yihua Yan (National Astronomical Observatory, China) - second meeting
Patricia Jibben (Center for Astrophysics, USA) - second meeting

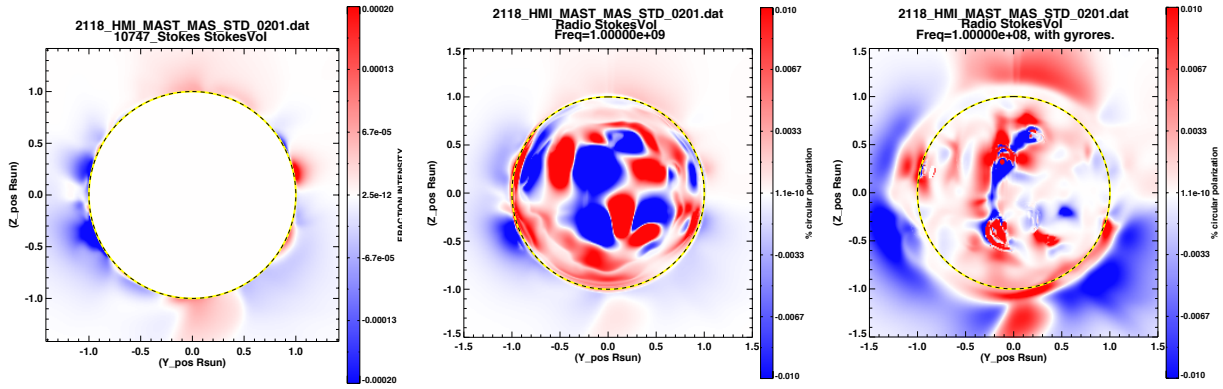
The team was active with posters and presentations at a range of international conferences, and with the following four publications to date:

- **Bak-Steslicka, U. et al.**, T*he spatial relation between EUV cavities and linear polarization signatures*, Proceedings of the International Astronomical Union, IAU Symposium, Volume 300, pp. 395-396, 2014
- **Schmit, D. and Gibson, S. E.** *The Formation of a Cavity in a 3D Flux Rope*, Proceedings of the International Astronomical Union, IAU Symposium, Volume 300, pp. 147-150
- **Gibson, S. E.** *Magnetism and the Invisible Man: The mysteries of coronal cavities,* Proceedings of the International Astronomical Union, IAU Symposium, Volume 300, pp. 139-146, 2014
- **Gibson, S. E.** *Coronal cavities: Observations and implications for the magnetic environment of prominences*, in Solar Prominences, O. Engvold & J.-C. Vial eds., Springer, in press, 2014**.**

A major goal for the team was to expand our FORWARD software (http://people.hao.ucar.edu/sgibson/FORWARD/) to promote coronal magnetism. The FORWARD suite of SolarSoft IDL

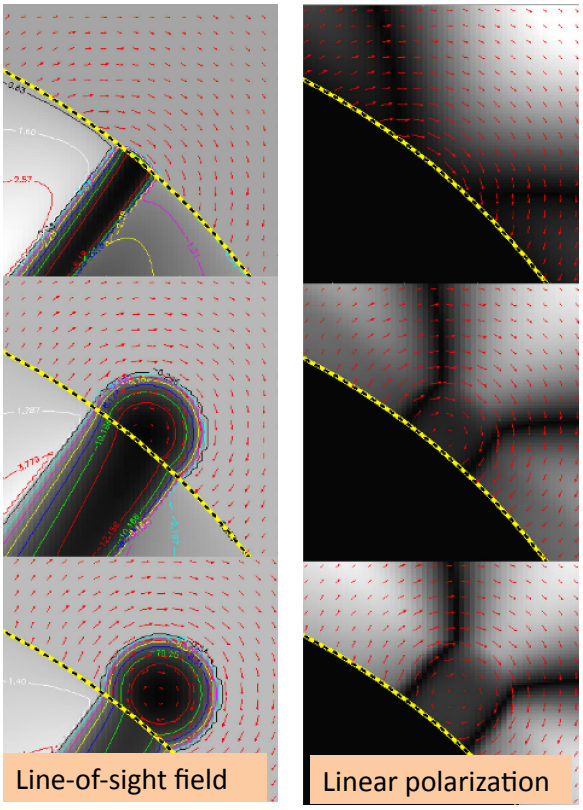
codes, developed originally by the ISSI team on Coronal Prominence Cavities, is a community resource for model-data comparison that may be used to synthesize a broad range of coronal observables. FORWARD enables "forward-fitting" of specific observations, and helps to build intuition into how the physical properties of coronal magnetic structures translate to observable properties. FORWARD includes several analytic models in its distribution, and may also be used with user-inputted data cubes from numerical simulations. Given such coronal models of density, temperature, and vector magnetic fields, many different synthetic observables may be produced through integration along a line of sight defined by the viewer's specified position in heliographic coordinates. FORWARD initially included routines to reproduce data from EUV/ Xray imagers, UV/EUV spectrometers, white-light coronagraphs, and, through interface with the Judge & Casini CLE polarimetry synthesis code for forbidden coronal lines, observations from infrared polarimeters.

To increase the capability of FORWARD in diagnosing the coronal magnetic field, we added multi-wavelength spectropolarimetric capabilities, including free-free and gyroresonance radio, and visible (green) forbidden line polarimetry. In addition, codes were written to allow permitted-line diagnostics of other visible and UV lines (the incorporation of these codes into FORWARD is underway). By including multiple wavelengths, it is possible to probe magnetic fields in different parts of the corona along the line of sight, thus removing ambiguity. The images below demonstrate this, illustrating differences in Stokes V circular polarization (proportional to line-of-sight-directed magnetic field) for infrared and radio frequencies.

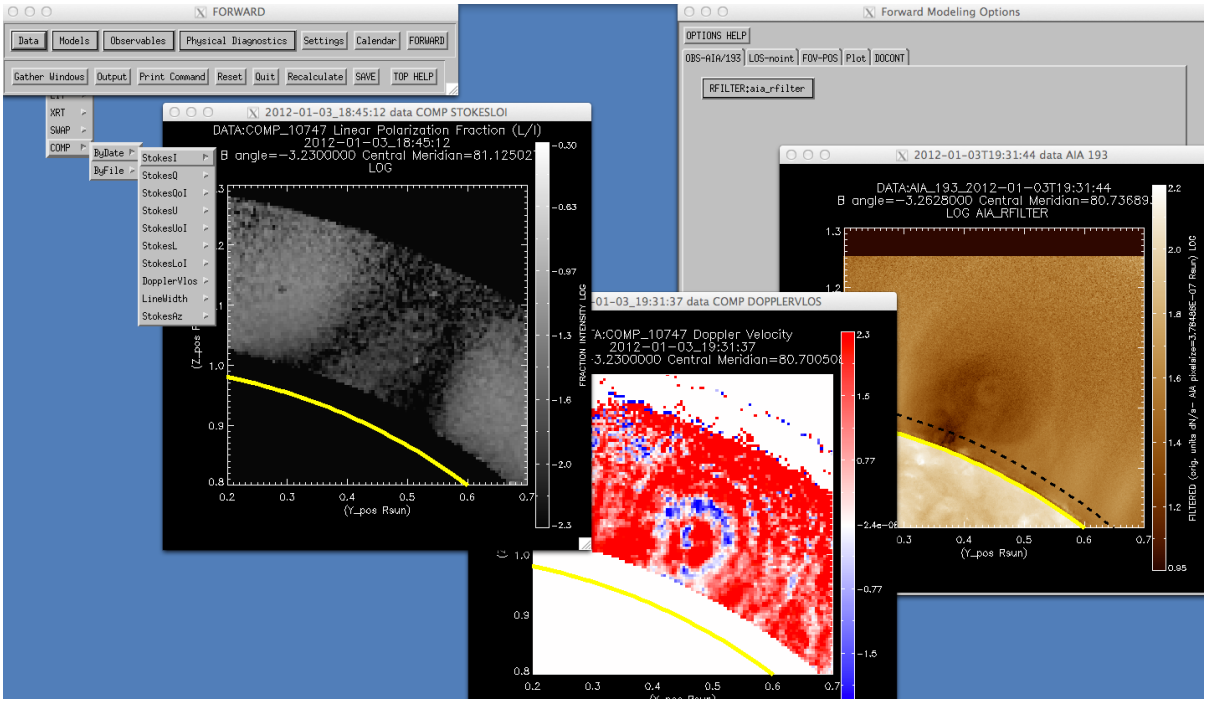


Another goal for the team was to obtain predicted observables at a range of wavelengths using Potential Field Source Surface and MHD simulations, in order to identify signatures of magnetic structures to be sought in existing and future coronal polarimetric data. To facilitate this, we introduced widget-controled interfaces between FORWARD and existing PFSS SolarSoft codes, and with the Predictive Science Incorporated coronal MHD simulation datacubes. Thus, by choosing a date within a calendar widget, users are able to generate synthetic data for the three-dimensional magnetic field configuration of any solar rotation within the past three decades (as

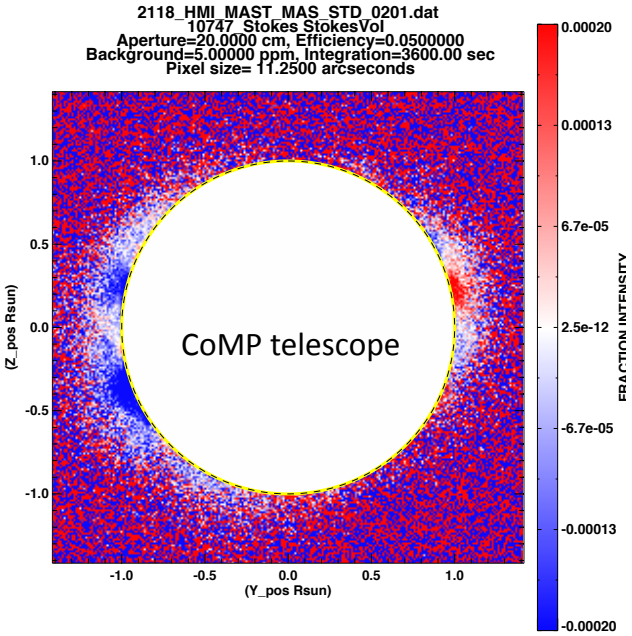
in the figure above). As before, FORWARD can also be used in parameter studies of analytic models, to investigate signatures such as linear-polarization "lagomorphs", rabbit-headed shapes introduced by magnetic flux ropes in the corona and prevalent in data from the Coronal Multichannel Polarimeter (CoMP). The images to the right show one such study.

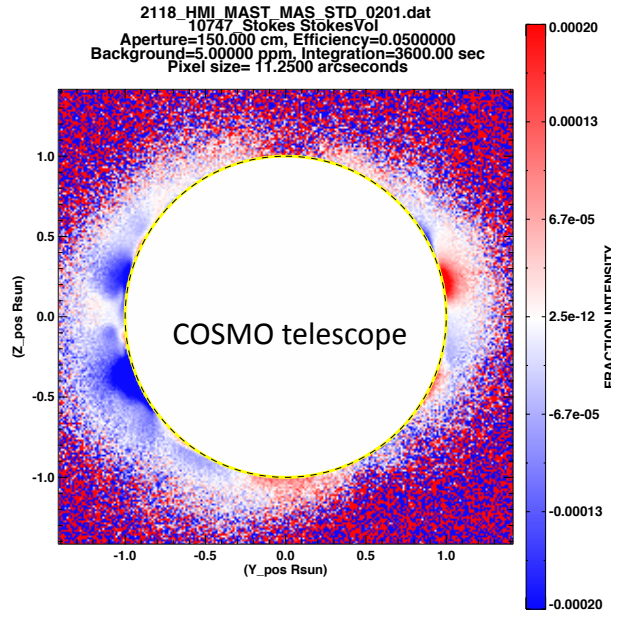


A third goal for the team was to compare model predictions to existing data, and to consider how multiwavelength data from future telescopes might best be used to constrain the 3D coronal magnetic field. In addition to studies with CoMP data, team members made use of eclipse data in the FeXIV (green) line taken by the CorMag telescope. Moreover, a campaign targeting a coronal prominence cavity was undertaken by team members, which included the Very Large Array radio telescopes, the CoMP telescope, and the Hinode spacecraft (data analysis is ongoing). Interfaces between FORWARD and web-served data (including the Virtual Solar Observatory) were added, making is easy for a user to access and display a variety of data side by side (see image below).



To increase the realism of comparison of model predictions to data such as these, the FORWARD codes were expanded to include photon noise. A widget interface allows the user to choose exposure time, telescope aperture, background, and resolution, thus enabling comparisons as in the images below which show the baseline capabilities of the 20 cm aperture CoMP telescope vs. the 1.5 m COSMO telescope for obtaining circular polarization measurements. For spectroscopic observables, FORWARD now also interfaces with the Chianti atomic database, with a widget interface to allow the user to customize choices of abundances, line widths, etc. in the synthesis of spectral lines. As follow-on to these advances, the team has been discussing how FORWARD might be taken to the next level, in which "instrument personality profiles" could yield synthetic data that appropriately takes into account the how a particular instrument's setup affects observation, including systematic errors. This would create a valuable planning tool for the design and use of future large telescopes.





Coronal Magnetometry: Which Way to Go Next?

A significant outcome of our team's meetings was to begin the process of developing an international community of scientists interested in the subject of coronal magnetism. We discussed how we might best nurture such a community, and have begun to take steps to do so. In particular, we have already sponsored a workshop to train users in the use of the FORWARD codes (in Boulder in September, 2013), and have organized sessions on Coronal Magnetism both at the COSPAR meeting in Moscow, Russia (August 2014) and the upcoming Fall American Geophysical Union meeting in San Francisco, CA, USA (December 2014). Student involvement in coronal polarimetric analysis is essential, and in addition to our young scientists several graduate students are working with members of our team on this subject. Moreover, members of this team from Europe and U.S. will continue to collaborate under the auspices of a European COST action. Finally, during our second meeting the team outlined a review paper on Coronal Magnetism, with the intention of proposing such a manuscript for submission to Space Science Reviews. Our goal will be to submit such a proposal by late 2014.