Astro2010 White Paper

# Coronal "Dark Energy" and Solar/Stellar Activity

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**Abstract.** Magnetic fields in stellar atmospheres are believed to play the major role in stellar activity such as flares and atmospheric heating. However, the spatial scales on which conversion of magnetic energy to other forms takes place are small and cannot be resolved in stellar observations. Solar observations of the magnetic fields in the atmosphere and the physical processes that lead to energy release remain our best prospect for advancing our understanding of stellar activity. This white paper summarizes the current state of observations of magnetic fields in the solar atmosphere, describes prospects for much improved measurements with new instruments, and discusses the connections to stellar science.

## Introduction

In the broad context of stars, we are well aware that the Sun is merely a placid, unassuming, middle–aged star by comparison with its younger and more active kin. Essentially all stars with convecting envelopes exhibit "solar-like" signatures of variability as a result of emerging and decaying regions of magnetic activity. However, X–ray and radio flares which we have observed for decades can only be detected if they are much larger than their solar analogs, even from the most nearby stars. For example, dMe flare stars, evolved cool subgiants in rapidly rotating binaries, and young pre–main–sequence stars all exhibit flare behavior, typically observed a significant fraction of the time, which is orders of magnitude more pronounced than "typical" solar flares, both in size, luminosity and temperature (e.g., Güdel, 2004; Guedel, 2006; Aschwanden et al., 2008).

The mere fact that we call such activity "solar–like" indicates that we think that it must be similar in physical nature to the activity (flares and coronal mass ejections) that we see on the Sun. However, the scale of such events on other stars clearly dwarfs solar behavior, and in order to understand the difference in scale of solar and stellar phenomena, we need to understand more about solar activity.

Solar activity is intrinsically tied to its magnetic field, the "dark energy" of the Sun's atmosphere: flares, filament eruptions and large coronal mass ejections all take place in the atmosphere above active regions that are identified at the solar photosphere by their concentrations of kilogauss magnetic fields. We have been able to measure line–of–sight magnetic field components at the photosphere for decades using circular polarization induced in spectral lines by the Zeeman effect. However, we also understand that the surface line–of–sight magnetic fields are sufficient to identify only the potential, non-free energy in the overlying atmosphere. Measurements of the field *vector* are needed to constrain the free energy in the overlying atmosphere which is available for conversion to other forms such as particle acceleration (Low & Lou, 1990, e.g.). Conversion of the *free* magnetic energy into directed particle energy must occur in the lower–density atmosphere above the surface. Particle acceleration to nonthermal energies cannot happen in the collision–dominated photosphere. The corona is therefore the prime suspect for energy release, being also the site where much energy can be stored because of its large volume, and where the conversion is expected to be fast.

In order to identify coronal magnetic configurations that lead to such energy releases in the Sun, we must either measure coronal fields directly or extrapolate measurements of the vector field where they can be accurately made. At present accurate measurements can be made only in the photosphere, from where they can be extrapolated upwards as a boundary value problem. But herein lie several problems. The system of equations plus constitutes a mixed elliptic-hyperbolic boundary value problem which has proven remarkably difficult to solve (Gary, 1989; McClymont & Mikić, 1994; Amari et al., 1999). The measured photospheric fields are in a high $\beta$ state, (thermal energy $\gg$ magnetic energy) that can sustain currents orthogonal to the magnetic field

direction, whereas the coronal fields are in a low–$\beta$ plasma that must be force–free ($\mathbf{J} \parallel \mathbf{B}$). Magnetic boundary conditions derived from photospheric measurements are manifestly not force-free, so that the boundary fields are inconsistent with the model itself. Further, the extrapolations are ill-posed (Low & Lou, 1990) in that they are very sensitive to the boundary conditions.

There has nevertheless been a concerted effort to develop nonlinear force–free–field extrapolation techniques, summarized by Schrijver et al. (2006), and to compare the results with EUV observations of magnetic field lines. However, more stringent tests (Barnes et al., 2006) of such extrapolations using actual measurements of magnetic field strengths in the corona have been much less extensive due to the difficulty of measuring magnetic fields in the chromosphere and corona.

We must conclude that measurements of surface magnetic fields for extrapolation should be done not in the photospheric high $\beta$ regime, but in the upper chromosphere where the plasma $\beta$ is less than one. This subject is also discussed in the white paper by Ayres and colleagues (Ayres et al., 2009). The purpose of the present white paper is to summarize activity in this area, to outline the science questions that will be addressed by measurement of the "dark energy" present in coronal and chromospheric magnetic fields, and to summarize briefly the relevance to stellar physics.

## Conversion of Magnetic Energy

We will not try to review this topic in depth, but wish to outline current solar paradigms in order to provide a framework for understanding stellar activity. The mechanism for conversion of free magnetic energy to other forms has not been identified and remains a topic of intense study. Magnetic fields alone cannot do work on a particle since they only exert forces orthogonal to particle motion, so electric fields (which can be produced by changing magnetic fields) must also be involved. Classic ohmic resistivity leads to dissipation rates which are much too slow to explain flares. *Reconnection* of magnetic fields is the main contender for impulsive energy release in the corona: oppositely–directed magnetic field components, driven towards each other, formed as the highly conducting system tries to preserve field topology and force balance, reconnect and release energy in the form of plasma flows out of the reconnection region, heating and turbulence. Less implusive dissipation of currents that are an intrinsic part of the non–potential fields are also expected to release magnetic energy in the form of heat.

All conversion mechanisms share a common property: due to the low resistivity of coronal plasma, the spatial scale in which efficient energy conversion takes place must be small. In the solar corona this scale is of order tens of meters, 3 or 4 orders of magnitude smaller than the spatial resolution of current solar instruments. If we are to understand flare and heating processes in stars e must first obtain and interpret observations of solar coronal magnetic fields.

Once magnetic energy has been converted to particle energy, other mechanisms can take over to produce the nonthermal energy distributions that we measure in the Sun via X–ray, $\gamma$–ray and radio observations. In the solar paradigm, these nonthermal particles transport energy from the corona to the chromosphere where it heats plasma to soft X–ray temperatures. The resulting hot plasma is responsible for the X–ray flares that we observe on the Sun with the GOES satellites, and presumably those on active stars that we observe with satellites such as Chandra and XMM.

## Science Questions

We presently have very little real data on the magnetic field in the corona and chromosphere: from EUV and soft X–ray images we can see those magnetic field lines that carry significant density,

but due to the density–squared dependence of the emissivity at these wavelengths, which enhances contrast in density, we cannot "see" field lines that do not carry high densities, and this complicates our interpretation of magnetic topologies in features of interest. The absence of routine synoptic measurements of coronal and chromospheric magnetic fields means that the most important science questions remain unanswered:

- **Flares**: what is the magnetic configuration in which energy is stored in the solar atmosphere in a state that can be released rapidly in solar flares? What is the mechanism that allows us to build up energy relatively slowly, yet releases energy rapidly once a flare starts?
- **Heating**: is coronal heating the product of the need for the magnetic field to preserve its topology and force balance, as Gene Parker and others have argued, or is wave motion generated below the photosphere a critical process? If the latter, what role do magnetic fields play in the dissipation?
- **Eruptions**: what is the magnetic configuration leading to filament eruptions and coronal mass ejections? This topic is covered in more detail in another white paper (Gibson et al., 2009).

These questions must be addressed if we are to extrapolate solar behavior to distant stars where spatial resolution is much poorer.

## Existing and future facilities

Instruments measuring the vector magnetic field in photospheric lines- and hence the high plasma-$\beta$ regime- are both operational (e.g., the Spectropolarimeter on the Japan-US satellite *Hinode*; the Advanced Stokes Polarimeter, SPINOR, DLSP, IBIS all at the National Solar Observatory, the Haleakala Stokes Polarimeter at Mees Solar Observatory, the MSFC Magnetograph now at the University of Alabama/Huntsville, other facilities overseas) and planned (e.g.the Helioseismic and Magnetic Imager on the Solar Dynamics Observatory, launch date late 2009). There are an increasing number of facilities that can obtain chromospheric vector magnetograms (SPINOR, IBIS for example), in the low-$\beta$ upper chromosphere. However, magnetically sensitive coronal lines are far weaker and easily swamped by light from the solar disk: for this reason they can presently only be observed above the limb using coronagraphic techniques. Proposed facilities that will be important for advancing this field include:

- The Advanced Technology Solar Telescope (ATST) is the next NSF/Astronomy project in the Major Research Equipment and Facilities Construction line. It is a 4–meter optical/IR telescope optimized for low-scattering coronagraph observations with resolution of order $0.2''$ and field–of–view $300 \times 300''$. It will not only be able to advance state-of-the art measurements of chromospheric magnetic fields, but also it will be acquire high–resolution vector magnetograph observations above the limb in coronal lines.
- The Frequency Agile Solar Radiotelescope (FASR) will exploit radio techniques to measure magnetic field strengths in the corona above active regions. This will be a full–disk instrument with spatial resolution scaling with frequency and hence measured magnetic field strength, continuously from $1''$ at 2000 G to $10''$ at 200 G.
- The COronal Solar Magnetism Observatory (COSMO), conceived as a new synoptic facility, will observe both chromospheric lines (He I 1083.0nm) on the disk and above the limb, and

coronal lines (Fe XIII 1074.7nm and 1079.8nm) above the limb. With a 1.5m singlet lens, it will observe a one–degree field of view with a resolution of a few arcseconds and a magnetic sensitivity of a few Gauss.

## Relevance to Stellar Physics

Observed Stellar flares are much larger than their solar counterparts, although future observational advances will significantly reduce the energetic gap with solar flares). Güdel (2004) reviews the properties of X–ray flares from cool stars. For some typical examples, we draw from his Table 4: flare luminosities on active cool stars close to the main sequence can reach almost a *solar luminosity* in X–rays alone! Soft X–ray emission measures $n^2\,V$ at temperatures of order 100 MK can be $10^{56}$ cm$^{-3}$, or more than 1000 times the largest solar flares, requiring a very high density over a large volume in the stellar corona. Güdel (2004) reports inferred scales of $10^{11}$ cm, more than a solar radius, even for flares on M dwarf stars that are much smaller than the Sun. Whereas white–light flares (flares detected in optical continuum emission) are rare on the Sun, they are common on active stars. Even the quiescent coronae in active stars can have X–ray luminosities that are $10^{-3}$ of the total stellar luminosity, compared to $10^{-6}$ or so for the quiet Sun.

Given these remarkable facts, several important questions then arise:

- Dissipation of magnetic energy in a highly conductive corona requires very small scale structures in dynamic reconnection layers or more sedately through current sheets formed in untidy geometries. Are such scales discordant with the very large physical scales inferred for stellar flares, and with the need to convert orders of magnitude more energy through small dissipation regions in the course of a flare? The Sun and stars apparently behave such that small scale dissipation can trigger a larger scale dynamic energy release, or vice versa, such as in an avalanche. Whatever the true physical scenario, it is difficult to imagine that we can explain the magnitude of such a conversion in stellar flares without first understanding the magnetic configuration in solar flares: the new facilities discussed above still cannot resolve the true dissipation scale in the Sun's atmosphere, but can, e.g., distinguish between many small dissipation regions distributed through a large coronal volume, or a few large scale current sheets.

- In the case of heating the steady corona, both wave and current–sheet dissipation explanations for heating draw upon convective motions below the photosphere, generating either wave turbulence or twisted magnetic field configurations. Neither explanation is likely to be testable in active stars: observations of the Sun remain the best hope we have for identifying the true mechanism, and understanding the differences in more active stars cannot be achieved until we understand what happens in the Sun.

- Are the physical processes that we can infer in the solar atmosphere capable of explaining the observations of very active stars, or are new physical processes needed?

- Addressing these questions could help with broader issues as well, including the role of magnetic fields in accretion disk evolution and interaction with young stars, debris disks and planet formation.

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