Coronal Prominence Cavities

A proposal for an ISSI International Team in Space Science

Abstract. The genesis of solar coronal mass ejections (CMEs) is both an intellectually intriguing, fundamental unsolved problem in plasma astrophysics, and a societally relevant subject critical to space weather prediction and mitigation. Understanding the pre-eruption state of the corona is a top priority for space science. A common and compelling feature of white-light CMEs is their three-part morphology of a bright expanding loop, followed by a relatively dark cavity, and lastly a bright core associated with an erupting prominence. It is also quite common for a prominence with a dark, semi-circular or circular cavity surrounding it to exist quiescently in the corona prior to the eruption. Multiple cases have been documented where the cavity and its enclosed prominence bodily erupt as CMEs (e.g. Figure 1). Coronal prominence cavities are thus clues to the state of the corona just prior to a CME, and may in fact be a signature of stored magnetic energy capable of driving the CME.

The magnetic structure of a coronal prominence cavity has implications for its thermal and dynamic properties. Cavity modeling thus needs to be constrained and motivated by multi-wavelength observations. The advent of new coronal magnetic field observations, high resolution soft-X-ray and extreme-ultraviolet observations, and coronal observations from multiple vantage points, along with recent advances in modeling, makes now an excellent time to make progress on this fundamental space physics problem. A concerted effort in observations and modeling is required, and to this end we have gathered a group of scientists whose combined experience covers multi-wavelength cavity observations and a variety of cavity models, both magnetohydrodynamic (MHD) and thermodynamic. The ISSI program is the ideal way to bring together this small, balanced, and international team to pin down the physics of cavities and in the process gain critical insight into CME initiation.

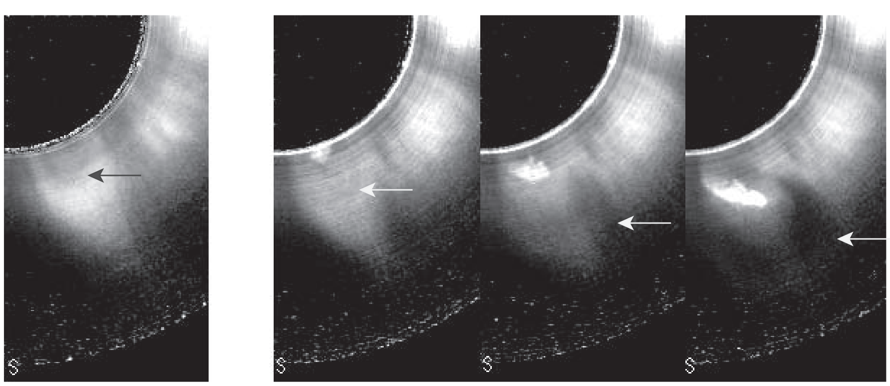

Fig. 1.— Quiescent cavity (left image: November 18, 1999) that erupts as CME (right three images: November 19, 1999) as observed by the Mauna Loa Solar Observatory (MLSO) Mk4 coronameter.

1. Scientific Rationale

Coronal mass ejections (CMEs) are spectacular solar eruptions and the primary drivers of "space weather" at the earth (for CME observational reviews, see *Pick et al.* (2006); *Hudson et al.* (2006), and for CME theory, *Forbes* (2000); *Zhang and Low* (2005); *Forbes et al.* (2006)). Cavities are commonly observed as part of a CME, but may also exist before eruption (*Sterling and Moore* 2004; *Gibson et al.* 2006). Such quiescent cavities appear as dark, semi-circular or circular regions, often surrounding a central prominence (relatively cool and dense plasma suspended in the solar corona), and embedded in a helmet-shaped white-light streamer (Figure 1, left). They are ubiquitous: several may be visible on a given day; and can be long-lived (on the order of months): either reforming or only partly erupting in CMEs (*Gibson and Fan* 2006b; *Su et al.* 2006; *Tripathi et al.* 2007, 2008). They provide clues to magnetohydrodynamic equilibrium states of the solar corona and to the processes which can destabilize these equilibria and drive coronal mass ejections.

One model for a cavity, both in the CME (*Gibson and Low* 1998; *Gibson and Fan* 2006b; *Lynch et al.* 2004; *Chen et al.* 2006) and as a precursor structure in conjunction with a quiescent prominence(*van Ballegooijen et al.* 1998, 2000; *Gibson and Low* 2000; *Aulanier and Schmieder* 2002; *van Ballegooijen* 2004; *Zhang and Low* 2004; *van Ballegooijen and Cranmer* 2008; *Fan and Gibson* 2006), is that of a magnetic flux rope of twisted field lines winding about an axial field line. However, the question of whether the flux rope is formed during the eruption, or whether the flux rope existed prior to the eruption, remains controversial. The existence of a pre-eruption flux rope has implications for the physics of CME initiation (*Priest and Forbes* 2002; *Zhang and Low* 2005; *Zhang et al.* 2006). Pre-eruption cavities have been argued to be evidence for a pre-eruption flux rope (*Low* 1996; *Zhang and Low* 2003). In order to test this, we need to determine 1) what is the range of magnetic configurations in MHD equilibria consistent with a quiescent cavity, and 2) how consistent are the stability and thermodynamic properties of such magnetic configurations with cavity observations, taking into consideration the effects of nonequilibrium processes such as magnetic flux and helicity emergence, photospheric motions, current sheet formation, coronal reconnections and resulting flows, and prominence formation and dynamics (*Lin and Forbes* 2000; *Lin et al.* 2001; *Kucera et al.* 2003; *Kucera and Landi* 2006; *Reeves and Forbes* 2005; *Zhang* 2006; *Reeves et al.* 2007; *Kucera and Landi* 2008).

It is therefore critical to obtain information about cavity plasma density, temperature, velocity, and ideally magnetic field, via multi-wavelength observations. Cavities have been observed in white light (*Gibson et al.* 2006), radio (*Marqué et al.* 2002; *Marqué* 2004), soft X-ray (Figure 2 (left)) and extreme ultraviolet (*Hudson et al.* 1999; *Hudson and Schwenn* 2000; *Sterling and Moore* 2004; *Heinzel et al.* 2008). Although these studies have provided some information about cavity density and temperature, many questions remain unanswered. In particular it is still not clear whether a cavity is hotter or cooler than its surrounding helmet streamer. The answer to that question is an important constraint on models of cavity magnetic field and heating mechanisms (*Zhang and Low* 2004; *van Ballegooijen and Cranmer* 2008; *Fuller et al.* 2008). In order to pin down density and temperature, multi-wavelength spectroscopic observations need to be taken, so that plasma diagnostic techniques may be applied (*Kucera et al.* 1998, 1999; *Schmieder et al.* 1999, 2003, 2004). It is also essential to consider the three-dimensional morphology and orientation of cavities, to propertly account for projection effects of non-cavity material into the line-of-sight (*Wiik et al.* 1994; *Fuller et al.* 2008). Finally, exciting new advances in coronal infrared (IR) magnetometry, e.g. the Coronal Multichannel Polarimeter (CoMP) (*Tomczyk et al.* 2008), will provide complementary ground-based observations of cavities (Figure 2 (right)).

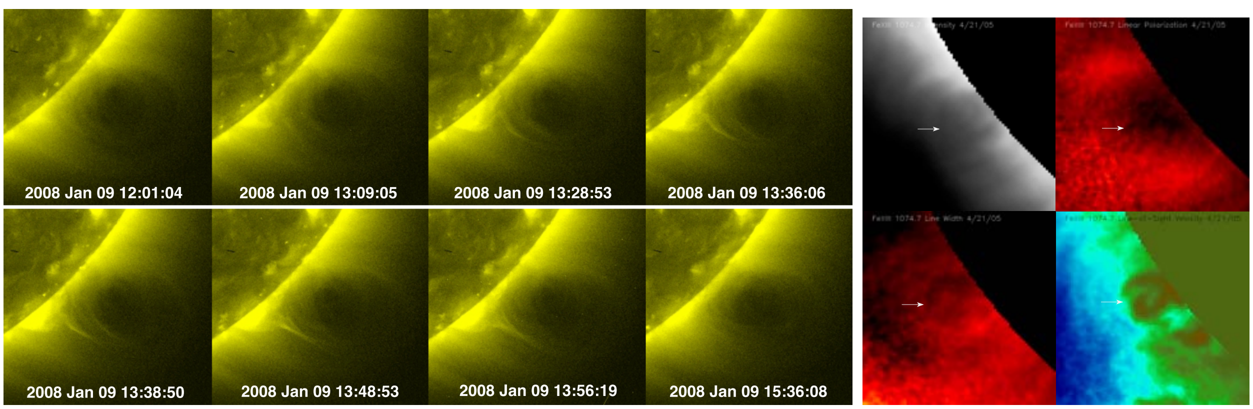

Fig. 2.— Left image array: January 9, 2008 Hinode-XRT cavity in soft-Xray with apparent reconnection event. Right image array: April 21, 2005 CoMP cavity in infrared (clockwise from upper left: Intensity, linear polarization, line-of-sight velocity, and line width.)

2. Scientific Goals

Observations. At our ISSI Team meetings we will review what observations exist, and then plan, obtain, and analyze new data to fill observational holes. We plan to:

1. Obtain multi-wavelength spectroscopic observations in cavities, and use these along with radio and white-light observations to establish cavity density and temperature vs. that of the surrounding bright streamer. We are particularly interested in how cavity density depletion relative to the streamer varies with radial height, and whether cavities are consistently hotter or cooler than their surrounding streamer.

2. Establish the three-dimensional morphology and orientation of these cavities in order to place error bars on plasma diagnostics (*Fuller et al.* 2008). We will use simultaneous observations at multiple viewing angles (e.g. using Earth and STEREO spacecraft solar limb observations and on-disk radio observations), and also monitor how cavities vary with time as they rotate past the limb. By assuming a tunnel-type cavity model, we will establish cavity length (e.g. longitudinal extent), cavity height as a function of this length, and cavity orientation relative to the line of sight (*Wiik et al.* 1994).

3. Obtain cavity IR coronal magnetometer observations (Figure 2 (right)), which will be available from CoMP synoptically beginning Summer 2008, and which will provide unique new information on cavity magnetic structure and line-of-sight flows.

4. Seek good examples of cases where cavities directly erupt as CMEs. We will look for evidence for cavity evolution immediately prior to or during eruption, including rising (expanding) cavities, evidence for reconnection, and evidence for reforming or only partially-ejected cavities (*Gibson and Fan* 2006a; *Birn et al.* 2006; *Tripathi et al.* 2008)

Modeling. Equally important will be the application of these data to models, to constrain and motivate their development (and, conversely, to identify observational holes based on what is needed to distinguish between models). We plan to:

1. Determine predicted observables for a range of MHD models. In particular, we will use model-predicted vector magnetic field, density, temperature, and velocity as inputs to calculate and generate pseudo-data to be directly compared to observations.

2. Use observations of the relative temperature and density of the cavity vs. the surrounding streamer, the degree of cavity roundness and boundary sharpness, and substructures within the cavity such as hot cores (*Hudson et al.* 1999; *Hudson and Schwenn* 2000)., as constraints on and motivations for models of cavity heating (*Low* 1996; *Zhang and Low* 2004; *Fuller et al.* 2008; *van Ballegooijen and Cranmer* 2008).

3. Study how non-equilibrium processes affect cavity magnetic structure and stability. Observational evidence for current sheet formation, reconnection, and flows both in quiescent and erupting cavities will motivate model development. We will address the questions of whether quiescent cavity models ought to be steady-state rather than static, and how magnetic equilibria may ultimately be lost in a CME.

3. Plans and Justification for ISSI International Team

Team: We have formed a well-balanced team representing a range of observing and modeling approaches and a comprehensive understanding of current and past coronal cavity studies (see bibliography and attached CVs). All have committed to attending the three meetings, and together represent six countries, half of which are ESA member states:

Sarah Gibson, U.S. (Leader/Coordinator), Aad van Ballegooijen, U.S., Terry Forbes, U.S., Hugh Hudson, U.S., Therese Kucera, U.S., Ben Lynch, U.S., Christophe Marqué, Belgium, Brigitte Schmieder, France, Alphonse Sterling, Japan, Kathy Reeves, U.S., Durgesh Tripathi. U.K., Mei Zhang, China.

Proposed meetings and expected output: We expect to have three meetings. At the first meeting (Winter 2008/2009) we will consider archival sources for multi-wavelength cavity data, and identify new observations that can be accomplished via observing campaigns which we will propose and carry out during the ISSI Team period. We will begin to compare cavity models to observations and to each other. At the second meeting (early Fall 2009) we will continue to intercompare observations and models, and begin coordination of one or more publications. At the final meeting (early Spring 2010) we will complete our project and finalize publication plans. Throughout this process we will maintain a small dedicated website to facilitate ongoing research, including processed data, model output, etc.

The ISSI facilities are well-suited to our needs (several of us have participated in ISSI workshops or International Teams in the past). We will use ISSI computing facilities primarily for web and email access, as we expect team members to bring laptop computers to facilitate coordinated analysis at the meetings. We expect the meetings to last 3-4 days each, for a total of 11 days. We request financial support as standardly given for ISSI teams, i.e. local support for all team members plus transportation expenses for the team leader. We may invite additional experts to our meetings at no additional cost to ISSI. Possible experts to be invited include Vincenzo Andretta (Italy), Spiro Antiochos (U.S.), B. C. Low (U.S.), James McAteer (Ireland), and Scott McIntosh (U.S.).

ISSI added benefit and project timeliness: The ISSI program emphasizes international collaboration and interdisciplinary research to investigate the results of space-research missions. Observations from new space missions such as Hinode and STEREO are providing unprecedented data on coronal cavities, that we have only begun to examine. The ISSI small team format is ideal for such analysis, since it allows modelers and observers from all over the world to gather in the same room and work together. We expect our team to make significant break-throughs, in particular with observations and modeling of cavity thermal, dynamic, and magnetic properties, in the process gaining critical insight into CME initiation.

REFERENCES

Aulanier, G., and B. Schmieder (2002), The magnetic nature of wide euv filament channels and their role in the mass loading of cmes, *Astron. and Astrophys..*, *386*, 1106.

Birn, J. T., T. G. Forbes, and M. Hesse (2006), Stability and dynamic evolution of three-dimensional flux ropes, *Journ. Geophys. Res.*, *845*, 732.

Chen, J., C. Marqué, V. A., J. Krall, and P. W. Schuck (2006), The flux-rope scaling of the acceleration of cmes and eruptive prominences, *Astrophys. Journ.*, *649*, 452.

Fan, Y., and S. E. Gibson (2006), On the nature of the x-ray bright core in a stable filament channel, *Astrophys. Journ. Lett.*, *641*, 149.

Forbes, T. G. (2000), A review on the genesis of coronal mass ejections, *Journ. Geophys. Res.*, *105*, 23,153.

Forbes, T. G., et al. (2006), Cme theory and models, *Space Science Reviews*, *123*, 251.

Fuller, J., S. E. Gibson, G. de Toma, and Y. Fan (2008), Observing the unobservable? modeling coronal cavity density, *Astrophys. Journ.*

Gibson, S. E., and Y. Fan (2006a), The partial expulsion of a magnetic flux rope, *Astrophys. Journ. Lett.*, *637*, 65.

Gibson, S. E., and Y. Fan (2006b), Coronal prominence structure and dynamics: A magnetic flux rope interpretation, *Journ. Geophys. Res.*, doi:10.1029/2006JA011871.

Gibson, S. E., and B. C. Low (1998), A time-dependent three-dimensional magnetohydrodynamic model of the coronal mass ejection, *Astrophys. Journ.*, *493*, 460.

Gibson, S. E., and B. C. Low (2000), Three-dimensional and twisted: An mhd interpretation of on-disk observational characteristics of coronal mass ejections, *Journ. Geophys. Res.*, *105*, 18,187.

Gibson, S. E., D. Foster, J. Burkepile, G. de Toma, and S. A. (2006), The calm before the storm: the link between quiescent cavities and cmes, *Astrophys. Journ.*, *641*, 590.

Heinzel, P., et al. (2008), Hinode, trace, soho and ground-based observations of a quiescent prominence, *Astrophys. Journ.*

Hudson, H. S., and R. Schwenn (2000), Hot cores in coronal filament cavities, *Adv. Space Res.*, *25*, 1859.

Hudson, H. S., L. W. Acton, K. A. Harvey, and D. M. McKenzie (1999), A stable filament cavity with a hot core, *Astrophys. Journ.*, *513*, 83.

Hudson, H. S., B. J.-L., and J. Burkepile (2006), Coronal mass ejections: overview of the observations, *Space Sci. Revs.*, *123*, 13.

Kucera, T. A., and E. Landi (2006), Ultraviolet observations of prominence activation and cool loop dynamics, *Astrophys. Journ.*, *645*, 1525.

Kucera, T. A., and E. Landi (2008), An observation of low level heating in an erupting prominence, *Astrophys. Journ.*, *673*, 611.

Kucera, T. A., V. Andretta, and A. I. Poland (1998), Neutral hydrogen column depths in prominences using euv absorption features, *Solar Phys.*, *183*, 91.

Kucera, T. A., G. Aulanier, B. Schmieder, N. Mein, and J.-C. Vial (1999), Filament channel fine structures in uv lines related to a 3-d magnetic mode, *Solar Phys.*, *186*, 259.

Kucera, T. A., B. De Pontieu, and M. Tovar (2003), Prominence motions observed at high cadences in temperatures from 10,000 to 250,000 k, *Solar Phys.*, *212*, 81.

Lin, J., and T. G. Forbes (2000), Effects of reconnection on the coronal mass ejection process, *Journ. Geophys. Res.*, *105*, 2375.

Lin, J., T. G. Forbes, and P. A. Isenberg (2001), Prominence eruptions and coronal mass ejections triggered by newly emerging flux, *Journ. Geophys. Res.*, *106*, 25,053.

Low, B. C. (1996), Solar activity and the corona, *Solar Phys.*, *167*, 217.

Lynch, B. J., S. K. Antiochos, P. J. MacNeice, Zurbuchen, F. T. H., and L. A. (2004), Observable properties of the breakout model for coronal mass ejections, *Astrophys. Journ.*, *617*, 589.

Marqué, C. (2004), Radiometric observations of quiescent filament cavities, *Astrophys. Journ.*, *602*, 1037.

Marqué, C., P. Lantos, and J.-P. Delaboudinere (2002), Multiwavelength investigation of a sigmoidal quiescent filament, *Astron. and Astrophys..*, *387*, 317.

Pick, M., et al. (2006), Multi-wavelength observations of cmes and associated phenomena, *Space Science Reviews*, *123*, 341.

Priest, E. R., and T. G. Forbes (2002), The magnetic nature of solar flares, *Astron. Astrophys. Rev.*, *10*, 313.

Reeves, K. K., and T. G. Forbes (2005), Predicted light curves for a model of solar eruptions, *Astrophys. Journ.*, *630*, 1133.

Reeves, K. K., H. P. Warren, and T. G. Forbes (2007), Theoretical predictions of x-ray and extreme-uv flare emissions using a loss-of-equilibrium model of solar eruptions, *Astrophys. Journ.*, *668*, 1210.

Schmieder, B., P. Kotrc, P. Heinzel, T. Kucera, and V. Andretta (1999), *ESA SP*, *448*, 439.

Schmieder, B., K. Tziotziou, and P. Heinzel (2003), Spectroscopic diagnostics of an h? and euv filament observed with themis and soho, *Astron. and Astrophys..*, *401*, 361.

Schmieder, B., Y. Lin, P. Heinzel, and P. Schwartz (2004), Multi-wavelength study of a high-latitude euv filament, *Solar Phys.*, *221*, 297.

Sterling, A. C., and R. L. Moore (2004), External and internal reconnections in two filament-carrying magnetic cavity solar eruptions, *Astrophys. Journ.*, *613*, 1221.

Su, Y., L. Golub, A. Van Ballegooijen, and A. Gros (2006), Analysis of magnetic shear in an x17 solar flare on october 28, 2003, *Solar Phys.*, *236*, 325.

Tomczyk, S., et al. (2008), An instrument to measure coronal emission line polarization, *Solar Phys.*, in press.

Tripathi, D., S. K. Solanki, H. E. Mason, and D. F. Webb (2007), A bright coronal downflow seen in multi-wavelength observations: evidence of a bifurcating flux rope?, *Astron. and Astrophys..*, *472*, 633.

Tripathi, D., S. E. Gibson, J. Qiu, L. Fletcher, R. Liu, and H. Gilbert (2008), On partially erupting prominences, *Astron. and Astrophys..*

van Ballegooijen, A. A. (2004), Observations and modeling of a filament on the sun, *Astrophys. Journ.*, *612*, 519.

van Ballegooijen, A. A., and S. R. Cranmer (2008), Hyperdiffusion as a mechanism for solar coronal heating, *Astrophys. Journ.*, *679*, in press.

van Ballegooijen, A. A., N. P. Cartledge, and E. R. Priest (1998), Magnetic flux transport and the formation of filament channels on the sun, *Astrophys. Journ.*, *501*, 866.

van Ballegooijen, A. A., E. R. Priest, and D. H. Mackay (2000), Mean field model for the formation of filament channels on the sun, *Astrophys. Journ.*, *539*, 983.

Wiik, J. E., B. Schmieder, and J. C. Noens (1994), Coronal environment of quiescent prominences, *Solar Phys.*, *149*, 51.

Zhang, M. (2006), Helicity observation of weak and strong fields, *Astrophys. Journ. Lett.*, *646*, 85.

Zhang, M., and B. C. Low (2003), Magnetic flux emergence into the solar corona. iii. the role of magnetic helicity conservation, *Astrophys. Journ.*, *584*, 479.

Zhang, M., and B. C. Low (2004), Magnetic energy storage in the two hydromagnetic types of solar prominences, *Astrophys. Journ.*, *600*, 1043.

Zhang, M., and B. C. Low (2005), The hydromagnetic nature of solar coronal mass ejections, *Ann. Rev. of Astron. and Astrophys.*, *43*, 103.

Zhang, M., N. Flyer, and B. C. Low (2006), Magnetic field confinement in the corona: the role of magnetic helicity accumulation, *Astrophys. Journ.*, *644*, 575.