"There is more to the solar corona than physics and mathematics."

Jeff Linsky

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**The low solar corona and the stars**

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- energetics
- the transition region
- heating the corona
- stellar coronae

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**Why the corona?**

- **astrophysical interest in general**
  - heating of the corona is one of the 10 most interesting questions in astronomy!
- **solar-terrestrial relations**
  - strongest variability in UV: <160 nm from corona/TR!
  - coronal mass ejections (CME):
    - satellite disruptions
    - safety of astronauts and air travel
  - geomagnetic disturbances
    - GPS
    - radio transmission
    - Oil pipelines
    - power supply
- **other astrophysical objects**
  - accretion disks of young stars: stellar and planetary evolution
  - ...
**Drawing vs. photography**

Spain, Drawing after eclipse, Warren de la Rue

Desierto, Spain, 40 s exposure, Angelo Secchi

from: Secchi / Schellen: Die Sonne, 1872

**CMEs: now and then ....**

SOHO / Lasco C3
20.4.1998
(with Mars and Saturn...)

compare:
 drawing of
G. Tempel
of the corona
during an eclipse
18.7.1860
The "global" corona: minimum of solar activity

Solar eclipse, 3. Nov. 1994, Putre, Chile, High Altitude Observatory / NCAR

The corona is structured by the magnetic field

1. magnetic fields in the photosphere ("solar surface") → Zeeman-effect
2. potential field extrapolation (or better)
3. compare to structures in the corona → "hairy ball"

Potential field extrapolation: Altschuler at al. (1977) Solar Physics 51, 345
The cycle of activity of the Sun

<table>
<thead>
<tr>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sun in white light</td>
<td>Big Bear Solar Observatory</td>
</tr>
</tbody>
</table>

11-years cycle of the Sun:
- sunspot number (since 1843)
- magnetic polarity (since 1908)
- magnetic activity

Driving mechanism:
- Magnetic field generating dynamo

The solar corona: minimum vs. maximum

<table>
<thead>
<tr>
<th>Minimum</th>
<th>Maximum</th>
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<tr>
<td>&quot;simple&quot; dipolar structure</td>
<td>complex magnetic structure</td>
</tr>
<tr>
<td>few active regions (sunspots)</td>
<td>many active regions</td>
</tr>
<tr>
<td>prominent coronal holes</td>
<td>almost no coronal holes</td>
</tr>
<tr>
<td>&quot;helmet streamer&quot; only at equator</td>
<td>&quot;helmet streamer&quot; at all latitudes</td>
</tr>
</tbody>
</table>

18. 3. 1988, Philippines                                               16. 2. 1980, India

High Altitude Observatory - NCAR
The solar corona: minimum vs. maximum

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<tr>
<td>The Sun Approaching Solar Maximum</td>
<td></td>
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<tr>
<td>Solar and Heliospheric Observatory, Extreme ultraviolet Imaging Telescope</td>
<td></td>
</tr>
</tbody>
</table>

- Early 1997
- Mid 1998
- Late 1999

The solar X-ray corona during the cycle

Yohkoh Soft X-ray Telescope (SXT), X-ray Emission at ≈1 nm, ≈2·10^6 K

1995 minimum
1991 maximum
100 x brighter!
Photospheric magneto-convection / Granulation

2D-simulation of a flux tube embedded in photospheric granulation (radiation-MHD)

≈ 2400 km x 1400 km, ≈ 18 min

observation in G-Band ≈ 430 nm
granulation (Ø ≈ 1000 km)
G-band bright points: small magnetic flux tubes, which are brighter than their surrounding

...well, the ultimate energy source is the fusion in the center of the Sun...

Chromospheric network: magnetic structure and flows

supergranulation
➢ flows define supergranulation boundaries
➢ magnetic field is transported to the boundaries

SOHO / MDI, 23.2.1996
magnetogram (b/w image)
flows (arrows)
network boundaries (yellow)
**Transition region: emission patterns**

- Transition region above chromospheric network
- Network built up by bright structures
- Loops across network-boundaries
- Low loops across cells

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**Magnetic loops in the low corona**

- Emission lines of Fe IX/X (17.1 nm)
  - $\approx 10^6$ K
- Be careful: light ≠ magnetic field

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See also Feldman et al. (2003), ESA SP-1274: "Images of the Solar Upper Atmosphere from SUMER on SOHO".


SUMER / SOHO
C III (97.7 nm)
$\approx$80,000 K
28.1.1996

Transition Region And Coronal Explorer (TRACE), NASA
considerations on the energetics

\[ F_{SW} = 0 \]
\[ F_{q} = 0.1 F_{H} \]
\[ F_{rad} = F_{q} = F_{H} \]

An “old” 1D temperature structure

\[ T \text{ following Vernazza et al. (1981) ApJS 45, 635} \]
Energy budget in the quiet Corona

magnetically closed

\[ F_{SW} = 0 \]
\[ F_{\text{rad}} = 0.1 F_{H} \]
\[ F_{q} = F_{H} \]

radiation \( \approx \) 100 % of energy input

magnetically open

\[ F_{SW} = 0.9 F_{H} \]
\[ F_{\text{rad}} = F_{q} = 0.1 F_{H} \]

radiation \( \approx \) 10 % of energy input

assume the same energy input into open and closed regions:

almost ALL emission we see on the disk outside coronal holes originates from magnetically closed structures (loops)!

Temperature in a static corona

Heating at the coronal base

\[ F_{H} = 4\pi r_{H}^2 f_{H} = 4\pi k_{c}^2 f_{0} \]

typical: \( f_{0} = 100 \text{ W/m}^2 \)

inner part: \( R_{c} < r < r_{H} \)

\( f_{q} = -\kappa_{s} T^{5/2} \frac{dT}{dr} \)

boundary condition:

\( T(r = R_{c}) << T_{C} \)

Integration:

\[ T_{C} = \left( \frac{7}{2} \frac{f_{0} R_{c}}{k_{0} r_{H}/R_{c}} \right)^{2/7} \]
The corona: a thermostat

1. thermal conductivity:

\[ f_0 = T^{3/2} \]
\[ T_C = f_0^{2/7} \]

- increased heating: \( T \)-Anstieg
- effective heat conduction
- only small \( T \)-increase
- similar for decreased heating

2. solar wind

- magnetically open regions: 90% of the energy into acceleration
- more heating \( \rightarrow \) even higher losses due to acceleration
- less energy for heating

<table>
<thead>
<tr>
<th>( f_0 ) [W/m²]</th>
<th>( T_C [10^6 \text{ K}] )</th>
<th>( ^{\rightarrow} ) like Sun</th>
</tr>
</thead>
<tbody>
<tr>
<td>17600</td>
<td>5.0</td>
<td></td>
</tr>
<tr>
<td>150</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>0.29</td>
<td>0.5</td>
<td></td>
</tr>
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changing the heating rate \( f_0 \)
by some orders of magnitude
leads to small changes
of the peak temperature
of the corona

following Leer (1998)

Where does this apply?

"old" 1D picture
(Unsöld ~1960)

"heated aluminum pipe"

large hot \((10^6 \text{ K})\)
coronal loops

small cool \((10^5 \text{ K})\)
coronal loops

700 000 km

500 000 km
The coronal base pressure

- dump heat in the corona $F_H$
  
  radiation is not very efficient in the corona ($10^6$K)

- heat conduction $F_q$
  
  transports energy down

- energy is radiated in the low transition region and upper chromosphere
  
  radiation depends on particle density

  pressure: $p \sim F_{\text{rad}}$

  $p_{\text{corona}} \sim F_H$

  increase the heating rate:
  
  more has to be radiated $\implies$ higher base pressure

  transition region moves to lower height!

  The "details" might change (e.g. spatial distribution of heating)
  
  but the basic concept remains valid!

investigating the transition region
An “old” 1D temperature structure following Vernazza et al. (1981) ApJS 45, 635

EUV emission lines from transition region and low corona and neutral lines & continua from the chromosphere.

Solar and Heliospheric Observatory / SUMER

- EUV-Spectrograph
- Solar Ultraviolet Measurements of Emitted Radiation
- spatial resolution: 2" (1" pixel) (1500 km)
- spectral resolution: $\Delta \lambda / \lambda \approx 30,000$
- wavelength range: 50 – 155 nm
- covering temperatures on the Sun: $5000 - 10^6$ K
- dynamics and structure of the transition region from the chromosphere to the corona
- accuracy for Doppler shifts: $\sim 2$ km/s
SUMER: spectral range (1st order)

Full spectral frame and spectral windows

full frame:
1024 spectral pixels ≈ 44 Å (1st order)

spectral window:
often 50 spectr. pxl ≈ 2 Å (1st order)
(or 25, 512, ...)

Problem:
sometimes windows not wide enough
(telemetry...)

Images by raster procedure
Doppler shifts in the transition region

**quiet Sun Doppler shifts** (along equator)
- low temperatures: $T < 3 \times 10^5$ K: redshifts
- high temperatures: $T > 4 \times 10^5$ K: blueshifts
- Doppler-shifts: flows ???
- (sound-) waves ???

**coronal holes**
- "coronal" temperatures: $T > 6 \times 10^5$ K: blueshifts
- coronal hole outflows: base of solar wind

**TR Doppler shift as a function of temperature**

- basically shows quiet Sun network line shifts
- similar for active region line shifts
- (Teriaca et al. 1999, A&A 349, 636)

**Doppler shifts**

SUMER

≈ $10^5$ K
≈ $6.5 \times 10^5$ K

Teriaca et al. 1999, A&A 349, 636
Questions to answer...

1. How can the persistent net line shift be produced at all?
2. How to get redshifts below $5 \times 10^5$ K, but blueshifts above?
3. What causes the large scatter of line shifts?

Understanding line shifts (a): single structure

Doppler shift as a function of temperature

"every loop has a corona":
- flows?
Understanding line shifts I: single structure

"every loop has a corona":
- flows ?
- waves ↔ Doppler shifts ?


Understanding line shifts II: multiple structures

do we have to deal with a lot of "single T structures" of different temperatures?

→ models for line shifts in isothermal loops ?

Dowdy et al. (1986) Solar Phys., 105, 35

3D models to understand structure!!
→ Peter, Gudiksen & Nordlund (2003)
What is the structure of the low corona?

Heating the quiet corona

Thinking of all the suggestions on coronal heating
I wonder how the corona stays that cool!

Rob Rutten, Utrecht
The open corona: ion-cyclotron heating

the ions "circle" around the magnetic field with the gyro-frequency:

$$\Omega_j = \frac{Z_j e B}{A_j m_j} \omega$$

Imagine an Alfvén-wave with a frequency $\omega$ and wave number $k$ propagating upwards.

If the frequency of the incident wave matches the gyro-frequency,

$$\omega - v_{\text{esc}} \cdot k = \Omega_j$$

the wave and the particles can interact efficiently!

[Also solve a wave equation...]

wave energy can be transferred to thermal and kinetic energy:

- preferential heating of the ions
- large "perpendicular" temperature $T_\perp$

Application to the solar wind: e.g.
Tu & Marsch (1997) SP 171, 363
Marsch & Tu (1997) SP 176, 87

Ion-cyclotron heating in the outer corona

observations with UVCS / SOHO (Ultra-Violet Coronagraphic Spectrograph)

- very broad line profiles in outer corona e.g. 500 km/s = 500·10^6 K in O VI !!
- Doppler-dimming analysis:
  - rapid acceleration
  - high ion perpendicular temperatures $T_\perp >> T_\parallel$

consistent with ion-cyclotron heating

spectral profile of O VI at 1032 and 1037 Å


spectral profile of O VI at 1032 and 1037 Å

UVCS / SOHO at 2.1 $R_\odot$ above limb
The closed corona: flux braiding

- 3D MHD model for the corona: 50 x 50 x 30 Mm Box (100^3)
- full energy equation (heat conduction, rad. losses)
- starting with down-scaled MDI magnetogram
- braiding of magnetic fields due to photospheric motions (Galsgaard, Nordlund 1995; JGR 101, 13445)
- heating rate $J^2 \sim \exp(-z/H)$
- coronal temperatures of $> 10^6$ K
- good match to TRACE images

First spectra from 3D models

- calculate spectra at each grid point (ionisation eq.)
- integrate along line-of-sight
- maps in intensity, shifts

observed Doppler shifts

synthetic average Doppler shifts
stellar transition regions

Corona of UV Cet directly resolved in radio using VLBI

(Benz et al. 1998, A&A 331,596)


What do we see of a stellar corona / TR ?

- photosphere: Doppler-(Zeeman)-imaging:
  stellar surface structures

- corona: emission seems to be dominated by active regions / flares
  "point sources" in the corona

XY Ursa Major
(A. Collier Cameron)

Sun

Yohkoh Soft X-ray Telescope (SXT), ≈1 nm, ≈2·10⁶ K
3D stellar corona: Doppler-Zeeman-Imaging

- **AB Doradus**
  - Cool active star (K2V)
  - \( T_{\text{eff}} \approx 4000K \)
  - Half as luminous as our Sun \( (0.4 \, L_\odot) \)
  - Fat rotator \( (50 \, \Omega_\odot) \)
  - Distance \( \approx 49 \) 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 \( \propto n_e^2 \)


Stellar coronal structure from eclipse mapping

- Mapping stellar X-ray coronae

  A "small" star with a corona is eclipsed by a "big" star without a corona

  Here:
  - \( \alpha \) Coronae Borealis (G5V, solar-like)

  Use the light curve of the eclipse to reconstruct the X-ray structures

Güdel et al. (2003)
A&A 403, 155
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.”
Is there anything left for solar physicists?

- activity increases with rotation (due to dynamo action)
  saturation for rapid rotation
- interpretation of on major contribution to X-rays
  depends on energy distribution of flares
  \[ \frac{dN}{dE} \propto E^{-\alpha} \]
  \( \alpha \gg 2 \): 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!

- new models for solar activity
  - what happens to
    > the quiet corona and
    > solar flares
  - when increasing the emerging magnetic flux?

Well, first we have to understand these phenomena on the Sun before thinking on stars!
Multi-component transition region spectra

- Multi-component spectra are present everywhere in the network!
- Implications for stellar coronae...

TR spectra of 31 Com (G0 III)
- Si iv (1394 Å)
- Si iv (1403 Å) with O iv blend
- C iv (1548 Å, 1551 Å)

Transition region line profiles of stars with various activity levels
- Profiles are normalized: same intensity and width of core component
- Width and strength of tail component increases with activity level!

Prominences and broad TR lines?

- Absorption transients in Hα:
  cool "clouds" of material out to co-rotation radius:
  "prominences"

- magnetic tension of closed loops might provide inward force to keep plasma in synchronous orbit outside co-rotation radius.
  (for AB Dor ~ 3 R☉)

- speculation by Collier Cameron (2001):
  could these prominences cause the transition region tail components?

This shows why it is important for solar physicists to discuss with stellar people...

Conclusions

- The corona is hot!
  - temperature is controlled by heat conduction ∝ T^{5/2} \nabla T
    this provides a "thermostat" (it is hard to change the coronal temperature...)
  - pressure of the corona is set by the heating rate \( \approx p \propto H \)
  - magnetically closed field regions appear brighter than open regions (less/no energy to accelerate the wind, all into radiation)

- The corona is dynamic and highly structured:
  - systematic persistent net Doppler shifts in transition region lines
  - superposition of loop-like and funnel-like structures

- Heating of the corona:
  - open regions: e.g. ion-cyclotron resonant absorption of Alfvén waves
  - closed regions: e.g. flux-braiding of magnetic field lines

- Stellar coronae:
  - resolving stellar corona by eclipse mapping or Doppler-Zeeman-imaging
  - are stellar coronae dominated by flares of all sizes?
  - construct models for various activity levels and compare to stars.....