Magnetic Fields in the Hertzsprung-Russell Diagram

Jeffrey L. Linsky

JILA/University of Colorado and NIST
Boulder, CO 80309-0440 USA

Abstract. Stellar activity consists of the phenomena that occur from the conversion of magnetic energy into heat, non-thermal particles, and kinetic energy after the energy in the magnetic field has been raised above its potential field value by mass motions. For stars located in different regions of the HR Diagram, the nature and magnitude of the mass motions responsible for stressing the field lines can be fundamentally different leading to a variety of activity phenomena. With this paradigm in mind, I lead a tour through the HR diagram, identifying those types of stars for which magnetic fields have been measured or inferred by reliable proxies. For each class of stars I identify the likely type of plasma flow that is stressing the magnetic fields to produce the observed active phenomena.

“Magnetic fields are to astrophysics what sex is to psychoanalysis.”

Henk van de Hulst (1988)

1. Roles that Magnetic Fields Play in Solar and Stellar Atmospheres

During this conference, we will have the opportunity to learn about the latest observations and theory concerning the measurement of magnetic fields and magnetic field controlled phenomena in the atmospheres of the Sun and late-type stars. Unfortunately, it is easy to lose sight of the important questions. From my perspective there are four fundamental questions:

1. How are magnetic fields regenerated in different types of stars?

2. What are the properties (e.g., structure, field strengths, filling factors, geometry, energy content) of magnetic fields in different types of stars?

3. What types of plasma motions stress the magnetic fields, leading to conversion into other types of energy (e.g., heat, non-thermal particles, kinetic energy)?

4. What observable manifestations of these energy conversion processes can be studied as stellar active phenomena?

In this review I will concentrate on the last two questions and make some comments concerning the second. I anticipate that others will address the first
and second questions in more detail. Since observers concentrate on the last question, I will start with it. It is difficult, however, to go back from the observed active phenomena to the physics of energy conversion (the third question), because different energy conversion scenarios could, in principle, lead to the same observable active phenomena. Theory can be an important guide in searching out the essential physics responsible for the observed phenomena. Let us begin by listing the various observable phenomena that magnetic fields can produce:

**Heating Processes:** MHD wave processes, rapid field annihilation processes

**Flares:** rapid enhancements of the emitted flux across the electromagnetic spectrum that result from rapid magnetic field annihilation events

**Isolation:** thermal isolation of adjacent plasma by suppression of conduction and convection

**Geometry of Structures:** magnetic flux loops and arcades; chromospheric network structures, spicules, coronal mass ejections, prominences

**Convection:** magneto-convection has different properties and cell sizes than normal convection

**Wind Acceleration:** Alfvén waves and other MHD wave acceleration mechanisms

**Non-thermal Particle Acceleration:** Maxwell’s equations say that \( \nabla \times \mathbf{H} - \frac{1}{c} \partial \mathbf{D} / \partial t = 4 \pi j / c \). Therefore, twisted magnetic fields create electric currents that accelerate charged particles.

**Turbulence:** spectroscopic turbulence can be produced by bulk motions created by magnetic fields

**Downflows:** downflows observed as redshifts in strong field regions

**Starspots:** The photosphere in sunspots and starspots appears dark because of the suppression of convective flux by strong magnetic fields. The location of the visible photosphere is depressed (the so-called “Wilson Depression”) because horizontal pressure balance requires lower gas pressures in spots, lower densities, and thus has less opacity.

**Zeeman Broadening:** Zeeman sensitive lines will be broader than non-sensitive lines and can increase line blanketing

**Polarization:** line and continuum polarization and depolarization processes

**Radio Emission:** gyrosynchrotron emission and maser radio emission are much brighter than thermal free-free emission.

A fundamental problem: Since the gas pressure scale height \( H = kT / \mu g \) is generally smaller than the magnetic field scale height, \( \beta = 8 \pi P_{gas} / B^2 \) changes from \( \beta > 1 \) below the photosphere to \( \beta < 1 \) above the photosphere. Thus below the photosphere convective motions shake the field lines, whereas above the photosphere the field geometry controls the motion of the plasma. What are the consequences of this behavior in a dynamic atmosphere?
2. A Tour Through the HR Diagram in Search of Magnetic Fields

Before we begin our tour, I should first describe my model of the relation of magnetic fields to solar/stellar activity. This can help us to concentrate on what I believe are the critical questions concerning magnetic fields. I think of solar/stellar activity according to the paradigm: Stellar activity consists of the phenomena that occur from the conversion of magnetic energy into heat, non-thermal particles, and kinetic energy after the energy in the magnetic field has been raised above its potential field value by mass motions. For stars located in different regions of the HR Diagram, the nature and magnitude of the mass motions responsible for stressing the field lines can be fundamentally different leading to a variety of activity phenomena. Although this paradigm may not include all activity phenomena, probably most workers in the field would accept it. Given this paradigm, here are some important questions to ask during our tour:

- What direct or indirect techniques can measure magnetic field properties?
- Are magnetic fields detected or inferred from the data?
- What are typical magnetic field strengths and fluxes?
- What is the magnetic field geometry?
- Is there evidence for active regions and star spots?
- What is the nature of the mechanical stresses on the magnetic field?

2.1. O and Early-B Stars

We begin our tour in the upper left hand of the HR Diagram where the hottest and most luminous stars live. I have not found any direct measurements of magnetic fields on these stars and it is difficult to measure sub-kilogauss fields from Zeeman broadening or splitting of spectral lines as the these stars rotate rapidly and their spectral lines are very broad. However, magnetic fields may eventually be measured using the Hanle effect (cf. Ignace, Nordsieck & Cassinelli 1997). The Copernicus satellite observed O vi emission lines, which are now understood as produced by Auger ionization (O iv $\rightarrow$ O vi) by X-rays from the shocked hot plasma in the radiation-driven winds of these stars. The presence of magnetic fields in some of these stars is inferred from the non-thermal radio emission spectrum seen in 24% of the O3–B2 luminous stars surveyed by Biegung, Abbott & Churchwell (1989).

White (1985) proposed a model in which Fermi acceleration by strong shocks in the wind accelerates electrons that emit by the synchrotron process. If this model is correct, then surface fields of a few Gauss are implied, and such fields could be primordial in these young stars. Also, Gagné et al. (1997) discovered periodic X-ray emission from $\theta^1$ Ori C (O7 V). They argue that the X-ray periodicity is due to absorption by the wind in an extended magnetosphere. This star may be an example of a high mass oblique rotator star like the chemically peculiar B and A stars. Babel & Montmerle (1997) estimate a stellar surface magnetic field of 300 G for this star. I conclude that for these stars the magnetic fields are stressed by bulk motions in the radiation-driven winds.
2.2. Magnetic Chemically Peculiar B and A Stars

On and near the main sequence from about spectral type B2 down to about A5 lie several types of magnetic chemically peculiar stars. Magnetic fields with simple geometries (dipoles and quadrupoles) and mean surface field strengths up to 34 kG [Babcock's star = GL Lac (B8p SiHeW)] are easily measured. The hotter stars in this group are generally helium-strong and the cooler stars are helium-weak and Si-strong. For many years their atmospheres have been described with oblique rotator models in which the magnetic and rotational poles are well separated. Many of these stars are luminous non-thermal radio emitters as shown by their negative spectral indices (Linsky, Drake & Bastian 1992). Also a few have now been identified as intrinsic X-ray sources, that is the X-ray emission is not from an unknown companion star (Drake et al. 1994). Non-magnetic chemically peculiar stars are not radio sources (Drake, Linsky & Bookbinder 1994). Linsky et al. (1992) proposed a wind-fed magnetosphere model in which the radiation-driven wind emerging far from the magnetic poles is trapped in the magnetosphere. Gas pressure and centrifugal acceleration distend the field lines near the magnetic equator, forming an equatorial current sheet and leading to electron acceleration and gyro-synchrotron emission. The non-thermal radio radiation and perhaps the X-ray emission are thus a consequence of the magnetic fields being stressed by the stellar wind and rotation.

2.3. Normal B and A Stars

I know of no magnetic field detections for stars without chemical peculiarities in the spectral range B4–A5. Since many of these stars are slow rotators or more rapid rotators seen pole-on, Zeeman measurements of absorption lines in polarized light would have detected strong dipolar fields or in unpolarized light would have detected the presence of kG fields. I also know of no detections of non-thermal radio emission from main sequence stars in this spectral range. X-ray emission was detected from < 3% of the field stars in the B4–B9 spectral range in the Grillo et al. (1992) Einstein survey, so it is difficult to say that these stars constitute a class of intrinsic X-ray emitters. Schmitt et al. (1993) detected a few late-B stars in their ROSAT survey of wide binaries, but concluded that the cause of the emission is a “puzzle.” Thus we have no direct or indirect information on the magnetic fields of these stars.

2.4. F–M Main Sequence Stars

If one were to observe the Sun as a star (i.e., as a point source), then the net magnetic flux would correspond to a uniform magnetic field strength of < 1 G because of the nearly complete cancellation of magnetic flux with opposite polarities. It would be extremely difficult to measure this average magnetic field with a Zeeman analyzer that compares the shift of line profiles measured in opposite circular polarizations. The failure of Zeeman polarization techniques to measure significant magnetic field strengths in main sequence stars with sub-photospheric convective zones is usually explained by these stars having very complex magnetic field geometries like the Sun. High resolution magnetograms reveal that most of the Sun has very weak photospheric fields, but in small clumps below the chromospheric network, typical field strengths of 1500 G are common. Thus kiloGauss fields with a variety of orientations are distributed across the solar
photosphere and presumably other dwarf stars awaiting a sensitive technique for their measurement. Even though sunspots have stronger magnetic fields, their contribution to the magnetic field in integrated sunlight is negligible as sunspots are dark in the optical and cover < 1% of the solar surface.

Robinson, Worden & Harvey (1980) pioneered a very successful technique to measure the Zeeman broadening of optical lines and splitting of near-infrared lines. They analyzed high resolution spectra in unpolarized light for which there is no cancellation of oppositely polarized magnetic fields. Saar (1990) developed this method further and used it to measure the mean unsigned magnetic field strengths (B) and filling factors (f) in the active regions of many stars. Saar assumed either a two-component atmosphere $F_{obs} = fF_{mag}(B) + (1 - f)F_{quiet}(B = 0)$ or a three-component atmosphere (including starspots), where $F$ refers to the radiative flux observed from the magnetic or quiet components of the atmosphere. Uncertainty in the $F_{mag}/F_{quiet}$ ratio leads to uncertainty primarily in the value of $f$. He then solved the radiative transfer equation in a Milne-Eddington atmosphere including the exact Zeeman patterns and magneto-optical effects in the line transfer. For each star he adopted published values for vsini and radial-tangential macro-turbulence. Saar (1995, 1996) has summarized this work which has lead to the following important conclusions concerning main sequence stars:

- Magnetic field strengths increase with B–V and decreasing $T_{eff}$ in main sequence stars,
- The inferred magnetic field strengths are close to their equipartition values, i.e., $B \approx B_{eq} = (8\pi P_{gas})^{0.5}$, with $P_{gas}$ evaluated where $T = T_{eff}$, except perhaps for the most active stars,
- Both the filling factor and the total magnetic flux ($fB$) increase as $P_{rot}$ and the Rossby number decrease until saturation is reached at large values of $f$. (Note that the divergence of flux tubes with height should depend on the value of $f$.)
- Vilhu (1994) showed that most activity indicators reach a maximum value (saturate) at high angular velocity ($\Omega_{sat}$), but when $\Omega > \Omega_{sat}$, $B$ may increase beyond $B_{eq}$ while $f$ stays at its saturated value.
- X-ray and Ca II surface fluxes are correlated with $fB$.

Although very successful in measuring global properties of stellar magnetic fields, the Zeeman broadening method provides no information on the three-dimensional (3-D) structure of the magnetic field across the stellar surface. A very different technique described by Donati & Brown (1997) and by Donati et al. (1997) called Zeeman Doppler imaging (ZDI) can map the radial, meridional, and azimuthal components of the magnetic field for rapidly-rotating stars using profiles of a large number of 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 entropy or optimal reconstruction techniques. Unlike the Sun, the field lines for these active stars are azimuthal in rings (3 for AB Dor). This 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. However, the ZDI technique likely misses most of the magnetic field because it does not see dark spots or weak field regions.

The existence of dark starspots, identified by photometric variability and Doppler images, is an important indirect indicator of stellar magnetic fields. Although sunspots cover less than 1% of the solar surface, starspots can cover as much as half of the observed hemisphere of stars in RS CVn systems like II Peg. Since starspots are very dark in the optical and near infrared, there are no measurements of starspot magnetic fields. Sunspot umbral fields are typically 3500 G, or about 2.3 times typical photospheric network fields. Whether or not starspot magnetic field strengths are similarly enhanced will require future Zeeman broadening measurements of molecular lines in the infrared.

Redshifted transition region lines (e.g., C II, Si IV, C IV) are one of several indirect indicators of magnetic fields in stellar atmospheres. Redshifts have been observed in solar spectra for a long time. Achour et al. (1995), for example, found that the redshift of the C IV 1548Å line is 6.2 km s\(^{-1}\) in quiet regions but is 13.0 km s\(^{-1}\) in active regions. Observations with SoHO/CDS and SoHO/SUMER show that redshifts are seen even in lines of Ne VIII formed at 650,000 K (Brynildsen et al. 1998) although see paper by Teriaca et al. in these proceedings. IUE spectra (e.g., Ayres, Jensen & Engvold 1988) and HST/GHRS spectra (e.g., Wood, Linsky & Ayres 1997) show redshifts in the transition region lines of late-type dwarfs and giants. Resonance and optically thin intersystem lines are both redshifted, confirming that the downflows are real and not an effect produced by optically thick lines formed in an atmosphere with a velocity gradient. Downflow velocities increase with line formation temperature between 3 \(10^4\) and 1 \(10^6\) K. Lower gravity stars (e.g., β Dra and Capella) show larger redshifts than main sequence stars (e.g., α Cen A, α Cen B, and ε Eri). Solar transition region models computed with a 2-D hydrodynamic code show that density perturbations in regions of strong density and temperature stratification cool radiatively to become condensations that flow downward by gravity (Reale et al. 1996). This effect is enhanced (as is observed on the Sun) in regions of vertical magnetic fields which constrain horizontal motions and conduction.

I conclude that for the F–M dwarf stars active phenomena result from the stressing of magnetic fields by convective motions.

2.5. Late-M Stars and Brown Dwarfs

Zeeman broadening analyses of near-infrared spectra have provided magnetic field measurements of M dwarfs as late as M4.5 V. Johns-Krull & Valenti (1996) measured \(B = 3.8 \pm 0.5\) kG covering 50 ± 13% of EV Lac and \(B = 2.6 \pm 0.3\) kG covering 50 ± 13% of Gl 729, but the line profiles indicate a distribution of field strengths across the surface or with depth. Strong magnetic fields in starspots may be contributing to the broadening of the observed line profiles. Field strengths of 4.0 kG and 4.3 kG have been measured for AD Leo (M4 Ve) and AU Mic (M2.5 Ve) by Saar (1994). Magnetic fields have not yet measured in the coolest M dwarfs and brown dwarfs, because these stars are too faint for high resolution spectroscopy. Nevertheless magnetic fields are almost certainly present as their internal structures are similar to the M4.5 Ve stars. I say this because there is no sharp change in the coronal heating efficiency as measured by
$L_z/L_{bol}$ between stars with radiative cores and convective envelopes (spectral type M 5 and earlier) and stars that are fully convective (cooler stars with $M < 0.3 M_\odot$ and brown dwarfs) (Fleming, Schmitt & Giampapa 1995). Also, Jupiter, which is structurally similar to a low mass brown dwarf, has a strong magnetic field. Rüdiger (1998) argues that late M dwarfs with fully convective cores probably have $\alpha^2$ dynamos because the stars do not show magnetic cycles.

One indirect indicator of strong magnetic fields on these stars is starspots that are identified by photometric variability. Doppler imaging is not yet feasible for these faint stars. Another indicator, flares, are readily observed at optical, UV, X-ray, and radio wavelengths. VB10 (M8 Ve) has been observed to flare in X-rays by the ROSAT HRI (Fleming 1998) with $L_z^{flare} \approx 10^{30}$ erg s$^{-1}$, and $L_z^{flare}/L_{bol}^{quiet} > 1.0$. Liebert et al. (1998) have observed an Hα flare on the M9.5 V star 2MASS J0149090+295613, which may be a brown dwarf. Outside of obvious flares, late M dwarfs are often bright X-ray sources with $L_x/L_{bol} \approx 10^{-3}$. In their ROSAT survey of all known K and M stars within 6 pc of the Sun, Schmitt, Fleming & Giampapa (1995) found that 94% are detected X-ray sources, the coolest detected source (by the Einstein satellite) being Gl 752B = VB 10. They argue that the smoothness of the $L_x$ distribution function and the occurrence of flares are evidence for these coronae to have a heating mechanism in common with the Sun, and that this mechanism is magnetic in character. The correlation of increased spectral hardness (and therefore higher coronal temperatures) with increasing $L_x$ is further evidence that the heating involves magnetic reconnection events. On the basis of X-ray surface fluxes for this sample of nearby stars, Mullan & Fleming (1996) argue that the coronae of at least the M stars with Hα emission (the so-called dMe stars) cannot be heated acoustically and therefore must be heated magnetically.

Typically brown dwarfs are rapid rotators. Basri (La Palma paper) reports that Kelu-1 (L2 star) has vsini = 40 km s$^{-1}$. Other brown dwarfs lie in the range 20–40 km s$^{-1}$. Neuhäuser & Comeron (1998) have very recently reported the first detection of X-rays from a young brown dwarf in the Chamaeleon I star forming cloud with $L_X = 2.57 \times 10^{28}$ erg s$^{-1}$, an X-ray luminosity typical of late-M dwarfs. There are as yet no observations of brown dwarfs in the radio or UV, but I anticipate detections at these wavelengths in the very near future. I conclude that for the late M dwarfs and brown dwarfs, like the warmer main sequence stars, active phenomena are a consequence of magnetic fields being stressed by convective motions.

2.6. RS CVn Systems

Magnetic fields have now been measured in several RS CVn systems using the Zeeman broadening technique. For example Bopp et al. (1989) reported $B = 2000 \pm 300$ G and $f = 0.66 \pm 0.14$ for the 17.4 day period VY Ari system (K3 III-IV + K3 III-IV). Using the Ti i 2.2µm line, Saar (1996) measured $B \approx 3000$ G and $f \approx 0.60$ for II Peg (K2-3 IV-V + ?), but the result may include a large spot contribution as the Ti I line is formed mainly in spots with $f_{spot} = 0.40 - 0.55$. Zeeman Doppler images, which are now published for six active stars including HR 1099 (Donati et al. 1990), show prominent azimuthal fields.

Starspots provide an important indirect indicator of strong magnetic fields. A recent analysis of 30 years of photometric monitoring of the 24 day period
HK Lac system (Oláh et al. 1997) provides information on the longevity and phase drifts of the large spots that together can cover up to 40% of the stellar surface. Doppler images of 13 RS CVn systems (Strassmeier 1996) also provide information on the location of large starspots. The high resolution HST/GHRS spectrum of the Fe xxi 1354Å line formed at $T = 10^7$ K in the Capella stars (G1 III + G8 III) shows that the high temperature coronal gas is stationary and therefore confined by strong magnetic fields (Linsky et al. 1998). For $n_e > 10^{12}$ cm$^{-3}$, the magnetic field must exceed 270 G to confine the hot gas.

In analogy with solar active regions (also called plages), areas of bright photospheric line emission are likely regions of strong magnetic fields. Plages on RS CVn systems are identified by rotational modulation of transition region emission lines (e.g., II Peg studied by Rodonò et al. 1987) and bright features in Doppler images in the Mg ii emission lines (e.g., Neff et al. 1989; Pagano et al. 1992). Plages have now been observed at the equator and at high latitudes ($\pm 50^\circ$). Plages cover 9% of the visible surface of AR Lac with emission line surface fluxes near the saturated heating rate (Linsky 1991).

There is a large literature concerning flares on RS CVn systems, but I call your attention to two very recent papers. In their analysis of the 1994 August 29 flare on UX Ari observed with ASCA and EUVE, Güdel et al. (1998) observed very hot plasma with $T \geq 100$ MK. Using a two-ribbon flare model, they find that $L_{\text{peak}} = 1.4 \times 10^{32}$ erg s$^{-1}$ with a loop length about 1$R_\odot$. A very interesting result is that the iron abundance increases from about 17% to 89% of solar during the flare, presumably due to the evaporation of solar abundance material from the lower atmosphere that fills the flaring loop. Osten & Brown (1998) studied four megaseconds of EUVE flare photometry on 16 RS CVn systems. In this unique data set with excellent statistics, they find that RS CVn systems flare 40% of the time, but short period systems like ER Vul ($P=0.70$ days, $R_1 \approx R_2 \approx R_\odot$, asini $\approx 3R_\odot$) flicker but do not show large flares. They conclude that the X-ray emitting regions are extended, because the duration of flares often exceeds the rotational period and eclipses are predicted but not seen. They find evidence that supports “quiescent” coronal heating by microflares in active stars: in the EUV $L_{\text{flare}} \propto L_{\text{quiet}}^{1.05}$. After they remove obvious flares, there is no obvious rotational modulation in the EUV flux in any of the 16 systems.

For the RS VCan systems, active phenomena result from the magnetic fields being stressed by convective motions and the interactions of adjacent magnetospheres.

2.7. Yellow and Red Giants

Linsky & Haisch (1979) proposed that a dividing line exists in the HR Diagram separating the yellow giants (spectral type K1 III and earlier), which have detected transition region emission lines, from the red giants (later spectral types), for which IUE spectra do not show detected emission lines. Ayres et al. (1981) found the same phenomenon in X-rays using Einstein data. What has happened to the so-called “Linsky-Haisch” dividing line, and is the boundary connected with some property of the magnetic field? The discovery of hybrid-chromosphere stars (e.g., Hartmann, Dupree & Raymond 1980) showed that the more luminous G Ib and K II stars have C iv and other emission lines, and the ROSAT survey of hybrid-chromosphere stars shows that many are also X-ray sources.
(Reimers et al. 1996). While the X-ray dividing line is confirmed for giants on the basis of a ROSAT 25 pc survey (Hünsch & Schröder 1996), very sensitive HST/GHRS UV spectra (Ayres et al. 1997) show Si iv 1394 Å and in some cases C iv 1448 Å emission from both yellow and red giants with a lower plateau at $f_{\text{Si iv}}/f_{\text{bol}} \approx 10^{-6}$. Stellar evolution calculations show that the yellow giants and hybrid stars are more massive, younger stars with high rotation rates, whereas the red giants are old, slowly rotating lower mass stars ($\leq 1.5M_\odot$). This suggests that the yellow giants and hybrid stars have magnetic fields and the red giants either have no magnetic fields (or submerged fields) with the Si IV emission ($T \approx 60,000$ K) due to purely acoustic heating, or the magnetic fields are very weak with the magnetic heating processes unable to heat the plasma to $10^6$ K. Which conclusion is correct?

Measuring magnetic fields in yellow giants is difficult because the spectral lines are broad, but Hubrig et al. (1994) obtained $>3\sigma$ detections for $\gamma$ Tau (K0 IIIab), $\epsilon$ Tau (G9.5 III), $\epsilon$ Leo (G1 II), and $\zeta$ Her (G8 III) on at least one occasion each. They measured the shift in line centroids between opposite circular polarizations. Thus the measurements refer to the net flux and not to typical field strengths. Although these results should be tested with Zeeman broadening measurements, they and the X-ray and UV data clearly indicate that the yellow giants must have significant magnetic fields.

There are no direct measurements of magnetic fields in red giant photospheres, but Chapman & Cohen (1986) have measured the magnetic field strength of VX Sgr (M4 Ia) by analyzing the Zeeman splitting in the OH maser 1665 and 1667 MHz features. They identified a magnetic field strength of $\sim 2$ mG at approximately 80 stellar radii, which implies a photospheric magnetic field strength of $\sim 0.5$ G if the field is spherically symmetric. Zeeman splitting for the 1612 MHz maser line (Szmyczak & Cohen 1997) indicate a magnetic field strength of 1.1 mG where the line is formed. M giants are not known to be X-ray or non-thermal radio sources, however HST/FOS images of $\alpha$ Ori (M2 Iab) show a bright feature in near-UV light that could be a convective cell or possibly result from magnetic activity (Gilliland & Dupree 1996). The high rates of mass loss for non-pulsating luminous M stars apparently can only be explained by Alfvén-driven winds. Although the calculations are only approximate, Hartmann & MacGregor (1980) found acceptable mass loss rates for $\alpha$ Boo (K1.5 III) when a photospheric magnetic field strength of 10 Gauss was used. Alfvén-wave driven models for $\alpha$ Ori (M2 Iab) imply photospheric magnetic field strengths of 1–5 G (Hartmann & Avrett 1984; Airapetian et al. 1998). Thus there is a case for weak magnetic fields in red giants and convective motions could stress these weak magnetic fields.

2.8. Pre-Main Sequence Stars

Johns-Krull & Valenti (1998) have measured a total magnetic flux of 4.0 kG for the cTTS star BP Tau from their analysis of IRTF CSHELL spectra of the Ti i 2.22328 $\mu$m lines. I do not know any other direct measurements of magnetic fields in PMS stars, but strong fields are indicated by measurements of non-thermal radio emission, flares, and starspots on several of these stars. The youngest of the observable pre-main sequence stars, the so-called "embedded protostars," are bright X-ray sources with $L_x/L_{\text{bol}}$ well above the level of saturated X-ray
emission, \( \frac{L_x}{L_{bol}} > 10^{-3} \). What can explain this result? Shu et al. (1997) propose that the X-ray emission from the embedded protostars consists of two components – a soft X-ray component produced in a magnetic corona like the somewhat older classical T Tauri stars and weak-lines T Tauri stars, and a second harder X-ray component produced where the magnetic fields of the star and the accretion disk interact. In the interaction region, field reconnection leads to electric currents that produce heating (and thus X-ray emission) and the acceleration of non-thermal particles. In their model stellar activity results from the stressing of stellar magnetic fields by convective motions and by interactions with the magnetic field of the accretion disk.

3. Conclusions

In this review of magnetic fields in the HR diagram, I have summarized the direct measurements of magnetic field properties in different types of stars and the indirect indicators (e.g., starspots, flares, non-thermal radio emission, and bright X-ray and UV line emission) of magnetic fields. Stellar activity phenomena are now thought to be the responses of a stellar atmosphere to the heating, non-thermal particle acceleration, and kinetic motions produced when stressed magnetic fields relax to lower energy states either by rapid field reconnection or by more gradual energy transfer. The critical point is that magnetic fields must be stressed (i.e., brought to a higher energy configuration) by some type of mechanical motion. For stars with convective zones, fluid motions below the photosphere where \( \beta > 1 \) jostle the field lines eventually, leading to reconnection above the photosphere where \( \beta < 1 \). However, this is not the only way of stressing the field lines. Shocks in the radiatively driven winds of O and early B stars, wind and centrifugal stretching of the magnetospheres of magnetic chemically peculiar stars, interactions with the fields of nearby stars in binary systems (e.g., RS CVn systems), and interactions with the fields of accretion discs for embedded protostars can also provide the stresses that lead to observable active phenomena. One should also look for other types of mechanical forces that can stress the fields leading to other active phenomena.

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