Activity in the Sun and Late-type Stars – What Have we Learned so Far

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Abstract. In my summary of this symposium on “Solar and Stellar Activity: Similarities and Differences” I will highlight those new observations and theory that provide answers to long-standing problems or provide some insight into their essential physics. I also call attention to the new phenomena revealed by the beautiful TRACE, SoHO, Yohkoh, and ground-based data presented at the meeting and suggest some major questions that should be addressed using the upcoming AXAF and XMM X-ray spectra and images. One example of important recent progress in the field of solar/stellar activity is the detailed calculations of wave propagation and heating in magnetic flux tubes that predict the observed dependence of chromospheric Ca II emission on stellar rotation from basal heating rates up to saturation. Other important accomplishments are the first detailed maps of the magnetic field structure on active stars like AB Dor revealed by Zeeman-Doppler imaging and the drift of Hα transient absorption structures with orbital phase.

“Blind belief in authority is the greatest enemy of truth.”
– Albert Einstein.

1. Introduction

I am certain that Brendan Byrne would be proud of what we have accomplished. The organizers of this symposium have properly honored his memory by scheduling talks on the most rapidly advancing topics of solar and stellar activity, which inevitably are the most controversial. The invited speakers and poster presenters have risen to the challenge by highlighting many critical issues and discussing the alternative ways in which they should be addressed. I am pleased that many of the speakers have called attention to the inadequacies of their data sets and theoretical models. Honest assessments of the shortcomings of both observations and theory is required for a scientific discipline to make real progress.

There is likely universal agreement that the underlying cause of the diverse phenomena that we call “stellar activity” lies in the interactions between magnetic fields and turbulent plasmas. Although one can write down the physical equations that describe these interactions, our understanding of how to apply these equations, even at an intuitive level, remains far from complete. For example, is the \( \alpha - \Omega \) dynamo operating at the interface between the convective envelope and the radiative core of the Sun responsible for generating magnetic
fields and the solar cycle, or is the magnetic field regenerated close to the surface as suggested by the recent TRACE\textsuperscript{1} images. SUMER\textsuperscript{2} and Yohkoh X-ray data may well have settled the long standing controversy as to the nature of the heating process in the solar transition region and corona. It now appears that magnetic reconnection events are the dominant heating mechanism, but we have no detailed physical models that can explain how this really happens or predict the heating rate based on observable quantities.

For many years people have argued that the Sun can serve as our “rosette stone” in which the secrets of stellar active processes can be revealed by observing our nearby bright star with very high spatial, spectral, and temporal resolution. Thanks to SoHO, Yohkoh, TRACE, and very high resolution observations from the ground, we now have better insight into these questions, but observations of stars, even as unresolved point sources, are providing important new information not readily obtained from the Sun. For example, the dependence of presumably non-magnetic basal heating on stellar properties (e.g., $T_{\text{eff}}$, $g$, and chemical composition), saturated heating in rapidly-rotating young stars, flares occurring in stellar-size magnetic loops, polar and near-polar spots (Brendan take note), and the very unsolar-like magnetic field distributions on stars in RS CVn systems revealed by Zeeman Doppler images cannot be learned by studying only one middle-aged, slowly rotating star. The cross-fertilization and synergy between solar and stellar studies can be breathtaking at times. Conferences like this one that bring together solar and stellar astronomers stimulate this cross-fertilization, whereas meetings covering topics only in solar or in stellar astronomy do not benefit from different perspectives. I will mention other examples of this cross-fertilization later.

2. Some Illustrious Quotes

The true flavor of a meeting cannot be appreciated from a bland summary of the conclusions of each speaker. To appreciate this flavor one should hear what, in their unguarded moments, they actually said. So I begin my summary with some direct quotes, ripped out of context and reassembled into a more logical order. Here is a sample of the more enticing quotes:

Suzanne Hawley: \textsuperscript{3} “It is strange to be in Armagh without Brendan as my host.”

Rob Jeffries: “Brendan was my thesis examiner, and boy did he give me a hard time.”

Sami Solanki: (referring to a very complex line profile) “I don’t know where the flow is, but Brendan would find it.”

\textsuperscript{1}The Transition Region and Coronal Explorer.

\textsuperscript{2}The Solar Ultraviolet Measurements of Emitted Radiation instrument on the Solar and Heliospheric Observatory (SoHO).

\textsuperscript{3}In this paper I identify the symposium speakers by printing their names in \textbf{bold face}. Some of their comments were indeed bold.
Suzanne Hawley: (referring to a scatter diagram) “There is a slight correlation here.”

Sami Solanki: (well after his allotted time had ended) “Since the chairman has not barked, I will now misuse this opportunity and speak for another 10 minutes.”

Antonio Lanza: (before showing another 20 viewgraphs) “I have only one viewgraph of interest to show.”

Sami Solanki: “I hate to criticize my own work.”

Fred Walter: (at the beginning of his talk on pre-main sequence stars) “In order to learn about the stars, don’t start with the Sun. That is hopeless. Active stars are not scaled-up Suns.”

Andrew Collier-Cameron: “When in doubt, you might as well invoke a magnetic field to solve the problem.”

Karel Schrijver: (referring to the statistical connectivity of surface and deep magnetic fields, he coined the term) “magneto-chemistry.”

Helen Mason: (referring to the present picture of the solar corona with hot and cool magnetic loops interleaved, she used the term) “magnetic junkyard.”

Peter Ulmschneider: (referring to the inadequate state of solar chromospheric models) “The truth lies somewhere between the Carlsson-Stein and Avrett calculations.”

Peter Ulmschneider: “It is very strange that we are learning more about physical processes at meter scales by studying point sources than by studying the Sun with high spatial resolution.”

Peter Ulmschneider: (referring to the inability of present hydrodynamic codes to properly treat heating by strong shocks) “There are presently no good calculations on the market.”

Alesandro Lanzafame: (after saying that systematic trends provide more trustworthy results than comparisons of spectra with semi-empirical NLTE models) “A good fit does not mean that you have a good model.”

Alesandro Lanzafame: (concerning the reliability of present generation spectroscopic diagnostics of chromosphere and transition region plasmas) “Today I will provide more doubts than answers.”

Andrew Collier-Cameron: (referring to whether velocity drifts in Hα absorption features seen in spectra of AB Dor are long-lived prominences or ejected clouds) “I am uncharacteristically attempting to find a middle ground.”

Bert van den Oord: (referring to the lack of spatial resolution and inadequate time resolution of stellar flare data) “This is about the situation in solar physics in the 1960s.”
Eric Priest: (referring to TRACE movies showing that the solar transition region is highly dynamic) "The old model looks a bit outdated."

Eric Priest: "Yohkoh has revealed a whole new MHD world."

Brendan Byrne: (sage advice from the past) "May the road rise to meet you."

3. Some Important Results and Interpretations concerning Solar/Stellar Activity

The rich variety of interesting new observations from instruments in space and on the ground, and the insightful interpretations of these observations presented during the meeting were a great delight to all of us. A portion of this material struck me as especially interesting either because it broke new ground, strengthened or demolished some of our preconceptions, or will likely provide the basis for future models. With apologies to those people whose ideas did not strike me quite this way, here is my summary:

3.1. New Perspectives on the Solar Magnetic Field

Long uninterrupted sequences of magnetograms obtained with MDI have changed some previously accepted ideas about the solar magnetic field. Schrijver described how the field arises at the surface in bipolar regions with a power law distribution of sizes and fluxes and then diffuses and disappears when it encounters fields of opposite polarity. Since on large scales the photospheric field is replaced in 4 months (at sunspot maximum) or 10 months (at sunspot minimum), the photospheric field forgets its past on these time scales. Thus the connectivity between surface and deep magnetic field lines must be statistical (a concept that he called "magneto-chemistry") rather than deterministic as assumed in the classical Babcock–Leighton dynamo model. Does this mean that the widely-accepted αΩ dynamo mechanism operating at the interface between the convective envelope and the radiative core must be replaced by a dynamo operating close to the solar surface?

On small scales the replacement of photospheric magnetic flux is far more rapid. Schrijver estimates that in very quiet regions on the solar surface the magnetic field is replaced about every 40 hours. Magnetic fields disappear from the photosphere mainly by subduction rather than cancellation, a process that produces no heating. However, the continual replacement of magnetic flux in the photosphere leads to field-line braiding, reconnection, and thus heating in the corona, likely along the lines proposed by Parker (1993). I encourage theoreticians to compute coronal heating rates from the evolution of the photospheric field as seen by MDI to see if the coronal energy budget can be explained by this process.

Mason pointed out that EIT images have completely demolished the old view that 10^5 K (transition region) plasma exists only at the footpoints of magnetic loops between coronal plasma and the chromosphere. Instead, the EIT

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4 The Michelson Doppler Imager instrument on SoHO.
5 The Extreme-Ultraviolet Imaging Telescope instrument on SoHO.
images show that hot \( T > 10^6 \) K and cool \( T \sim 10^5 \) K loops are interspersed in a model that has been called the "magnetic junkyard" (e.g., Dowdy, Rabin & Moore 1986). Thus the corona is magnetically disconnected from the transition region, and typical pressures of transition region and coronal plasma are not related by hydrostatic equilibrium. This situation provides guidance to those who wish to model stellar atmosphere structure from UV, EUV, and X-ray fluxes. One can infer an emission measure distribution from the data, but it is highly unrealistic to then infer the properties of a one component model structure in hydrostatic equilibrium. The "magnetic junkyard" model simply explains why stellar coronal pressures inferred from density sensitive line ratios are typically much larger than pressures of the \( 10^5 \) K plasma. The SUMER instrument on SoHO has discovered that macro-spicules at the limb appear to be spinning, leading to their being called "tornados". Are the spinning macrospicules flux tubes filled with chromospheric material?

From their analysis of HRTS\(^6\) ultraviolet spectra, Dere et al (1987) published the surprising result that the cross-sectional area of bright features in the transition region are very small (< 70 km) and the filling factors also very small (< 0.01). Mason noted that filling factors of \( 10^{-2} \) down to perhaps \( 10^{-5} \) are implied by SoHO ultraviolet spectra, confirming the HRTS results. If the bright emission points in the transition region are confined by the magnetic field, then the magnetic flux loops are very thin (as is shown in the spectacular TRACE images) and the filling factors measure the cross-sectional area of strong fields on the Sun. Schneider showed theoretical models of solar magnetic field evolution that can explain erupting prominence observations.

3.2. New Observations of Stellar Magnetic Fields

Linsky provided us with a tour through the HR Diagram, identifying the types of stars for which magnetic fields are measured or inferred from reliable proxies and summarizing the many roles that magnetic fields can play in stellar atmospheres. For late-type stars, photospheric magnetic fields can now be measured with a variety of techniques using both unpolarized and polarized light. Beginning with the pioneering work of Robinson, Worden & Harvey (1980), a very successful technique has been to measure the Zeeman broadening of optical lines and splitting of near-infrared lines in unpolarized light. Using this technique, Saar (1990) showed that photospheric field strengths increase with decreasing \( T_{eff} \) in main sequence stars consistent with the equipartition of gas and magnetic pressure, and that the magnetic flux and filling factors increase with stellar rotation rate and Rossby number. This method does not, however, provide information on the distribution or three-dimensional structure of the magnetic field across the stellar surface.

Donati and Collier-Cameron described the Zeeman Doppler imaging (ZDI) technique that can map the radial, meridional, and azimuthal components of the magnetic field for rapidly-rotating stars using profiles of some 2000 spectral lines in circularly polarized light. Zeeman-Doppler images are now available for six active stars (including AB Dor and HR 1099) using the maximum

\(^6\)The High Resolution Telescope Spectrograph rocket experiment.
entropy or optimal reconstruction techniques. The ZDI technique is described by Donati & Brown (1997) and by Donati et al. (1997). Unlike the Sun, the field lines for these active stars are azimuthal in rings (3 for AB Dor). The technique now allows one to follow the magnetic field evolution in active stars and to monitor stellar magnetic cycles directly rather than through a proxy like the Ca II H+K flux. Collier-Cameron said that for AB Dor the azimuthal field predicted from potential field extrapolations of the observed radial magnetic field agrees well with the observed azimuthal field. This gives the technique additional credibility. However, Solanki pointed out that the ZDI technique likely misses most of the magnetic field because it does not see dark spots of weak field regions.

Recent studies have provided new information on the geometry of stellar magnetic fields in addition to field strengths and magnetic fluxes. Walter showed that very large prominence-like magnetic loops are inferred for naked T Tauri stars (NTTS) and other active stars. Collier-Cameron showed that for AB Dor the rotation periods of Hα transient absorption features are the same as spots at latitudes of 60°–70°. Since the Hα absorbing clouds/prominences with lifetimes of about 1 week often lie outside the co-rotation radius (about 3 stellar radii), this active star appears to have giant magnetic loops that are anchored at high latitudes on opposite hemispheres.

The evidence for spots lying near the poles of active stars (unlike the case for the slowly rotating Sun) is increasing since Byrne (1996) and Strassmeier (1996) last debated the topic, and the picture is becoming more complex. As you recall, the main evidence for polar spots comes from Doppler imaging of active stars where the filling-in of the cores of absorption lines with no change with rotational phase is usually interpreted as indicating the absence of continuum emission at the rotational poles. Both authors identified other mechanisms that could make absorption lines less deep in active stars than in quiescent stars including greater heating of the upper atmosphere, different micro-turbulence, and magnetic splitting. Solanki called attention to the Bruls, Solanki & Schüssler (1998) plage models that show that some lines used for Doppler imaging have filled-in cores but not of the type observed in the spectra of active stars. Lanza & Rodonò showed Doppler images indicating that rapidly-rotating stars have polar spots, while more slowly-rotating stars have high latitude spots not at the poles. They also reviewed the evidence for very large spots or spot groups (spot filling factors as large as 0.60 for II Peg) and preferred longitudes for spots on stars in RS CVn systems.

3.3. New Studies of Stellar Flares and Coronae

Although the optical and near-UV continua contain most of the radiative energy loss from flares on M dwarf stars, realistic models that can explain the time dependence of this energy loss are in short supply. For this reason the dynamic flare model atmospheres presented by Abbett and Hawley were a highlight of the meeting. Using the Carlsson & Stein (1997) radiative hydrodynamic code, Abbett and Hawley solved for the radiative and dynamic response of the photosphere and chromosphere to a beam of non-thermal particles propagating down along a flux tube from the magnetic energy release site in the corona. The initial response of the atmosphere is increased photoionization that increases
the electron density and H⁻ opacity, thereby decreasing the continuum intensity. This is probably the explanation for the “pre-flare dips” seen in the near infrared continuum before Hα brightenings in some flares. Next is a “gentle” phase in which the photosphere can radiate all of the input energy from the beam in the hydrogen and H⁻ continua with an increase in temperature. In this stage the emission lines are symmetric as there are no mass motions. When hydrogen becomes highly ionized and cannot radiate the input energy, the atmosphere explodes with a large shock wave removing the input energy largely as kinetic energy. The code predicts shifted, distorted, and doubled emission lines similar to what is observed during flares. I consider this work to be a highlight of the meeting because it demonstrates that models that properly include the essential physics can explain many of the diverse flare phenomena that have puzzled observers and theoreticians alike for many years.

X-ray emission from flares on M dwarf stars and close binaries (RS CVns, Algols, and W UMæs) are often explained by analogy with solar compact flares (short time-scales) or two-ribbon flares (longer time-scales). The usual explanation for the factor of 10⁸–10⁹ larger energy release in large stellar flares compared to large solar flares is that the flare volumes in active stars are much larger than for the Sun. This explanation should have been scrutinized at the meeting. Even if it is right, this explanation begs the question of why the flare volumes are so much larger in active stars. Is this because individual flux loops are larger (as in the case of AB Dor), or that much larger arcades of loops can be flare sites in stars with much larger magnetic fluxes than the Sun?

An important result obtained from the analysis of ROSAT and ASCA X-ray energy distributions and EUVE spectra is that the inferred abundances of metals with low first ionization potentials in the coronae of Algols and RS CVns are typically 1/3 to 1/10 of the abundances measured in the solar photosphere, but are similar to what is measured in the solar corona (the so-called FIP effect). Mathioudakis reminded us that the inferred metal abundances are sensitive to the amount of high temperature plasma in the assumed coronal model. Van den Oord explained that the low coronal abundances are due to settling in hydrostatic equilibrium. During flares one observes a return to normal abundances most likely due to the evaporation of photospheric material into the corona. An example is the 1994 August 29 flare on UX Ari (Güdel et al. 1998). However, SoHO and TRACE observations reveal that the solar atmosphere is highly dynamic and thus mixing processes must be included in any diffusion calculations for the Sun and presumably other stars. Realistic calculations are needed in order to better understand the FIP effect.

3.4. New Models of Heating Mechanisms

The question of whether the outer atmospheres of stars with convective zones are heated primarily by the dissipation of acoustic waves, MHD waves, or magnetic reconnection events (now often called “microflaring”) has been a major theme of solar/stellar physics for more than half a century. What new results concerning this question were presented at this meeting?

The Ca II H₂V grains, the transient bright features that appear in the violet peaks of the Ca II emission on small-scales have often been cited as evidence for localized magnetic heating events. The new TRACE observations described by
Rutten now show that the grains are not spatially correlated with the magnetic field, but instead are naturally produced by upwardly propagating acoustic waves generated by pistons in the photosphere. The TRACE data also suggest that the bright internetwork grains are produced by weak shocks in the chromosphere. These weak shocks likely account for the basal flux chromospheric heating rate seen in the internetwork regions and in very slowly-rotating stars (Buchholz, Ulmschneider & Cuntz 1998). The enhanced chromospheric emission in the network and active regions on the Sun and in active stars requires some type of magnetic heating process.

Ulmschneider and Cuntz summarized some major advances that are being made in computing the heating rates of MHD waves in stellar chromospheres. Ulmschneider showed that convective buffeting of magnetic flux tubes in the solar photosphere can generate longitudinal MHD wave fluxes with $2 \times 10^8$ erg cm$^{-2}$ s$^{-1}$ and transverse MHD wave fluxes 15 times larger. In principle, these wave modes contain sufficient energy in these modes to heat stellar chromospheres, especially when one includes a spectrum of wave periods and allows for different period waves to overtake slower waves to form super-shocks. The critical issue is how to properly treat strong shocks where "there is presently no good calculation on the market."

Cuntz presented an insightful set of calculations of the propagation of MHD waves in K2 V stars. He computed the MHD waves fluxes for atmospheres with photospheric field strengths $B_0 = 2100$ G, roughly the equipartition value, and magnetic fluxes given by an empirical relation of $B_0 f_0$ with $P_{\text{rot}}$. In his models the flux tube cross-sectional areas increase with height until the upper chromosphere is completely filled. For slowly rotating stars, the small magnetic filling factors in the photosphere imply that the flux tube cross sections increase rapidly with height so that the upward propagating MHD waves are spread out over a large area and therefore shock high in the atmosphere where the density is low. The computed Ca II H+K flux is therefore small. For rapidly rotating stars the opposite is true, so that the MHD waves spread out slowly with height and therefore shock low in the chromosphere where the densities are large. As a consequence, the chromospheric heating rate is large (c.f. Fawzy, Ulmschneider & Cuntz 1998). From my perspective the important point is that we saw calculations that incorporate much of the essential physics of MHD wave heating and predict the dependence of the Ca II H+K surface flux on $P_{\text{rot}}$ in agreement with observations. In particular, the sum of acoustic and MHD wave heating explains the chromospheric heating rate from the basal flux level (pure acoustic waves in the very slowest rotators) to the saturated heating rate of the most rapid rotators without the need for microflares or other heating mechanisms in the chromosphere.

Above the chromosphere other heating mechanisms become important. In her review of the SUMER observations, Mason said that the small-scale bidirectional flows seen in $10^8$ K emission lines, which were first noted in HRTS data, are correlated with the position of transition region explosive events, which are likely produces by microflares. Wood, Linsky & Ayres (1997) have interpreted the broad wings of transition region lines in active stars as produced by microflare events, as the fraction of the emission line fluxes in the broad wings
increases with the X-ray and C IV surface fluxes. The EIT and CDS data show that the sum of many microflare events, which are generally assumed to be magnetic reconnection events, may explain 60% or more of the coronal heating. The microflares typically occur in regions of complex polarity. Priest concludes that these important results from SoHO are producing a paradigm shift in the question of how the corona is heated. X-ray spectroscopy with the upcoming AXAF and XMM satellites will provide powerful diagnostics of the coronal plasmas that hopefully will provide constraints on the heating mechanism. In particular, solar coronal loops appear to be isothermal and require uniform heating rates. Priest argued that small current sheets may be required to heat these loops. Güdel, Guinan & Skinner (1997) found that the emission measure of high temperature coronal plasma decreases with age. This important result must be explained by models of microflare heating.

Mason told us that the Chianti atomic data base for emission line spectroscopy is being extended to \( \lambda < 50 \) \( \AA \) for this purpose. One positive aspect of the delayed launch dates for AXAF and XMM is that the Chianti code extensions should be available in time to analyze these exciting X-ray spectra.

Pallavicini described the recent SAX satellite observations of extremely hot flares from UX Ari and AB Dor with \( kT_2 = 9.6 \) keV and 20–50 keV photons. If these flare plasmas are thermal, as typically assumed, then the temperatures are about \( 10^8 \) K. Since SAX detected only a small number of hard X-ray photons, it is hard to distinguish between X-ray spectra from thermal and non-thermal electron energy distributions. The detection of hard X-rays from non-thermal distributions of electrons during impulsive solar flares makes it likely that some or all of the hard X-rays from stellar flares are non-thermal. Future observations with SAX and XTE are needed to answer this question. Then we can address the question of whether the heating of coronae during flares and outside of detected flares is the same phenomena only on different scales.

4. Some important unanswered questions concerning Solar/Stellar Activity

Many solar/stellar activity phenomena do not yet have an adequate explanation. I list here some of the more interesting questions as brought to our attention by the various speakers in the hope that progress will be reported soon:

**Mathioudakis:** How can one explain densities of \( 10^{12} \) cm\(^{-3} \) at \( T \geq 10^7 \) K in “nonflaring” coronae as inferred from EUVE spectra? The implied gas pressures are \( \sim 10^4 \) that of the solar corona, and the required magnetic fields needed to confine the plasma exceed 200 Gauss. Are coronal fields this strong consistent with measured photospheric fields? During flares the inferred densities are even higher, implying larger magnetic field strengths.

**Stern:** What is the explanation for supersaturation \( (R_x = L_x/L_{bol}) \) turns over at low \( N_R = P_{rot}/\tau_{conv} \)? This phenomenon is seen in rapidly rotating

\(^7\)The Coronal Diagnostic Spectrometer instrument on SoHO.
stars in young clusters like α Per. (Collier-Cameron suggested that the co-rotation radius moves in to the corona for such stars.)

**Hawley:** Does $R_x = L_x/L_{bol}$ turn over in the lowest mass stars in clusters?

**Stern:** Why are binary stars (including wide binaries) more X-ray luminous than single stars of the same age and spectral type?

**Stern:** After 17 years of observations, why is there no evidence for stellar X-ray activity cycles? The Mt. Wilson Ca II H+K line program has identified cycles in many G and K stars, but as yet no cycles have been identified in the X-ray data. Is this due to the sparse sampling by X-ray satellites or is there another explanation?

**Jeffries:** Why is there a large spread in $v_{sini}$ for clusters younger than the Hyades?

**Jeffries:** Why is $<L_x>$ a factor of 2 different in clusters of the same age (e.g., Hyades and Praesepe)?

**Solanki:** Why is there a log normal distribution of sunspot sizes? What are the implications for stars with very large spots (e.g., II Peg with spots covering 40% of the visible surface)?

**Solanki:** In penumbral outflows why is the flow velocity horizontal when the magnetic field is inclined?

**Solanki:** Can the observed filling in of line cores in rapidly rotating active stars be explained by plages rather than the usual interpretation of polar spots?

**Lanza:** Why does the amplitude of differential rotation decrease as the rotation velocity of stars increase?

**van den Oord:** Why are the most intense flares observed on the brightest stars (e.g., RS CVns and Algols)?

**van den Oord:** What is the physical explanation for the Güdel–Benz law: $L_x = 10^{15.5±0.5} L_R$? This relation is unexpected because the X-ray emission is thermal whereas the radio emission from active stars is non-thermal.

**Phillips:** Why are hot points observed by the Yohkoh satellite at the tops of solar coronal loops when conduction should make the loops isothermal in about 2 seconds?

**Ulm Schneider:** What is the correct way to treat strong shocks (e.g., heating and propagation)? Also, it is important to look for short period waves produced by small shocks.

**Lanzafame:** What are reliable plasma diagnostics given the following problems:

- contribution functions are typically broad, covering a range of plasma temperatures and densities leading to a difficult inversion uniqueness problem;
- ionization can be out of collisional equilibrium, especially for the Li-like and Na-like ions;
- the fraction of the aperture filled with bright emission for solar observations is uncertain and the filling factor for stars is unknown; and
- the essential physical processes are difficult to model given the highly dynamic atmospheres, diffusion, turbulence, and complex frequency redistribution. (He suggested in his talk that a search for trends and common behavior of different lines that may lead to conclusions that do not depend heavily on these problems.)

**Priest:** How does one construct an accurate theory for 3-D reconnection?

**Priest:** Why is the transition region so dynamic?

**Hawley:** Why does the Hα emission from M dwarfs not appear to decay with age as do other activity indicators for F, G, and K stars? This new result was unexpected since previously more limited surveys of M dwarfs indicated a decrease in Hα emission with age.

**Pallavicini:** If solar coronae consist of many loops at different temperatures, then it will be difficult to derive the temperatures, loop lengths, and filling factors for these different loops uniquely even with high quality X-ray spectra obtained by *AXAF* and *XMM*.

To this list I will add a few more critically important questions:

- What exactly do we mean by the term “activity” and how should it be characterized?
- Are all phenomena that we call “active” predominately magnetic in character?
- Does the full range of stellar active phenomena occur on the Sun, even rarely?
- Are there active phenomena on stars for which solar phenomena are not useful prototypes?
- What mechanical forces other than convection can produce active phenomena?
- Are active phenomena in close binary stars and pre-main sequence stars qualitatively different from phenomena on single stars?
- Why are active phenomena in some stars as much as $10^4$ times more energetic than in the Sun?
- Which magnetic heating modes are most important in different types of stars and for different temperatures and densities?
- What role does the geometry of the magnetic field play in heating?
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References