A New Non-Solar Paradigm for Active Stars

Frederick M. Walter\textsuperscript{1} and P. Brendan Byrne\textsuperscript{2,3}

Abstract:

The solar analogy is generally accepted for interpretation of stellar activity, yet coronal and chromospheric data of active stars often show very non-solar-like characteristics. Rather than beginning with the Sun and extrapolating backwards, we begin with the pre-main sequence stars and extrapolate forward in time. Among the youngest active stars, above the main sequence, there is strong evidence for quasi-dipolar magnetic fields. Time-series spectroscopy of chromospheres of diverse active stars shows characteristics consistent with matter trapped in a magnetic canopy. Radio observations suggest highly extended radio coronae. We present new and published data in support of a new paradigm for stellar activity based on the decay of large-scale organized magnetic fields.

1. On the Solar Paradigm

Magnetic activity is ubiquitous among the low mass stars. That the activity levels range over 4 orders of magnitude among outwardly similar stars is difficult to explain within the confines of the solar analogy.

Observations have revealed some very non-solar-like characteristics in active systems, and a dipolar magnetic configuration has become accepted for T Tauri stars. Rather than beginning with the Sun and working backwards, we re-examine stellar activity by beginning with the pre-main sequence stars and evolving them forward.

The solar analogy can be stated as follows:

1. The heating of the chromosphere/transition region/corona is related to the magnetic field. Decades of solar and stellar data have borne this out, from the correlation of solar Ca\textsuperscript{ii} K emission core flux with magnetic field strength (Skumanich et al. 1975) through the correlations of stellar magnetic flux $fB$ and activity with Rossby number $R_0$ (Saar 1994).

2. The shape of the atmospheric structures are determined by the magnetic field. This is obvious from solar images. The coronal and chromospheric magnetic fields, for any reasonable densities, are force-free, and the geometry of the outer atmosphere must conform to the magnetic field.

\textsuperscript{1}Dept. of Physics and Astronomy, SUNY Stony Brook
\textsuperscript{2}Armagh Observatory, N, Ireland
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3. The general morphology of the magnetic field is comparable to the observed solar magnetic field. *This we question.* The high volume emission measures observed in active stars are difficult to reconcile with a solar-like compact corona. In the Sun, the lower chromosphere and transition region are geometrically-thin; to increase its volume significantly (once the filling factor approaches unity) one would have to decrease the temperature gradient in the outer atmosphere, contrary to the general correlation between coronal activity level and peak coronal temperature. There is direct evidence for large coronal volumes in the very active stars from radio maps (e.g., Mutel et al. 1985)*3. *There is indeed evidence to suggest that this part of the Solar analogy needs revision.*

The evidence for the breakdown of the Solar paradigm is threefold, and is observed in many diverse kinds of stars.

1. **Confined cool material exists at relatively large distances above the photosphere,** suggesting that the magnetic field is well-organized, and retains significant flux density, on large scales. *The solar field is organized on small scales.*

2. **Infalling cool material is seen in many active stars.** While the transition region lines of the Sun (Bruecker 1981) and active stars (e.g., Ayres 1984) do exhibit persistent small redshifts, the *large-scale dynamics of the solar atmosphere are mainly characterized by coronal mass ejections.*

3. **Magnetic flux seems to emerge at high latitudes in the photosphere.** *Solar magnetic flux emerges preferentially at low latitudes, with polar coronal holes.*

These phenomena exist among a number of types of stars, including the classical and naked T Tauri stars, the ultra-fast rotators, and the dMe and RS CVn systems.

2. The Menagerie

Our sample of active stars consists of

**The classical T Tauri stars** (cTTs), which consist not only of a central star, but also of a circumstellar disk. The cTTs are accreting: line profiles suggest accretion columns at high latitude rather than accretion through a boundary layer (Hartmann et al. 1994). The Shu et al. (1994) model for the star–disk interaction, with the star and disk are coupled at the co-rotation radius through a magnetic field, explains the slow rotation, through disk-braking (Edwards et al. 1993), inner holes in the dust distribution, and the inferred high-latitude accretion. A dipolar, or low order multipole field, with kGauss surface strength, suffices. The field must emanate at high latitudes, and thread the disk at the equator at heights of a few stellar radii. Note that this field must be generated in the star; the

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*3The solar white-light corona also approximates a large dipolar volume*
presence of the disk is not relevant to its existence. The model does not exclude the existence of solar-like fields with small scale lengths at low latitude. Indeed, the coronal X-ray emission may in part be solar-like, from hot compact loops.

The Naked T Tauri stars (nTTs; Walter et al. 1998) are young, low mass pre-main sequence stars which are not actively accreting and show no evidence for circumstellar disks. In fact, the only difference between the nTTs and the cTTs is the lack of a disk, and the consequent lack of accretion columns and loss of rotational disk-braking. Since the disk is irrelevant to the generation of the stellar magnetic field, one would expect the nTTs field morphology to mirror the cTTs field morphology, with a large-scale dipolar pattern and perhaps underlying higher-order solar-like multipoles.

The Ultra-Fast Rotators (UFRs) are generally single G-M stars near the zero-age main sequence with rotation periods less than about a day. We include the dMe stars in this category. AB Dor (Innis et al. 1985), “Speedy” Mic (Anders et al. 1993), and HK Aqr (Byrne et al. 1996) are prime examples of UFRs.

The RS CVn systems are tidally-locked, rapidly rotating subgiants in close binary systems. Rotation periods are typically a few days; surface angular velocities are comparable to those of the UFRs and the PMS stars. Surface gravities, radii and effective temperatures are comparable to those of the PMS stars.

3. Evidence for Confined Cool Material at Large Distances

There is spatially-extended material about AB Dor in cool prominences or Hα clouds (Collier Cameron et al. 1990; see Figure 1). We have also followed these absorbing structures in Mg II and C IV (Walter et al., in preparation).

Likewise, the dMe stars HK Aqr (Byrne, Eibe, & Rolleston 1996) and RE1816+541, (Eibe et al. in preparation) have cool prominences co-rotating with the star at heights of 0.3 to 2.4 stellar radii above the photosphere. van den Oord et al. (1997) conclude that the neutral hydrogen clouds seen in this type of star are held in a large-scale magnetic field in the equatorial plane and are dynamically stable.

There is overwhelming evidence for extended chromospheres and coronae among the RS CVn systems. The Hα/Hβ ratio in UX Arietis is similar to that in solar prominences (Heunemomorder et al. 1989), suggesting a low density, extended source. Hall & Ramsey (1994) modeled the Hα profiles of four RS CVn systems as prominence-like structures with scale heights of order $R_\ast$.

Mg II k Doppler images of AR Lacertae have revealed the presence of distinct bright regions (plages) on the K star. Some discrete structures have velocity amplitudes in excess of $v \sin i$, suggesting the existence of structures suspended above the surface but in rigid rotation with the photosphere (Neff et al. 1989). A pronounced dark hemisphere on the G star in AR Lac in the 1987 Mg II Doppler
image (Neff et al. 1989) is likely due to absorption of the chromospheric \textit{Mg II} emission by an extended cool prominence with a size of order 3 $R_{\odot}$.

X-ray light curves of AR Lac show that primary eclipse is often longer than expected for a pure geometric eclipse, which could suggest the presence of extended structures above the limb of the foreground star$^4$. The 1984 light curve shows a slow egress (White et al. 1990). The 1993 light curve (White et al.

\footnote{Eclipse light curves suggest that most of the coronal X-rays do arise in compact structures of approximately solar scale in AR Lac (Walter, Gibson, & Basri 1983)}
1994) shows a slow ingress, but egress is consistent with geometric occultation of the background star. Four months later, the EUVE DS/S light curve showed ingress consistent with geometrical obscuration, but egress was slow (Figure 2). A simple model (Walter 1995) requires obscuring material out to about 6 $R_\odot$, with $n_e$ of $10^{11}$ to $10^{12}$ cm$^{-3}$, which is at the upper end of the range observed in solar prominences.

![Graph](image)

Figure 2. The EUVE DS light curve (Walter 1995) of AR Lac. Left: The solid line is the expected light curve for purely geometrical eclipses, scaled to the mean out-of-eclipse level. Primary eclipse has a depth of 42%, and is clearly asymmetric on egress. A flare coincides with secondary minimum. Right: Simple geometrical model of the obscuration needed to account for the attenuation seen on egress from primary eclipse. The K star defines the origin; the G star is plotted at the five phases observed following primary minimum. The shaded area is optically thick.

VLBI observations of RS CVn systems show magnetospheres with sizes of a few stellar radii, (e.g., Lestrade et al. 1984; Mutel et al. 1985). The observed sizes, and the circular polarization, require large-scale, quasi-dipolar magnetic field configurations with coronal field strengths of order 10 G.

There is also evidence, from VLBI maps, that nTTs (HDE 283447; Feigelson et al. 1994) and dMe stars possess RS CVn-like extended magnetospheres. Alef et al. (1997) show that the radio source associated with YY Gem has a FWHM of 2.1 stellar diameters.

4. Evidence for Infalling Matter

There is growing evidence for either transient high-velocity accretion events or continuous low-level mass infall, seen as redshifted absorption in Hα line profiles. Such absorption events are seen in nTTs (Wolk & Walter 1996), UFRs, (AB Dor
and BD +22°4409; Eibe et al., in preparation), dMe stars (Panagi, Byrne, & Houdebine 1991), and RS CVns (e.g., Hall & Ramsey 1992).

A good example of a sporadic absorption event in a nTTs\footnote{The nTTs may not be completely naked, which complicates any interpretation. However, they have quantitative similarities to the RS CVn systems, which are most definitely not pre-main sequence.} is shown in Figure 3. Transient downflows in Hα similar to those seen in PMS stars have been seen in the SB1 RS CVn star II Peg (K2 IV), in Hα (Figure 4) and He i 10830Å (Byrne 1987, Byrne et al. 1997, in preparation). The asymptotic velocity is close to the escape velocity suggesting infall from a large height. Similar events in other RS CVn stars has been discussed by Hall & Ramsey (1992).

Figure 5 shows an assortment of Hα line profiles showing evidence for continuous infall in UFRs, RS CVns, and nTTs. The “quiescent” Hα profile of the quintessential UFR AB Dor shows an absorbed red wing. Assuming an intrinsically symmetric Hα line profile, this requires the presence of material falling at close to the escape velocity. The rapidly rotating late-type dwarf BD +22°4409 (Jeffries et al. 1994) also shows clear evidence of permanent inflow in Hα (Eibe, Byrne & Robb, in preparation). They suggest that this is further evidence for large-scale magnetic structures in the meridional plane with downflow towards the footpoints (analogous to T Tauri models).

5. Evidence for High Latitude Magnetic Flux Emergence

Evidence for high latitude magnetic flux emergence mainly comes from Doppler images of nTTs, UFRs, and RS CVns. Dark polar caps or dark regions at high
Figure 4. Hα line profiles of II Peg which clearly show the appearance of transient absorption events on timescales of 2 days. The lower plot is the difference spectrum. The asymptotic velocity is close to the escape velocity, suggesting infall from a large height.

latitude are interpreted as starspots. There are many references to and discussions of these images\(^6\) in the proceedings of IAU Colloquium 176 (Strassmeier & Linsky 1996). In the cTTs, the evidence for high latitude flux emergence comes from emission line profiles, which suggest that accretion occurs at high latitude (Hartmann et al. 1994). The Shu et al. (1994) model of the star–disk interaction involves large-scale, dipolar fields, which naturally accommodates the high latitude accretion.

Doppler images of nTTs show evidence for high latitude field emergence in the presence of high latitude spots (e.g., Joncour et al. 1994; Strassmeier et al. 1994). Most Doppler images of RS CVn systems show high-latitude dark features which are interpreted as dark spots e.g., Vogt & Hatzes (1996).

6. A New Paradigm for Active Stars

All these diverse classes of active stars exhibit non-solar-like observational characteristics which suggest the presence of large-scale, global magnetic fields. To explain these phenomena, we start with the cTT stars, and the Shu et al. model of a large-scale, quasi-dipolar field emerging at high latitude and threading the disk at a few stellar radii above the photosphere. The disk is irrelevant to the existence of the magnetic field, so the large-scale field must be a consequence of the rapid rotation and/or the fully convective nature of the star.

\(^6\)including some skepticism about the physical reality of polar spots (e.g., Byrne 1996)
After the disk dissipates at an age of a few million years, there are no discernable differences between the typical nTT and cTT stars. The nTTs are luminous radio sources (Brown et al. 1996); their similarities to the RS CVn systems suggest that they still possess strong large-scale magnetic fields. It seems reasonable to conclude that the magnetospheres of the nTTs are still dominated by the large-scale, quasi-dipolar fields evident in the cTTs.

Since the properties of the activity in the nTTs, the UFRs and dMe stars, and the RS CVn systems are similar, we hypothesize that the large-scale field remains strong in these stars. Note that the nTTs and the RS CVns occupy similar places in the H-R diagram (although the internal structures are very different). The large scale fields seem to dominate in dwarfs with rotation periods less than a few days, and in subgiants with periods of less than about 10 days.
All active stars have large X-ray flares. Reverting to the (now discredited) solar analogy, we expect large flares to be accompanied by coronal mass ejections (CMEs). In the Sun, the CME joins the general flow of the solar wind. However, consider what might happen if a CME occurred under the canopy of a strong quasi-dipolar magnetic field. If the energy density of the field is high enough, it will trap the ionized CME material. This material will then drain back to the surface along magnetic field lines, impacting at high latitudes, but a component may remain trapped in the equatorial plane. Stars inclined to the line of sight by about the latitude of the magnetic footpoints (like AB Dor) will show accretion velocities close to the free-fall velocity; in systems with lower inclinations the absorption will be at smaller (though still redshifted) velocities (like BD +22° 4409).

Our new paradigm is this: the large-scale, organized magnetic field dominates the activity in the most active stars. There is also a small-scale, solar-like field, which may account for much of the high density transition region and coronal gas. The large-scale field must decay, most likely as the stellar rotation slows, as the underlying complex field decays.

The origin of the large-scale field is unknown. In the solar-like case, the buoyant magnetic field naturally concentrates into small-scale flux tubes. Is there something special that happens at rapid rotation either to suppress the small-scale structures, or to enhance the strength of the large-scale structures? The quasi-dipolar field may be the far-field limit of a solar-like small-scale field. The Sun does have a quasi-dipolar far-field, as reflected in the shape of the white-light corona, albeit strongly distorted by the solar wind. Perhaps the relative energy densities in the stellar wind and the far-field determine whether or not the overall magnetic field is solar-like.

If the magnetospheres of active stars are indeed dominated by large-scale closed fields, and not by small scale fields, there will be important consequences. One is that the observed chromospheric and coronal emission will arise in at least two environments, one compact and solar-like; the other extended and perhaps at lower density. This may provide a natural explanation for the appearance of two discrete temperature components in many active stars. Secondly, the closed magnetic field configuration will affect spindown rates. A change in magnetic field configuration may obviate the need to appeal to magnetic saturation (e.g. Barnes & Sofia 1996) to moderate rotation rates.

The solar paradigm has proven a valuable tool to direct our interpretation and to aid our understanding of stellar chromospheres and coronae. Nonetheless, the Sun is a very inactive star, and the solar analogy is hard-pressed to explain many of the phenomena peculiar to the active stars. We suggest that the time has come to begin at the beginning, and to consider stellar activity in terms of both a solar-like component and a more-rapidly-decaying mode controlled by large scale, quasi-dipolar magnetic fields.
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Flares and Flare Stars

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