50 (38) years of Stellar X-ray astronomy

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50 Years of X-ray Astronomy
Outline:

- X-rays from the Sun
- Stellar X-ray astronomy: 
  X-ray emission throughout the HR-diagram
- Stellar X-ray astronomy: 
  Plasma diagnostics of hot plasmas
- (Some) Open problems
THE IDENTIFICATION OF THE CORONAL LINES

(George Darwin Lecture, delivered by Professor Bengt Edlén on 1945 October 12)

The coronal emission lines are superimposed on the continuous radiation of the inner parts of the solar corona, the region of their appearance extending from the top of the chromosphere to a height generally not exceeding 10 minutes of arc (half a million kilometers) from the Sun's limb. The lines are responsible for only a small fraction of the total intensity of the corona.

The infra-red part of the spectrum. At present, as a net result of all observations, the wave-lengths of some twenty coronal emission lines have been established. Six of these lines are much stronger than the rest. These conspicuous lines are: \( \lambda 3388, \lambda 5303, \lambda 6374, \lambda 7892, \lambda 10747 \) and \( \lambda 10798 \). None of the coronal lines has been observed in a laboratory light-source and there is no real coincidence of lines nor with any line in the chromospheric spectrum. The coronal lines were in fact a unique feature of the solar corona until in 1932 a number of them showed up in the spectrum of the recurrent nova RS Ophiuchi. Recently the coronal lines have
Why study X-ray emission?

X-ray emission is a good proxy for magnetic flux!
Pevtsov et al. (2003)

\[ L_x \sim \Phi^{1.1} \]

Quiet Sun

Stars

"knee"

Sun

Magnetic flux, Mx

L_x, erg s^{-1}
- X-ray emission diagnoses magnetic flux
- Magnetic flux is difficult to measure for stars
- What about X-rays from stars?
The Sun as an X-ray source

\[ L_x = 2 \times 10^{27} \text{ erg/sec} \]  

at solar max!

Placed at a distance of 10 pc:

\[ f_x = 1.8 \times 10^{-13} \text{ erg/sec/cm}^2 \]

Sensitivity limit of ROSAT all sky-survey:

\[ f_{x,\text{lim}} \sim 2 \times 10^{-13} \text{ erg/sec/cm}^2 \]

Only nearby sources detectable?
EVIDENCE FOR X-RAY EMISSION FROM CAPPELLA

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ABSTRACT

X-ray emission in the range from 0.2 to 1.6 keV has been detected from an area of the sky which contains the binary star system Capella. The X-ray source is at most a few arc minutes in extent and shows no spectral turnover at low energy, consistent with a nearby source. We suggest Capella as the source of this emission and that this object belongs to a new class of galactic X-ray sources with a luminosity of $10^{31}$–$10^{34}$ ergs s$^{-1}$. Emission from this class of objects is variable, predominantly below 2 keV, and originates from nearby stellar objects.

Subject headings: spectra, X-ray — stars, individual — X-ray sources
Abstract. Stellar coronae were among the first predicted X-ray sources. Because of their relatively low X-ray luminosities, however, they have been discovered only during the last few years.

In the present paper the current state of stellar coronal X- and UV observations has been reviewed, including some preliminary observational results from the HEAO-1 and IUE satellites, but still without any result from the recently launched X-ray satellite HEAO-2.

Late 1978 about two dozens of stellar soft X-ray sources have been detected, e.g., normal stars like the Sun (e.g., $\alpha$ Cen), very active stars ($RS CVn$ systems), and possibly a corona around an intermediately hot white dwarf ($Sirius P$).

The observational results of various objects have been discussed and compared with X-ray luminosity predictions based on minimum-flux coronal models.
First revolution in stellar X-ray astronomy

Soft X-ray imaging!
Einstein Observatory
1978 - 1981

Launch: Nov 13 1978
Vaiana et al. (1981)

First X-ray HR-diagram with 143 stars!
ROSAT all-sky survey
$0.01 \ L_{\text{Sun}}$

Wright et al. (2010)
Main results:

- X-ray emission from all stars with outer convection zones
- Minimal flux
- Rotation-activity relation
- Activity-age relation
- Solar phenomena on stars (cycles, flares)
Which stars do we see as X-ray sources?
Detection rates of bright stars in RASS (flux limited sample)

Onset of convection

„A-hole“
Volume-limited sample of F,G,K,M dwarfs: $F_X$ vs. $M_V$

What is the meaning of the minimal flux?
Solar Irradiance Reference Spectrum (Woods 2009)

Taken in April 2008 during extended solar minimum!
In PSPC-band pass: $F_X = 9000 \text{ erg/cm}^2/\text{sec}$

$L_{X,\text{tot, min}} = 5.5 \times 10^{26} \text{ erg/sec}$

SIRS Solar spectrum

Schmitt (2011)
Volume-limited sample of F,G,K,M dwarfs: $F_X$ vs. $M_V$

Minimum Sun in 2008

Age-activity connection
Hyades cluster (Stern et al. 1994)

X-ray luminosity vs. B-V color diagram showing the Hyades cluster and the Solar Max level.
X-ray luminosities of solar-like stars

- Field stars < 25 pc
- Field stars < 7 pc
- Pleiades
- Hyades
- IC 2602
- Sun
Rotation-activity connection
RELATIONS AMONG STELLAR X-RAY EMISSION OBSERVED FROM EINSTEIN, STELLAR ROTATION AND BOLOMETRIC LUMINOSITY

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First X-ray activity vs. rotation diagram by Pallavicini et al. (1981)!
Pizzolato et al. (2003)

- Saturation limit
- Solar level
- Hot stars
- Rossby number

\( \log \frac{L_x}{L_{bol}} \) vs. \( \log R_e \)
Solar phenomena on stars:

Flares

Cycles
Giant X-ray flare on Algol observed with BeppoSAX
(Schmitt & Favata 1999)
Consistent with thermal emission
COUP 331 (Czesla et al. 2008)
COUP 331 (Czesla et al. 2008)

Fe 6.4 kev fluorescence line appears for the first 20 ksec of flare 2!
Sun

61 Cyg A

61 Cyg B

HD81809


0.165
61 Cyg A: A full X-ray cycle covered!

Minmax: Factor 4

Robrade et al. (2011)
Second revolution in stellar X-ray astronomy

High-resolution X-ray spectroscopy
ASCA (CCD) : Algol 1996

The graph shows the normalized counts per second per keV against channel energy (keV) for the X-ray spectrum of Algol. The elements O, Mg, Si, Ne, and Fe are labeled on the graph. The X-axis represents channel energy in keV, ranging from 0.5 to 10 keV, and the Y-axis represents the normalized counts per second per keV, ranging from $10^{-3}$ to 1.
50 Years of X-ray Astronomy

LETGS raw spectrum (of Algol 80 ksec) 2000

Counts/0.01 Å bin

200
400
600

λ / Å

128.79 Å

carbon edge
detector artefact
Diagnostic capabilities:

- Plasma temperature
- Plasma density
- Elemental composition
- Optical depth effects
- Doppler effects
Chandra LETGS:

OVIII Ly$_\alpha$

hot

OVII triplet

cool

Algol (81.4 ksec)

Capella (219 ksec)

Procyon (141 ksec)
Ness et al. (2004)
Robrade & Schmitt (2007)
LETGS spectra of O\textsc{vii}

OVII triplets for Algol and Capella

- (r): LETGS spectra of OVII
- (f): LETGS spectra of OVII
- (i): LETGS spectra of OVII
X-ray spectrum of TW Hya (CTTS): **OVII triplet**

Stelzer & Schmitt (2004)  TW Hya
Schmitt et al. (2005)  BP Tau

forbidden line almost absent !

\[ n_e \geq 10^{13} \text{ cm}^{-3} \]  \textbf{metal-depleted}
\[ T \approx 2.8 \times 10^6 \text{ K} \]  \textbf{accretion shock !}
\[ L_X \approx 10^{30} \text{ erg/sec} \]
New Topics:

- Stellar X-ray jets
- Extrasolar planet host stars
The X-ray jet of the CTTS DG Tau

Guedel et al. (2008)
The inner X-ray jet of DG Tau

Schneider et al. (2008)
Extreme levels of X-ray irradiation on Hot Jupiters around active stars!
A little comparison ……

X-ray irradiation on solar system and extrasolar planets

<table>
<thead>
<tr>
<th></th>
<th>$L_{X,\text{host}}$ (cgs)</th>
<th>$a$ (AU)</th>
<th>$F_X$ (cgs)</th>
<th>$T_{\text{eff}}$ (K)</th>
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</thead>
<tbody>
<tr>
<td>Earth</td>
<td>$10^{27}$</td>
<td>1</td>
<td>0.35</td>
<td>300</td>
</tr>
<tr>
<td>Jupiter</td>
<td>$10^{27}$</td>
<td>5.2</td>
<td>0.013</td>
<td>120</td>
</tr>
<tr>
<td>51 Peg b</td>
<td>$5 \times 10^{26}$</td>
<td>0.052</td>
<td>65.4</td>
<td>1250</td>
</tr>
<tr>
<td>CoRoT 2b</td>
<td>$4 \times 10^{29}$</td>
<td>0.028</td>
<td>$1.8 \times 10^5$</td>
<td>1800</td>
</tr>
</tbody>
</table>

**CoRoT 2b is the planet with the largest known X-ray irradiation!**
(Some) Open issues:

- Nonthermal X-ray emission?
- Energetic particle production?
- Dopplershifts?
- Line profiles?
- Jets and accretion spots?