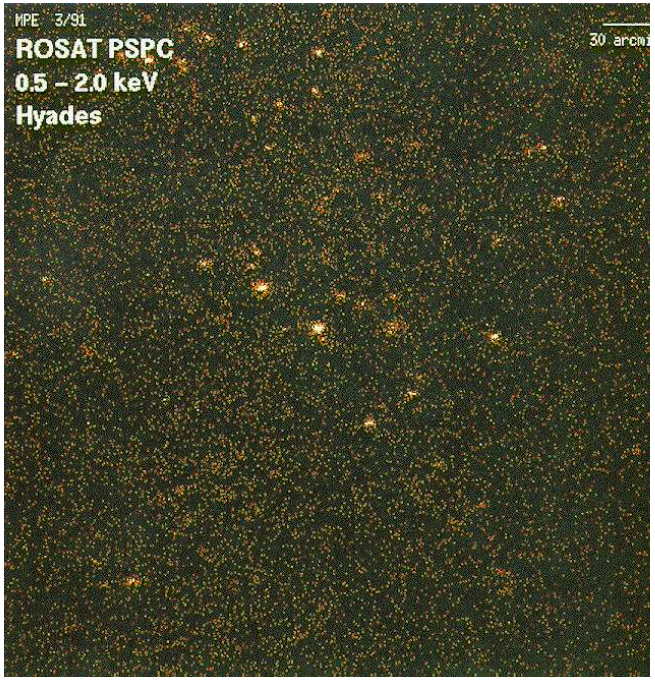
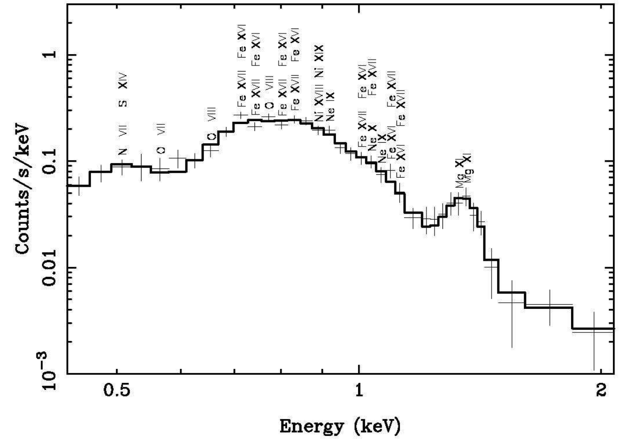


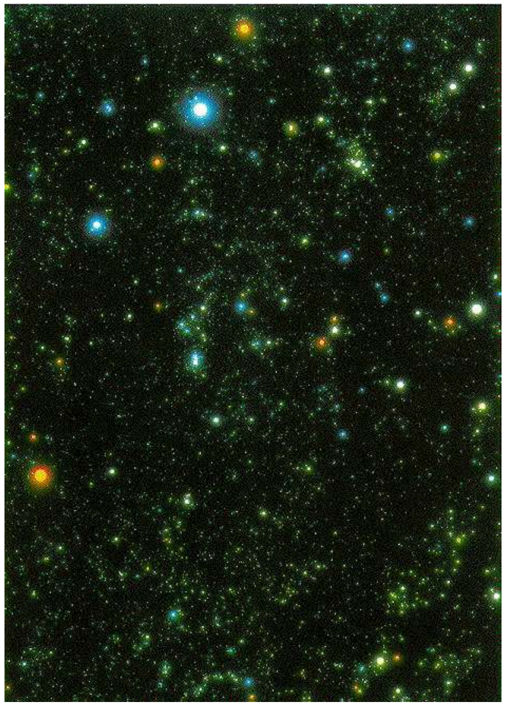
ROSAT image of the Hyades

Stellar X-Rays, IV



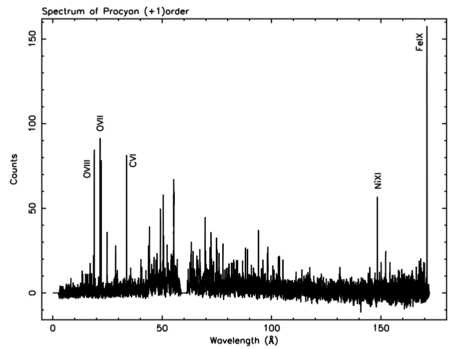
Spectrum of α Cen can also be explained with coronal plasma emission.
General result: Stars of earlier type than G are even stronger X-ray emitters than the Sun
X-ray luminosity is correlated with presence of magnetic fields.
Explanation: Stars with outer convection zones have strong coronae.

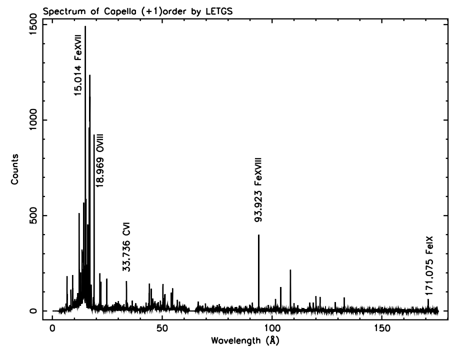
Mewe et al., 1998, A&A 339, 545



ROSAT image of the Orion region; colors denote the hardness ratio, i.e., the hardness of the X-ray spectrum

Stellar X-Rays, V



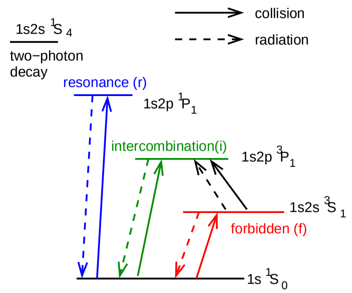


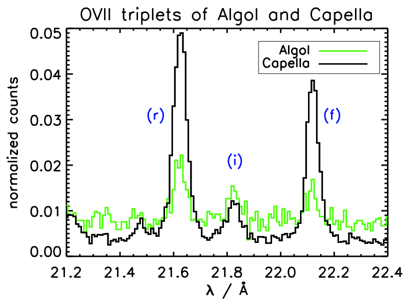
Chandra HETGS, Weisskopf et al., 2001

Plasma diagnostics using lines from He-like ions gives temperatures between 0.5 and 10 MK for Capella (G8), and 0.4 to 2 MK for Procyon (F5)

$\Longrightarrow$ Coronae have multi-temperature structure

High-resolution X-ray Spectroscopy, I





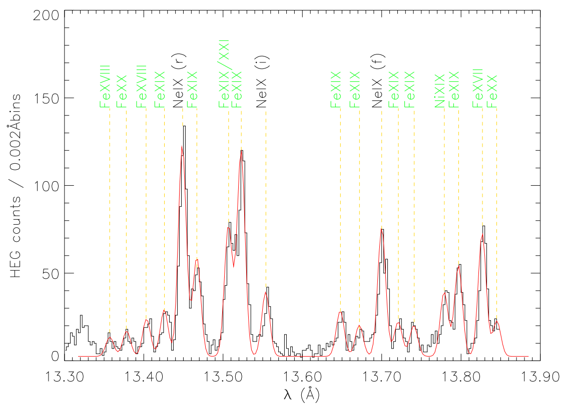
(Güdel, 2004, after J.U. Ness)

He-like triplets (e.g., C V, N VI, O VII, . . . , Si XIII) allow us to measure coronal density: Flux ratio of forbidden and intercombination line:

$$R = \frac{R_0}{1 + n_e/N_c} = \frac{f}{i} \qquad (5.3)$$

where R_0: intensity at low n_e, N_c: critical density (around $10^{10}\,\mathrm{cm}^{-3}$).
need to know photospheric radiation field since this enhances $^3S_1 - {}^3P_{1,2}$ transitions – compare Algol (suppressed) and Capella (normal)!

High-resolution X-ray Spectroscopy, II

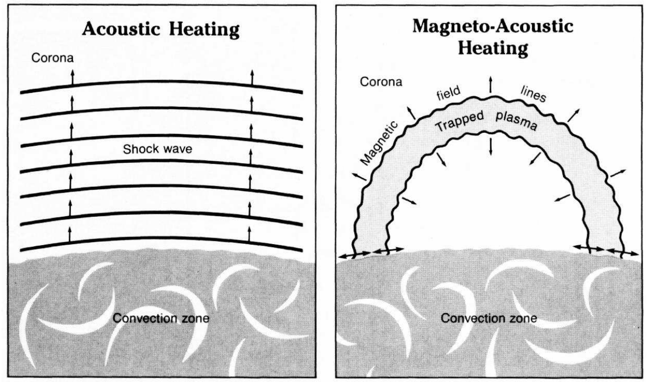


(Güdel, 2004, after J.U. Ness)

A problem in the analysis of He-like ions is blending with lines Fe lines $\Longrightarrow$ danger for instruments with lower resolution!

Typical densities found: Inactive stars have $n_e < 10^{10}\,\mathrm{cm}^{-3}$, and active stars have $n_e \sim$ several $\times\, 10^{10}\,\mathrm{cm}^{-3}$.

Heating the Corona

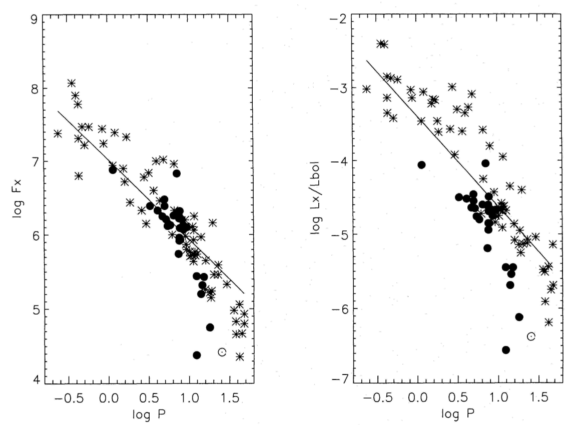


Acoustic heating: acoustic waves penetrate into corona. ruled out due to dependency of L_X on rotational speed.

Magneto acoustic heating: Heating by waves and/or particles induced from magnetic fields at the bottom of the corona (magnetic reconnection?).

X-ray activity is connected to magnetic fields!

Dependency on the rotational period, I

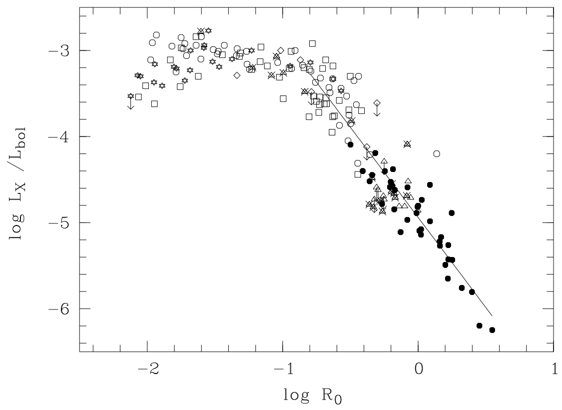


Magnetic activity depends on stellar rotation
$\Longrightarrow$ presence of outer convection zones
$\Longrightarrow$ L_X decreases with rotational period P.
Empirical result (Pallavicini et al., 1981):

$$L_X \sim 10^{27}\,\mathrm{erg\,s^{-1}}(v \sin i)^2 \qquad (5.4)$$

Hempelmann et al., 1997

Dependency on the rotational period, II



(Güdel, 2004, Fig. 4)

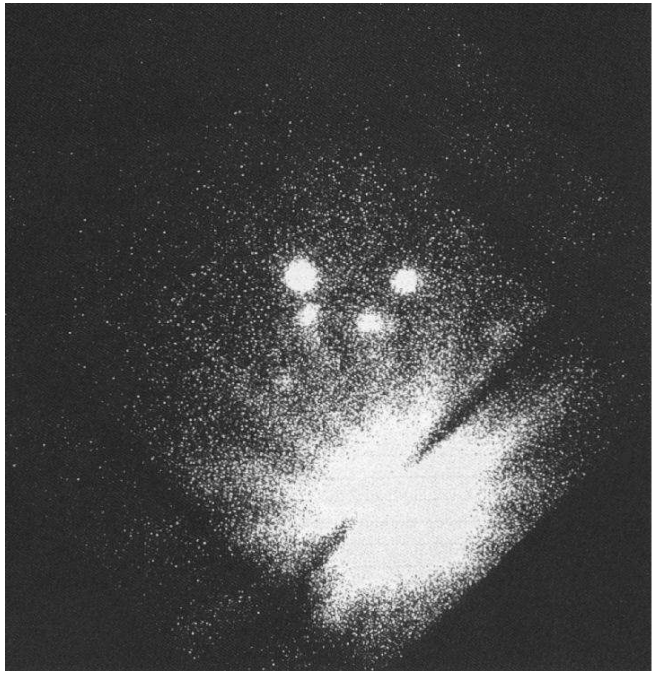
A good indicator for the efficiency of the dynamo generating the corona is the Rossby number, Ro, defined as

$$\text{Ro} = P/\tau_c \qquad (5.5)$$

where:

- P: rotational period,
- τ_c: convective turnover time.

Studies of large cluster samples: $L_X/L_{bol} \propto \text{Ro}^{-2}$ and a saturation to $L_X \sim 10^{-3} L_{bol}$ below Ro $\sim$ 0.1.



Einstein satellite, 1978 December 15, three weeks after launch. Pointing at Cyg X-3 for calibration purposes: other sources are early type stars related to the Cyg OB2 association.

$\Longrightarrow$ Since early-type stars (spectral types O, B) do not have coronae, origin of X-rays must be different than that of late-type stars.

(Charles & Seward, Fig. 5.2)

Saturation

Results from more detailed study of late-type stars (see Güdel, 2004, for details):

- For non-saturated stars, rotation period alone is good indicator for L_X/L_{bol}.
- The saturation period depends on mass, M:
  - For $M = 1.05\,M_\odot \longrightarrow P_{sat} \sim 1.5$ d
  - For $M = 0.7\,M_\odot \longrightarrow P_{sat} \sim 3.5$ d
  - For $M < 0.7$ P_{sat} rapidly increases $\Longrightarrow$ there is a progressively higher L_X for smaller masses.
- Once saturated, L_X/L_{bol} is independent of P or M

Stars between F and M are capable of maintaining coronae up to $L_X \sim 10^{-3} L_{bol}$.

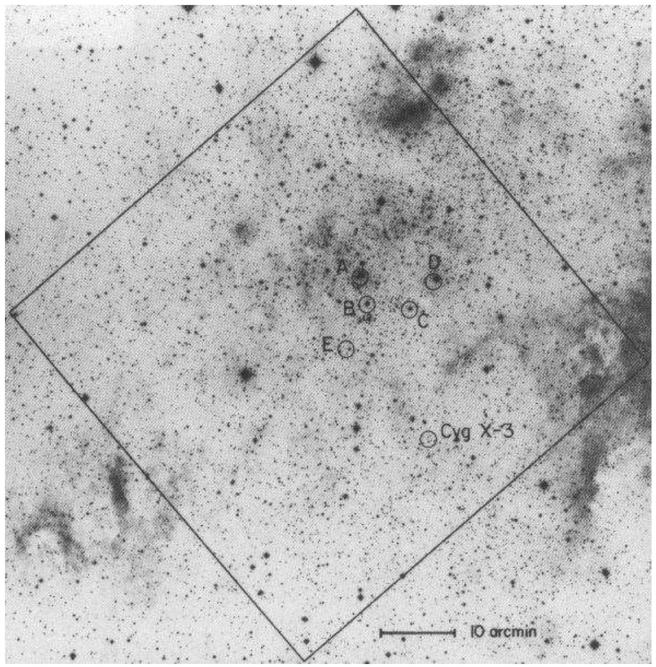
Possible explanations of saturation phenomenon:

- internal dynamo saturates

  i.e., dynamo is at maximum efficiency
- surface filling factor of Φ becomes unity

  i.e., whole stellar surface filled with active regions; however, if Sun were maximally filled, then $L_X \sim 10^{29}$ erg s^{-1}, i.e., $L_X/L_{bol} \sim 10^{-4} \Longrightarrow$ must posit larger coronal sizes.
- coronal height limited

  For lower P point where centrifugal force = gravitational force moves inwards $\Longrightarrow$ limits size of corona ("coronal stripping").



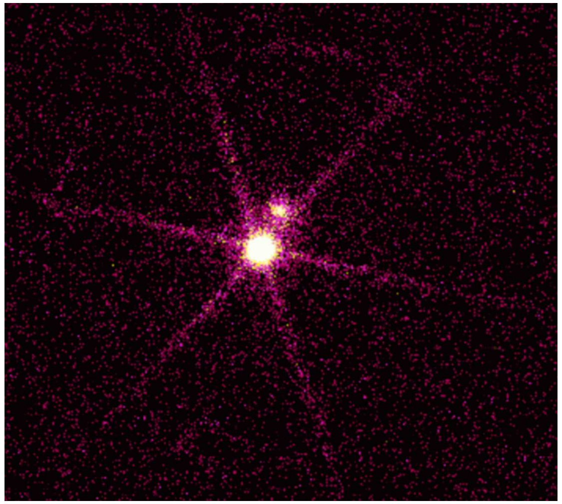
Detected X-ray sources are O-stars in the Cyg OB2 association.

Distance 2 kpc $\Longrightarrow$ X-ray luminosity must be very large ($L_X \sim 10^{32}$ to 10^{34} ergs^{-1}).

$\Longrightarrow$ O-stars are the most luminous stellar X-ray sources!

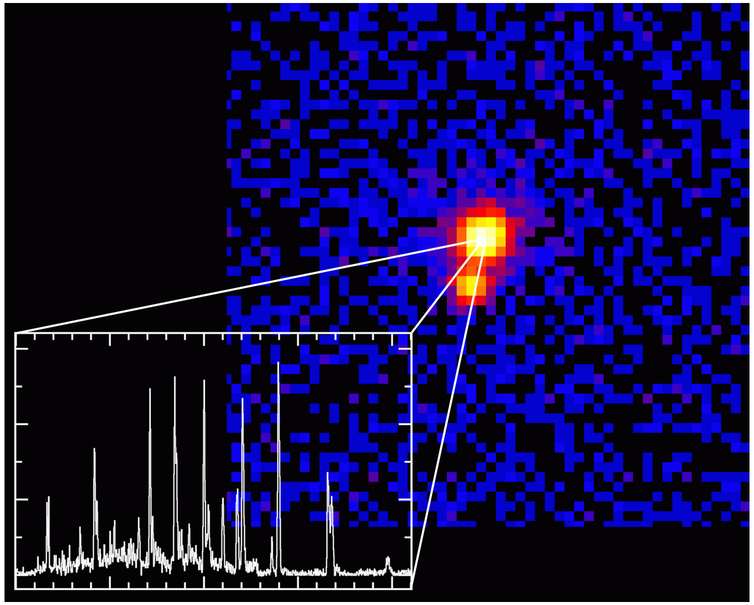
(Charles & Seward, Fig. 5.3)

Sirius A and B



Sirius: Both, WD (bright) and normal O star emit X-rays!

Chandra Image of Sirius (courtesy CXC)



High resolution grating spectrum of the O-star ζ Ori Spectral analysis reveals broad lines, indicating evidence for the wind picture.

ζ Ori (courtesy CXC)

O-Star Winds and X-rays

What is the origin of X-rays from early type stars?

Facts:

- O-stars have strong winds, driven by radiation pressure ($T \sim 40000$ K, $L \sim 5 \times 10^5 L_\odot$, $L_X/L_{bol} \sim 10^{-7}$).
- High mass loss rates: $10^{-6}\,M_\odot\,yr^{-1}$, terminal velocity $3000\,km\,s^{-1}$ (Sun: $300\,km\,s^{-1}$).
- X-ray spectral shape is thermal, optically thin, $T \sim 10^7$ K.

A-stars have lower wind rates and smaller X-ray luminosity.

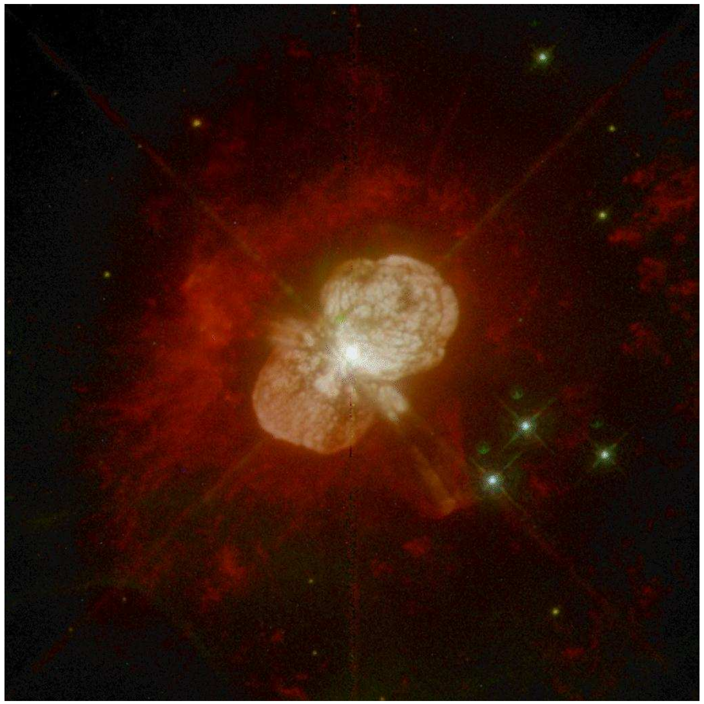
Models:

Corona:

- Ruled out since spectrum is wrong!

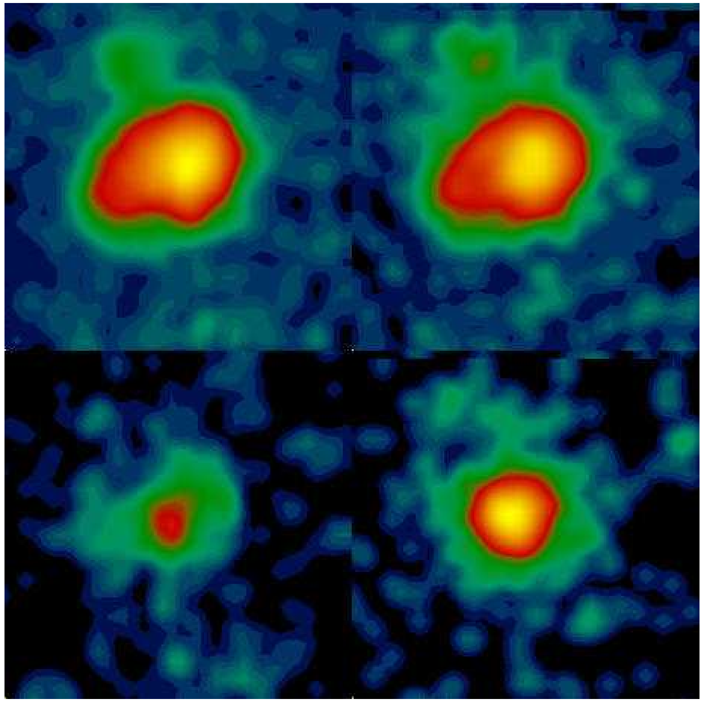
Shocks in stellar wind:

- Radiatively driven clumps ploughing through stellar wind (Lucy & White, 1980),
- Forward shocks (Lucy, 1982)



X-rays from binary stars:
η Car as an example.
η Car: Outburst in 1843, expellation of $\sim 1\,M_\odot$ (Homunculus nebula).
Object is a Luminous Blue Variable, $M \sim 70\,M_\odot$, has O-star companion with similar mass.

Eta Carinae, HST-WFPC2)



η Car as seen by the ROSAT PSPC, left: 1992 June, right: 1992 December $\Longrightarrow$ Strong variability on short timescales! Luminosity: $L_X \sim 5 \times 10^6\,L_\odot$. Modulation of X-ray emission with orbital period

$\Longrightarrow$ Possible explanation for X-rays: shocks in colliding stellar winds.

(courtesy M. F. Corcoran)

Chandra image of η Car

$\Longrightarrow$ Emission from a ring?

courtesy CXC