THE ANNOTATED STARS

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Vinay Kashyap

Overview

The Solar Analogy

⋆ The idea that coronal emission on normal stars is similar to that seen on the Sun)

The Forest: X-rays across the HR diagram

⋆ A broad overview of stellar X-ray emission

- heating mechanisms
- coronal structure
- fundamental parameters

The Trees: Spectral analysis

⋆ detailed description of typical stellar spectral analysis, designed to fit in with Randall Smith's talks on atomic physics and high-resolution spectral analysis

- Low-res spectra:
  temperatures, fluxes, and metallicity
- High-res spectra:
  temperature distributions, emission measures, abundances

The Roots: The Sun

⋆ a reality check on what we know and how much more needs to be understood

⋆ TRACE pictures and movies are available online at
http://vestige.lmsal.com/TRACE/POD/TRACEpod.html

THE NEAREST STAR

- Sun-Earth Connection
  - "space weather" affects satellites
    ⋆ after all, we live within the atmosphere of the Sun
  - activity affects climate
    ⋆ solar activity and terrestrial climate appear to be correlated, viz., Maunder minimum and "Little Ice Age"
- Solar corona
  [First X-ray image of Sun, Giacconi et al. (1965)]
  ⋆ notice lack of emission from the surface and the blobby nature of the emission
  - hot (million-degree) plasma
    [SOHO EIT image in 171 Å passband, dominated by emission from Fe IX at 10^6 K, from Saturday, 2002 Aug 16]
  - dominated by magnetic loop structures
    ⋆ note: lack of emission from surface, extent of emission above the surface (i.e., X-ray emission comes from the hot atmosphere), emission clustered around "active regions" coincident with sunspot activity, and loop like structures reminiscent of magnetic field lines
  - dynamic environment
    [SOHO EIT image in 195 Å, from c.2 years ago]
- Stellar coronae
  - ubiquitous, and copius
    [HR-diagram showing where stellar X-ray emission has been detected, from Rosner, Golub & Vaiana 1985, ARA&A 23, 413]
    ⋆ the gap at $B - V \approx 0$ is real, and is due to the changeover from one type of emission in hot early-type stars – from hot plasma in shocks in stellar winds – to another type in cool late-type stars – coronal emission dominated and maintained by dynamo action
    ⋆ $\frac{L_x}{L_{bol}} \sim 10^{-6}$ for hot stars, and increases to $\sim 10^{-3}$ for dMe stars
    ⋆ mechanism of X-ray emission at low-mass end is uncertain, because fully convective stars dampen dynamos, leaving only turbulent dynamos
  - tuning the Sun
    ⋆ stellar observations allow us to explore the parameters that define stellar activity and thus help better understand solar activity

STELLAR X-RAY EMISSION

[Milestones in the study of stellar coronae, compiled by Jeremy Drake]

- Why do the exist, how are they heated?
  [Heating the Solar (& Stellar) Corona]
  - Magnetic reconnection?
  - Alfvénic wave heating?
  - ¿?
- What determines coronal structure?

  Simple answer: Magnetic fields

  Correct answer:
  [Coronal Loops: The essential physics]
- What are the fundamental parameters?
  ⋆ twiddle the knob, turn the dial, monte-carlo the sun
  [X-ray surface flux as a function of spectral type, showing the range of activity]
  - Dynamo activity: Rotation and convection
    [L_x v/s $v \sin i$ from Rosner, Golub, & Vaiana, 1985, ARA&A, 24]
    ⋆ activity is strongly correlated with rotation, because of stronger dynamo action, which leads to greater magnetic field generation
  - Age: evolution, mass-loss
    ⋆ evolution changes convective properties, mass-loss leads to angular momentum loss and consequent rotational braking
  - Composition: Radiative loss function
    [radiative loss rates for solar photospheric, solar coronal, and highly metal depleted atmospheres]
    ⋆ recall also that the the radiative loss figures prominently in the loop energy balance
  - Gravity: field topology and stability
  - Environment: binary companions

Heading the Solar (& Stellar) Corona

Wave dissipation:

– Acoustic waves have low basal fluxes $\sim 2 \cdot 10^6 - 10^5$ ergs s^{-1} cm^{-2}, and dissipate below the chromosphere (relevant for very low-mass stars; e.g., Haisch & Schmitt 1996)
– Alfvén waves dissipate inefficiently, and short period waves (1-10 sec) required (may drive massive winds on late-type giants)

Magnetic reconnection:

– release of magnetic energy in an impulsive event
– "Nanoflares" (Parker 1988), motivated by HXR events distribution
– avalanches in a self-organized critical system (Lu & Hamilton 1991)

Coronal Loops: The Essential Physics

Energy Balance:

$$E_H + \mathcal{F}\cdot\mathbf{v} = \nabla\cdot\mathbf{F_c} - E_R + \nabla\cdot\left(\left[\frac{1}{2}\rho v^2 + U\right]\mathbf{v} + \rho\mathbf{v}\right)$$

where E_H is the local heating function, $\mathcal{F}$ is the volume force exerted by gravity and momentum deposition, $\mathbf{v}$ is the flow velocity, $\mathbf{F_c}$ is the conductive flux, $F_c(s) = -\kappa T^{5/2}\frac{dT}{ds}$, $E_R \propto n_e^2 P(T)$ is the radiative loss, $\rho = m_H n_e$ is the density, U is the thermal energy density. The gradient in the pressure p is balanced by gravity. For large pressure scale heights, $\frac{dp}{ds} = 0$ and $\mathbf{v} = \mathbf{0}$ (where s is the coordinate along the loop),

$$E_H + E_R - \nabla\cdot\mathbf{F_c} = 0$$

Scaling laws

⋆ see Rosner, Tucker, Vaiana 1978, ApJ for details of derivation

⋆ relaxing some of the assumptions such as constant pressure will change the indices below, but not in a qualitatively significant manner

$$T_{max} \propto (p_0 L)^{\frac{1}{3}}$$

⋆ p_0 is the base pressure

$$E_H \propto p_0^{7/6} L^{-5/6}$$

$$n_e^2 \frac{ds}{d\log T} \propto T^{3/2}$$

⋆ this is the so-called DEM, the Differential Emission Measure, which is usually the goal of the spectral analysis

⋆ as written, has units of $[cm^{-5}]$, but sometimes has dV replacing ds, to give units of $[cm^{-3}]$

Spectra
Or, How do we find out what we want to know?

Thermal Emission
– optically thin emission from collissionally excited plasma in local thermal equilibrium

Low-resolution spectra
– dominant temperatures and fluxes
– metallicity
⋆ a controversial subject, because it is difficult to set the continuum properly – see Randall Smith's talk on high-resolution spectroscopy

High-resolution spectra [σ Gem MARX spectrum, showing the large number of diagnostic lines]

- Select lines spanning temperature range of interest
  [AD Leo spectrum, which will be used as an example]
- Measure fluxes of selected lines
  ⋆ see Randall Smith's talk on hi-res spectroscopy for details and pitfalls; here assume good lines have been selected and fluxes have been correctly measured
- Infer the emission measure distribution
  (and **error bars!**)

$$
\begin{aligned}
I_{ul} &= AK_{ul} \int_{\Delta T_{ul}} G_{ul}(n_e, T) n_e^2(T) \, dV(n_e, T) \\
&= AK_{ul} \int_{\Delta T_{ul}} G_{ul}(T) \left\{ n_e^2(T) \frac{dV(T)}{d \log T} \right\} \, d \log T
\end{aligned}
$$

⋆ where the intensity I_{ul} of a transition from an upper-level to a lower-level $u \to l$ is written as the product of the abundance A of the element, a distance and wavelength dependent factor K_{ul}, and the summed contribution over volume of the radiative loss, which is the product of the atomic emissivity $G_{ul}(n_e, T)$ and n_e^2
⋆ the emissivity is usually approximated as a function of T, see Randall Smith's talk on high-res spectroscopy for complications resulting from density dependence
⋆ the function within the curly brackets is the Differential Emission Measure, or the DEM, which serves as a good summary of the structure of the corona, and can be used to predict the emission at other passbands, constrain the heating theories, etc.
[emission measure curves for selected Fe lines, derived by assuming δ-function DEMs, upper limits to the true DEM]
[DEM derived from just the Fe lines]
⋆ no complications due to abundance anomalies
[DEM extended to other temperatures using lines from other elements]
[EM curves for all elements, along with derived DEM, for HR1099]
⋆ very important to include a measure of the measurement uncertainty in the DEM, because it is easy to obtain unphysical DEMs
⋆ See Kashyap & Drake (1998 ApJ, 503, 450; and references therein) for a description of the assumptions, limitations, and construction of DEMs

- Rinse, lather, repeat
  ⋆ very important to iterate by checking the fluxes in other lines and in the continuum
  ⋆ there is no software program that will do all this for you, human intervention is critical
  ⋆ some software programs that may help are:
  PINTofALE (http://hea-www.harvard.edu/PINTofALE/),
  ISIS (http://space.mit.edu/CXC/ISIS/),
  CHIANTI (http://wwwsolar.nrl.navy.mil/chianti.html),
  APEC (http://cxc.harvard.edu/atomdb/sources_apec.html)
- [X/Fe] via lines and [Fe/H] via continuum
  [how to measure abundances, AD Leo: compute fluxes using DEM derived assuming certain abundance (e.g., solar), then compare predicted to observed ratio to simply rescale]
  [compare predicted and observed continuum for HR1099]
  ⋆ see Randall Smith's talk on hi-res spectroscopy on pitfalls of setting the continuum

[how the DEM seems to change with activity; plot by Jeremy Drake]