MAGNETIC FIELDS IN THE HR DIAGRAM

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Solar and Stellar Activity: Similarities and Differences
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"If the Sun did not have a magnetic fields, it would be as uninteresting a star as most astronomers believe it to be."

attributed to ROBERT B. LEIGHTON

"Magnetic fields are to astrophysics what sex is to psychoanalysis."

HENK VAN DE HULST (1988)

ROLES THAT MAGNETIC FIELDS PLAY IN SOLAR AND STELLAR ATMOSPHERES

Heating Processes: MHD wave processes, rapid field annihilation processes

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

Isolation: thermal isolation of adjacent plasmas by suppression of conduction and convection

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

Convection: magnetoconvection has different properties and cell sizes than normal convection

Wind: Alfvén waves and other MHD waves drive winds which are important for the removal of angular momentum on the main sequence

Nonthermal Particle Acceleration: Maxwell's equations say that $\nabla \times H - (1/c)\partial D/\partial t = 4\pi J/c$. 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 nonsensitive lines and can increase line blanketing

Polarization: line and continuum polarization and depolarization processes

Radio Emission: gyrosynchroton 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. What are the consequences of this behavior in a dynamic atmosphere?

1 A Tour Through the HR Diagram in Search of Magnetic Fields

A tentative paradigm: Stellar activity results from the rapid relaxation of magnetic fields that are stressed by different types of mass motions for stars located in different regions of the HR Diagram.

Questions to ask during our tour:

- What direct or indirect techniques can measure magnetic fields 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 O and early B stars

- Magnetic fields cannot be measured directly (via Zeeman broadening or polarization) because stars rotate rapidly and line widths are broad.
- Magnetic fields may eventually by measured using the Hanle effect (Ignace, Nordsieck, & Cassinelli ApJ 486, 550 (1997)).
- 24% of the O3–B2 luminous stars surveyed by Beiging, Abbott, & Chruchwell ApJ 340, 518 (1989)) show nonthermal radio emission probably from shocks in the wind.
- Gagné *et al.* ApJ 478, L87 (1997) discovered periodic X-ray emission from θ^1 Ori C (O7 V). They argue that the X-ray periodicity is due to absorption by the wind in an extended magnetosphere. This may be an example of a high mass oblique rotator star like the chemically peculiar B and A stars.
- Donati *et al.* (MNRAS 333, 55 (2002)) measured a magnetic field of 1.0 ± 0.1 in θ^1 Ori C using spectropolarimetry (Stokes V). The field is inclined 42 degrees with respect to the rotation axis. This young (0.6 Myr) massive (44 times solar) star is likely a high mass analog of the CP Bp stars. This is the first measurement of a magnetic field (presumably fossil) in an O-type star. X-rays could be explained by a shock where the magnetically-confined winds from both hemishpheres collide.

Magnetic fields are stressed by bulk motions in unstable radiatively driven winds.

3 Chemically peculiar B and A stars

- Strong magnetic fields (up to 34 kG in Babcock's star = GL Lac (B8p SiHeW)) are easily measured because the structure of the field is simple (dipoles and quadrupoles).
- Oblique rotator model.
- Strong nonthemal radio emission observed in many stars (Linsky, Drake, & Bastian ApJ 393, 341 (1992)). Nonthermal emission is indicated by negative spectral indicies.
- X-ray emission observed in a few stars (Drake *et al.* ApJ 420, 387 (1994)).

- Linsky *et al.* (1992) wind-fed magnetosphere model.

Magnetic fields are stressed by winds stretching out the field lines near the equator and rotational forces.

4 Normal B and A stars

- No magnetic field measurements.
- No nonthermal radio emission detected.
- X-ray emission detected from $< 3\%$ of the B4–B9 field stars by Grillo et al ApJS 81, 795 ((1992)), but could be previously unknown late-type or PMS companions that are difficult to detect because they are faint and low mass compared to the primary.

5 F–M main sequence stars

No detections of field with the Zeeman polarization technique, but Robinson, Worden, & Harvey (ApJ 236, L155 (1980)) demonstrated that Zeeman broadening can be measured.

Saar's method for analyzing Zeeman-broadened spectral lines:

- Assume a 2-component atmosphere $F_{obs} = fF_{mag}(B) + (1 - f)F_{quiet}(B = 0)$ or a 3-component atmosphere (include starspots). f = filling factor. F_{mag} = flux in the magnetic region. Problem: is $F_{mag} = F_{quiet}$? Are magnetic regions bright like solar faculae or dark like solar spots and pores?
- Solve the RT equation in a Milne-Eddington atmosphere with full Zeeman patterns and magneto-optical effects in the line transfer.
- Adopt values for vsini and radial-tangential macroturbulence.
- See Saar review papers in IAU Symposia 138 and 154 and in "Magnetohydrodynamic Phenomena in the Solar Atmosphere - Prototypes of Stellar Magnetic Activity".

A summary of the results from Saar and collaborators using data analyzed with the above approach:

- 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 $T = T_{eff}$. B_{eq} increases to cooler stars because P_{gas} increases at optical depth unity with decreasing H^- opacity. $B/B_{eq} > 1$ in 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: THIS CHANGES THE DIVERGENCE OF THE FIELD WITH HEIGHT.**]

- Vilhu (A+A 133, 117 (1994)) showed that most activity indicators reach a maximum value (saturate) at high angular velocity (Ω_{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.

Redshifts in stellar transition region lines (e.g., C II, Si IV, C IV).

- Redshifts of transition region lines have been observed in solar spectra for a long time.

- Achour *et al.* (ApJ 435, 945 (1995)) found that in quiet regions the redshift of the C IV 1548Å line is 6.2 km/s, compared to 13.0 km/s in active regions.

- SOHO/CDS and SOHO/SUMER observations show that redshifts are seen even in lines of Ne VIII formed at 650,000 K (Brynildsen *et al.* Solar Physics, 181, 23 (1998)).

- Redshifts studied in spectra of late-type dwarfs and giants by Ayres and collaborators beginning in 1980 with IUE and HST/GHRS. Resonance and intersystem lines are redshifted confirming that the downflows are real. Velocities of lines increase between 3×10^4 and 1×10^5 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).

- GHRS spectra confirm these trends and show that Procyon is a little anomalous (Wood *et al.* ApJ 478, 745 (1997)).

- Solar transition region models models computed with a 2-D hydrodynamic code show that density perturbations in regions of strong density and temperature statification cool radiatively to become condensations that flow downward by gravity (Reale *et al.* A&A 316, 215 (1996)).

Observations that support microflare heating of 10^5 K gas.

- Dere *et al.* (Solar Physics 123, 41 (1989)) studied transient broad TR line profiles observed in solar active regions. They called this phenomena "transition region explosive events" and argued that they are produced by small flares, the socalled "microflares"
- GHRS spectra of the Si IV and C IV lines in AU Mic (M0 V) are inconsistent with single Gaussian shape, but can be fit with the sum of a narrow and a broad Gaussian. The broad Gaussian is interpreted as microflare heating. (Linsky & Wood ApJ, 430, 342 (1994))
- Wood *et al.* ApJ 478, 745 (1997) fit double Gaussians GHRS line profiles of 11 dwarf and giant stars. All stars except β Gem (K0 III) and Procyon (F5 IV-V) show clear evidence of excess emission beyond the narrow Gaussian. They conclude:
  - Nonthermal velocities derived from the widths of the narrow Gaussians depend on gravity for main sequence stars ($\xi_{NC} \propto g^{-0.68}$), but saturate at the sound speed for low gravity. This could represent heating by Alfvén waves.
  - Nonthermal velocities derived from the widths of the broad components are highly supersonic. They interpret these high velocities to plasma expelled from magnetic reconnection sites at high velocities.
  - f_{BC}/f_{tot} increases with "activity" as measured by surface fluxes in Mg II, C IV, and X-rays.

Magnetic fields are stressed by convective motions.

6 Late-M Stars and Brown Dwarfs

- Using the Zeeman broadening technique Johns-Krull & Valenti (ApJ 459, L95 (1996)) measured magnetic fields with infrared spectra for M dwarfs as late as spectral type M4.5 Ve. They measured $B = 3.8 \pm 0.5$ kG covering $50 \pm 13\%$ of EV Lac and $B = 2.6 \pm 0.3$ kG covering $50 \pm 13\%$ 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 (IAU Symp 154 (1994)).

- Magnetic fields not yet measured in the brown dwarfs, but are likely. (Jupiter has a strong mag. field). Predictions in Mohanty *et al.* ApJ 571, 469 (2002). Valenti *et al.* (Cool Stars 11, p. CD-1579) think that the FeH band lines near 9950Å should be useful in future measurements of brown dwarf magnetic fields.

- Berger (ApJ 572, 503 (2002)) used the VLA to measure steady and flare radio emission from 3 L dwarfs (as late as L3.5). Radio emission is much stronger than predicted from radio vs. X-ray relation. So rapidly-rotating L dwarfs are gyrosynchrotron emitters and thus must have magnetic fields.

- There is no sharp change in L_x/L_{bol} when crossing the radiative/convective core boundary at $M \approx 0.3 M_\odot$ (spectral type M5). Fleming *et al.* (1993) ApJ, 410, 387; Giampapa *et al.* (1996), ApJ 463, 707.

- Late M dwarfs are often bright x-ray sources at the $L_x/L_{bol} \approx 10^{-3}$.

- Rudiger and Keuker (in Very Low-Mass Stars and Brown Dwarfs, Cambridge University press 2000, p. 204) argue that late M dwarfs and probably also brown dwarfs with fully convective cores probably have α^2 dynamos because the stars do not chow magnetic cycles.

- The very late M dwarf VB10 (M8 Ve) was observed to flare by the ROSAT HRI (Fleming, ApJ 533, 372 (2000)) and both quiescent and flare x-ray emission was detected by Chandra (Fleming et al ApJ 594, 982 (2003)).

- Evidence of flaring on an L5 dwarf star (Liebert *et al.* AJ 125, 343 (2003)).

- Brown dwarfs are rapid rotators. Basri (La Palma paper) reports that Kelu-1 (L2 star) has vsini = 40 km/s. Other brown dwarfs lie in the range 20–40 km/s. Rotation much faster than convective turnover time, so "fast rotators".

- Neuhauser & Comeron (Science 282, 83 (1998)) 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.

Magnetic fields are stressed by convective motions.

7 RS CVn Systems

Magnetic field measurements of RS CVn systems:

VY Ari (HD 17433). For this K3 III-IV = K3 III-IV system with $P_{rot} = 17.4$ days, Bopp *et al.* (ApJ 339, 1059 (1989)) measured $B = 2000 \pm 300$ G, $f = 0.66 \pm 0.14$.

II Peg. For this K2-3 IV-V + ? system using the Ti I 2.2μm line, Saar *et al.* ("Stellar Surface Structure" 1996). measured $B \approx 3000$ G and $f \approx 0.60$. But the Ti I line is formed mainly in spots with $f_{spot} = 0.40 - 0.55$.

HR 1099 Zeeman Doppler imaging by Donati *et al.* A&A, 232, L1 (1990).

Capella HST/GHRS spectra of the Fe XXI 1354Å line formed at $T = 1 \times 10^7$ K in the Capella stars (G1 III + G8 III) show that the high temperature coronal gas is stationary and therefore confined by strong magnetic fields (Linsky *et al.* ApJ, 492, 767 (1998)). For $n_e > 10^{12}$, $B > 270$ G.

HK Lac Oláh et al (A+A 321, 811 (1997)) analyzed 30 years of photometry to provide information of longevity and phase drifts of large spots.

13 RS CVn systems Strassmeier ("Stellar Surface Structure" 1996) summarized Doppler images of starspots on these systems.

A new study of EUVE photometry of 16 RS CVn systems (Osten and Brown ApJ 515, 747 (1999)):

The largest data set on stellar flares. 4 megaseconds of flaring out of 10 megaseconds of good observations. Good for statistical studies.

Variability. 31/32 observations are statistically variable. RS CVn systems flare 40% of the time.

Flickering in short period systems. The short period system ER Vul (P=0.70 days, $R_1 \approx R_2 \approx R_\odot$, asini $\approx 3R_\odot$) flickers but no big flares.

Magnetosphere extended. X-ray emitting regions extended because duration of flares often $> P_{rot}$ and no eclipses seen although predicted. No evidence for active longitudes.

Microflare heating. Evidence that "quiescent" coronal heating is by microflares in active stars: in EUV $L_{flare} \propto L_{quiet}^{1.05}$. After subtract obvious flares, no obvious rotational modulation in the EUV flux for all 16 systems.

Evidence for plages (active regions) on RS CVn systems:

- Rotational modulation of TR emission lines (e.g., II Peg by Rodonò *et al.* (A&A 176, 267 (1987)).

- Doppler imaging in Mg II chromospheric emission lines (e.g., Neff *et al.* A&A, 215, 79 (1989); Pagano *et al.* in Cool Stars, Stellar Systems, and the Sun (1992)); Busa *et al.* A+A 350, 571 (1999)). Plages have now been observed at the equator and at high latitudes ($\pm 50°$). Plage sizes as large as 9% of the visible surface. Surface fluxes near the saturated heating rate (Linsky in Mechanisms of Chromospheric and Coronal Heating (1991)).

Analysis of the 1994 August 29 flare on UX Ari observed with ASCA and EUVE (Güdel *et al.* ApJ, 511, 405 (1999)):

- Very hot plasma during the flare ($T \geq 100$MK).

- Analyzed with a two-ribbon flare model. $L_{peak} = 1.4 \times 10^{32}$ erg/s. Loop lengths about $1 R_\star$.

- Fe abundance increases from about 17% to 89% solar during the flare.

Magnetic fields are stressed by convective motions and the interactions of adjacent magnetospheres.

8 Yellow and Red giants

- No photospheric magnetic field measurements, x-ray emision, or nonthermal radio emission from red giants.

- HST/FOS images of α Ori (M2 Iab) show a bright feature in near-UV light that could be a convective cell or result of magnetic activity (Gilliland & Dupree ApJ, 463, L29 (1996)).

- Cool giants like Arcturus show Si IV emission and often C IV emission (Ayres et al ApJ 491, 876 (1997)). Are these layers heated by pure acoustic waves or some type of magnetic heating mechanism?

What has happened to the so called “Linsky-Haisch” dividing line?

- Linsky & Haisch (ApJ 229, L27 (1979)) originally proposed a dividing line in the HR Diagram separating yellow giants (K1 III and earlier) with detected TR emission lines from red giants (K2 III and later) without detected emission on the basis of IUE spectra. Is the boundary connected with some property of the magnetic field?

- Ayres *et al.* (ApJ, 229, L27 (1981)) found the same phenomenon in X-rays using AXAF data.

- Discovery of hybrid-chromosphere stars by Hartmann, Dupree, & Raymond (ApJ ApJ 236, L143 (1980)).

- Confirmation that an x-ray dividing line does exist for giants on the basis of a 25 pc survey with ROSAT (Hünch & Schröder A&A, 309, L51 (1996).

- ROSAT survey of hybrid-chromosphere bright giants and supergiants shows that many are x-ray sources (Reimers *et al.* A&A, 310, 813 (1996)).

- One conclusion: Red giants are old, slowly-rotating low mass stars (($\leq 1.5 M_\odot$), whereas the yellow giants and hybrid stars are more massive, younger stars with high rotation rates.

- New HST/GHRS UV spectra of giants by Ayres *et al.* (ApJ, 491, 876 (1997)) shows Si IV 1394Å emission from both yellow and red giants with a lower plateau at $f_{SiIV}/f_{bol} \approx 10^{-8}$.

- Two possible conclusions: Either the red giants have no magnetic fields (or submerged fields) and the Si IV emission ($T \approx 60,000$ K) is due to purely acoustic heating, or the magnetic fields are weak with the magnetic heating processes unable to heat the plasma to 10^6 K. Which conclusion is correct?

Convective motions could stress the magnetic fields if they are present.

9 Premain Sequence Stars

- Johns-Krull *et al.* (ApJ 516, 900 (1998)) IRTF CSHELL spectra of the Ti I 2.22328 μm lines in the cTTS star BP Tau shows a total magnetic flux of 2.6 kG.

- Nonthermal radio emission often detected.

- Many PMS stars are bright X-ray sources with $L_x/L_{bol} > 10^{-3}$, above the saturated heating level. Why? Heating by inflow and/or interaction between the stellar and disk fields.

- Bipolar outflows are presumably magnetic.

- Shu *et al.* (Science 277, 1475 (1997)) proposed 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 nonthermal particles.

Magnetic fields are stressed by convective motions and by interactions with the magnetic field of the accretion disk.