Suggested reading

• M. Güdel “X-ray astronomy of stellar coronae” (A+A Reviews 12, 71 (2004)).
• M. Güdel & Y. Nazé “X-ray spectroscopy of stars” A+A Reviews, 17, 309 (2009)
• Stelzer et al. “The UV and X-ray activity of the M dwarfs within 10 pc of the Sun” MNRAS 431, 2063 (2013)
Topics to be covered

- How does the X-ray flux from host star influence exoplanets?
- Ionization equilibria (collisional and non-equilibrium)
- X-ray instruments and capabilities
- X-ray spectral energy distributions
- Examples of high-resolution stellar spectra
- Techniques for building models of stellar coronae
- Diagnostics of temperature, density, emission measure, and flows
- What types of stars have coronae
- Flux-flux correlations
- Coronal geometry
- Rotation and age effects, saturation, and supersaturation
- Evidence for accretion onto pre-main sequence stars
- A model of star-disk interactions
How does the X-ray flux of host stars influence exoplanets?

• X-rays penetrate deep into exoplanet atmospheres and protoplanetary disks.

• X-rays photoionize and heat the ionospheres and exospheres of exoplanets. Ions such as \( \text{H}_2^+ \) and \( \text{H}_3^+ \) start chemical processes in exoplanet atmospheres.

• X-rays provide much of the energy that drives mass loss from close-in exoplanets.
EUV and X-ray absorption per cm$^2$ by H and metals (Morrison&McCammon 1983)

- For $E=0.02$eV (620Å), $\sigma=2.5 \times 10^{-18}$ cm$^2$
- For $E=1$keV (12.4Å), $\sigma=2.5 \times 10^{-22}$ cm$^2$.
- Photon penetration depth = $1/\sigma n$ cm.
- $1$pc = $3.1 \times 10^{18}$ cm, so $\tau$ = 8 per pc at $E=0.02$eV and $\tau$ = 0.0008 per pc at 1 keV.
Ionization equilibria - terminology

- **Collisional ionization equilibrium (CIE, \(T_e=T_{\text{ion}}\)):** statistical steady state determined by balance of collisional ionization and radiative and dielectronic recombination in an optically-thin plasma (examples are Raymond-Smith and Mekal plasma codes).
- **Ionizing plasma (\(T_e>T_{\text{ion}}\)):** example of a plasma behind a shock. Look for 6.4 keV line of cold Fe photoionized by >6.7 keV hard X-rays.
- **Recombining plasma (\(T_e<T_{\text{ion}}\)):** example of a post-flare plasma with recombination faster than ionization.
- **Frozen-in plasma:** at very low electron densities the ionization is determined by past events. Solar wind.
- **Note:** \(\lambda(\text{Å})=12.4/E(\text{keV})\).
- Many data reduction tools and X-ray satellite archives located at http://heasarc.gsfc.nasa.gov/
Line and continuum emission in collisional ionization equilibrium

All plasmas at 1 keV, unabsorbed:
- **Black** APEC calculation of CIIE plasma with Mazzotta et al. ionization balance.
- **Blue** Raymond Smith calculation (divided by 100) of CIIE plasma
- **Green** Bremsstrahlung
- **Red** Blackbody

Note that at high temperature, the APEC continuum calculation exceeds the bremsstrahlung, due to the extra radiative recombination continuum.

Randall Smith “Collisional Plasmas: A Users Guide”
Collisional ionization equilibrium calculations (Bryans et al. (ApJS 167, 343 (2006))

- For Fe XII to Fe XXVII using new theoretical and laboratory dielectronic recombination rates and new radiative recombination rates.
- Note that Fe XVII and Fe XXV dominate over wide temperature ranges.
- Near $10^7$ K, Fe XVII through Fe XXIII are all abundant.
Emissivities for Fe and O line blends from the MEKAL data base (Telleschi 2005)
## Spectrometers to record stellar coronal properties

<table>
<thead>
<tr>
<th>Epoch</th>
<th>Instrument/mode</th>
<th>Range (Å)</th>
<th>Resolution ($\lambda/\Delta \lambda \times 10^{-3}$)</th>
<th>Grasp (Å)</th>
<th>Comments</th>
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<tbody>
<tr>
<td>1990–97</td>
<td><em>HST</em> GHRS (LOW)</td>
<td>1150–3200</td>
<td>2</td>
<td>290</td>
<td>high $A_{\text{eff}}$</td>
</tr>
<tr>
<td></td>
<td>(MED)</td>
<td></td>
<td>25</td>
<td>25–50</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(ECH)</td>
<td></td>
<td>80</td>
<td>8–16</td>
<td>low $A_{\text{eff}}$</td>
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<tr>
<td>1997–</td>
<td><em>HST</em> STIS (LOW)</td>
<td>1140–1740</td>
<td>2.5</td>
<td>610</td>
<td>long slit, high $A_{\text{eff}}$</td>
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<tr>
<td></td>
<td>(MED)</td>
<td></td>
<td>10</td>
<td>40</td>
<td></td>
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<tr>
<td></td>
<td>(M-ECH)</td>
<td></td>
<td>30–45</td>
<td>620</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(H-ECH)</td>
<td></td>
<td>114</td>
<td>270</td>
<td>low $A_{\text{eff}}$</td>
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<tr>
<td>1999–</td>
<td><em>FUSE</em></td>
<td>905–1188</td>
<td>20–35</td>
<td></td>
<td>full range medium $A_{\text{eff}}$</td>
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<tr>
<td>1992–</td>
<td><em>EUVE</em></td>
<td>70–760</td>
<td>0.3</td>
<td></td>
<td>full range ISM abs, low $A_{\text{eff}}$</td>
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<tr>
<td>1999–</td>
<td><em>Chandra</em></td>
<td>3–160</td>
<td>1–2 (60–160 Å)</td>
<td></td>
<td>full range best res, &lt; 1 keV</td>
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<tr>
<td></td>
<td>LETG</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>HETG</td>
<td>1.2–14 (HEG)</td>
<td>1 (@1 keV)</td>
<td></td>
<td>full range low $A_{\text{eff}}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.5–31 (MEG)</td>
<td>0.5 (@1 keV)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(1999)</td>
<td><em>XMM</em> RGS</td>
<td>5–35</td>
<td>0.2 (@1 keV)</td>
<td></td>
<td>full range high $A_{\text{eff}}$</td>
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<tr>
<td>(2000)</td>
<td><em>Astro-E</em> XRS</td>
<td>1–30</td>
<td>0.5 @6 keV</td>
<td></td>
<td>full range best res, &gt; 2 keV</td>
</tr>
</tbody>
</table>
Low resolution X-ray spectral energy distributions: the youngest star has the hottest coronal plasma \((\log T_{av} \approx 7.0)\) and the oldest star the coolest \((\log T_{av} \approx 6.2)\)

Guinan & Ribas (ASP Conf. Ser. 264, 139 (2002))
Information in moderate resolution spectra: XMM/RGS (E/ΔE=100-500)

- Hotter plasmas show continuum emission at λ<12Å.
- Hotter plasmas show strong Ne X and Fe XX emission.
- Cooler plasmas show bright Fe XVII emission.
Chandra X-ray spectra of two active binary systems: Capella (G0 III + G8 III) and HR 1099 (K1 IV + G5 V, P=2.84 days)

Ayres et al. (ApJ 549, 554 (2001))
The observed line flux: \[ F_j = \frac{1}{4\pi d^2} \int A\varphi_j(T)Q(T) \, d\ln T \]

Emissivity of a line per unit emission measure: \( \varphi_j \)

Differential emission measure:
\[ Q(T) = \frac{n_e n_H \, dV}{d \ln T} \]

Problems:
1. Since the differential emission measure depends on density squared, there is no simple way of inferring the volume corresponding to each range of temperature.
2. There is a range of shapes of \( Q(T) \) that will produce the same observed spectrum.
Different emission measure distributions starting from the same observed spectra using emission lines and continua.

The different EM distributions result from different plasma codes and different ways of fitting together the $\phi(T)$ curves for each spectral line.

- Probably realistic assumptions: collisional ionization equilibrium, optically thin plasmas, most of the plasma is thermal, low-density limit spectra. **BUT**
- Coronal plasmas are inhomogeneous (wide range of temperatures and densities).
- Coronal abundances usually are not photospheric.
- Atomic data often not accurate or complete.
- Spectra are often noisy and weak lines often provide the only information on temperatures and densities.
- Inversion of the observed spectrum to obtain physical parameters is highly degenerate (i.e., many solutions result in similar synthesized spectra).
Emission measures of G stars with increasing rotation rate and decreasing age (Güdel+Yaze 2009)

\[ L_X \approx 1.61 \times 10^{26} \bar{T}^{4.05\pm0.25} \text{ ergs s}^{-1} \]

\[ \bar{T} \approx 12.2 P_{\text{rot}}^{-0.50\pm0.08} \text{ MK} \]

\[ L_X = 4.04 \times 10^{30} P_{\text{rot}}^{-2.03\pm0.35} \text{ ergs s}^{-1} \]

\[ L_R \approx 1.69 \times 10^9 \bar{T}^{5.29\pm0.74} \text{ ergs s}^{-1} \text{ Hz}^{-1} \]

\[
\begin{align*}
\log [L_x (\text{Sun})] &\approx 27.3 \\
\log [L_x(\text{Sun})/L_{\text{bol}}(\text{Sun})] &\approx -6.3 \\
\text{X-ray saturation at } \log [L_x/L_{\text{bol}}] &\approx -3.0 \\
(\text{occurs when } P_{\text{rot}} \approx 1.0 \text{ days})
\end{align*}
\]
Properties of coronae of solar-like stars (Telleschi et al. 2005)
Stellar X-ray emission is highly variable: hard and soft X-ray flare on Proxima Cen (Güdel et al. 2002)
Electron density from line ratios of helium-like ions

- \( n_l (n_e C_{lu} + B_{lu} J) = n_u (A_{ul} + n_e C_{ul}) \) and \( B_{lu} J \) small.
- \( n_u/n_l \sim n_e \) when densities are low, \( n_e C_{ul} < A_{ul} \)
- Since \( A_r \gg A_i \gg A_f \), there are density ranges where population ratios are density sensitive.
- \( R = f/i = R_0/(1+n_e/N_c) \), \( R_0 \) is low density ratio, \( N_c \) is where \( R \) drops to \( R_0/2 \).
- Note \( f \rightarrow i \) transition at 1630Å (O VII) and 2279Å (C V).

- Observations of Capella (upper) and HR 1099 (lower)
- Chandra HEG (solid lines) with higher resolution
- Chandra MEG (dots) lower resolution and higher throughput
- Note blended Ne IX intersystem line
Table 2. Density-sensitive He-like triplets\textsuperscript{a}

<table>
<thead>
<tr>
<th>Ion</th>
<th>$\lambda (r, i, f)$ (Å)</th>
<th>$R_0$</th>
<th>$N_C$</th>
<th>log $n_e$ range\textsuperscript{b}</th>
<th>$T$ range\textsuperscript{c} (MK)</th>
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<tr>
<td>C v</td>
<td>40.28/40.71/41.46</td>
<td>11.4</td>
<td>$6 \times 10^8$</td>
<td>7.7–10</td>
<td>0.5–2</td>
</tr>
<tr>
<td>N vi</td>
<td>28.79/29.07/29.53</td>
<td>5.3</td>
<td>$5.3 \times 10^9$</td>
<td>8.7–10.7</td>
<td>0.7–3</td>
</tr>
<tr>
<td>O vii</td>
<td>21.60/21.80/22.10</td>
<td>3.74</td>
<td>$3.5 \times 10^{10}$</td>
<td>9.5–11.5</td>
<td>1.0–4.0</td>
</tr>
<tr>
<td>Ne ix</td>
<td>13.45/13.55/13.70</td>
<td>3.08</td>
<td>$8.3 \times 10^{11}$</td>
<td>11.0–13.0</td>
<td>2.0–8.0</td>
</tr>
<tr>
<td>Mg xi</td>
<td>9.17/9.23/9.31</td>
<td>$2.66^d$</td>
<td>$1.0 \times 10^{13}$</td>
<td>12.0–14.0</td>
<td>3.3–13</td>
</tr>
<tr>
<td>Si xiii</td>
<td>6.65/6.68/6.74</td>
<td>$2.33^d$</td>
<td>$8.6 \times 10^{13}$</td>
<td>13.0–15.0</td>
<td>5.0–20</td>
</tr>
</tbody>
</table>

\textsuperscript{a}data derived from Porquet et al. (2001) at maximum formation temperature of ion

\textsuperscript{b}range where $R$ is within approximately [0.1,0.9] times $R_0$

\textsuperscript{c}range of 0.5–2 times maximum formation temperature of ion

\textsuperscript{d}for measurement with Chandra HETGS-MEG spectral resolution

Is it possible to measure stellar coronal gas velocities with current X-ray spectrometers?

- Doppler shifts of the Ne X 12.1Å line of HR 1099 with Chandra HEG (resolution ~300 km/s)
- Data binned at 30, 60, 120 s
- Thick solid line is predicted radial velocity of the K1 IV star. Thin line is for the G5 V star.
- Probably see changing radial velocity of the K1 IV star but no flows or flare Doppler shifts.
- Also no Doppler shifts seen for quiescent and flaring σ² CrB (Osten et al. ApJ 582, 1073 (2003))
Coronal lines in the UV (HST/STIS, res. 3 km/s) and FUV (FUSE, res. 20 km/s)

Redfield et al. (ApJ 585, 993 (2003))
Log \( T_{\text{max}} \) = 6.8, \( \Delta V \approx 0 \) km/s, \( \xi \approx 0 \) km/s

Pagano et al. (A+A 415, 331 (2004))
Log \( T(\text{max}) \) = 6.13, \( \Delta V \approx 0 \) km/s
Fe XII 1349 Å and Fe XXI 1354 Å in the spectrum of the dM3e flare star AD Leonis

Ayres et al. (ApJ 583, 963 (2003))
Fe XIII 3388 Å line observed in the M5.5 dwarf CN Leo by Fuhrmeister et al. (A+A 468, 221 (2007))

- VLT/UVES spectrum shows the narrow Ti II line blended with the broad Fe XIII line
- Fe XIII produced in the cool (T≈2x10^6 K) component of the corona
- Corresponding XMM-Newton RGS spectrum of CN Leo
What types of stars have coronae? (Güdel Astron. Astrophys. Rev. 12, 71 (2004))

Colors indicate the data sources (mostly ROSAT All Sky Survey (RASS)) and the study of the young stars in the Chamaeleon cluster.


Fig. 2. Hertzsprung-Russell diagram based on about 2000 X-ray detected stars extracted from the catalogs by Berghöfer et al. (1996) (blue), Hünsch et al. (1998a,b) (green and red, respectively), and Hünsch et al. (1999) (pink). Where missing, distances from the Hipparcos catalog (Perryman et al. 1997) were used to calculate the relevant parameters. The low-mass pre-main sequence stars are taken from studies of the Chamaeleon I dark cloud (Alcalá et al. 1997; Lawson et al. 1996, yellow and cyan, respectively) and are representative of other star formation regions. The size of the circles characterizes log \( L_X \) as indicated in the panel at lower left. The ranges for the spectral classes are given at the top (upper row for supergiants, lower row for giants), and at the bottom of the figure (for main-sequence stars).
What types of dwarf (main sequence) stars show X-ray emission? (Güdel Astron. Astrophys. Rev. 12, 71 (2004))

- **O and early B stars** are X-ray sources due to shocks in their radiatively-driven unstable winds: \( \log \left( \frac{L_x}{L_{\text{bol}}} \right) \approx -7 \). Magnetic shocks can produce high temperatures. \( \log L_x = 30-33 \). No flares detected.
- **Nonmagnetic B2-A5 stars**: thin convection zones that do not have classical \( \alpha \Omega \) dynamos. X-rays not seen except from cooler companions (often previously unknown).
- **Magnetic chemically peculiar Bp and Ap stars**: some are X-ray sources at \( \log \left( \frac{L_x}{L_{\text{bol}}} \right) \approx -6 \). Perhaps due to winds from the poles trapped in dipolar magnetic fields colliding at the magnetic equator.
- **Herbig AeBe stars**: pre-main sequence stars with deep convection zones and coronal activity like cool stars (flares, high temperatures, etc.)
What types of dwarf (main sequence) stars show X-ray emission? (Güdel Astron. Astrophys. Rev. 12, 71 (2004))

• **Spectral type A7 to early F**: Hottest dwarf star to show steady X-ray emission is Altair (A7 V), log (L_x/L_{bol}) = -7.5 and cool corona (~1MK). Rapidly rotating star with thin convective zone and weak dynamo.

• **Sun**: log (L_x/L_{bol}) = -7 (minimum) to -6 (maximum). Mean log L_x=27.3. 11 year solar cycle.

• **Spectral type mid-F to late-M**: solar-type coronae with flares, log (L_x/L_{bol}) = -7 to -3 depending on rotation rate, and active regions. Convective zone deepens to cooler stars. α-Ω dynamo produces large number of magnetic bipoles emerging at surface and complex magnetic fields in the coronae.

- Thermal x-ray emission $L(x)/L(\text{bol})$ decreases by more than a factor of 30 at spectral type M6.
- Nonthermal radio (gyrosynchrotron) emission $L(\text{radio})/L(\text{bol})$ similar to warmer stars.
- Why does the ratio of thermal to nonthermal emission change dramatically at M6 (3000K)?
Correlation of coronal X-ray and chromospheric Lyman-alpha emission

- Very good correlation for F5-K7 stars because little flaring.
- Correlation with scatter for M0-M5 stars because of flaring.
- Thermal emission measures heating rates.
A possible picture of interacting magnetic fields in close binary systems

- What would happen if the magnetic fields (anchored in starspots) of two stars interconnect?
- Footpoint motions due to differential rotation and convection twist and stretch the field lines producing currents, flares and heating.
- Uchida & Sakurai in Activity in Red Dwarfs, p. 629 (1983)
Fig. 16. Two examples of eclipses and the corresponding coronal image reconstructions. *From top to bottom:* Light curve of the YY Gem system (from Güdel et al. 2001a, observation with *XMM-Newton* EPIC); light curve of the AR Lac system (after Siarkowski et al. 1996, observation with *ASCA* SIS); reconstructed image of the coronal structure of, respectively, YY Gem (at phase 0.375) and AR Lac (at quadrature). The latter figure shows a solution with intrabinary emission. (The light curve of AR Lac is phase-folded; the actual observation started around phase 0; data and image for AR Lac courtesy of M. Siarkowski.)
Does rotation control activity?

- $L_x \approx 10^{27} \, (v \sin i)^2 \, \text{erg/s}$ (Pallavicini et al. (1981))
- **Nonsaturated regime**: $\log [L_x/L_{\text{bol}}] \sim (R_0)^{-2}$ and $R_0 = P_{\text{rot}}/t_\text{c}$ (Rossby)
- **Saturated regime**: $\log [L_x/L_{\text{bol}}] \approx -3$ regardless of $P_{\text{rot}}$ but beginning of saturation depends on mass.
- Saturation may indicate feedback of strong magnetic fields on differential rotation and thus the dynamo efficiency.
- Surface flux $F_x \sim P_{\text{rot}}^{-2}$
- Stars spin down due to mass loss with lever arm determined by strength of coronal magnetic fields, depth of convective zone, and rotation locking with disk. M stars take longest. Why?
- See Pizzolato et al. (A+A 397, 147 (2003)).

Circles (Pleiades), squares (IC 2602, IC 2391), stars (α Per), triangles (Hyades singles), crossed triangles (Hyades binaries), diamonds (IC 4665), filled circles (field stars) Randich (2000)
Does age control activity?

Stelzer et al. (MNRAS 431, 2063 (2013))
X-ray luminosity functions for groups of stars with increasing age (see Güdel 2004)

- Decrease in luminosity function (fraction of stars with X-ray luminosities $> L_x$) for star groups with increasing age (from young clusters $\rightarrow$ Pleiades $\rightarrow$ Hyades $\rightarrow$ Field stars).
- Left: masses 0.5 to 1 $M_{\text{sun}}$; right: 0.25 to 0.5 $M_{\text{sun}}$. 
Premark sequence star classes (Feigelson & Montmerle ARAA 37, 363 (1999)) [A great review]

<table>
<thead>
<tr>
<th>Properties</th>
<th>Infalling Protostar</th>
<th>Evolved Protostar</th>
<th>Classical T Tauri Star</th>
<th>Weak-lined T Tauri Star</th>
<th>Main Sequence Star</th>
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<td>Age (Years)</td>
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<td>$10^5$</td>
<td>$10^6 - 10^7$</td>
<td>$10^6 - 10^7$</td>
<td>$&gt;10^7$</td>
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<td>mm/Infrared Class</td>
<td>Class 0</td>
<td>Class I</td>
<td>Class II</td>
<td>Class III</td>
<td>(Class III)</td>
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<td>Disk</td>
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<td>Thick</td>
<td>Thick</td>
<td>Thin or Non-existent</td>
<td>Possible Planetary System</td>
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<td>X-ray</td>
<td>?</td>
<td>Yes</td>
<td>Strong</td>
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<td>Weak</td>
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<td>Thermal Radio</td>
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<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
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<tr>
<td>Non-Thermal Radio</td>
<td>No</td>
<td>Yes</td>
<td>No ?</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>
Age dependence of stellar activity (Preibisch & Feigelson (ApJS 160, 390 (2005))). 98% of stars in COUP ONC survey were X-ray detected.

Left to right: field stars, Hyades, Pleiades, Orion Nebular Cluster

• = 0.9-1.2 $M_{\odot}$; □ = 0.5-0.9 $M_{\odot}$; + = 0.1-0.5 $M_{\odot}$
Evolutionary tracks toward the zero age main sequence with TMC stars indicated. Star type indicates degree of disk veiling.
More interesting phenomena when magnetic fields of protostars and accretion disks interact

- Bright UV and X-ray emission from the star heat and ionize the outer layers of the disk driving the disk wind and accretion
- Collimated bipolar jets from star (many theories)
- Dust particles in inner disk are melted by flare heating → CaAl-rich inclusions seen in solar system meteorites
- Disks (observed in the IR) dissipate in ≈5Myr
Additional slides
Comparison of Fe XII and Fe XXI luminosities with soft X-ray luminosity for active stars

Ayres et al. (ApJ 583, 963 (2003))

- Hotter stars have more emission at larger photon energies (shorter wavelengths).
- Hottest plasma produces 6.7 keV emission of Fe XXV and Fe XXVI.
- Cooler plasma has weak continuum above 1.5 keV so that emission lines and blends are visible.
What happens at the cool end of the main sequence?

- Beyond M5 stars are fully-convective and a change (?) in the dynamo, but no change in $\log (L_x/L_{bol})$.
- Coolest field star with continuous X-ray emission was VB 8 (M7e V) but sensitivity bias.
- Chandra observations of the L3.5 star 2MASSJ00361617+ shows $\log[L_x/L_{bol}]<-4.7$ but radio emission (Berger et al. ApJ 627, 960 (2005)).
- Old brown dwarfs ($M<0.07M_{sun}$) predicted not to be steady X-ray emitters due to neutral photospheres. No electrical currents and thus no heating [?].

The brown dwarf Roque 14 in the Pleiades (age 100 Myr) was detected at $L_x \approx 3 \times 10^{27}$ erg/s, but may be a flare (Briggs & Pye MNRAS 2004)
X-ray emission from very cool M dwarfs (Robrade + Schmitt 2009)

- These are all fully convective M dwarfs.
- Log (L_x) = 27.3 average value for the Sun.
- Log (L_x/L_{bol}) = -7 (quiet Sun) to -6 (active Sun).
Correlation of $R_x = L_x / L_{bol}$ with $R_{CIV} = L_{CIV} / L_{bol}$


Fig. 2—X-ray/C IV flux-flux diagram. Normalization by the bolometric fluxes removes the twin biases of different distances and diameters. Shaded zones represent (1) G-K dwarfs (the circled dot marks cycle-average solar ratio), (2) “X-ray-deficient” Hertzsprung gap giants (Simon & Drake 1989), (3) hyperactive RS CVn binaries, (4) active dump (G8–K0) giants, (5) inactive but still coronal K0 giants, (6) G-K supergiants, and (7) noncoronal (≥ K1) red giants. Filled red circles mark α Boo ("α"), α Tau ("τ"), and three comparison stars: Cap ("C"), β Gem ("β"), and γ Dra ("γ"). Vertical blue bars connect earlier ROSAT upper limits with the new Chandra measurements.
Ionization rate in disk plane (z=0) and scale heights above/below for $N=1.3 \times 10^{20}$ cm$^2$ thick disk at 1 AU from the accreting TTS star LkCa 15 (Skinner+Gudel 2013)

$\log(L_\chi)=31.4$
Activity cycles (yes/no) seen in X-rays (Robrade et al. 2002)
Dielectronic and Radiative Recombination Rates

- Radiative recombination: \( X^{i+1} + e^- \rightarrow X^i + \text{continuum photon} \).
- Dielectronic recombination: \( X^{i+1} + e^- \rightarrow X^i \) (doubly excited) \( \rightarrow X^i \) (excited) + line photon.
- DR rates often far exceed RR rates (in both CIE and photoionized plasmas) due to resonances at low energies.

Example of Fe XV \( \rightarrow \) Fe XIV from Altun et al. (A+A 474, 1051 (2007)). Also many previous papers in a series.
Corona/wind dividing line

- A steep drop in emission from $10^5$ K plasma (Linsky & Haisch ApJ 229, L27 (1979)) and X-rays detected for giants cooler than about K2 III.

- Coincident with a rapid increase in stellar wind flux in cooler giants.

- Input energy changes from heating corona to driving a cool wind. Maybe a change from closed to open magnetic fields due change in dynamo or lower gravity or?


Crosses: X-ray detected brown dwarfs
Circles: not detected brown dwarfs

Extinction detected brown dwarf
X-ray luminosities (squares) and Chandra detection limit for ONC.
XMM-Newton Extended Survey of the Taurus Molecular Cloud (XEST) (Güdel et al. A+A 468, 353 (2007) and following papers)

- Nearest large star forming region (140 pc).
- X-ray images and RGS spectroscopy (1.3 Ms total exposure = 15 days).
- Detected 85% of CTTS and 98% of weak-line TTS. 139/169 detected.
- Ongoing star formation for last 1-2 Myr.
- TMC map with extinction (grey scale), CO contours, XMM fields, and TMC members (circles)
X-wind model of magnetic field geometry and gas flow for protostars with disks (Shu et al. Science 277, 1475 (1997))

- Helmut streamer and reconnection ring are null surfaces with electric currents out of the diagram
- Near balance of $\Omega_*$ and $\Omega_x$ at inner edge of gaseous disk where shared field lines
- When $\Omega_* \neq \Omega_x$, field line wrap $\rightarrow$ shear and sporadic reconnection events (flares) with hard X-ray emission which are observed
- Observed funnel flows are variable and torque the star
- There are additional complications when the stellar magnetic field axis is not aligned with the stellar rotation axis.

The X-wind model assumes that the star and disk both have magnetic fields and thermally-driven winds.
Information on stellar coronal properties from the Fe XVIII line profiles

• Far Ultraviolet Spectroscopic Explorer (FUSE) spectra with resolution 20 km/s.
• Observed only in active stars and solar flares because requires plasma at log T = 6.8.
• No significant Doppler shifts indicate that the hot plasma is not expanding. Probably confined in magnetic structures.
• Line widths are approximately thermal indicating that coronal heating is not by shocks.
• Rapidly rotating stars (e.g., 31 Com and AB Dor) show broader profiles indicating that the emitting plasma is extended.
• Flux in Fe XVIII 974 Å line is proportional to ROSAT soft X-ray flux.
• FUSE also observed the Fe XIX 1118 Å line.
Comparison of iron ionization fractions

Lower ionization states shifted to lower temperatures due to higher ionization rates and lower dielectronic recombination rates than earlier calculations.
Higher ionization states shifted to higher temperatures due to increased DR rates.
Model of a protostar with an accretion disk (Camenzind Rev. Mod. Astr. 3, 234 (1990))

- Central stars not rapid rotators so accretion flow torque must be balanced by ang. momentum loss through currents from star to disk (magnetic field is not force-free)
- Field lines beyond the corotation radius drive a disk wind centrifugally
- Disk winds are collimated into bipolar jets with radius≈500 AU
Structures in the solar corona

- Ideal MHD equations
- Plasma fully ionized with high conductivity

\[
\rho \left[ \frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla) \mathbf{v} \right] = \frac{1}{\mu_0} (\nabla \times \mathbf{B}) \times \mathbf{B} - \nabla p - \rho \nabla \Phi
\]

\[
\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}), \quad \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0.
\]

Zurbuchen (Annual Reviews of Astronomy and Astrophysics 45, 297 (2007))
Schematic representation of the physical processes that shape the magnetic field in the corona and heliosphere (Zurbuchen (2007))
TRACE Images of soft X-ray (Fe X + Fe XI) loops on the Sun. Note tangled loops on the right.

- Assume magnetic loops in hydrostatic equilibrium (height < 1 pressure scale height), constant pressure and cross-section area, no flows, uniform heating. $2L =$ loop length.
- $T_{\text{apex}} = 1400(pL)^{1/3}$
- $L_x \approx 6 \times 10^{16} (R_*/R_{\text{sun}})^2 f T^{3.5}/L$
- Fluctuations in the local heating rate lead to dynamically unstable states inside the loops. Leads to evaporation of chromosphere gas at footpoints and thus loop brightenings
Empirical basis for the RTV scaling relations (Rosner et al. (1978))
Analysis of Einstein IPC observations of the AR Lac system

- AR Lac (G2 IV-V + K0 IV) eclipsing RS CVn system with P=1.98 days.
- 60% of X-rays from cooler star.
- X-rays from $>10^5$ magnetic loops with $0.02R_{\text{star}}$ heights with pressures and densities like small solar flares.
- Also an extended component for the K star corona.

<table>
<thead>
<tr>
<th>Star</th>
<th>Spectrum</th>
<th>Extended</th>
<th>$n_e^b$</th>
<th>Compact</th>
<th>$n_e^b$</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>AR Lac</td>
<td>G2 IV+K0 IV</td>
<td>$\approx 1$</td>
<td>0.29</td>
<td>0.01</td>
<td>4–6</td>
<td>1</td>
</tr>
<tr>
<td>AR Lac</td>
<td>G2 IV+K0 IV</td>
<td>1.1–1.6</td>
<td>0.2–0.8</td>
<td>0.06</td>
<td>$&gt; 5$</td>
<td>2</td>
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<tr>
<td>AR Lac</td>
<td>G2 IV+K0 IV</td>
<td>0.7–1.4</td>
<td>0.3–0.8</td>
<td>0.03–0.06</td>
<td>6–60</td>
<td>3</td>
</tr>
<tr>
<td>AR Lac</td>
<td>G2 IV+K0 IV</td>
<td>$\approx 1$</td>
<td>0.12–1.8</td>
<td>–</td>
<td>–</td>
<td>4</td>
</tr>
<tr>
<td>Algol</td>
<td>B8 V+K2 IV</td>
<td>0.8</td>
<td>...</td>
<td>–</td>
<td>–</td>
<td>5</td>
</tr>
<tr>
<td>Algol$^d$</td>
<td>B8 V+K2 IV</td>
<td>–</td>
<td>–</td>
<td>$\approx 0.5$</td>
<td>$\geq 9.4$</td>
<td>6</td>
</tr>
<tr>
<td>Algol$^d$</td>
<td>B8 V+K2 IV</td>
<td>–</td>
<td>–</td>
<td>0.1</td>
<td>$\leq 3$</td>
<td>7</td>
</tr>
<tr>
<td>TY Pyx</td>
<td>G5 IV+G5 IV</td>
<td>$\approx 1$–2</td>
<td>0.02–3</td>
<td>–</td>
<td>–</td>
<td>8</td>
</tr>
<tr>
<td>XY UMa</td>
<td>G3 V+K4 V</td>
<td>–</td>
<td>–</td>
<td>$\leq 0.75$</td>
<td>...</td>
<td>9</td>
</tr>
<tr>
<td>VW Cep$^d$</td>
<td>K0 V+G5 V</td>
<td>0.84</td>
<td>5</td>
<td>–</td>
<td>–</td>
<td>10</td>
</tr>
<tr>
<td>$\alpha$ CrB</td>
<td>A0 V+G5 V</td>
<td>–</td>
<td>–</td>
<td>$\approx 0.2$</td>
<td>$\leq 3$</td>
<td>11</td>
</tr>
<tr>
<td>$\alpha$ CrB</td>
<td>A0 V+G5 V</td>
<td>–</td>
<td>–</td>
<td>$\approx 0.1$</td>
<td>0.1–3</td>
<td>12</td>
</tr>
<tr>
<td>EK Dra</td>
<td>dG0e</td>
<td>–</td>
<td>–</td>
<td>$\approx 0.2$</td>
<td>$\geq 4$</td>
<td>13</td>
</tr>
<tr>
<td>YY Gem</td>
<td>dM1e+dM1e</td>
<td>–</td>
<td>–</td>
<td>0.25–1</td>
<td>0.3–3</td>
<td>14</td>
</tr>
<tr>
<td>V773 Tau$^d$</td>
<td>K2 V+K5 V</td>
<td>$\approx 0.6$</td>
<td>$\geq 20$</td>
<td>–</td>
<td>–</td>
<td>15</td>
</tr>
</tbody>
</table>

Notes. $^a$ Extended structures of order $R_*$, compact structures significantly smaller.

$^b$ Electron density in $10^{10}$ cm$^{-3}$ for extended and compact structures, respectively.

$^c$ References: 1 Walter et al. (1983); 2 White et al. (1990); 3 Ottmann et al. (1993); 4 Siarkowski et al. (1996); 5 Ottmann (1994); 6 Schmitt and Favata (1999); 7 Schmitt et al. (2003); 8 Preš et al. (1995); 9 Bedford et al. (1990); 10 Choi and Dotani (1998); 11 Schmitt and Kürster (1993); 12 Güdel et al. (2003b); 13 Güdel et al. (1995); 14 Güdel et al. (2001a); Skinner et al. (1997).

$^d$ Refers to observation of eclipsed/modulated flare.

- Solid lines are FIP fractionation ($A/A_{\text{photo}}$).
- Dashed line is pondermotive ($jxB$) acceleration.
- First ionization potentials: Ne (21.6eV), Ar (15.8), O (13.6), H (13.6), Si (8.2), Fe (7.9), Na (5.1), K (4.3).
- O and H are tightly coupled by charge-exchange reactions.
- Wave energy density assumed 0.04 ergs cm$^{-3}$ (quiet Sun)
Range of $R_x = \frac{L_x}{L_{bol}}$ for main sequence and evolved stars (Ayres et al. ApJ 583, 963 (2003))

Oval area: clump stars with He-burning cores.
Red area: supergiants with strong winds.
For what type of stars are coronae not observed or unobservable?

Hybrid stars: an exception to the corona/winds dividing line?

- Some class II (K bright giants) and class Ib (G and K supergiants) show cool winds and hot gas (X-rays and C IV).
- \( L_x = 10^{27} \) to \( 10^{30} \) erg/s (X-ray deficient) and high coronal temperatures.
- Probably >2M\(_{\text{sun}}\) stars that have rapidly evolved from MS and with winds and dynamos (structure inhomogeneous ?) Hünsch & Schröder (A+A 309, L51 (1996)).
- Regions in figure: 1 (F-K V), 2 (G I, fast rotating HG stars), 3 (G-K0 III), 4 (K1-2 III).

X-ray properties of young brown dwarfs (Preibisch et al. (2005))

- 9/34 known brown dwarfs in Orion Nebular Cluster detected in COUP survey (9.7 days).
- Low detection rate probably due to extinction.
- Many obvious flares and probably continuous flaring.
- X-ray properties similar to M dwarfs, so no obvious change at the stellar/substellar boundary.
- Young BDs have similar X-ray properties to field (older) M dwarfs of same Teff, so ionization in the photosphere may control X-ray properties.

Solid line is linear regression fit to the low mass stars in the ONC.
Do coronal abundances differ from photospheric abundances and does this depend on activity?

- Coronal abundances relative to Fe in the stellar photosphere for the Telleschi et al. sample of solar-type stars.
- For the less active stars, the high First Ionization Potential ions (FIP>13.5 ev) have decreased abundances compared to the low FIP ions (FIP EFFECT).
- For the more active star, the high FIP ions have increased abundances relative to low FIP ions (INVERSE FIP EFFECT).
- Is this effect real? What can explain the effect if real?
Examples of FIP bias (coronal/photospheric abundances relative to oxygen) for magnetic closed and open solar structures (Feldman Physica Scripta 24, 681 (1981))

**Enrichment of low-FIP elements in the solar corona in closed magnetic structures increasing with time. Why?**
Example of an inverse FIP effect in the active binary HR 1099 ($P_{\text{rot}} = P_{\text{orb}} = 2.84$ days)

FIP and inverse FIP phenomenology

- Inverse FIP seen only in the most active stars (young MS and rapidly-rotating giants)
- Solar-like FIP seen when \( \log \left[ \frac{L_x}{L_{bol}} \right] < -4 \)
- Flares temporarily remove the inverse FIP pattern and then the pattern reverts to inverse FIP

Abundances during a flare (red) and quiescent times (black) for the active binary \( \sigma^2 \) Cor Bor (Osten et al. ApJ 582, 1073 (2003))

- In the upper chromosphere high-FIP elements are largely neutral and low-FIP elements are ionized.
- There is a steep temperature gradient at the interface between the chromosphere and corona. So a steep electron density (and thus index of refraction) gradient.
- Alfvén waves are traverse waves of the magnetic field.
- Consider a coronal magnetic flux tube with footpoints in the chromosphere.
Consider Alfvén waves propagating through the interface up from the solar chromosphere or down from the corona.

Pondemotive (Lorenz) force:
\[ j \times B / c = (\nabla \times B) \times B / (4\pi) \]

- Alfvén waves are refracted at the interface due to the change in index of refraction with \( n_e \),
  \( n = [1 - (\omega_p/\omega)^2]^{1/2} \). \( \omega_p^2 \approx n_e \).
- Increased wave pressure where \( n \) is large forces ions to a region of lower \( n \).
- Low frequency Alfvén waves (\( \omega_{cyc} = eB/mc \)) push ions to lower density (upward): FIP effect.
- High frequency Alfvén waves push ions to higher density (downward): inverse FIP effect.

Plots of Alfvén wave electric field vs. distance below the interface. “on res” corresponds to transmission maximum at 207 s period (the loop fundamental frequency). “low freq” is a wave period of 1000 s. Positive gradient of wave electric field gives an upward force.
Predictions of the Laming (2004) model concerning FIP and inverse FIP

• Why do closed magnetic loops show FIP fractionation and open field loops not? For closed loops Alfven waves reflect between footpoints many times and for open field regions the waves go through only once.
• Why does the fractionation increase with time? Many reflections increase the effect.
• Why do active stars show an inverse FIP effect? Need a negative gradient of the wave electric field. Active stars likely have higher frequency Alfven waves \((\omega_{\text{cyc}} = eB/mc)\), then the force on ions is downward to higher densities.
What is a (simple mean-field kinematic) $\alpha$-$\Omega$ dynamo?

- Originally proposed by Parker (ApJ 122, 293 (1955)) to explain solar 22 year magnetic cycle (field reversal every 11 years or so).
- Theory has been developed by many people but see Dikpati et al. (ApJ 631, 647 (2005)).
- $\Omega$-effect: differential rotation (faster at the equator) winds up the initial poloidal (dipolar) field creating a toroidal field. Models place the $\Omega$-effect mainly at base of convective zone (interface dynamo) or distributed in the convective zone (distributed dynamo).
- $\alpha$-effect: regenerates a poloidal field of opposite polarity due to cyclonic turbulence or field cancellation.
Comparison of structures of the solar corona with that of a very inactive giant (e.g., Arcturus)

- Buried corona model (left) proposed by Ayres et al. (ApJ 598, 610 (2003)).
- X-ray emission weak (1/10,000) of Sun because absorbed by overlying cool chromosphere.
- C IV and N V not absorbed because UV wavelengths longer than 912Å
Synchronous binary systems: RS CVn, W UMa, and Algol

- Binary systems containing a convective star become tidally synchronous ($P_{\text{rot}} = P_{\text{orb}}$) in $10^9 (P_{\text{orb}} / 20 \text{ days})^4$ years (Zahn A+A 57, 383 (1977)).
- Thus close binaries are rapid rotators and very active (X-rays, C IV, chromospheres, flares, active regions)
- RS CVn class (typically G-K V and K IV, $P_{\text{orb}} < 20 \text{ days}$ usually, cooler star is more active)
- BY Dra class (typically both stars M V)
- W UMa class (contact binaries, usually G V, $P_{\text{orb}} = 0.1$ to 1.5 days)
- Algol class (B-A star and a G-K IV star that fills its Roche lobe, mass transfer likely, cooler star active)

- X-ray properties of a large sample of RS CVn systems.
- Two component fits (T and volume emission measure for hot and cool components).
- \( \frac{L_x}{L_{bol}} \) often at saturation level \((10^{-3})\).
- Flares are common and small flares may provide most of coronal heating.
Properties of coronae in short period binaries learned from eclipses (see Güdel 2004)

- X-ray light curves require the coronae to be asymmetric, inhomogeneous, and extended.
- Evidence for bright hemispheres facing each other suggesting that magnetic fields connect the two stars (Uchida & Sakurai 1984, 1985) that can provide heating between the stars.
- Extended structures likely contain the hottest plasma (low density). Likely where nonthermal electrons and synchrotron radio emission originates.
- Compact structures have very high pressures ($P_{\text{gas}}>100$ dynes/cm$^2$) and thus strong magnetic fields ($B>50$ G) to confine the plasma.
Wavelength ranges of different instruments: XMM-Newton (5-35 Å), Chandra (1.2-360 Å)
$n_e(T)$ for the quiescent coronae of $\sigma^2$ CrB (Osten et al. ApJ 582, 1073 (2003))

- Electron densities from He-like triplets and Fe XXI and Fe XXII line ratios.
- Indicates a factor of 1000 increase in $P_{\text{gas}} = nkT$ with increasing $T$.
- This is only possible if the hot gas is confined by magnetic fields ($B > 600$ Gauss).
What happens as stars evolve off the main sequence?

- **Hottest (coronal) X-ray emitting giant**: Canopus (F0 II) $\log L_x = 6\times10^{29}$ erg/s.
- **Herzsprung-gap stars**: rapidly-evolving stars with growing convective zones.
- **FK Comae giants**: very rapidly-rotating giants with hot ($T$ up to 40 MK) luminous ($L_x \geq 10^{32}$ erg/s) coronae. (Merged binaries?)
- **Coronal graveyard**: giants cooler than mid-K: extremely weak X-ray sources. Arcturus (K1 III) $L_x = 1.5\times10^{25}$ erg/s, $\log (L_x/L_{bol}) = -10.7$ (1/10,000 times the average Sun value). The least active corona on a star detected so far.
XEST detection statistics and $L_x$ distribution for TMC (Güdel et al. A+A 468, 353 (2007))

Table 12. XEST X-ray detection statistics.

<table>
<thead>
<tr>
<th>Object type</th>
<th>Members surveyed</th>
<th>Detections</th>
<th>Detection fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protostars</td>
<td>20 (21)</td>
<td>8 (10)</td>
<td>40% (48%)</td>
</tr>
<tr>
<td>CTTS</td>
<td>65 (70)</td>
<td>55 (60)</td>
<td>85% (86%)</td>
</tr>
<tr>
<td>WTTS</td>
<td>50 (52)</td>
<td>49 (50)</td>
<td>98% (96%)</td>
</tr>
<tr>
<td>BDs</td>
<td>16 (17)</td>
<td>8 (9)</td>
<td>50% (53%)</td>
</tr>
<tr>
<td>Herbig</td>
<td>2</td>
<td>2</td>
<td>100%</td>
</tr>
<tr>
<td>others/unident.</td>
<td>6 (7)</td>
<td>4 (5)</td>
<td>67% (71%)</td>
</tr>
<tr>
<td>Total</td>
<td>159 (169)</td>
<td>126 (136)</td>
<td>79% (80%)</td>
</tr>
</tbody>
</table>

Notes:
Numbers in parentheses include Chandra observations. Source near L1551 IRS5 not considered (non-detection for XEST-22-040)

Most stars have log $[L_x/L_{bol}]$ in the range $10^{-3}$ to $10^{-4}$.