Stellar coronae and the Sun

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solar eclipse, 11.8.1999, Wendy Carlos and John Kern

Nice movie of $\alpha$CenA in C IV (1548 Å)

Tom Ayres (2004)
What do we see of a stellar corona?

- photosphere: Doppler-(Zeeman)-Imaging:
  structures on stellar surface

- corona: emission concentrated in few active regions
  or dominated by flares:
  "point sources" in the corona

XY Ursa Major
(A. Collier Cameron)

Yohkoh Soft X-ray Telescope (SXT), \( \approx 1 \text{ nm}, \approx 2 \times 10^6 \text{ K} \)

Comparing photosphere and corona: the Sun

MDI / SOHO white light
Nov 16, 1999
Yohkoh Soft X-rays
Doppler imaging – principles

longitude: position of "bump"  
latitude: way of "bump" trough profile

time series of spectra

surface structures

Stellar photospheres → stellar coronae

stellar surface structures using Doppler imaging

Sun

HD 12545    XX Tri

stellar photospheres can look quite different than the Sun !!

How do stellar coronae look like ??

Vogt & Penrod (1983)

J.B. Rice: Doppler Imaging Techniques


stellar coronae

Sun
**Stellar coronal observations in the radio**

Angular resolution of a telescope:

\[
\phi \propto \frac{\lambda}{D}
\]

Very Long Baseline Interferometry

- \(D = \) diameter of Earth
- \(\lambda = 10\) cm (typical radio)
- \(\Rightarrow\) resolution \(\phi\) down to 1/1000 arcsec (=mas)

**Radio corona:**

- Radio emission of electrons circling around magnetic field

(Where do all these speedy electrons come from... ?)

**Surface structures of an X-ray corona**

A total eclipse of a "young Sun" (G5V):

\(\alpha\) Coronae Borealis

- X-ray bright secondary: G5V \(R_\alpha = 0.90 R_\odot\)
- X-ray dark primary: A0 V \(R_\alpha = 2.89 R_\odot\)
- Period: 17.35 days

X-ray lightcurve

8 hrs
active star
(α Coronae Borealis; G5 V; Güdel et al. 2003)

quiet star
(Sun; G2 V; Yohkoh)

Flare on Algol B

Eclipsing binary: Algol A (B8 V) X-ray dark
Algol B (K2 III) X-ray bright

Eclipse results in asymmetric light curve


XMM / Newton
Where does the X-ray emission come from in active stars?

higher “filling-factor” than Sun?

- not enough space on the surface
- and: also stellar X-rays are structured

stellar corona are not only brighter, they have also

- high densities
- high temperatures

Could it be flares?

Güdel (2003):

“A stochastic flare model produces emission measure distributions similar to observed DEMs, and predicts densities as observed in ‘quiescent’ sources.”

Flares vs. background …

- activity increases with rotation (due to dynamo action) saturation for rapid rotation
  - scaled-up solar-like magnetic activity?
- interpretation of major contribution to X-rays depends on energy distribution of flares
  \[ \frac{dN}{dE} \propto E^{-\alpha} \]
  - \( \alpha > 2 \): flare dominated
  - \( \alpha < 2 \): flares not sufficient
- thinkable scenarios:
  
  **flare-scenario**
  - same “quiet” corona as Sun
  - extra magnetic energy goes into flares of all sizes
  - light curve only due to flares

  **background scenario**
  - increased magnetic activity leads to higher densities and temperatures of the quiet corona
  - plus some more stronger flares
  - light curve quiet background plus flares!
Appearance of corona in a multi-loop simulation

Potential field extrapolation → simple 1D static loop models to many field lines

Energy flux into loop: 

\[ F_B = \alpha B_{\text{max}}^2 L_{\text{int}} f(B_{\text{max}}) \]

Free parameters: \( \beta \), \( \lambda \)

[best fit values] [1.0 ± 0.5 ] [-0.7 ± 0.3 ]

Quenching to account for sunspots being X-ray dark:

\[ f(B) = \exp \left( -\frac{B^2}{500 G^2} \right) \]

Real Sun

YOHKOH/SXT

2000/12/01

Best fit

SXT (simulated)

3D stellar corona: Doppler-Zeeman-Imaging

- **AB Doradus**
  - Cool active star (K2V)
  - \( T_{\text{eff}} \approx 4000\text{K} \)
  - Half as luminous as our Sun (0.4 \( L_\odot \))
  - Fat rotator (50 \( \Omega_\odot \))
  - Distance ≈ 49 light years

- Structures on the surface in intensity and magnetic field using Zeeman-Doppler-imaging (ZDI)

- Potential field extrapolation (source surface at 5 \( R_\odot \))

- Pressure at coronal base: \( p \propto B^2 \)
  - At open field lines: \( p=0 \)

- Emissivity \( \propto n_e^2 \)

From the stars to the Sun: EUV profiles

Sun: 1" x 1" network

“full Sun”: αCen A (G2 V)

non-Gaussian line profiles:
- mixture of surface structures?
- center to limb effect?
- signature of heating process?

Sun (G2 V): average quiet Sun


Sun: average Doppler shifts at disk center


Doppler shifts: spatially resolved vs. full disk

BUT: can we compare Sun at disc center with a whole star??
- center-to-limb variations of I, w, v\(D\)
- structures on the stellar disk, e.g. AR

PROBLEM:
no Sun-as-a-star EUV spectrometer with sufficient spectral resolution!!

How to compare Sun and stars?
e.g.: net line shift
- amazing match between Sun and αCen A
- BUT: – Sun at disc center – full stellar disk!!
Signatures of small-scale activity?

- spectra usually well described by double Gaussians!

>> what is the nature of these two components?

One possible interpretation:

- small scale activity (explosive events) causes flows \( \sim v_A \) excess emission in line wings

solar-like \( \rightarrow \) active stars:

asymmetric spectra of lines at \( \sim 10^5 \) K

SUMER full disk scan: C IV (1548 Å)

\( \sim 10^6 \) spectra on the disk

construct a full disk spectrum from this raster

Problems:

- not a snapshot
- \( \sim 24 \) hours scan
- "stability" of the spectrograph

Thermal (in)stability of SUMER

- The spectral line moves on the detector: quasi-periodic ±1 pixel (10 km/s) (period ~2 hours)
- Wavelength accuracy limited by thermal stability

Constructing the full disk spectrum

- Do a Gaussian fit to each spectrum
- Correct Doppler shifts for quasi-periodic variation
- Use intensity, width and corrected shift to calculate “corrected spectra”
- Sum these spectra to get sun-as-star spectrum
First EUV Sun-as-a-star spectrum

Composing the integral (total) solar spectrum from a SUMER full-disk raster map

- full-Sun spectrum similar to α Cen A!
  - but net redshift reduced by factor 1/3!

modeling distribution of line intensities and shifts on the solar disk:
- non-Gaussian profiles of solar-like stars are due to distribution of surface structures and not signature of heating process

Problem so far: no full-Sun EUV spectrometer with high spectral resolution!

Comparing the Sun to αCen A

What do we learn from the full-Sun spectrum?
- broad component: signature of cell-network structure (few information on heating process)
- narrow component: shift indicative for magnetic flux in chromospheric network vis. magnetic activity

Consequences for Sun vs. αCen A:
- Sun and αCen have similar structure of super-granulation / chromospheric network
- αCen A has much higher redshift
  - is there more energy density in the super-granulation?
    - αCen A has ~25% lower surface gravity (Morel et al. 2000, A&A 363, 675)
  - is αCen A much more active than quiet Sun?
    - However: no EUV cycle on αCen A on time scale comparable to Sun (Ayres et al 1995, ApJS 96 223)
- less active regions on αCen A but a stronger network?
Luminous cool giants: wind detection?

- asymmetric spectra of lines at $\sim 10^5$ K (e.g. C III 977 Å, O VI 1032 Å)
- spectra usually well described by double Gaussians!
  >> what is the nature of these two components?

One possible interpretation:
- single Gaussian fit only to red part of the spectrum
  >> excess absorption in blue wing: mass outflow?
    → does it work physically?
    → is it unique?

The Sun "seen as a cool giant"

- "cool giant wind detection procedure" used by Dupree et al. (2005) applied to the Sun-as-a-star spectrum of C IV (1548 Å)
- full-Sun looks similar to cool giants!!

- line asymmetry of cool giants signature of stellar surface structures?
  → e.g. large convection patterns on giants
    >> and simulated by Freytag et al. (2002) AN 323, 213
Inferring the structure of stellar coronae

Multi-loop model:

- Construct the corona as a superposition of many loops.
- Currently: static loops
  - 0D (constant $T, p$)
  - Constant $p$
  - 1D static approximation

Example: use 1D models with different heating functions $E_H \sim B^{\alpha}$ where $\alpha$

Different approach – spectroscopy:

- Use stellar spectra and derive average coronal properties through an inversion
  - $T, p, L$ (e.g. Ness et al. 2004, ……)
- How reliable are such inversions?
- What is the inferred “average” property?

XMM / Newton X-ray observatory

XMM 58 mirror module
X-ray density diagnostics: He-like ions

principle: a simple 3 level atom

normal
meta
stable

collision
relaxation

a more complicated case: He-like ions

\[ 1s^2 \bar{S}_0 \rightarrow 2s^2 \bar{P}_1 \rightarrow 1s^2 \bar{S}_1 \]

two–photon decay

\[ 1s^2 \bar{P}_1 \rightarrow 1s^2 \bar{S}_1 \]

\[ 1s^2 \bar{S}_0 \rightarrow 1s^2 \bar{P}_1 \]

resonance (r)

\[ 1s^2 \bar{P}_1 \rightarrow 1s^2 \bar{P}_1 \]

intercombination (i)

\[ 1s^2 \bar{S}_0 \rightarrow 1s^2 \bar{S}_1 \]

forbidden (f)

O VII 22.1 Å / 21.8 Å

\[ \log n \left[ \text{cm}^{-3} \right] \]

Differential emission measure – DEM

\[ F = \int \nu A_{21} n_2 \, dh \]

\[ G(T, n_e) = h \nu A_{21} \frac{n_2}{n_e} \]

excitation

\[ \frac{\partial}{\partial T} \]

DEM:

\[ DEM = n_e^2 \left( \frac{dT}{dh} \right)^{-1} \]

\[ F = \int G(T, n_e) \ DEM \, dT \]

- \( G(T) \): atomic physics
- \( DEM \): thermodynamics \((n, T)\)
- same for all lines!!

given a set of observed emissions \( F \) for lines with known \( G(T) \):
- density-temperature structure \( DEM(T) \)

iterative procedure; ill-posed problem

is this the "typical coronal temperature"?
Testing stellar inversions: coronal scale height

Input: heating flux & loop length distribution

DEM inversion $\rightarrow$ DEM & $T$

scaling laws: temperature & density

$\log T \approx 6.4$

$\log n \approx 9.2$

$L \approx 100 \text{ Mm}$

$\log T \approx 6.7$

$\log n \approx 9.9$

$\log n \approx 9.2$

$\log T \approx 6.4$

$\log n \approx 9.9$

$L = \frac{V}{A_*} = \frac{\text{DEM} T_{\text{max}}}{n^2} \approx 80 \text{ Mm}$

$EM_V = \int n^2 dV = A_* \int n^2 d\tau, dT = \text{DEM} A_* T_{\text{max}}$

emitting volume $V = EM_V / n^2$

$Zacharias, Peter & Ness (in progress)$

"Forward inversions": results & future

An inversion

- overestimates the "typical" temperature
- overestimates the "typical" density
- gets right order of coronal extension (!)

To be done:

- model multi-loop coronae with more realistic static loops: $T(s), p(s)$ given through analytical approximations (Aschwanden & Schrijver 2002, ApJS)

- test static loops using dynamically evolving loops
  - compare analytic approximation to up-to-date loop models e.g. with $E_{14-\sin(\omega t)}$

- do analytical multi-loop model for a full 3D MHD coronal model
  - is the multi-loop approach meaningful?
Summary / lessons learnt

- stellar surface structures through Doppler imaging
- stellar coronae through less reliable techniques, e.g. eclipse mapping
- stellar corona are concentrated in small active regions (filling factor?)
- are stellar coronae dominated by flares?
- stellar EUV emission line profiles are not symmetric
  (probably also in X-rays, but there we do not have the sufficient resolution...)
- are asymmetries due to
  - heating process itself?
  - small scale transient events: nano-/micro-/etc flares?
  - absorption effects due to wind?
  - stellar surface structures?
- (forward) stellar coronal models can help to interpret stellar structures
  - can we reliably infer temperatures, densities, abundances?
  - what do these "average" quantities mean?