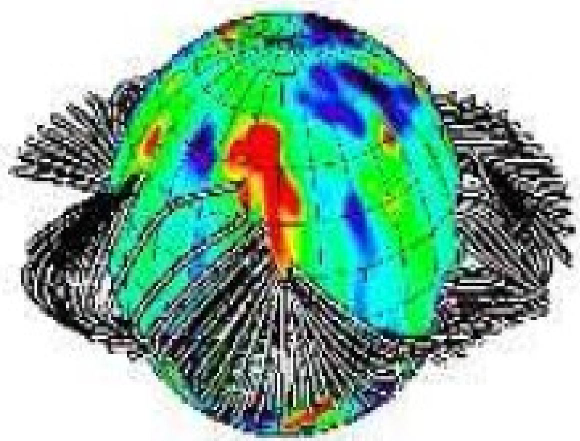
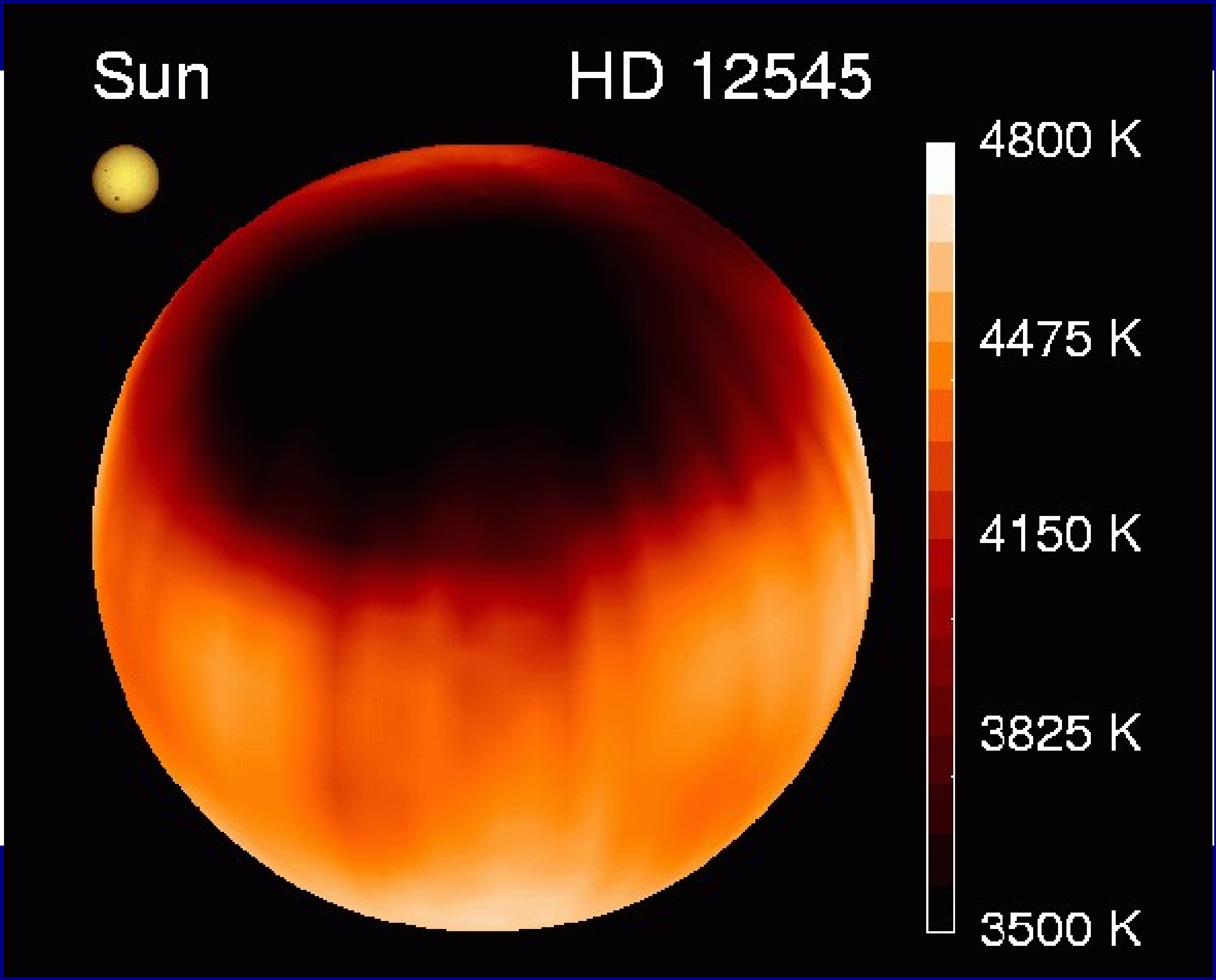
Stellar Magnetic Activity

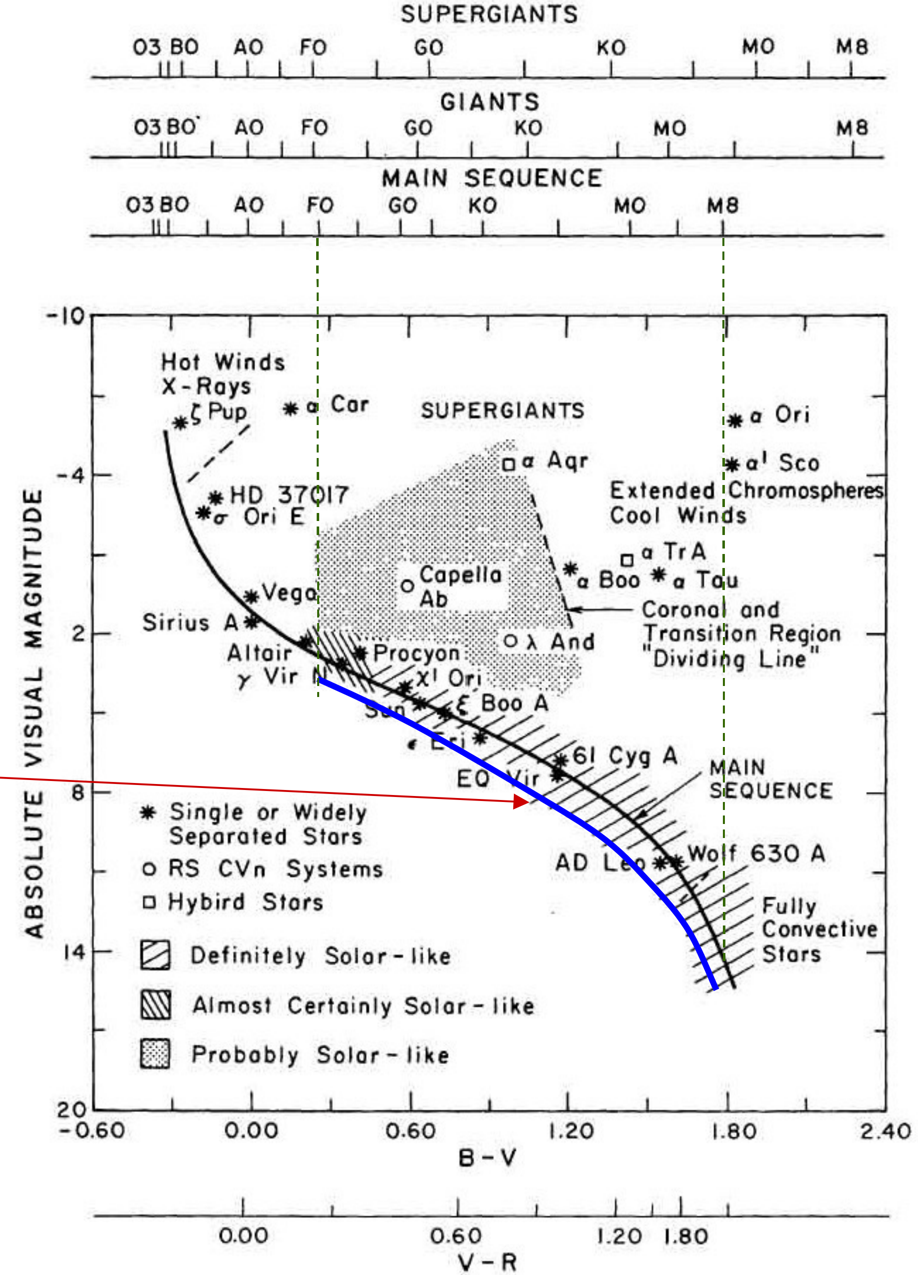




Who's active, Who's not

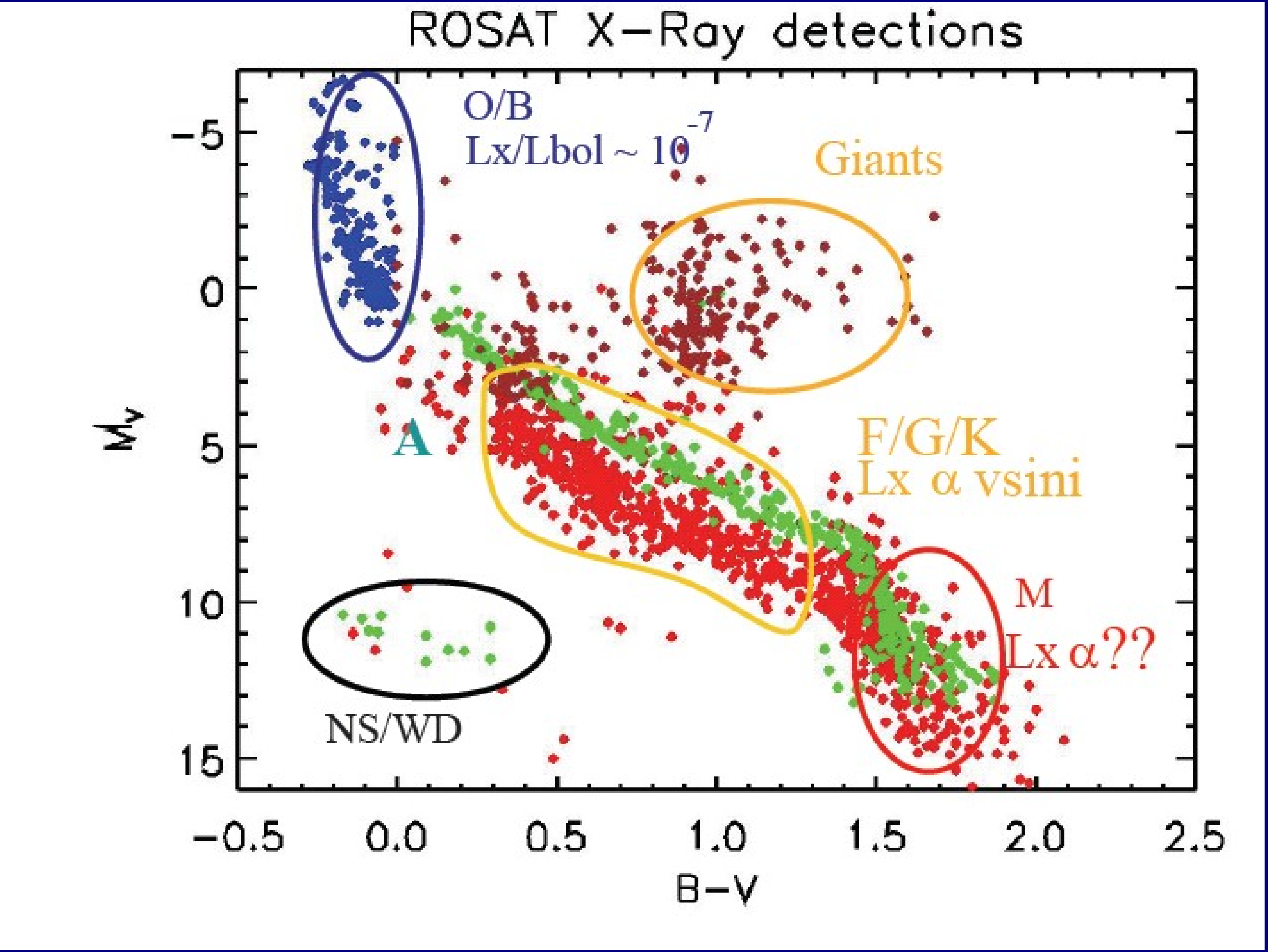
Evidence of magnetic activity

Activity on main sequence: types **F → M**



(From Linsky 1985)

Ubiquity of stellar X-ray emission

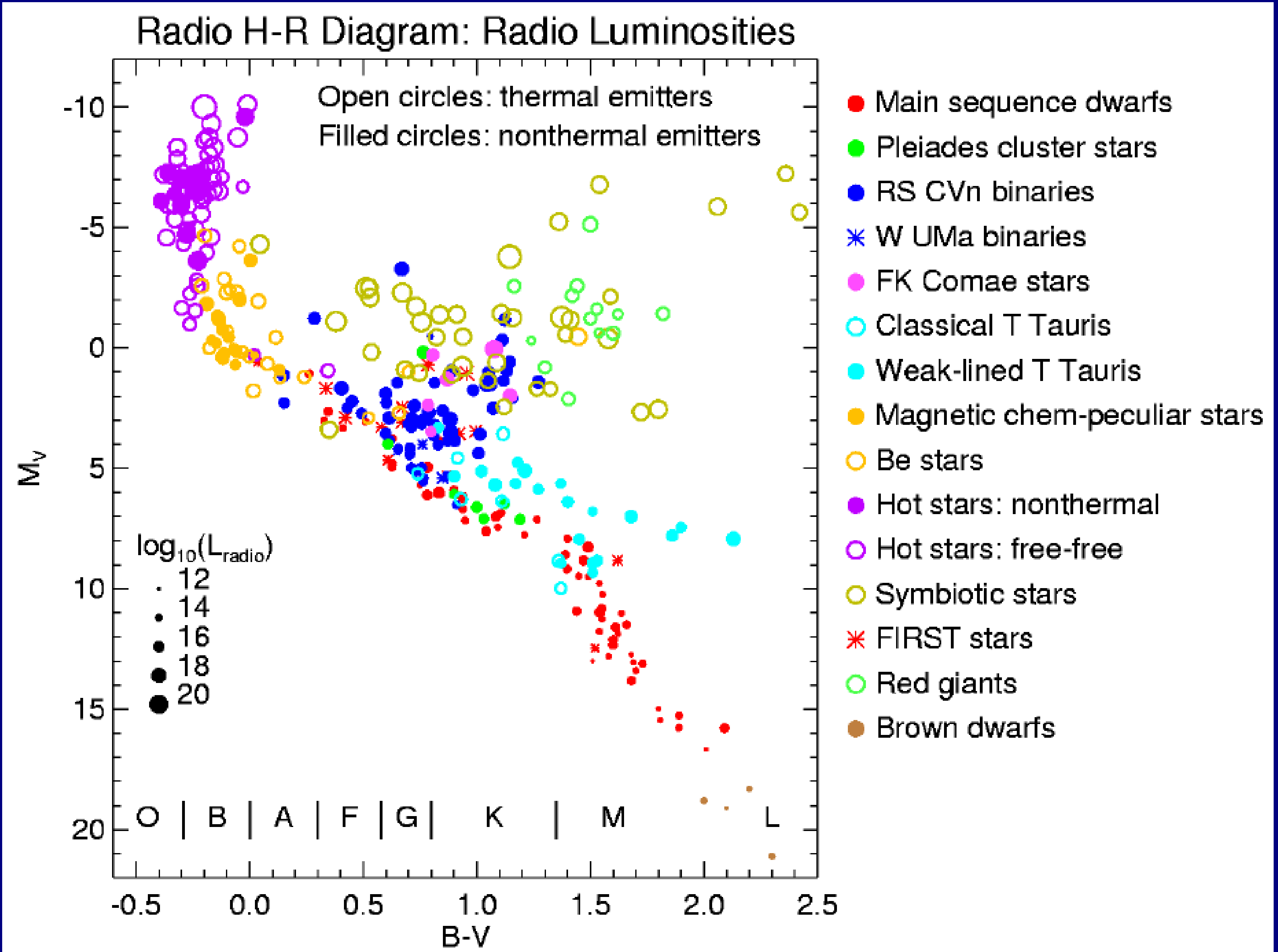


http://www.iiap.res.in/admin/PostDocuments/vinay_20060620.pdf

X-ray emission throughout the HR diagram

- Hot stars (O - early B) are strong X-ray emitters
  ➡ shock-heating throughout radiatively driven winds
- Late B/early A stars are probably not X-ray emitters (TbC)
- All cool dwarfs (F to M) with outer convective zones are X-ray sources with a large range of X-ray emission levels at each colour
  ➡ heating by dynamo generated magnetic fields
- No decrease of coronal efficiency (L_x/L_{bol}) for fully convective stars (later than ~ M7)
- Late-type giants (cooler than ~ K2 III) are not X-ray sources but possess massive cool winds (Dividing Line)

Roberto Pallavicini



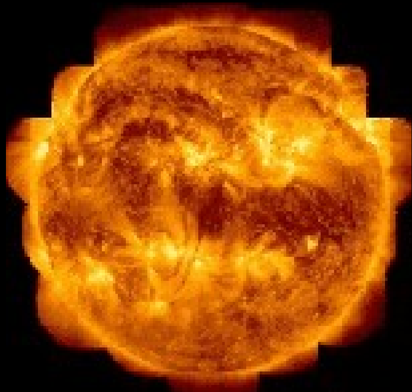
Radio H-R Diagram: Radio Luminosities
Open circles: thermal emitters
Filled circles: nonthermal emitters
Main sequence dwarfs
Pleiades cluster stars
RS CVn binaries
W UMa binaries
FK Comae stars
Classical T Tauris
Weak-lined T Tauris
Magnetic chem-peculiar stars
Be stars
Hot stars: nonthermal
Hot stars: free-free
Symbiotic stars
FIRST stars
Red giants
Brown dwarfs
log10(Lradio)
12
14
16
18
20
O
B
A
F
G
K
M
L
MV
-10
-5
0
5
10
15
20
B-V
-0.5
0.0
0.5
1.0
1.5
2.0
2.5

Magnetic Activity:

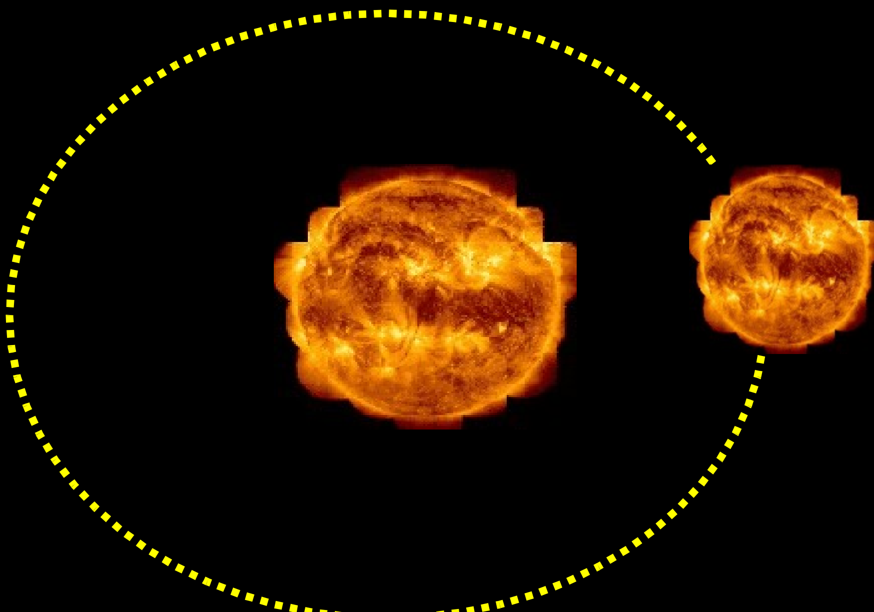
Flaring activity (radio wavelenghts , X-rays)

Spots

Cromospheric activity

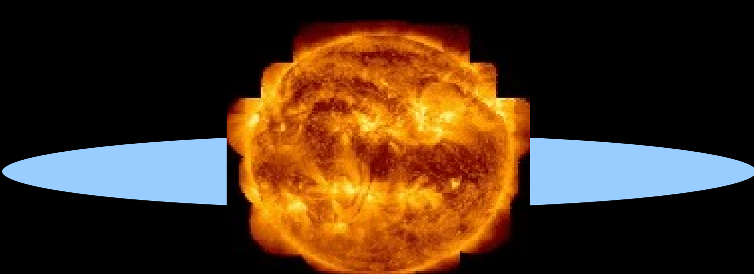


Single cool stars



RS Cvn binary systems

T Tauri stars



The Phenomenon of Stellar Activity

1. Red dwarfs and BY Dra phenomenon
2. Solar-type stars
3. RS CVn stars
4. T Tauri stars

Svetlana V. Berdyugina:

http://solarphysics.livingreviews.org/Articles/lrsp-2005-8/

Red dwarfs and BY Dra phenomenon

Red dwarfs are main-sequence stars with the mass range from 0.08Mo . to 0.5 Mo .. The lower mass limit is the critical mass for hydrogen burning in the central cores of stars with solar abundances, while the upper limit corresponds to the **spectral class M0**. The radii of the red dwarfs span from 0.2R o . to about 0.6Ro . while their effective temperatures are in the range of 2500 K - 4000 K. Thus, red dwarf stars are cooler, smaller, and less massive than the Sun. Correspondingly their luminosities range from 0.1% to about 8% of the solar luminosity. They constitute, at least, 80% of the stellar population in the Galaxy.

Remarkable magnetic activity expressed in extremely strong optical flares. **Large spots on the stellar surface, much cooler than the undisturbed photosphere, cover up to 10% of the stellar surface.**

In addition to the starspot activity, these stars possess powerful chromospheres and coronae, whose activity is exhibited in strong UV, X-ray, and radio emissions and flares.

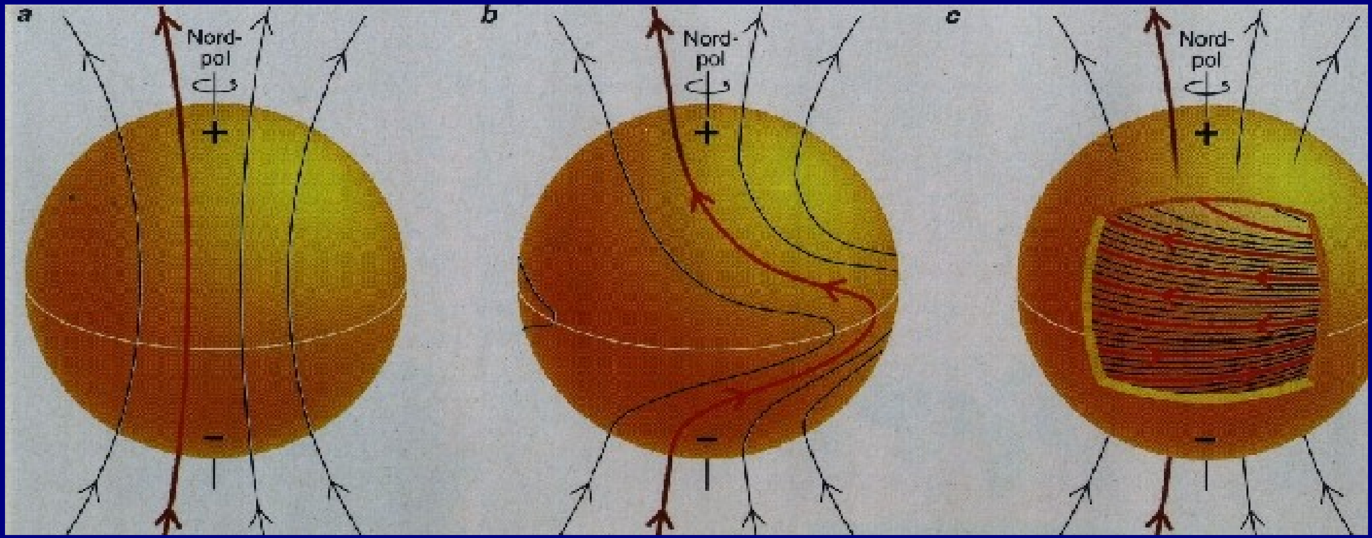
Turbulent Dynamo ?

- May work for fully convective M dwarfs

Solar Dynamo

Generation of toroidal (azimuthal) field by shearing a pre-existing poloidal field by <u>differential rotation</u> (Ω-effect)

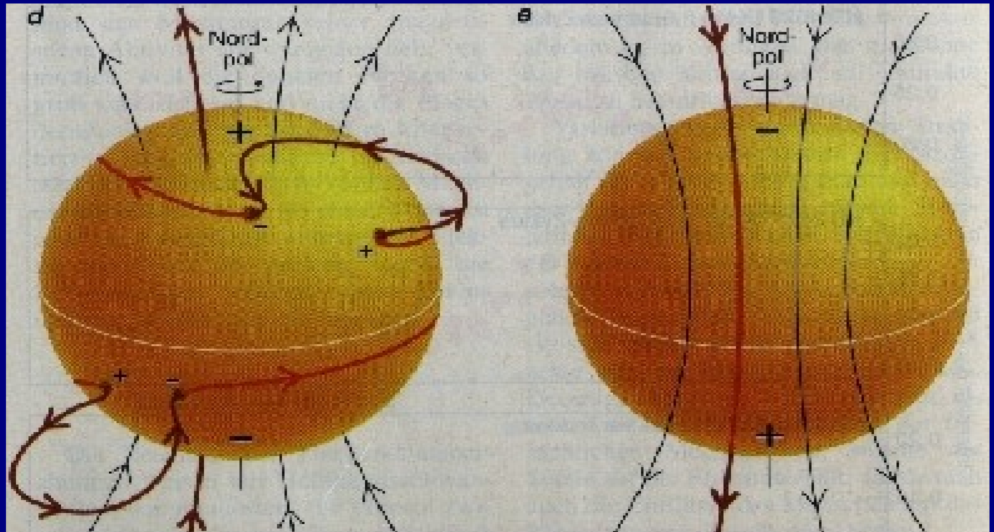
Re-generation of poloidal field by lifting and twisting a toroidal flux tube by convection and rotation (α-effect, helical turbulence).



poloidal → toroidall

by

„OMEGA effect“



toroidal → poloidal

by

„ALPHA effect“

Turbulent Dynamo Model

- Solar “intranetwork” *magnetic fields
- Vary little during the solar cycle
- Magnetic fields produced by **random convective motions**
  - No rotation or differential rotation needed
  - No radiative-convective boundary needed
- Field forms flux tubes, rise to surface, merge with regions of opposite polarity, and are destroyed
- No cycles
- **Coverage uniform over the stellar surface**

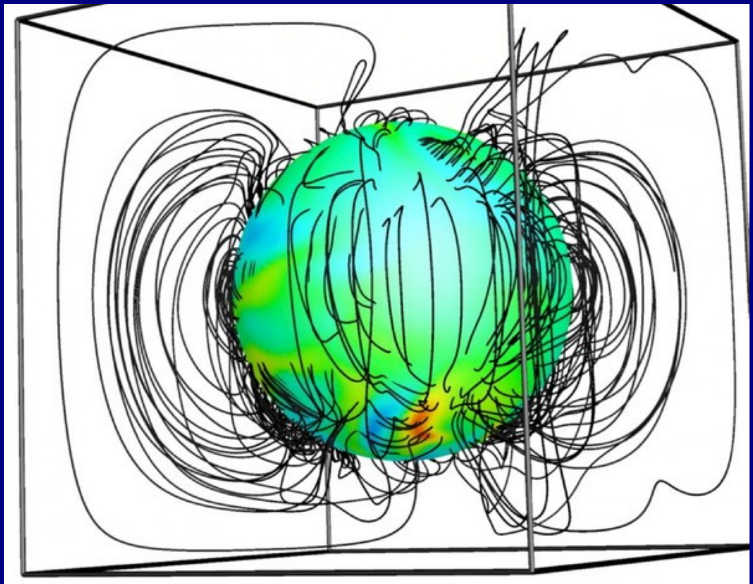
- **May work for fully convective M dwarfs**

---

* The names `intranetwork' and `turbulent magnetic fields' are used to represent the solar magnetic fields of mixed polarities at the **smallest scales** of the spatial spectrum. Since the spatial separation of the opposite polarities is small, and since the magnetic flux of each small-scale magnetic element is tiny, they can only be made partly visible in `deep' magnetograms

- Conventional wisdom:
turbulent dynamos produce ***small-scale*** surface magnetic fields

BUT: Dobler et al. (2005, AN 326,254), (2006, ApJ 638,336):



A turbulent dynamo in a fully convective star can also produce ***large-scale*** surface magnetic fields

- Recent results for the Sun (e.g. Bueno et al. 2004):

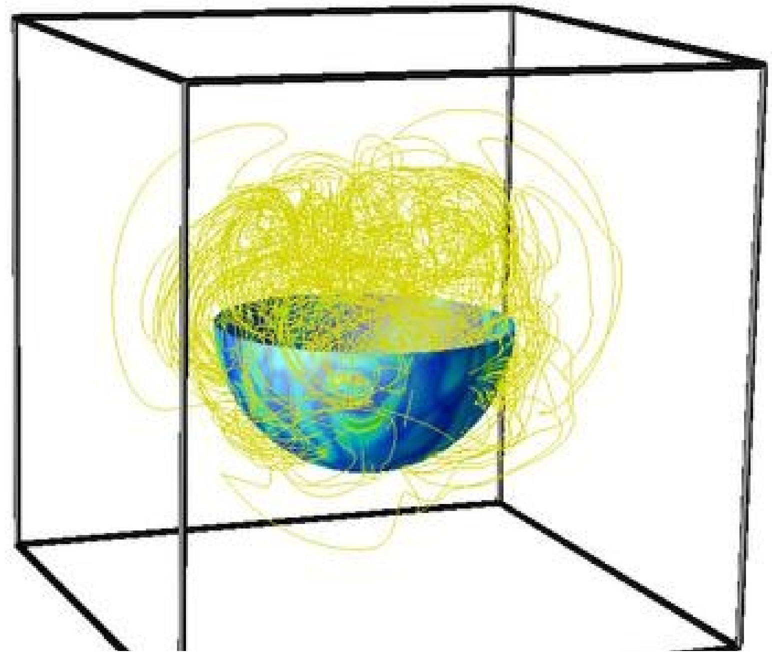
$\alpha-\Omega$ dynamo + **turbulent dynamo**

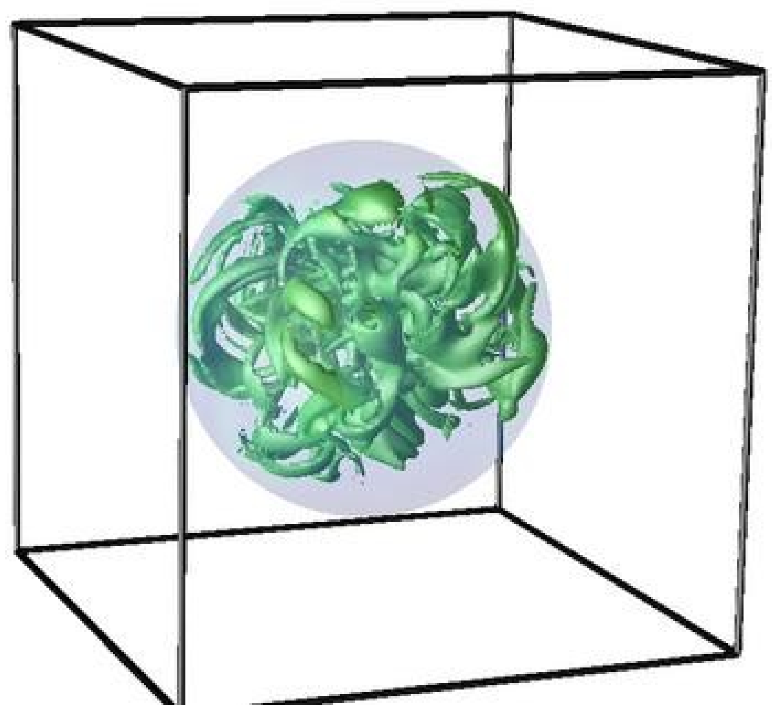
→ activity-rotation relation

→ small-scale intranetwork fields

M Dwarf Magnetic Field Models

- Red dwarf stars of type M5 or smaller are fully convective
- Turbulent motion generates and enhances magnetic fields
- Fields appear the form of solar (or stellar) spots, or flares
- Simulated magnetic fields in fully convective stars





Wolfgang Dobler: http://www.kis.uni-freiburg.de/~dobler/

The Phenomenon of Stellar Activity

1 Red dwarfs and BY Dra phenomenon

2 Solar-type stars

3 RS CVn stars

4 T Tauri stars

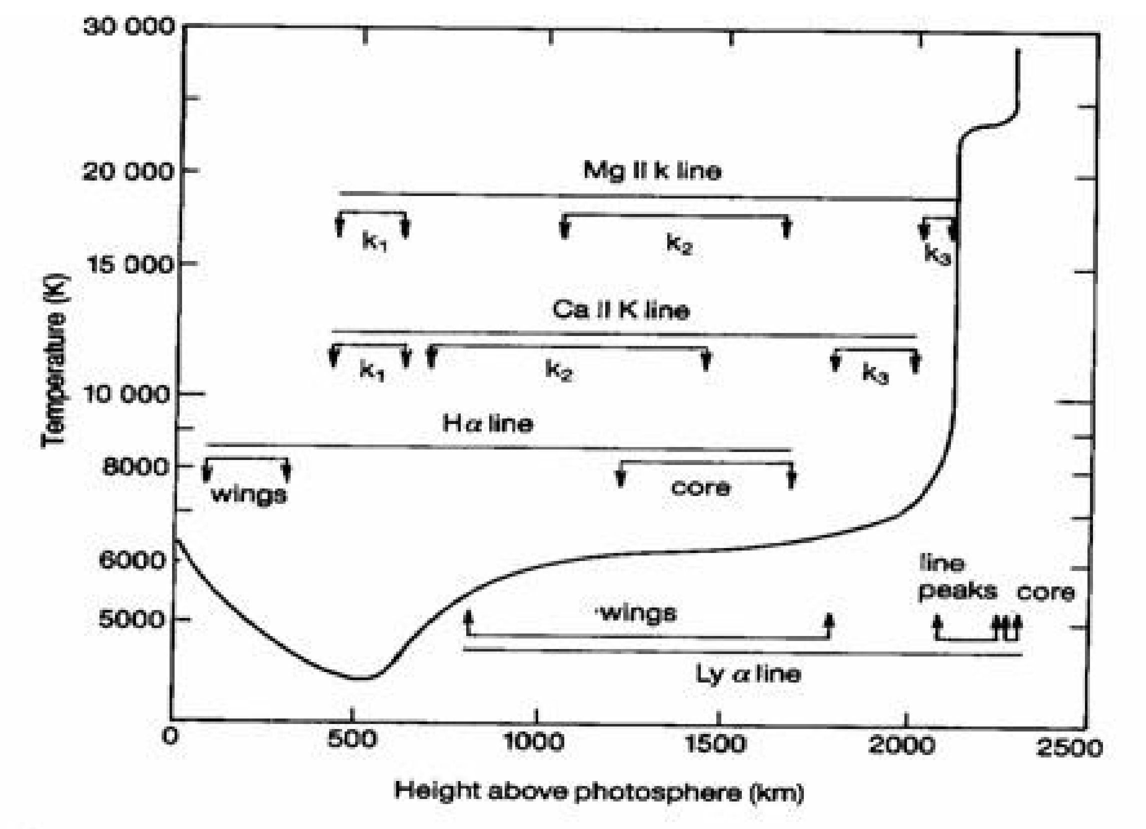
.2 Solar-type stars

Stars on the lower main-sequence are known to show chromospheric activity similar to that on the Sun which is detected, e.g., in the Ca II H & K emission (Wilson, 1978).

Svetlana V. Berdyugina:

http://solarphysics.livingreviews.org/Articles/lrsp-2005-8/

The Chromosphere



Remember the Sun:

Temperature decreases to the TMI

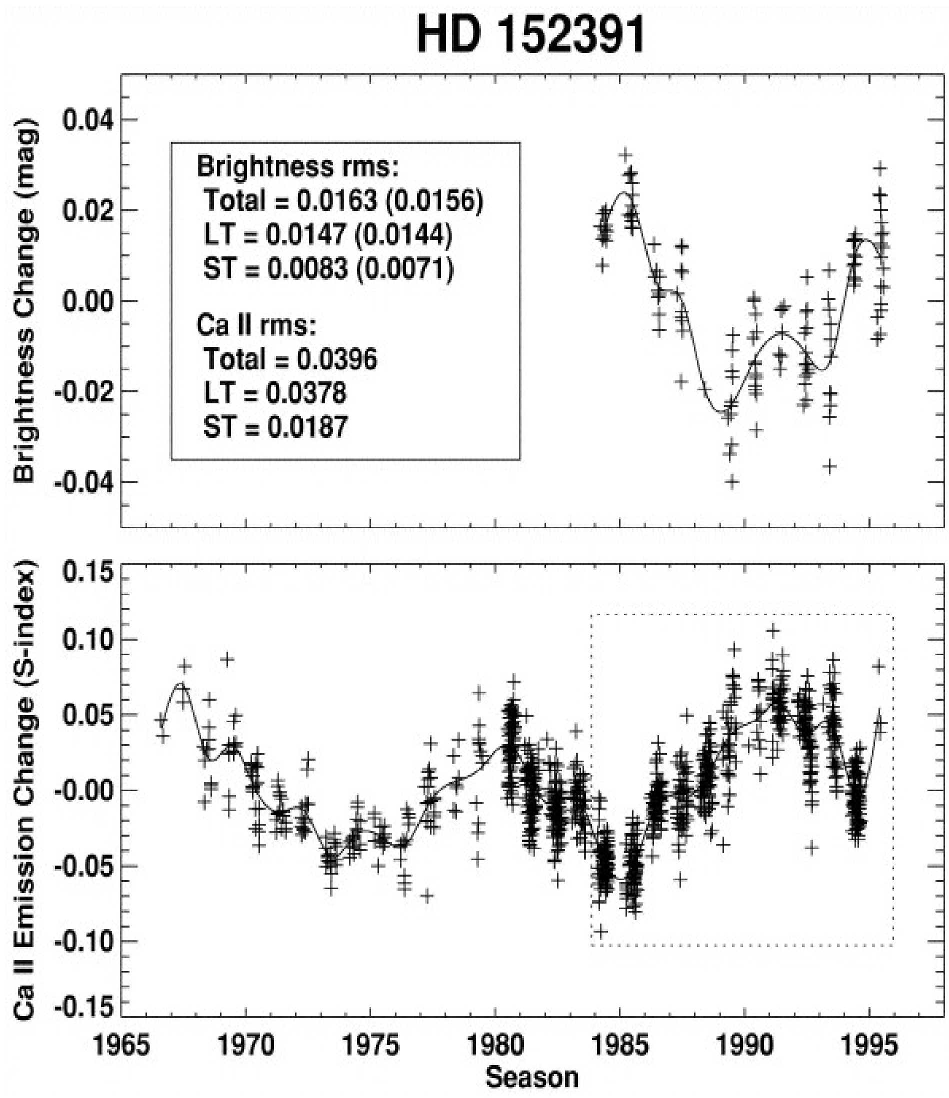
Magnetic heating (non-radiative) causes the temperature to rise to a plateau near 7000K (chromosphere); density falls by orders of magnitude

Plateau results from a balance between magnetic heating and radiative cooling from **collisionally excited** Ha, Ca II K, Mg II k – the principal diagnostic lines formed in the chromosphere

Long-term, synoptic observations of the spectroscopic and photometric behavior of Sun-like stars has been performed at select observing sites for nearly 40 years. Most of the spectroscopic data have been collected at the Mount Wilson Observatory (MWO), beginning in March 1966 with Olin Wilson's initial observations of the cores of Ca II H&K lines in a set of 139 Sun-like stars.

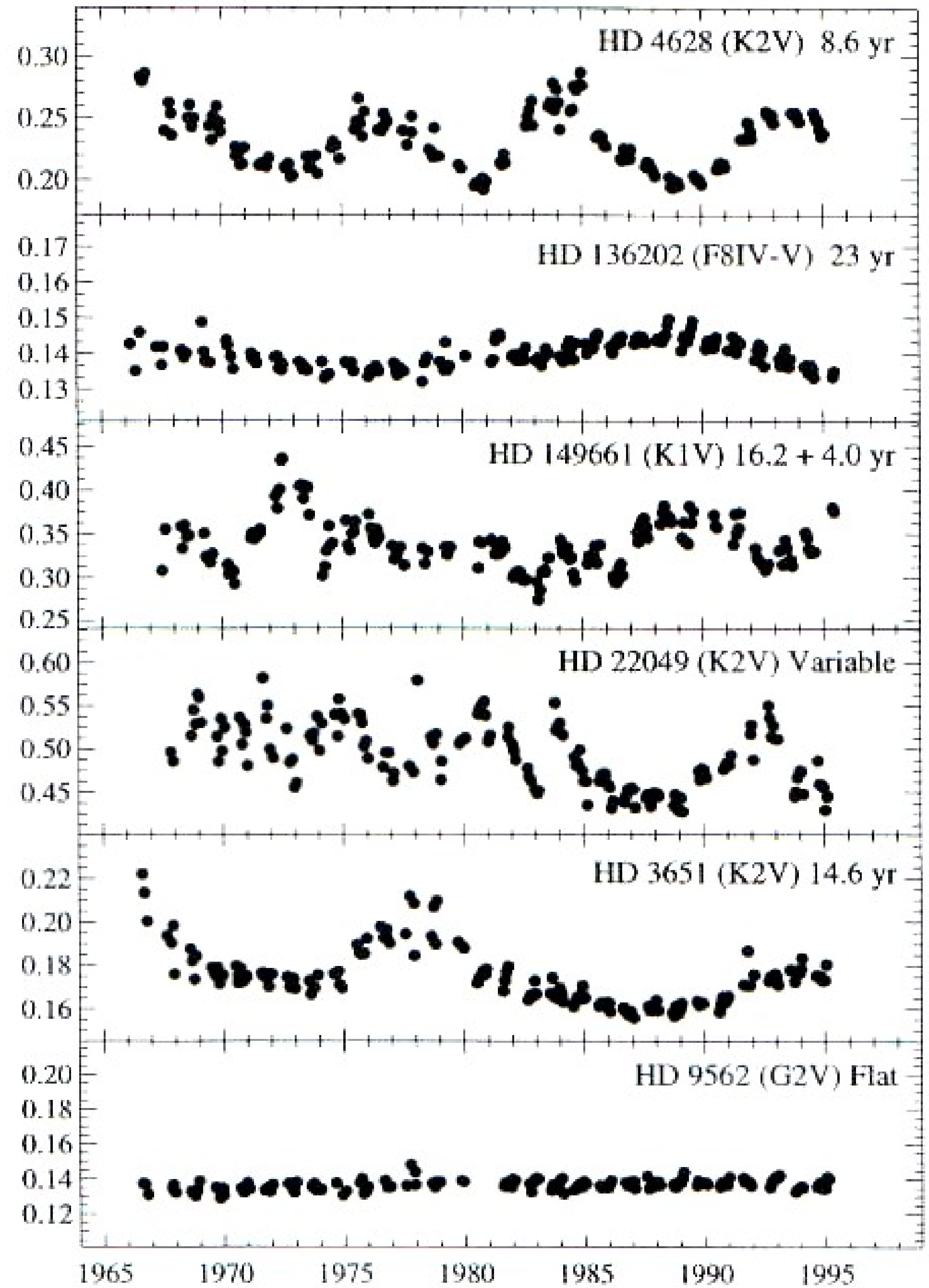
Monitoring of stellar activity (CaII H&K)

- Extension of the Mt. Wilson survey
- Search for activity cycles
- Surveys to search for active stars



Activity Cycles

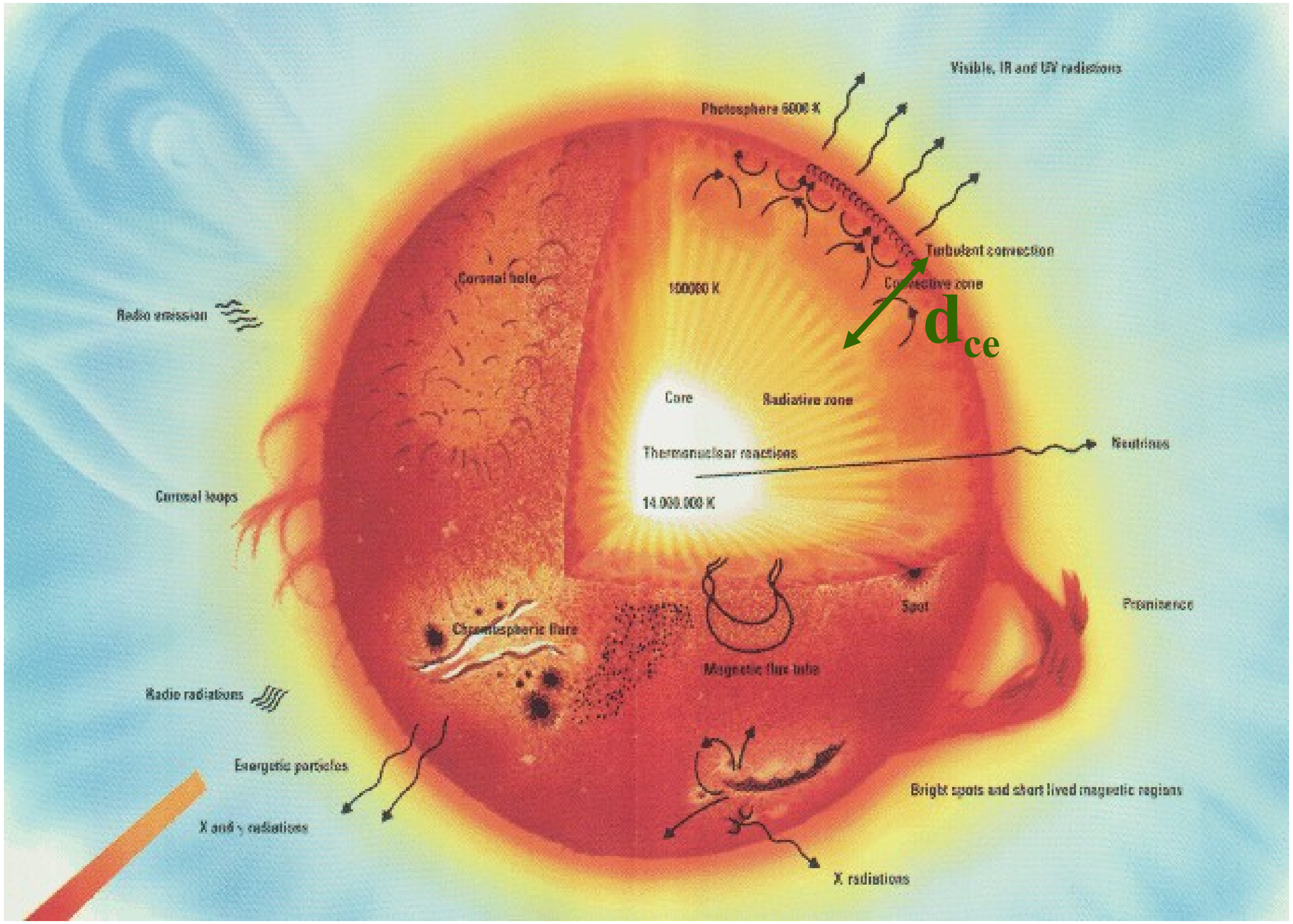
- Long term chromospheric activity indices for several stars showing different patterns of activity cycles



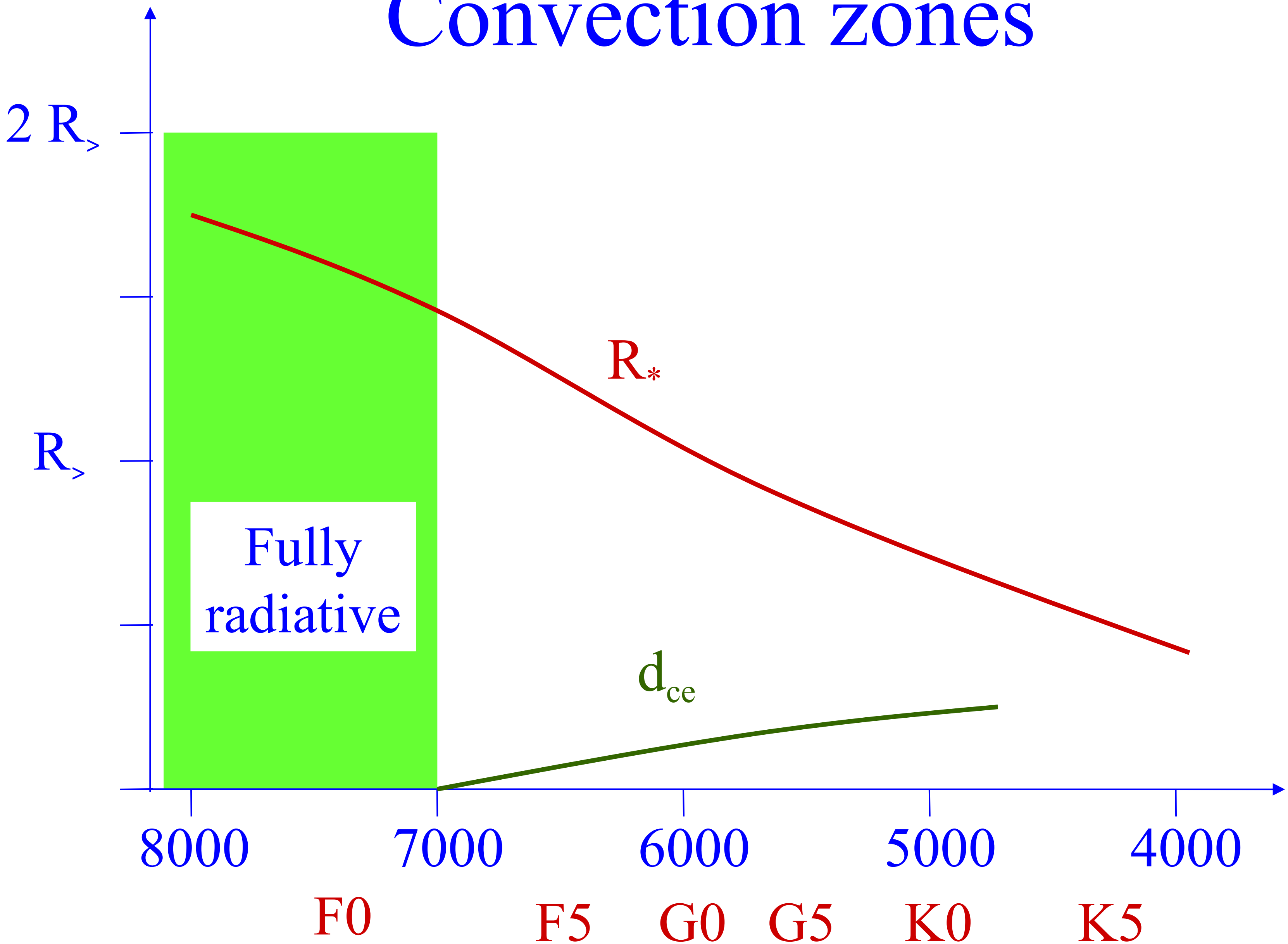
.

The solar variations in the visual continuum (total irradiance) , **which never exceed a few tenths of a percent,** are clearly associated with the disk passage of sunspots . Similar stellar variability found for stars of spectral type from F7 to K2**.** Thus, the **starspot phenomenon in solar-type stars peaks** seemingly at the effective temperature range from **6400 K to 4900 K.**

Convection zone



Convection zones

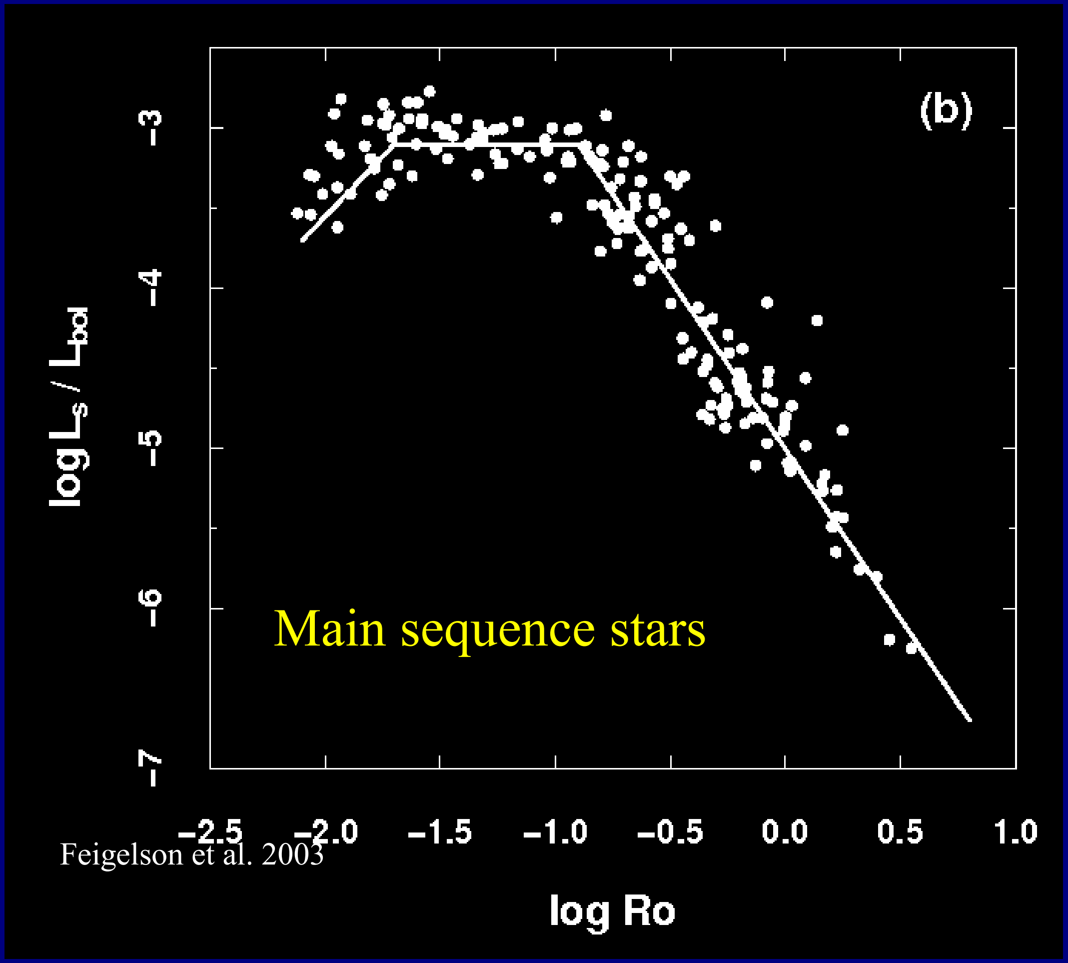


It was firmly established that magnetic activity in solar-type stars declines with age and that it is closely related to a loss of angular momentum throughout the main-sequence lifetime (Skumanich, 1972; Noyes et al., 1984; Baliunas et al., 1995; Güdel et al., 1997).

Thus, young stars exhibit high average levels of activity and rapid rotation, while stars as old as the Sun and older have slower rotation rates and lower activity levels.

Connection to dynamo theory

Rossby Number $Ro = \dfrac{\text{Rotation period } P_{rot}}{\text{Convective turnover time } \tau_c}$



Prediction for $\alpha-\Omega$ dynamo:

$L_X/L_{bol} \propto Ro^{-2}$

Dynamo saturation for $Ro \leq 0.1$

Thomas Preibisch
http://www.mpifr-bonn.mpg.de/staff/tpreibis/3-02-preibisch.pdf

Age-Activity Relation

- In solar-type stars, age-activity relation is well defined
- Young stars have stronger Ca II K line emission (flux proportional to $t^{-1/2}$)

The Phenomenon of Stellar Activity

1 Red dwarfs and BY Dra phenomenon

2 Solar-type stars

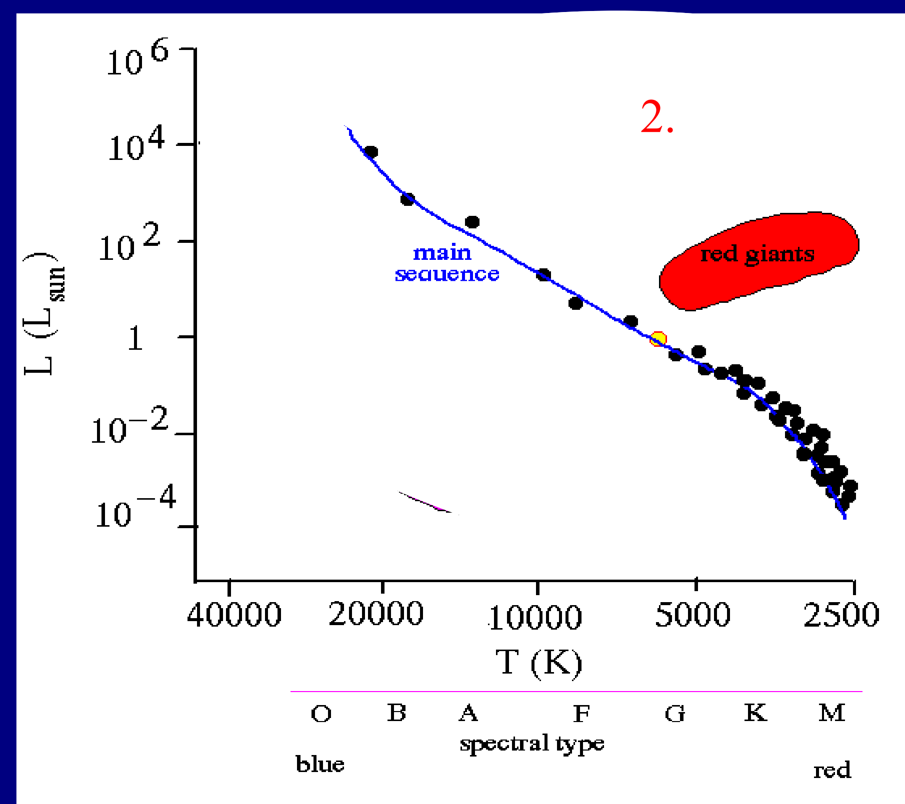
<u>3 RS CVn stars</u>

4 T Tauri stars

www.astro.psu.edu/users/niel/astro485/lectures/lecture13

RS Cvn systems

1. close binary (tidally locked)
   $P_{rot} = P_{orb}$



2. active star: evolved (giant)

3. large dark spots

RS CVn stars represent a class of **close detached binaries** with the more massive primary component being a G-K giant or subgiant and the secondary a subgiant or dwarf of spectral classes G to M.

They show optical variability
interpreted as the rotationally modulated effect of cool spots on their surfaces.

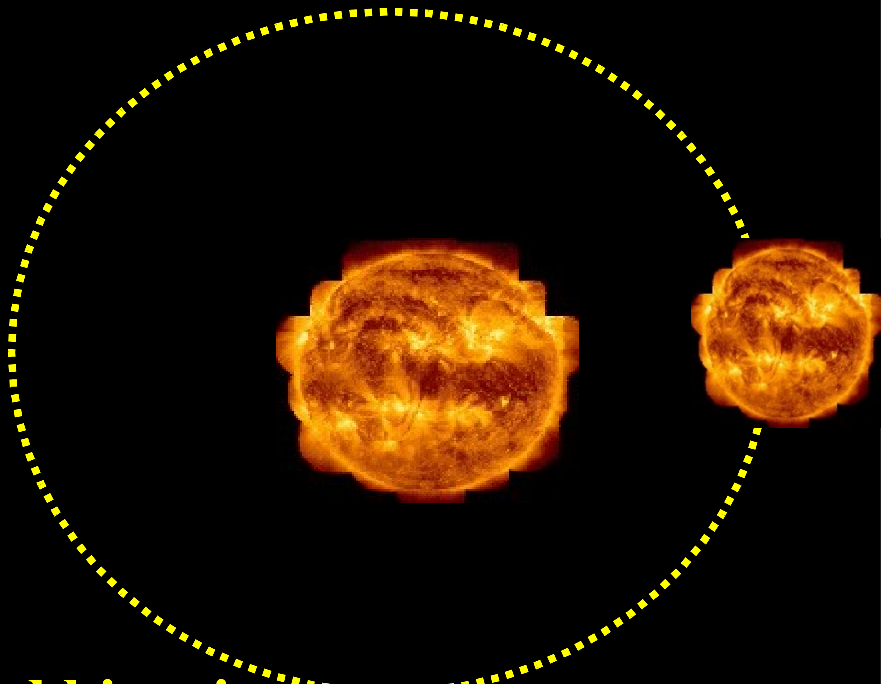
The primary appears more active than the secondary.

Svetlana V. Berdyugina:
http://solarphysics.livingreviews.org/Articles/lrsp-2005-8/

Since they are tidally locked close binaries, they are also fast rotators. Thus, similar to other cool active stars, RS CVn-type variables are remarkable due to strong chromospheric plages, coronal X-ray, and microwave emissions, as well as strong flares in the optical, UV, radio, and X-ray.

Large amplitude brightness variations of RS CVn stars imply the presence of enormous starspots on their surfaces covering up to 50% of the visible disc. Remarkable activity and high luminosity of these stars make them favourite targets for light curve modelling, Doppler imaging and spectral line analysis. Most of the present knowledge on starspots is based on studies of this type stars.

Tidal forces between the components of a close binary lock the rotational periods to the orbital one

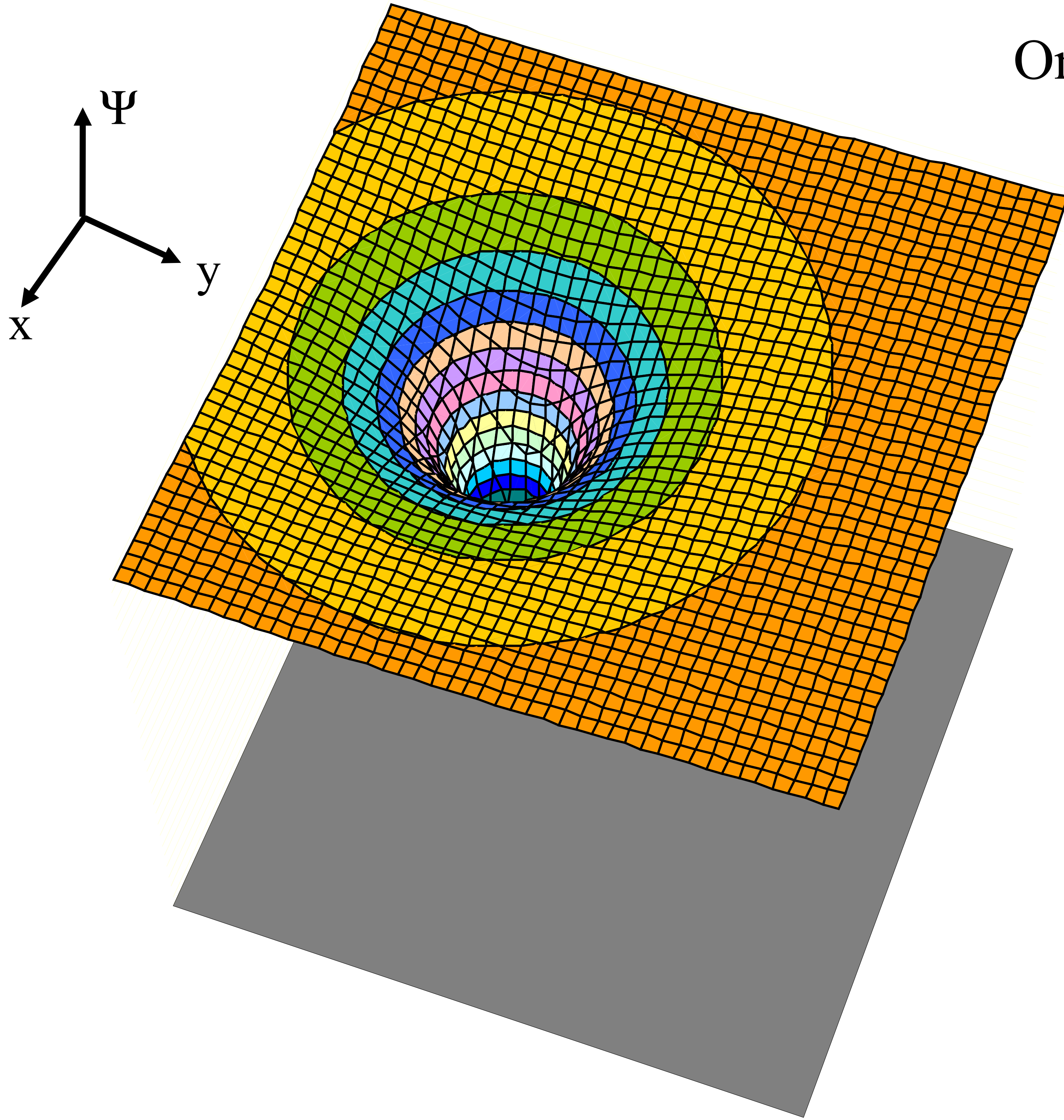


RS CVn stars represent a class of **close detached binaries**

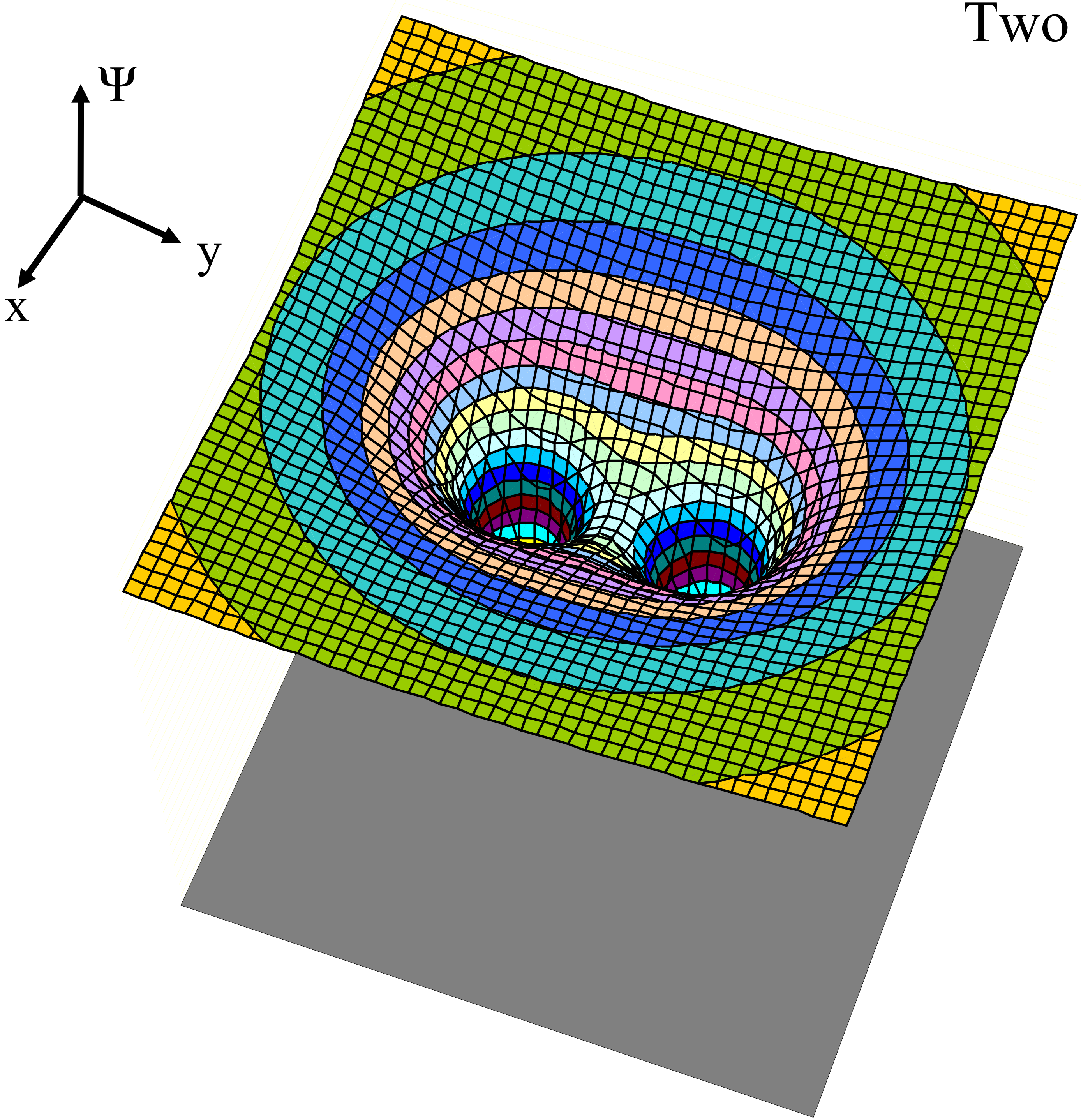
What does this potential function look like?

$$\Psi$$

One Star



Two Stars



The Phenomenon of Stellar Activity

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T Tauri stars

T Tau-type stars are pre-main-sequence stars of about one solar mass at an age of a few million years, still surrounded by disks of gas and dust remaining from their formation.

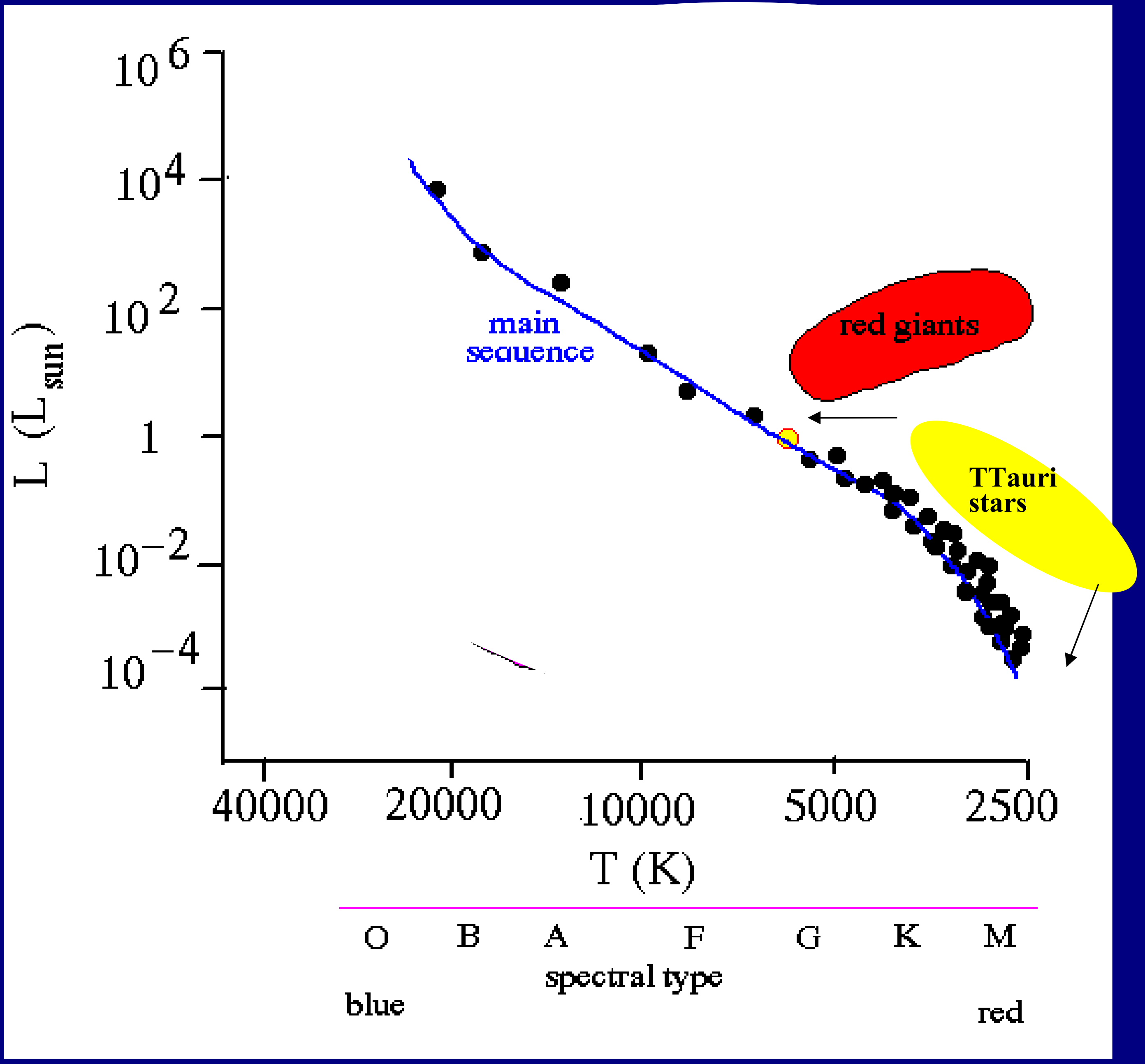
A subgroup of T Tau stars with weak emission spectra and little, if any, IR excess radiation, called weak-line T Tau stars, show periodic brightness variations with amplitudes up to 0.5 mag which are caused by very large cool active regions
. Properties of T Tauri type stars were recently reviewed by Petrov (2003).

weak-line T Tauri Stars

Pre-main sequence star

large dark spots similar to RS Cvn's

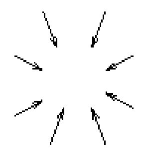
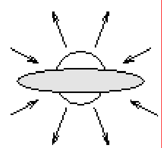
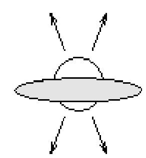
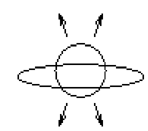
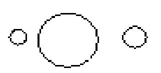
No-disk (weak-line TTauri)



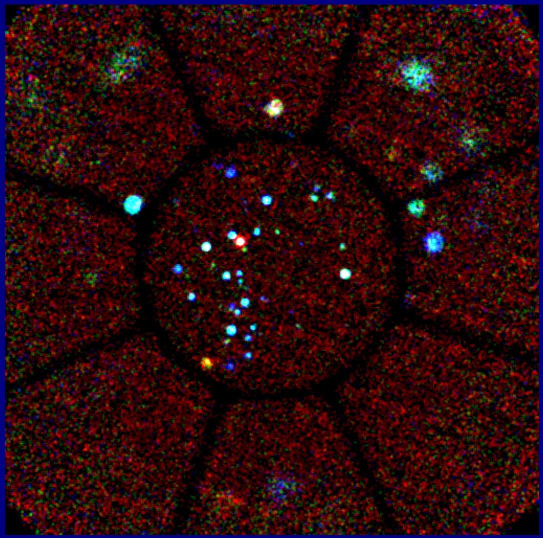
Pre-Main Sequence late-type stars

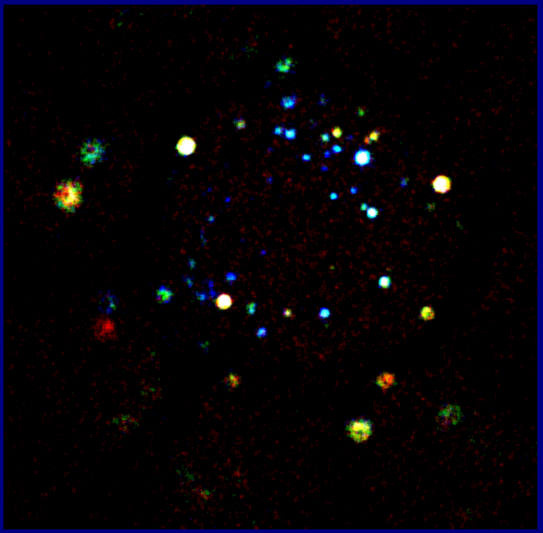
- Late-type stars (F-M) still contracting to the MS

Evolutionary Stages

Properties	Infalling Protostar	Evolved Protostar	Classical T Tauri Star	Weak-lined T Tauri Star	Post-T Tauri star Herbig (1978)	Main Sequence Star
						
Age (years)	10^4	10^5	$10^5 - 10^6$	$10^5 - 10^7$	$10^7 - 10^8$	$> 10^8$
mm/Infrared Class	Class 0	Class I	Class II	Class III		(Class III)
Infall and Mass loss	Infall + Collimated Outflow	Infall + Open Outflow	Strong Wind	Weak Wind		Very Weak Wind
Disk	Yes	Thick	Thick	Thin or Non-existent		Possible Planetary System
X-ray	Not Detected	Yes	Strong	Strong		Weak
Radio	Thermal	Thermal + Non-thermal	Thermal	Non-thermal		Non-thermal

EINSTEIN / ROSAT / ASCA observations of star forming regions:





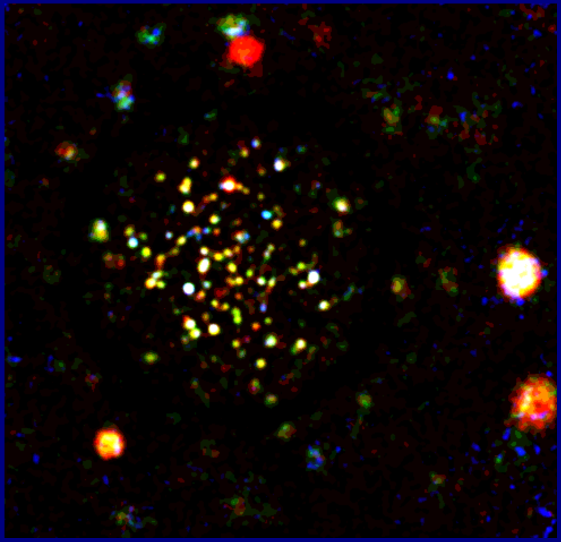
T Tauri stars are strong X-ray sources

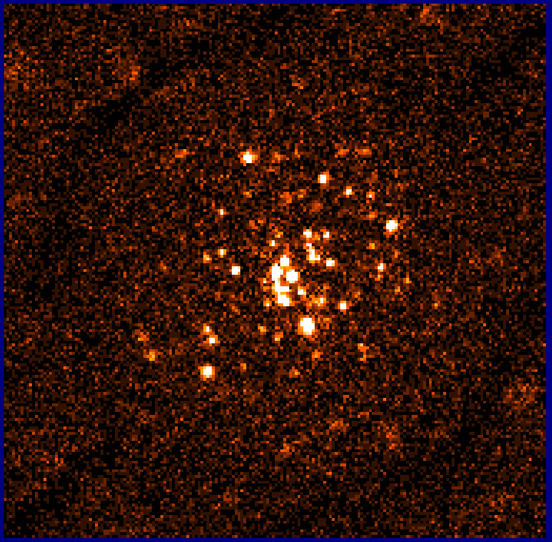
$L_X \sim 10^{28} - 10^{31}$ erg/s

→ $\sim 1000 \times L_{X\odot}$

$T_X \sim 10 - 30$ MK

→ $\sim 10 \times T_{X\odot}$

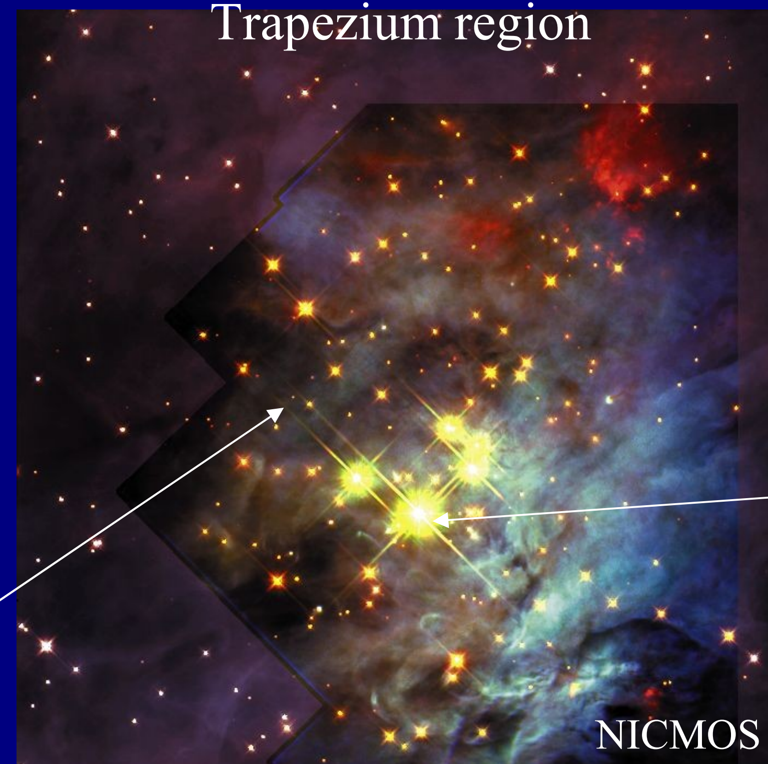




Thomas Preibisch
http://www.mpifr-bonn.mpg.de/staff/tpreibis/3-02-preibisch.pdf

Ideal Target: The **Orion Nebula Cluster** (ONC)

- luminosities, ages, and masses known for more than 900 members
- mean age ~ 1 Myr



Brown dwarf candidate $0.01\ M_\odot$

θ^1 Ori C **O7** $40\ M_\odot$

Thomas Preibisch
http://www.mpifr-bonn.mpg.de/staff/tpreibis/3-02-preibisch.pdf

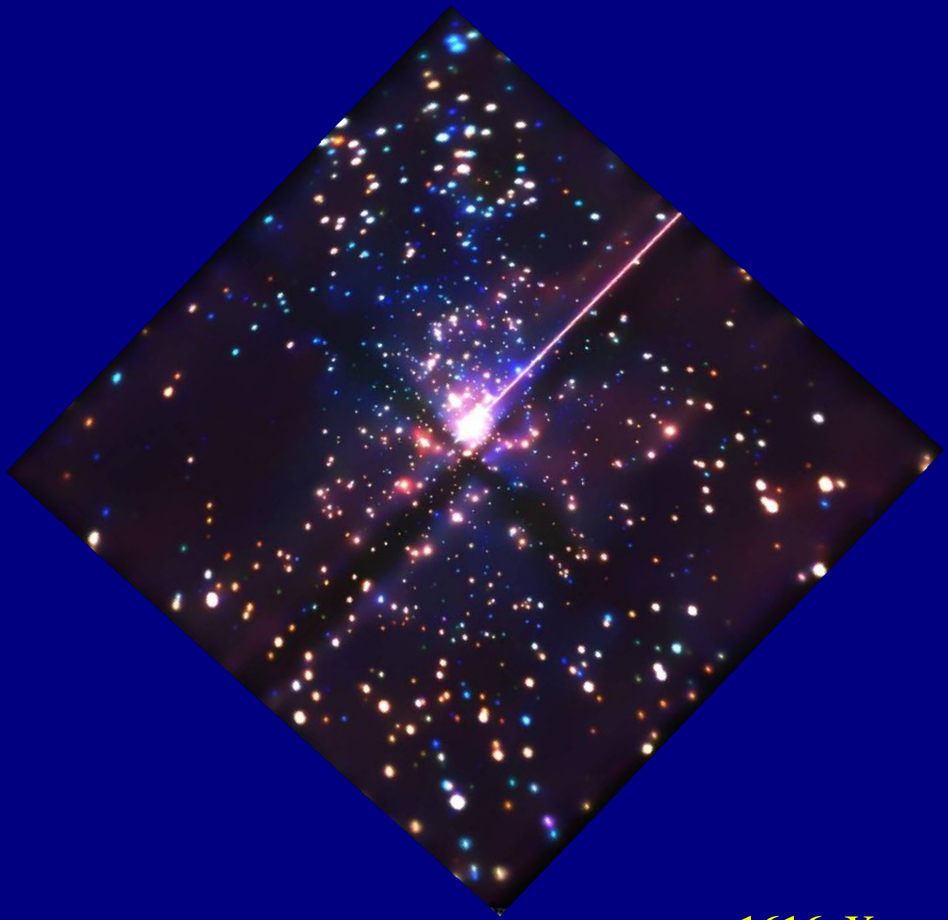
Solution: *C*handra *O*rion *U*ltradeep *P*roject (COUP)

PI: Eric Feigelson

8 - 21 January 2003:

ONC observed for

840 ksec = 10 days



COUP true color image
0.5 – 8 keV, 17' x 17'

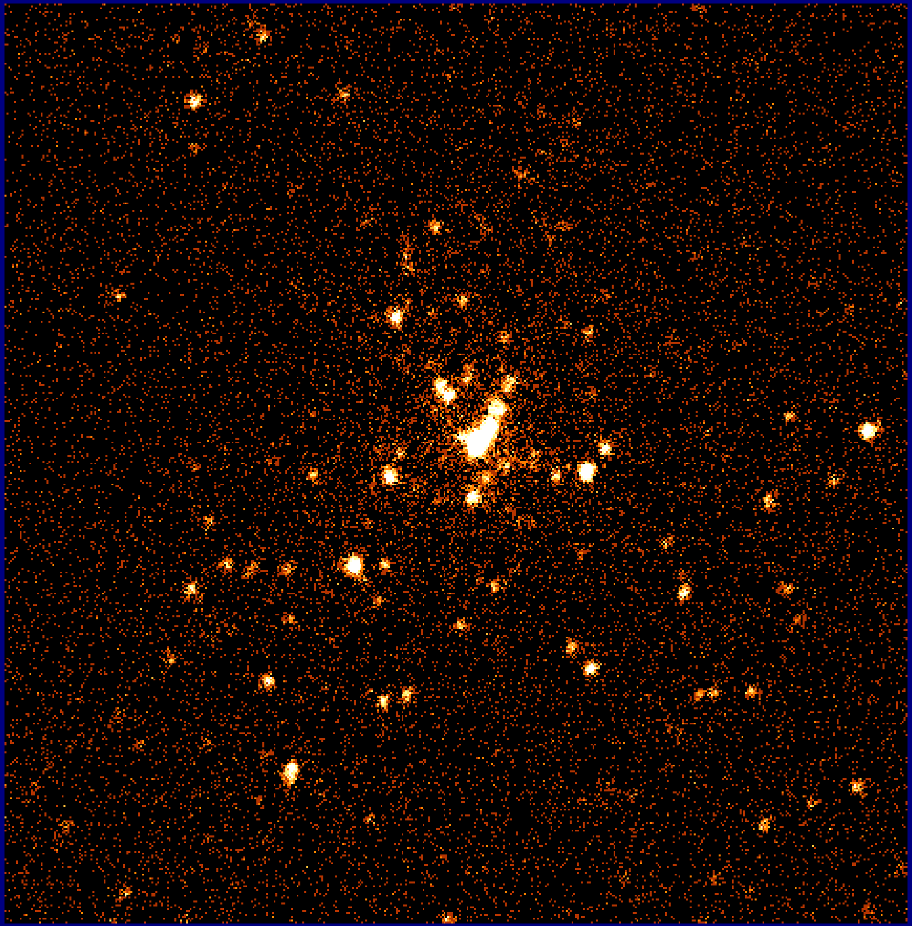
1616 X-ray
sources detected

Deepest X-ray observation ever obtained of a star forming region

Thomas Preibisch
http://www.mpifr-bonn.mpg.de/staff/tpreibis/3-02-preibisch.pdf

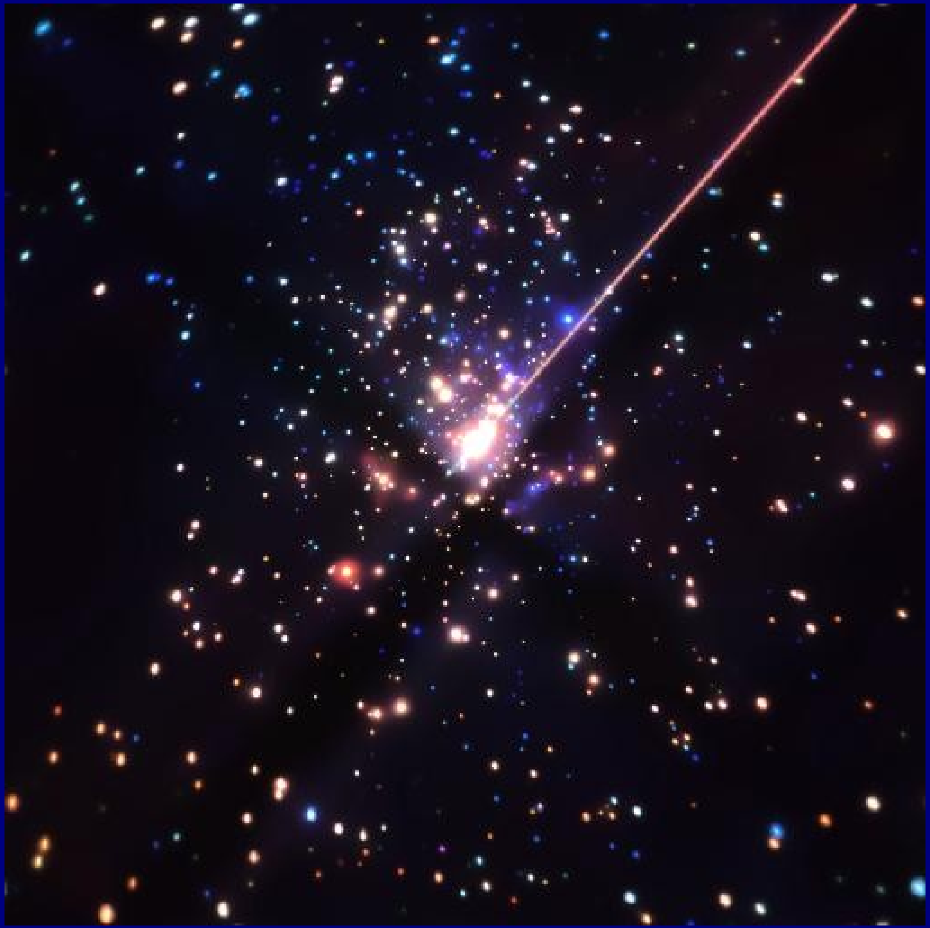
ROSAT HRI (0.2 – 2.0 keV)

exposure time: 28 000 sec



COUP Chandra (0.5 – 8.0 keV)

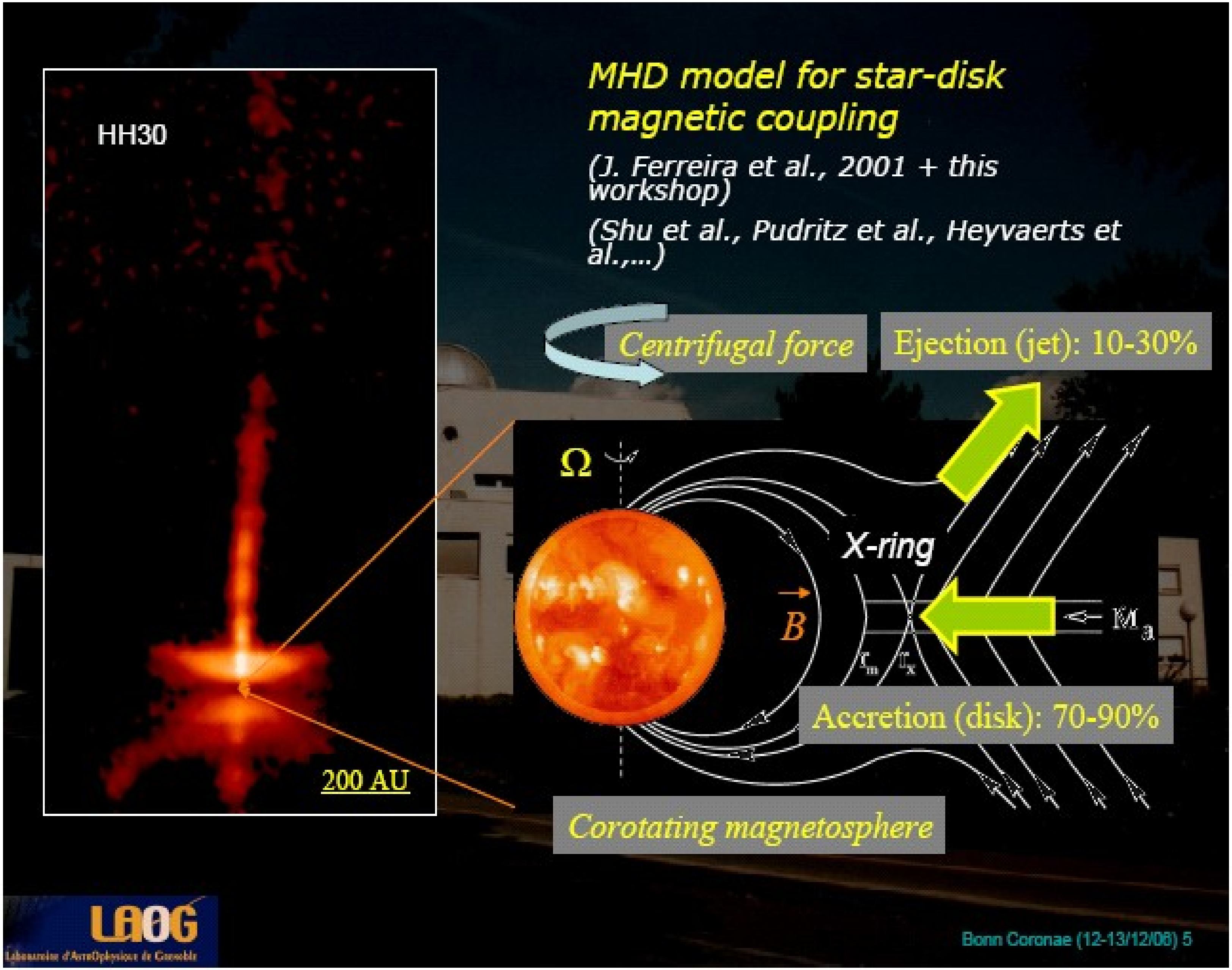
exposure time: 838 100 sec



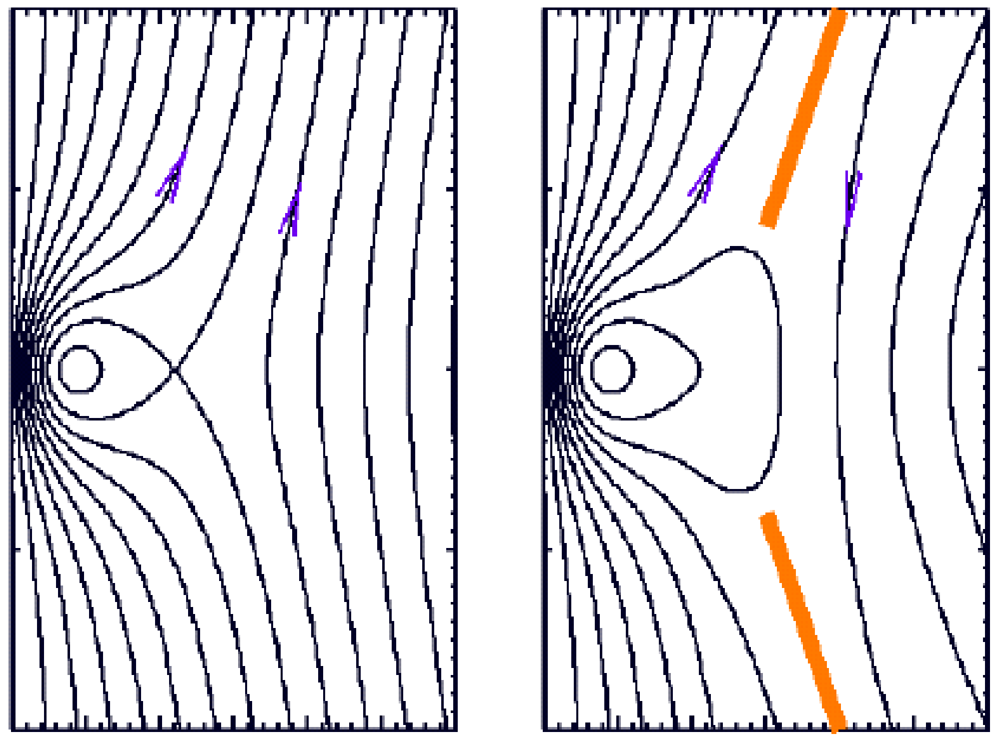
ROSAT HRI		COUP Chandra
resolution: 5"	5 x	resolution: < 1"
297 sources in 40' x 40'	8 x	1616 sources in 17' x 17'
$L_{X,lim} = 5 \times 10^{29}$ erg/sec	250 x	$L_{X,lim} = 2 \times 10^{27}$ erg/sec

Thomas Preibisch

http://www.mpifr-bonn.mpg.de/staff/tpreibis/3-02-preibisch.pdf



http://www.mpifr-bonn.mpg.de/staff/tpreibis/coronae/contributions/3-01-montmerle.pdf



Stellar field aligned with ambient field
→ formation of X-point

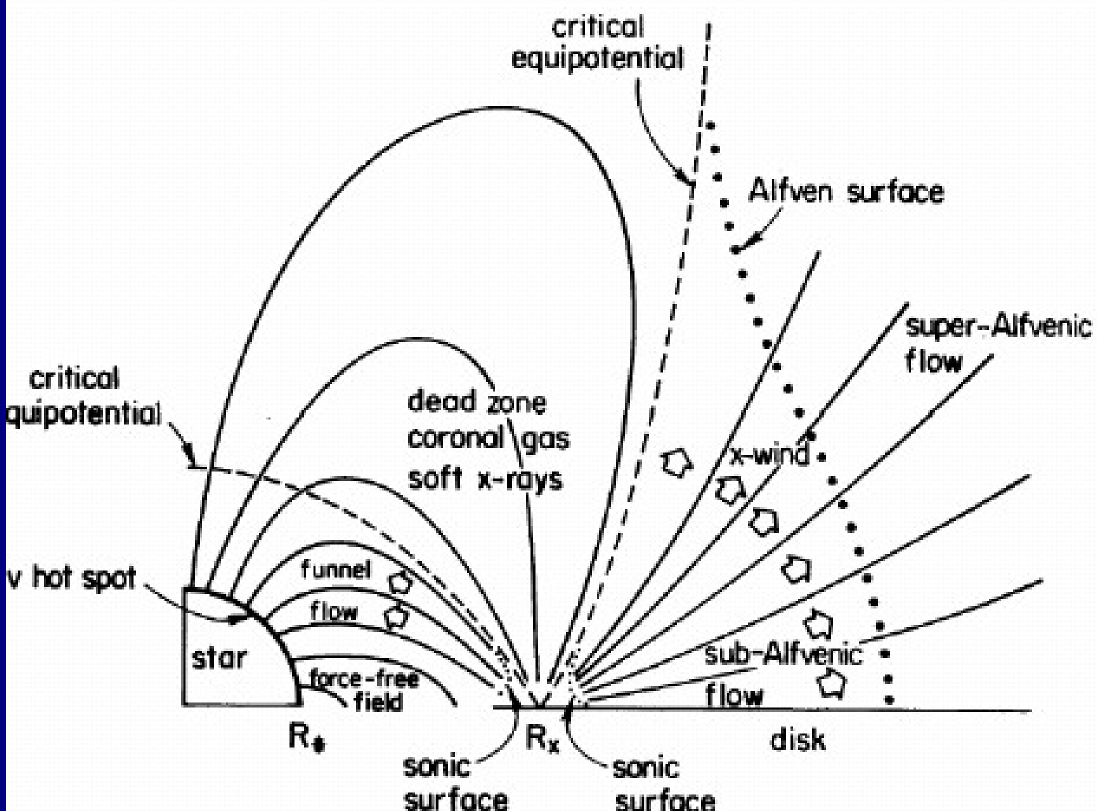
Stellar field anti-aligned
→ current sheet

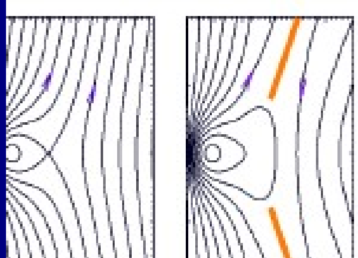
If external field is dragged in.
or if stellar field shows reversals

If field is due to dynamo

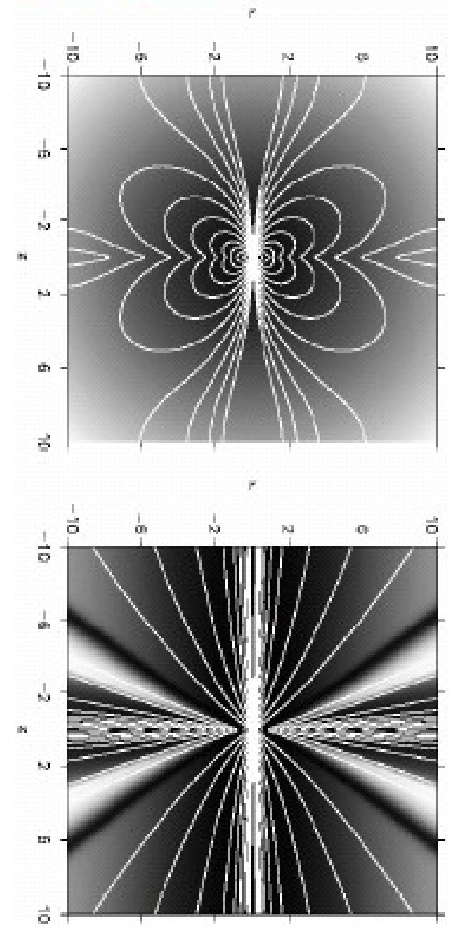
http://www.mpifr-bonn.mpg.de/staff/tpreibis/coronae/contributions/4-10-brandenburg.pdf

Wind and accretion





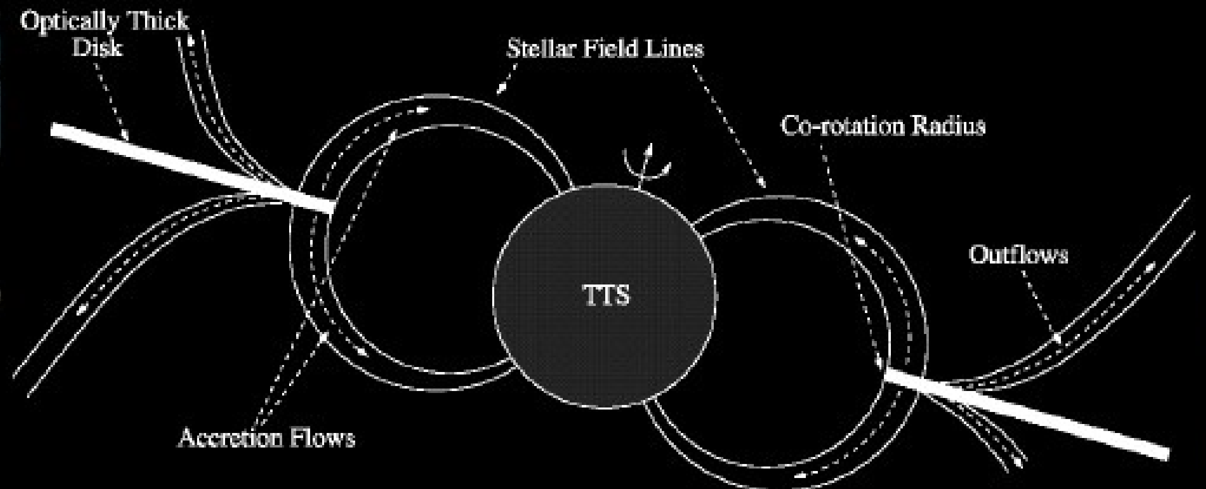
X-wind
(Shu et al. 1994)



Simulation
(Fendt & Elstner 2000)

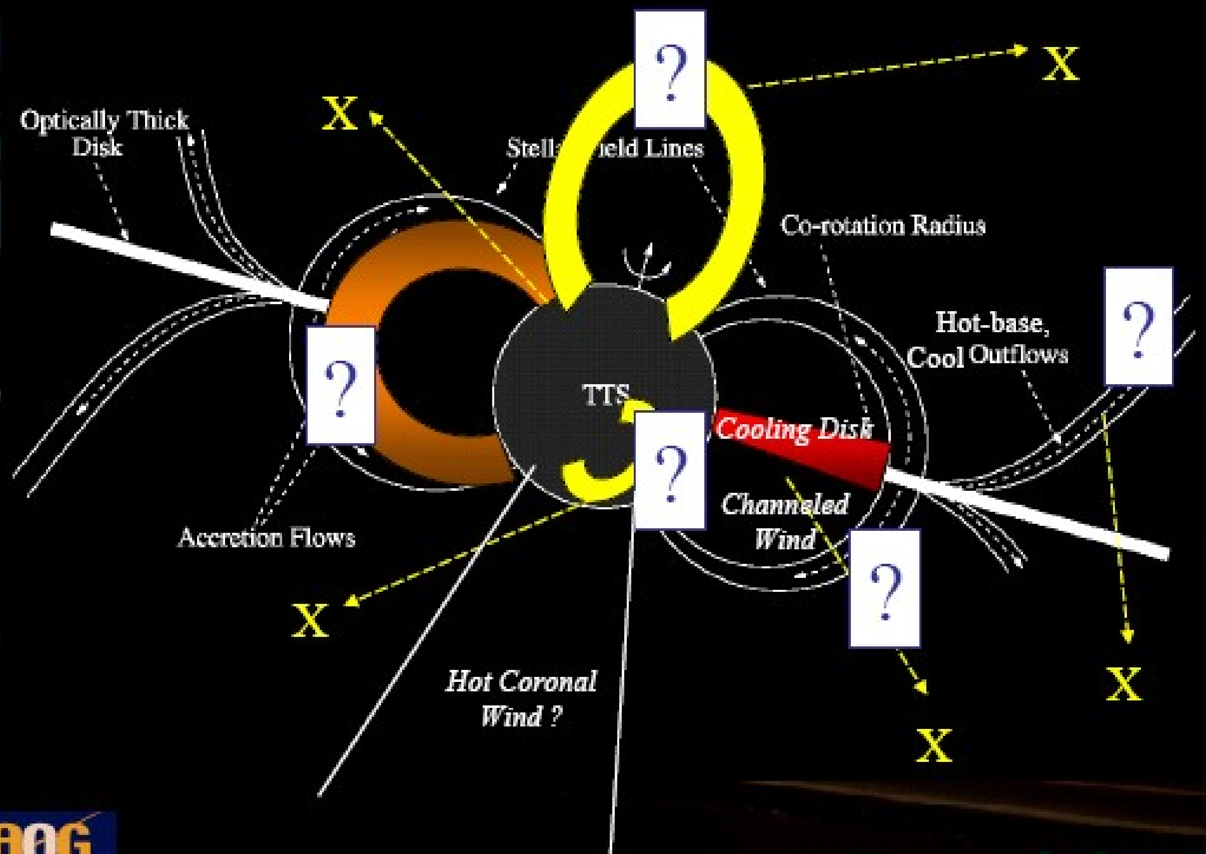
http://www.mpifr-bonn.mpg.de/staff/tpreibis/coronae/contributions/4-10-brandenburg.pdf

The magnetic structure of a "classical" (= accreting) T Tauri star



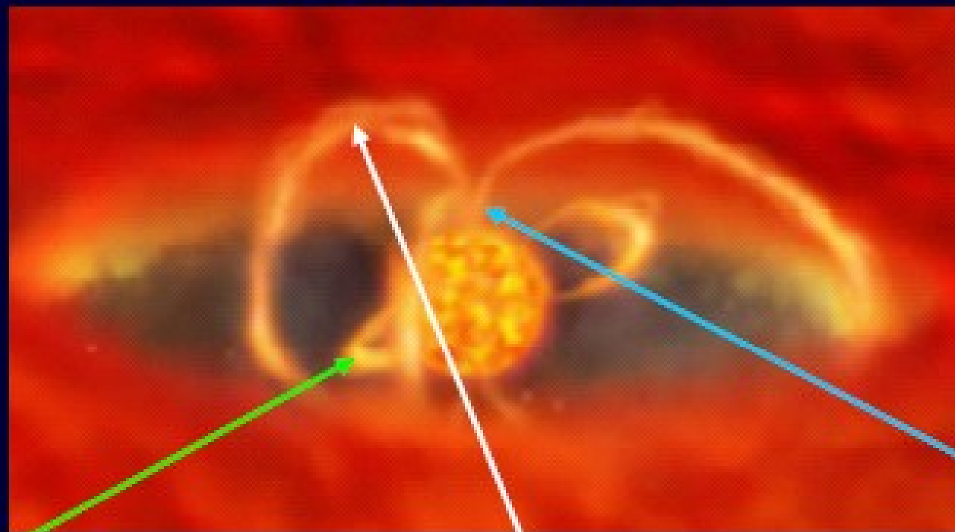
Stassun 2001

A complex accretion-ejection configuration...



The Origin of the X-ray emission from T Tauri stars

Main possibilities:



``normal´´ (solar-like ?) **coronal loops** $l \leq R_\star$

extended loops $l > R_\star$ star-disk coupling (?)

accretion shocks (only in accreting stars, not in weak-line TTS!)

What is the *dominant* source of X-ray emission in the *majority of* the TTS ?

Thomas Preibisch
http://www.mpifr-bonn.mpg.de/staff/tpreibis/3-02-preibisch.pdf

1.) X-ray activity and accretion

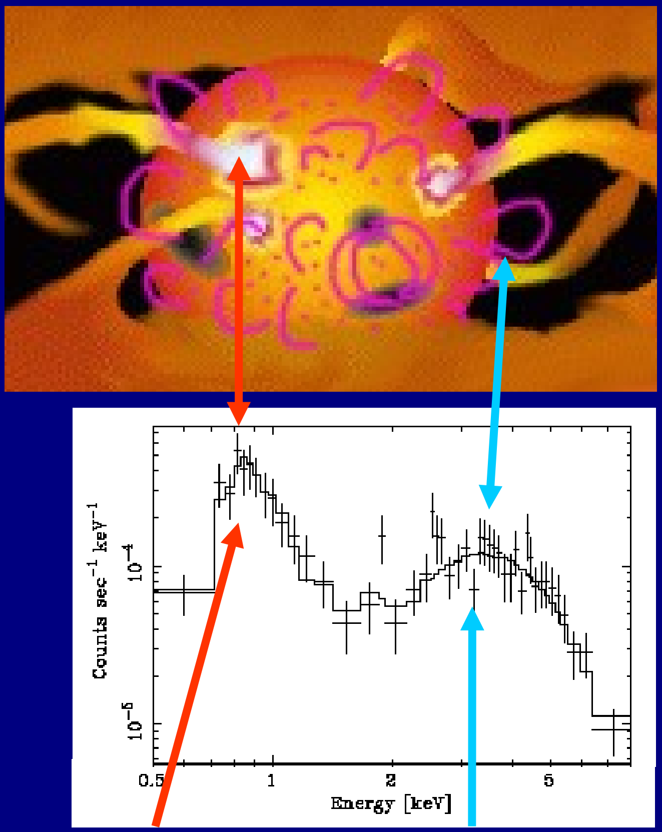
Magnetospheric accretion shocks:

v ≤ 300 km/sec → T ~ 1-3 × 10^6 K

X-ray emission from accretion shocks is also seen in other classical T Tauri stars

(e.g. BP Tau, CR Cha, SU Aur; Robrade & Schmitt 2006)

but coronal component is by far dominant.



Thomas Preibisch
http://www.mpifr-bonn.mpg.de/staff/tpreibis/3-02-preibisch.pdf

How important is X-ray emission from accretion shocks ?

$L_X \geq L_{acc}$ for many T Tauri stars

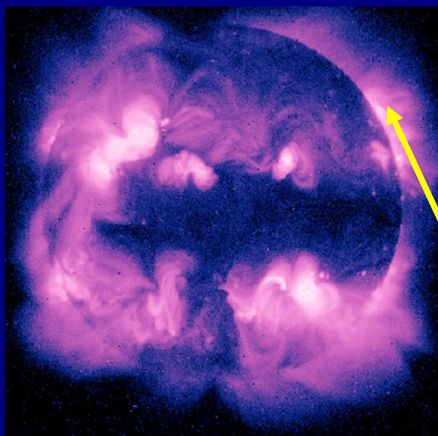
→ X-ray emission cannot come
from accertion shocks

→ accreting T Tauri stars have *lower* X-ray luminosities

Thomas Preibisch
http://www.mpifr-bonn.mpg.de/staff/tpreibis/3-02-preibisch.pdf

Possible explanation for the "X-ray deficit" in accreting stars:

non-accreting star



accreting star

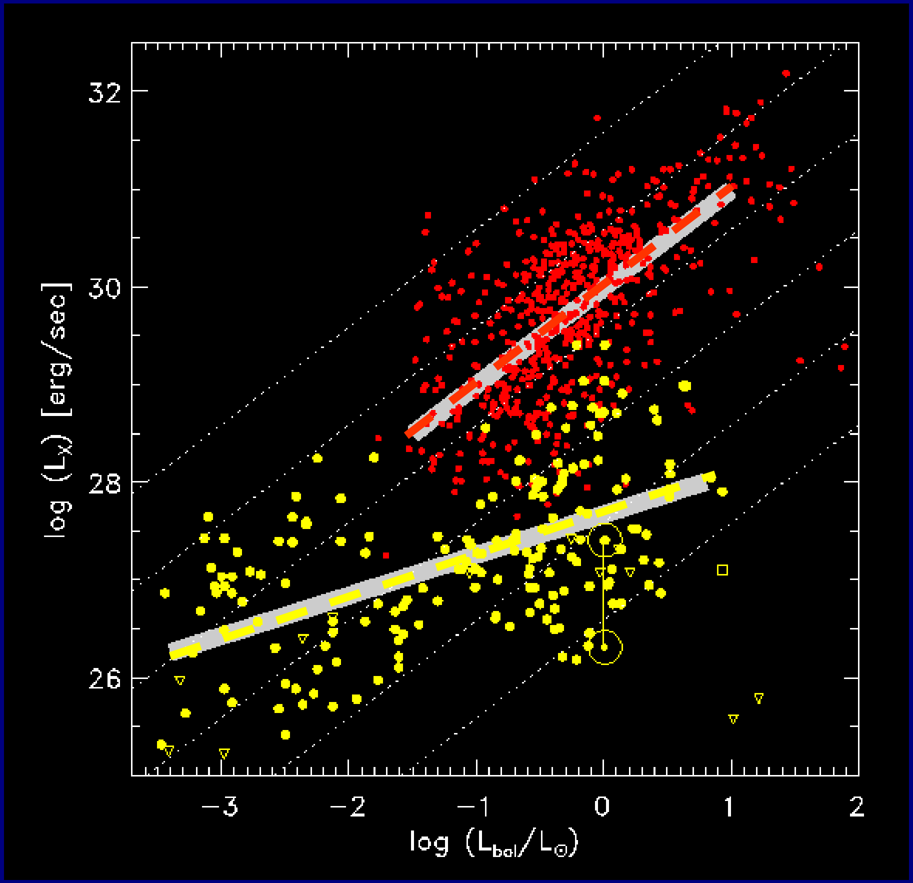
**Low-density,
hot coronal loops
emit X-rays**

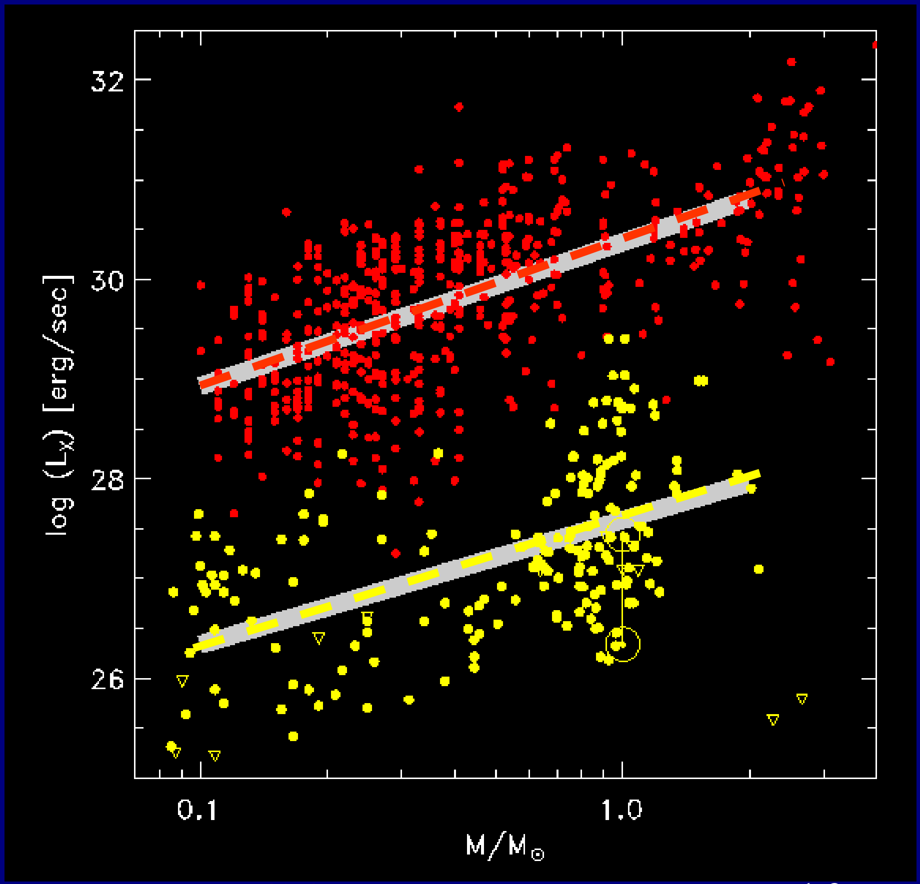
**Some fraction of the loops
are mass-loaded and
cooled by accreted matter
→ no X-ray emission**

Thomas Preibisch
http://www.mpifr-bonn.mpg.de/staff/tpreibis/3-02-preibisch.pdf

2.) Coronal Properties

- **COUP**: *complete* sample of the ONC TT star population
- **NEXXUS**: ***complete*** sample of G,K,M main-sequence field stars (Schmitt & Liefke 2004)





COUP: $L_X \propto L_{bol}^{1.0}$

NEXXUS: $L_X \propto L_{bol}^{0.4}$

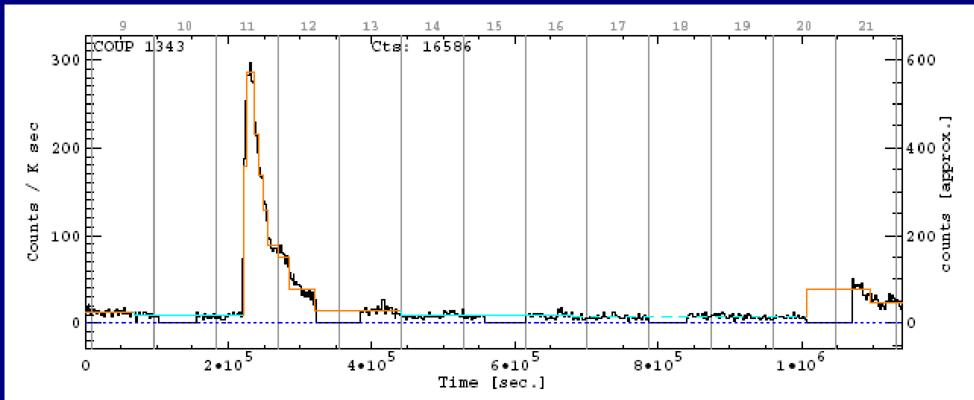
COUP: $L_X \propto M_\star^{1.3}$

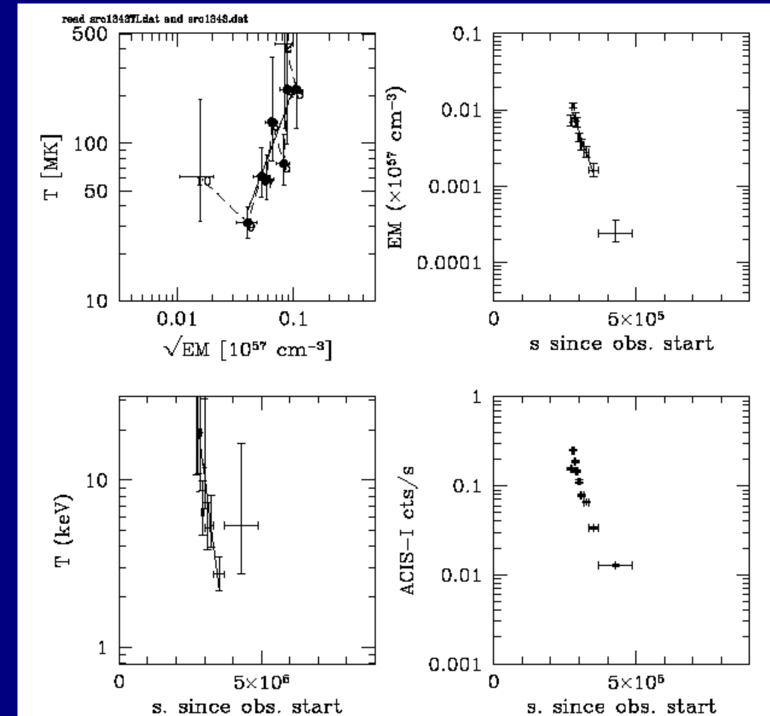
NEXXUS: $L_X \propto M_\star^{1.4}$

Thomas Preibisch
http://www.mpifr-bonn.mpg.de/staff/tpreibis/3-02-preibisch.pdf

MHD modeling of large flares

Favata et al.





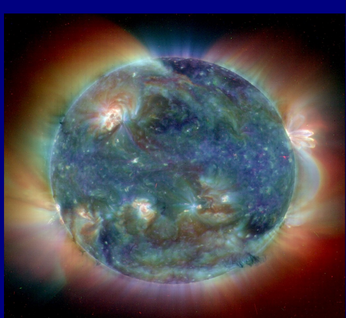
Example: COUP 1343, τ = 12 hours

loop length = 1 x 10^{12} cm ~ 10 x $R_\star$

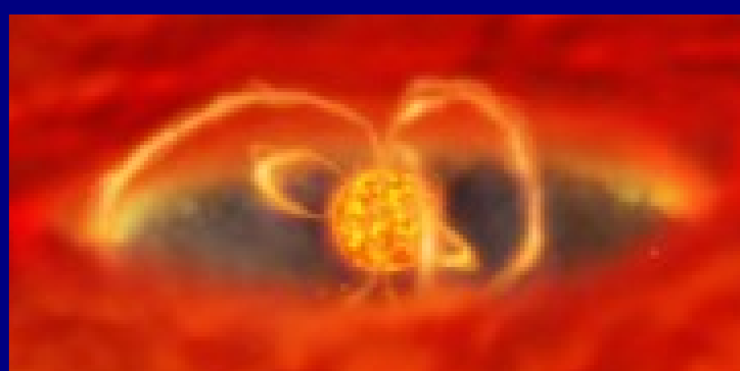
plasma density = 2.3 x 10^{10} cm^{-3}

magnetic field strength = 150 G

Most inferred loop lengths ≤ $R_\star$



Sun:
1 <~ 0.1 $R_\odot$

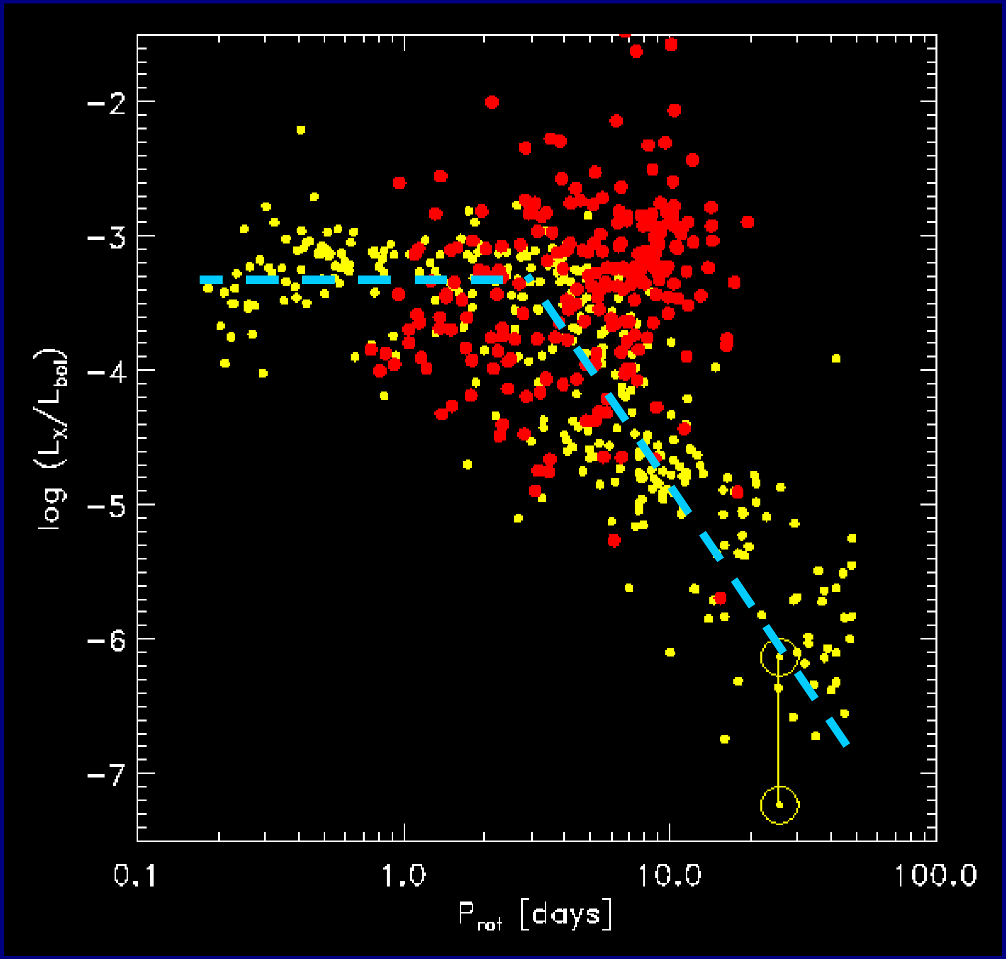


Illustration

but loop lengths of 5 - 20 $R_\star$ are found for *a few* stars

Thomas Preibisch
http://www.mpifr-bonn.mpg.de/staff/tpreibis/3-02-preibisch.pdf

3.) X-ray activity, rotation, & dynamos



- **Main-sequence stars:**

  activity - rotation relation

  - $L_X \propto P_{rot}^{-2}$
  - saturation at log (L_X / L_{bol}) ~ −3 for $P_{rot} \leq 3$ days

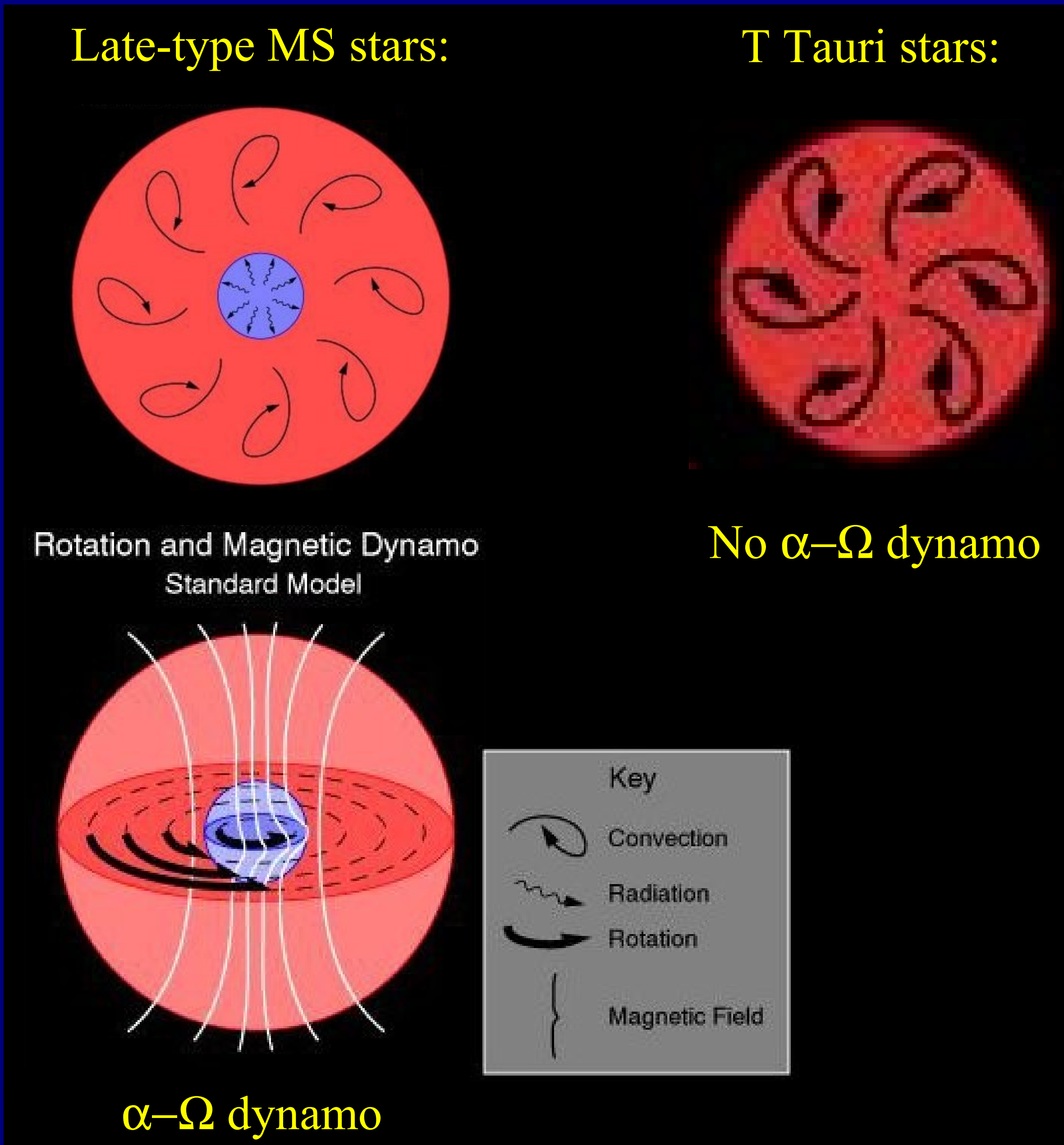
- **T Tauri stars:**

  no activity - rotation relation

  even slow rotators are highly active

Thomas Preibisch
http://www.mpifr-bonn.mpg.de/staff/tpreibis/3-02-preibisch.pdf

What kind of dynamo works in T Tauri Stars ?



fully convective

→ solar-type α–Ω dynamo cannot work

Alternative models for magnetic field generation:

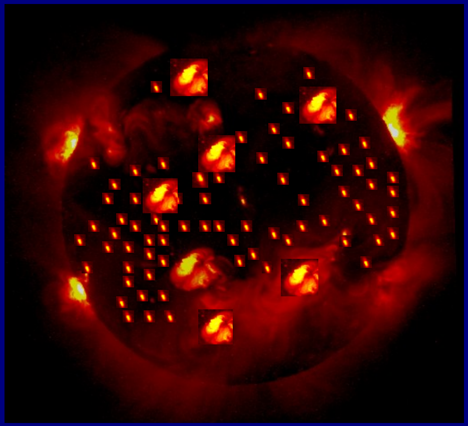
- **α^2 dynamo** ☒
  strongly rotation-dependent

- **turbulent dynamo** ☑
  works throughout the whole convection zone

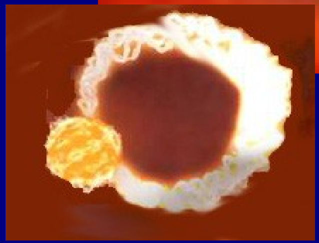
  only weakly dependent on rotation

http://www.mpifr-bonn.mpg.de/staff/tpreibis/3-02-preibisch.pdf

TTauri stars CONCLUSIONS:



Dominant coronal component:
numerous very dense small-scale structures and moderate sized loops (turbulent dynamo ?)



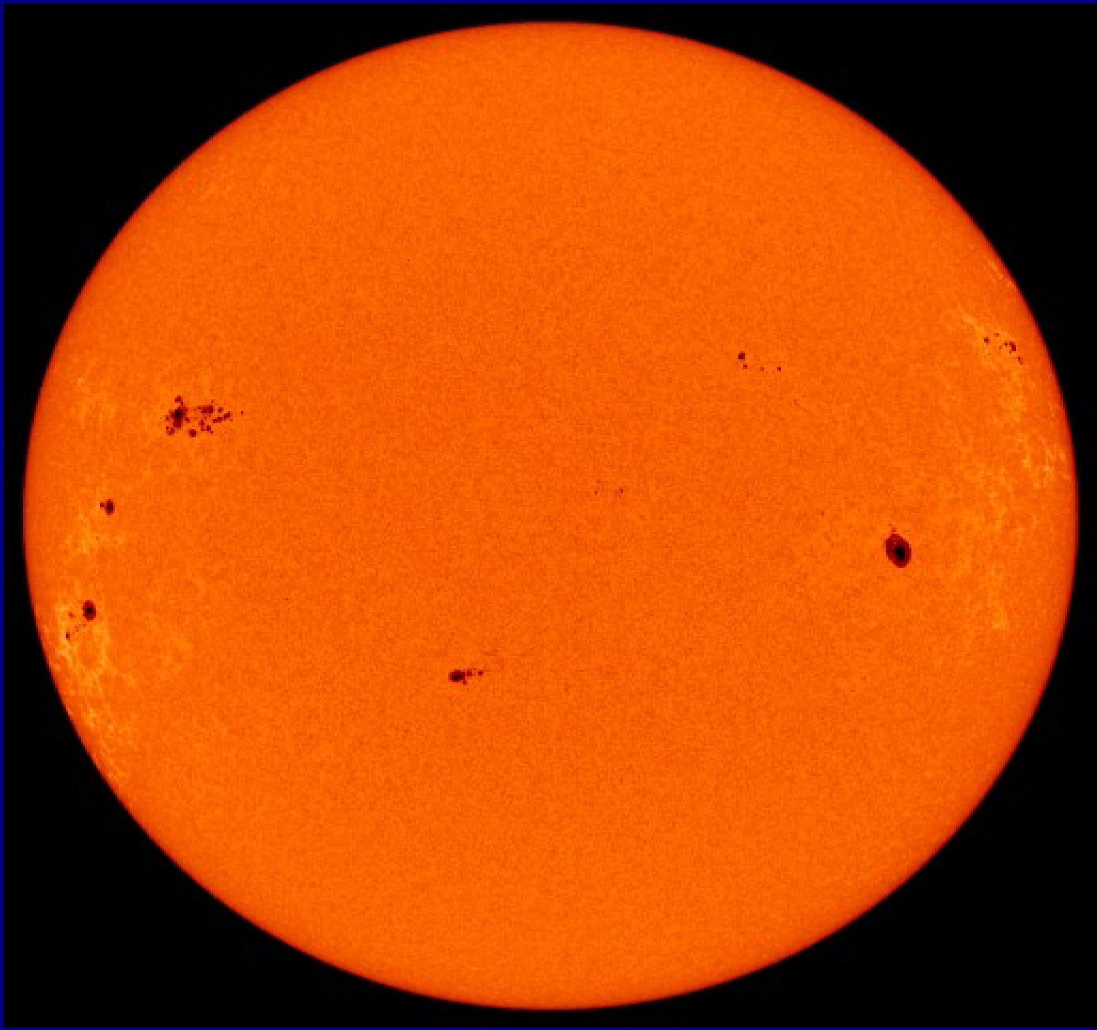
Additional component in some stars:
very large loops,
possibly connecting star & disk
→ strong flares

In some accreting stars:
X-ray emission from accretion shocks

http://www.mpifr-bonn.mpg.de/staff/tpreibis/3-02-preibisch.pdf

Sunspots / Stellar spots

- Sunspots evolve at medium latitudes
- Move towards equator
- Develop cycle of apprx. 11Yrs
- SOHO image from Jan 27, 2002 (near activity maximum)



Mapping Starspots

1.Direct imaging – limited application

2. Photometric light curves

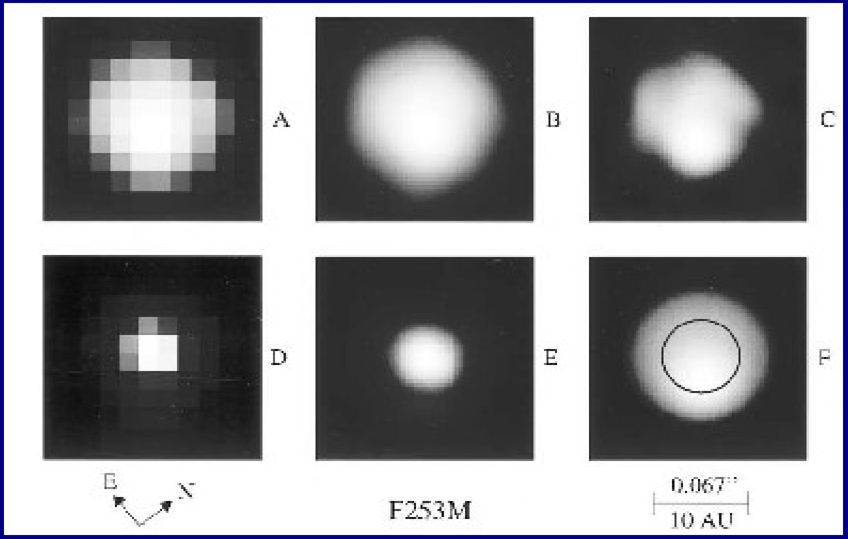
3.Doppler imaging

(Intensity vs. radial velocity vs. time

See Vogt and Penrod 1983 PASP, 95, 565)

Direct imaging of starspots

- Faint Object Camera of HST
- Only very large & very near objects observable
- Only object observed so far is α Orionis

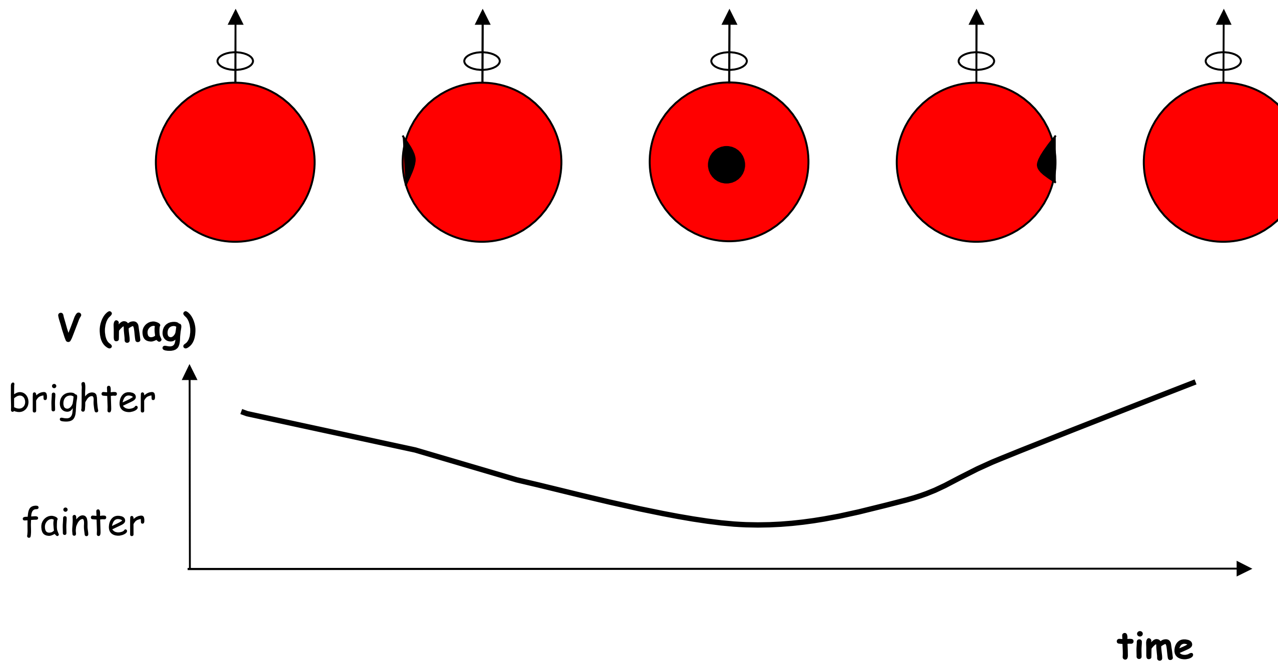


'direct' image of Betelgeuse
Gilliland & Dupree 1996, ApJ

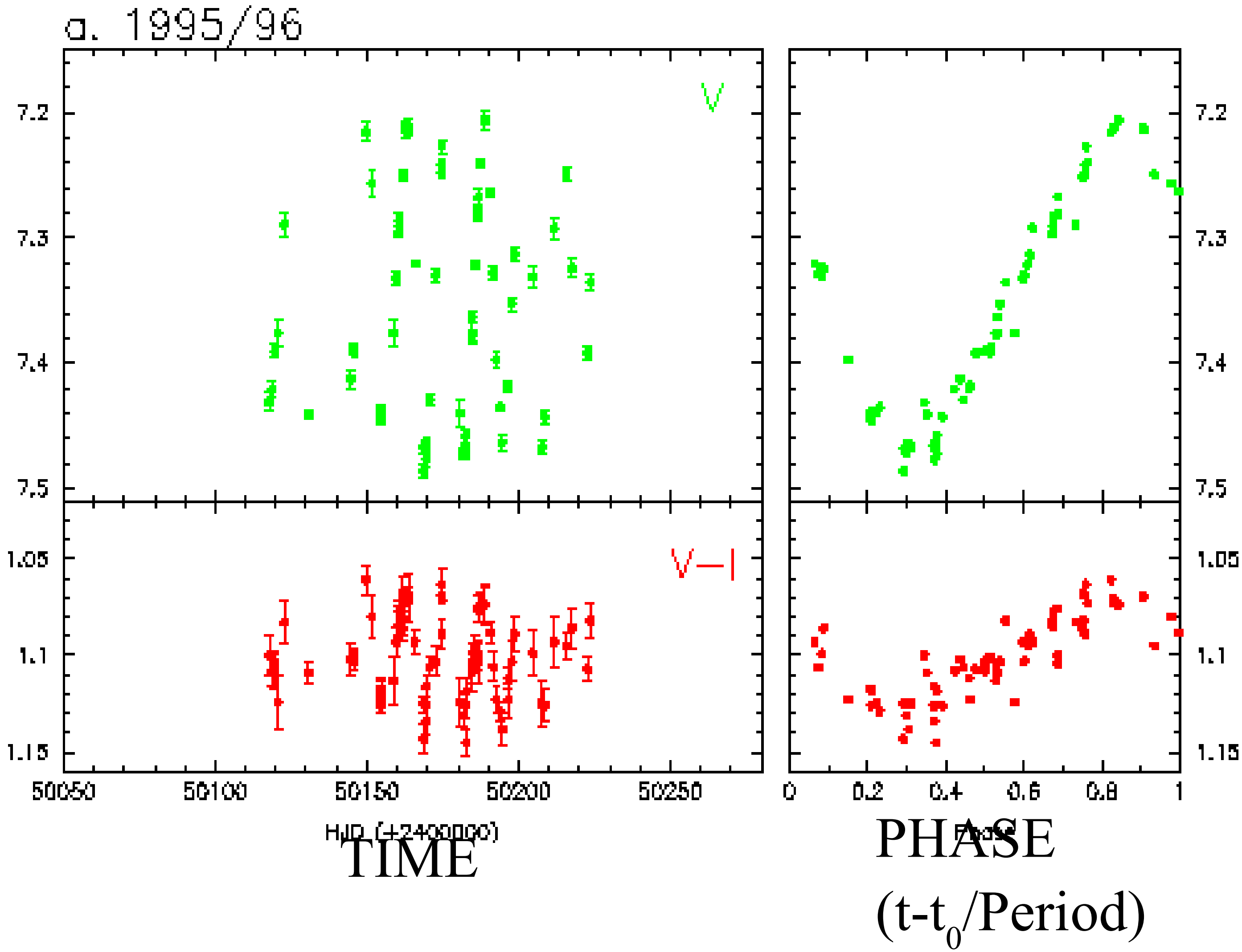
K.G. Strassmeier

- cold spots on their surface

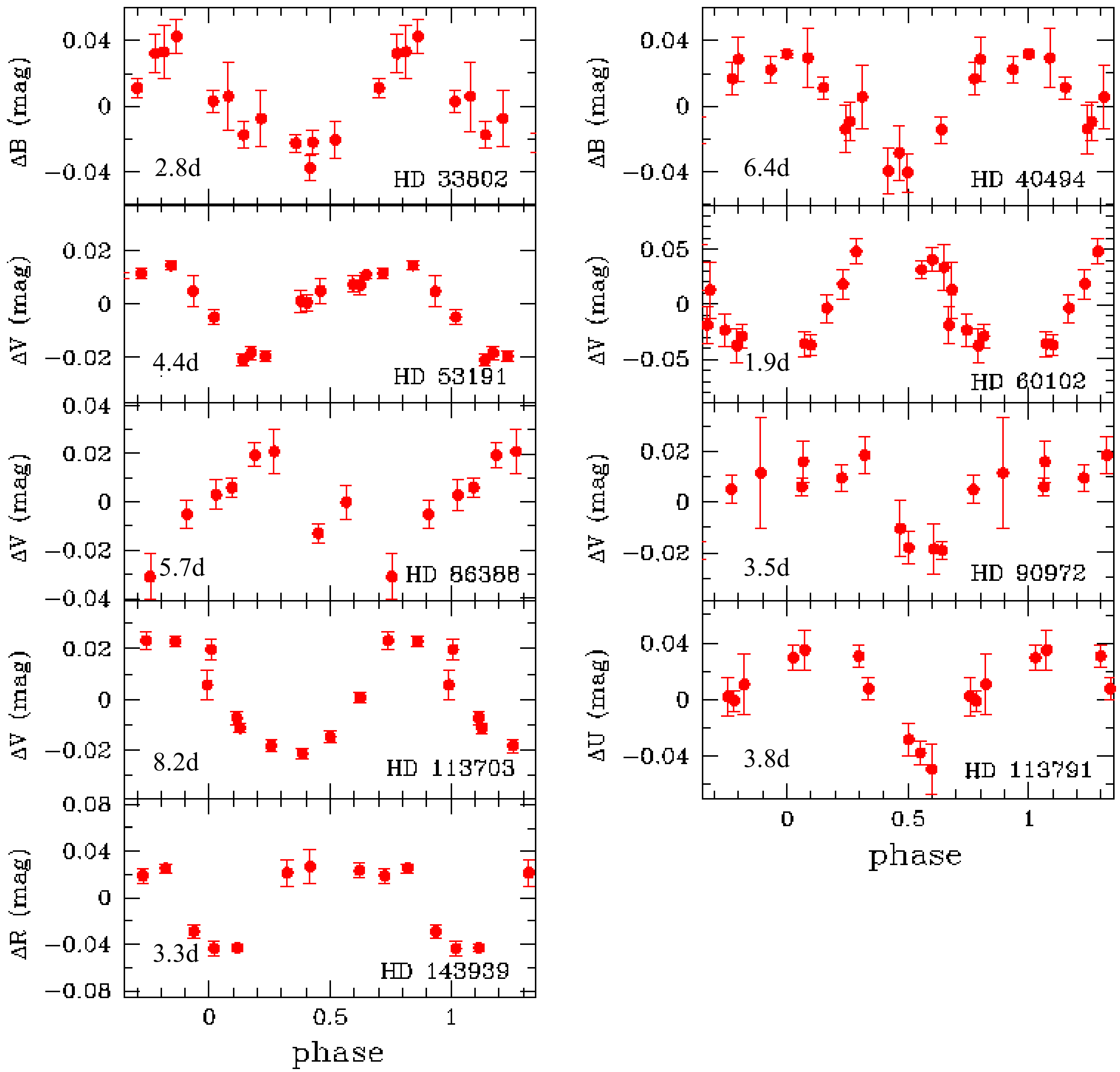
Modulation of the stellar light due to spots



- Stars exhibit (rotational) periodic light variations



• Phase-folded lightcurves of Lindroos PTTS

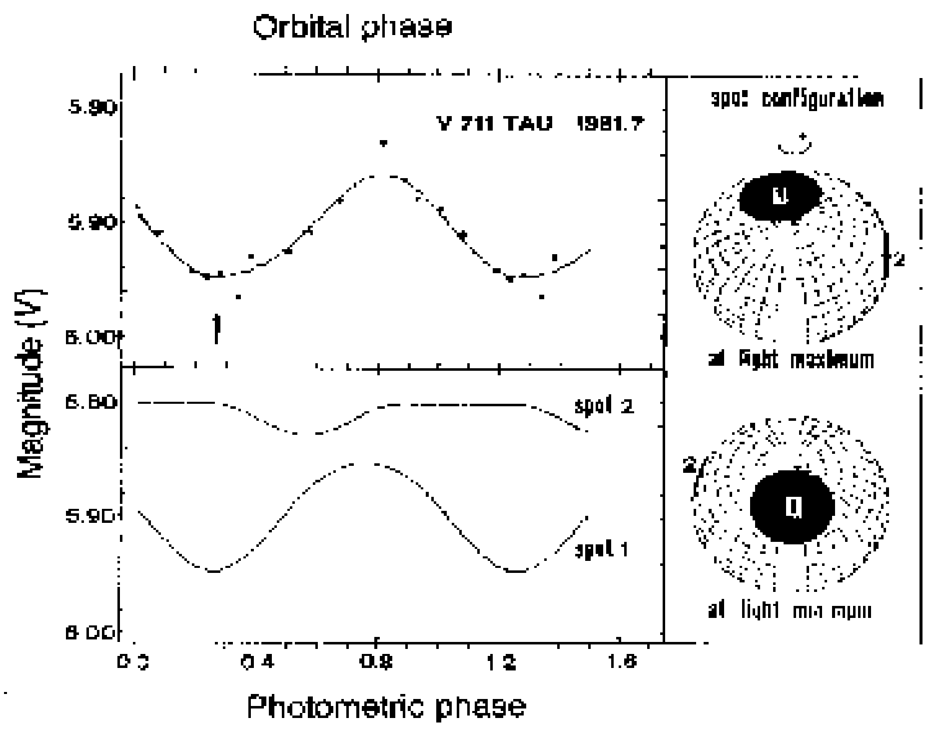


- Periodic modulations in 9 stars (out of 12)
- Periods between 1.9 – 8.2 d

Huélamo, Fernández, Neuhäuser and Wolk, 2002, A&A, in prep

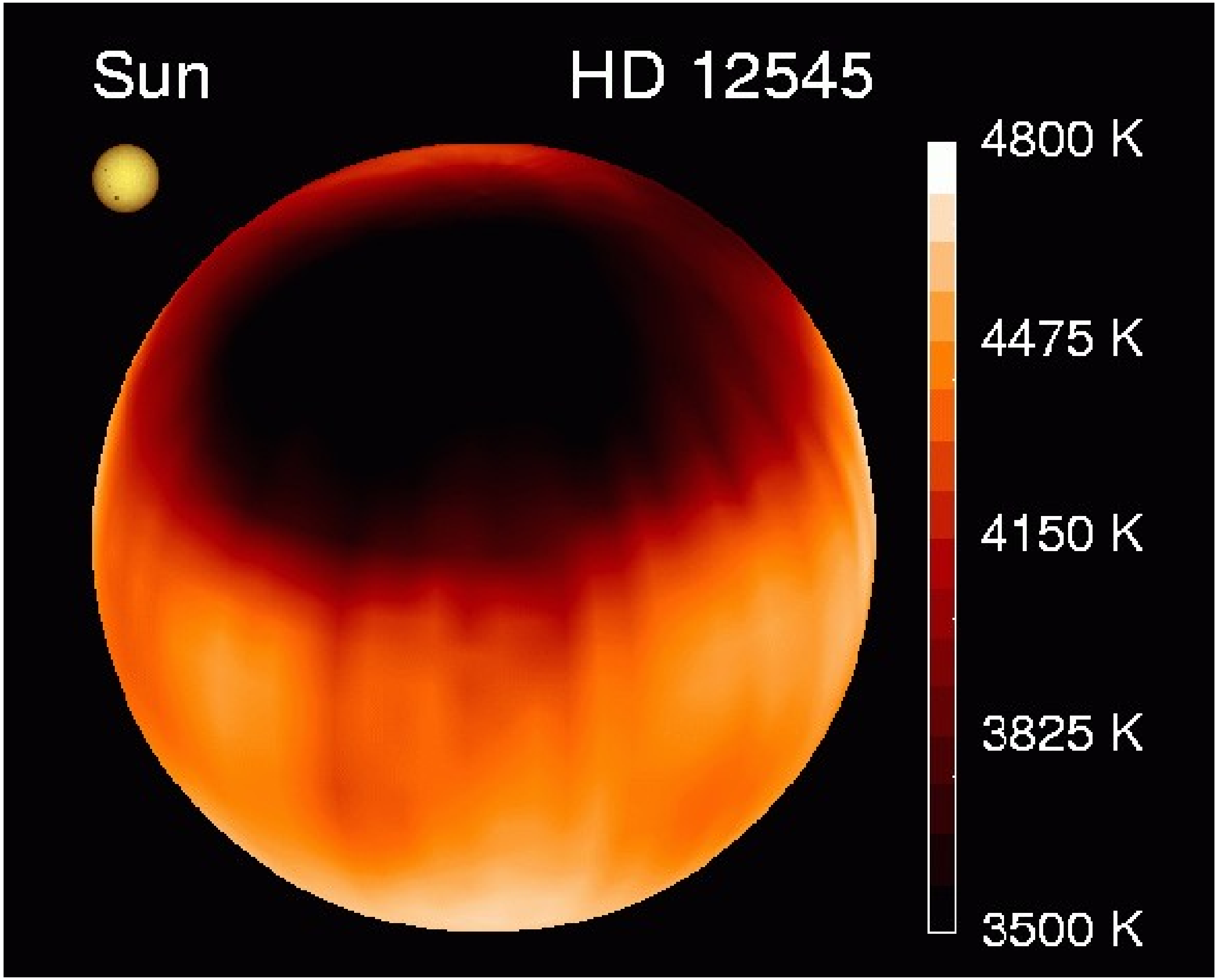
Photometric spot models

- Positions and sizes of spots are optimised
- Several bandpasses (V,R,I,..) are used for inversion
- Only simple spot configurations can be retrieved



K.G. Strassmeier

Doppler imaging

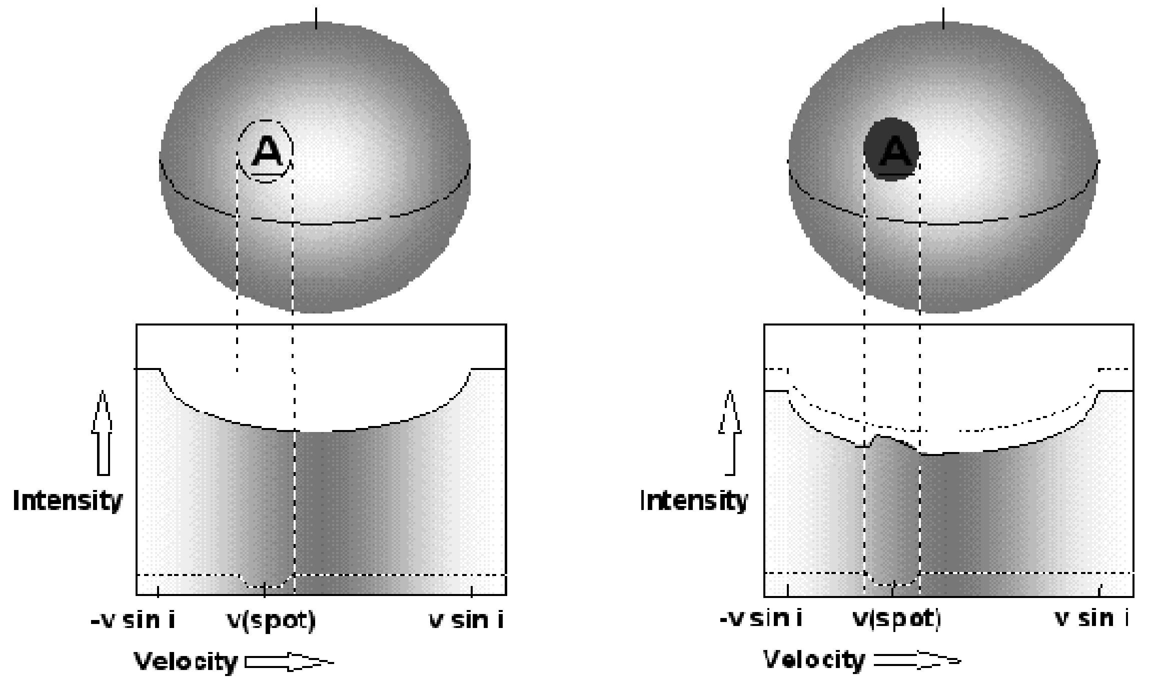


Starspots are the fingerprints of magnetic field lines and thereby the most important sign of activity in a star's photosphere.

However, they cannot be observed directly (see slide 62, only very large & very near objects are directly observable).

Therefore, an indirect approach called 'Doppler imaging' is applied, which allows to reconstruct the surface spot distribution on rapidly rotating, active stars.

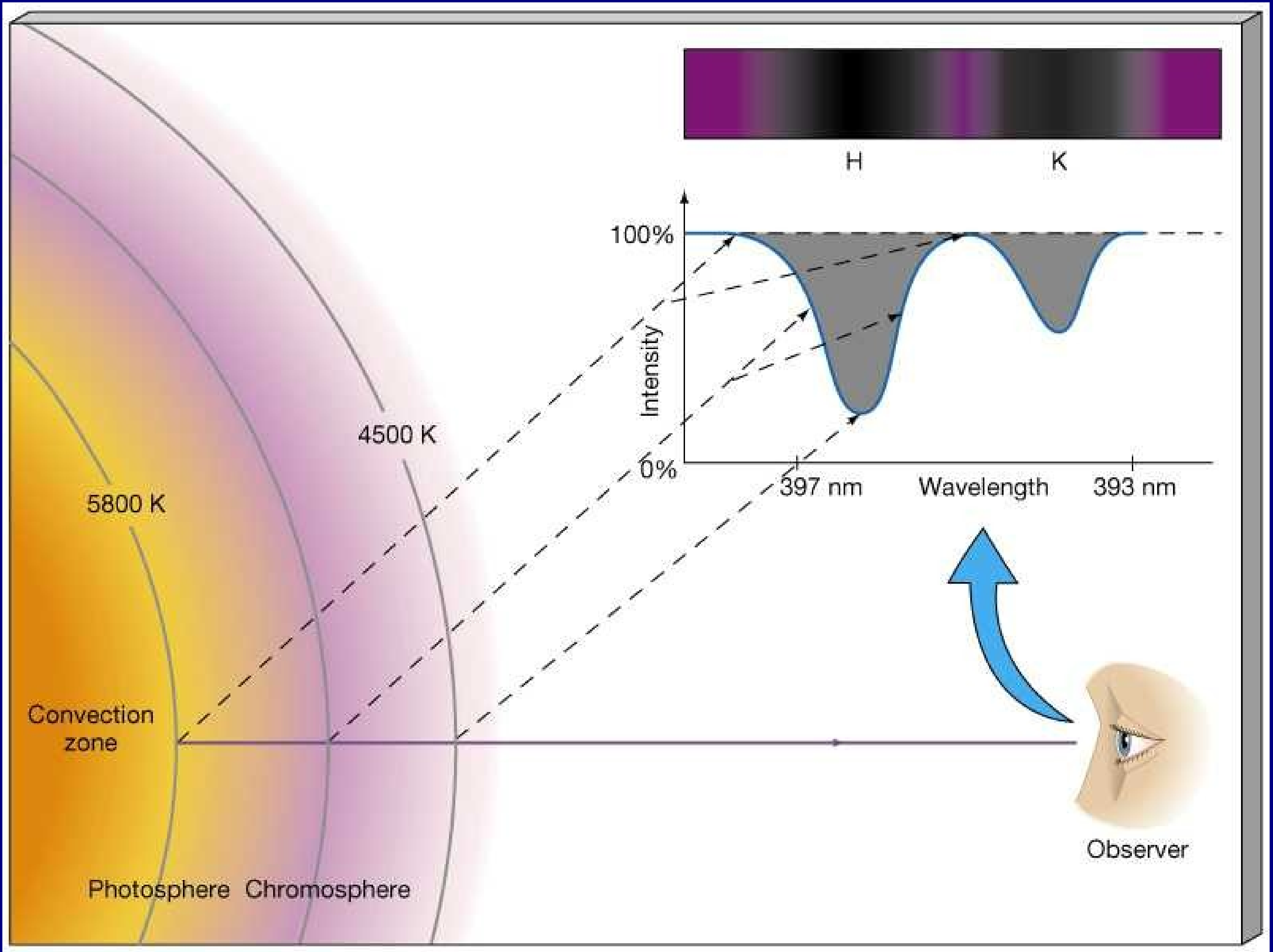
Principle of Doppler imaging



K.G. Strassmeier

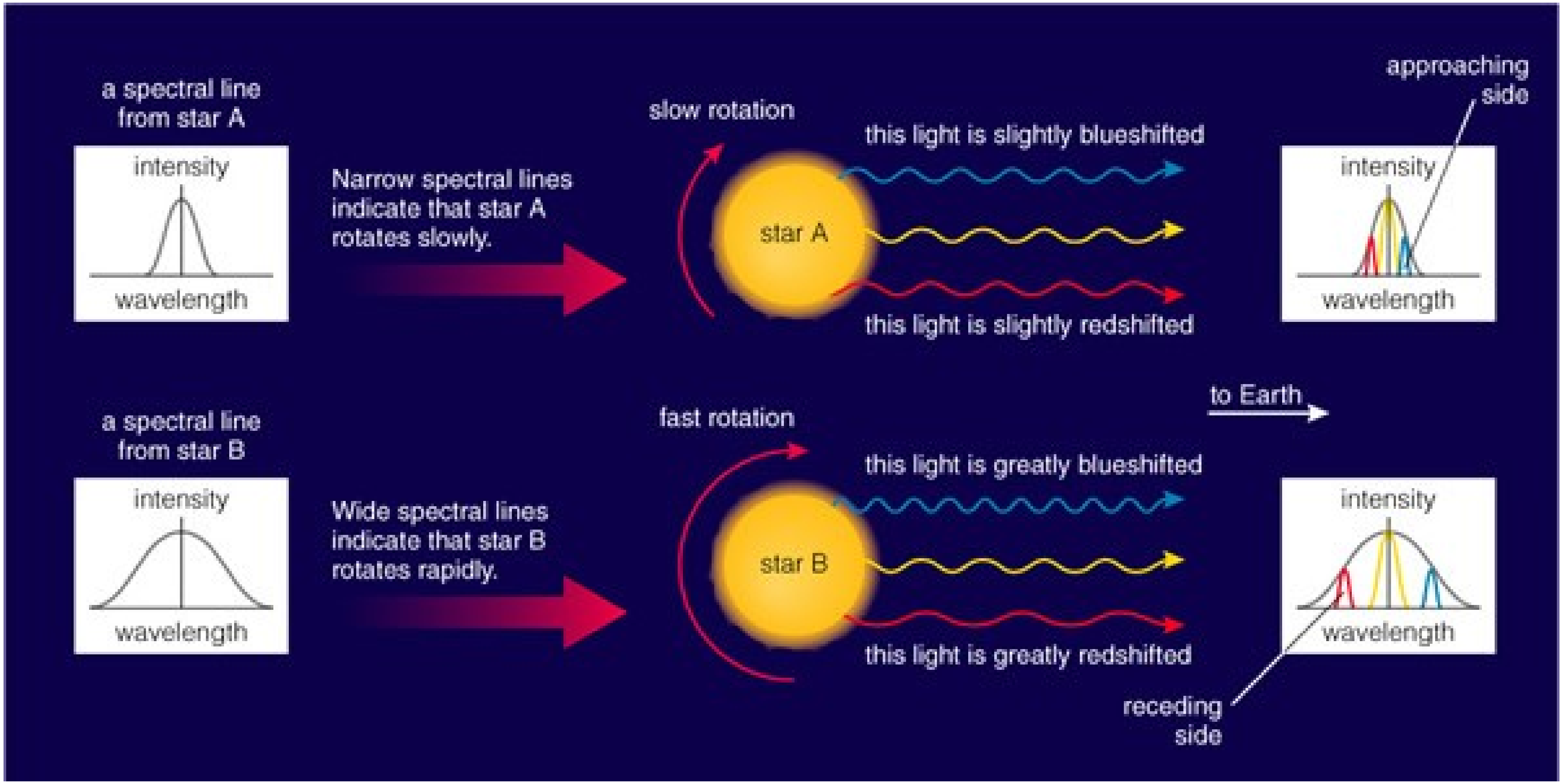
Doppler imaging is a technique, which uses a series of spectral line profiles, of a rapidly rotating star, to compute the stellar surface temperature distribution.

Spectral line formation



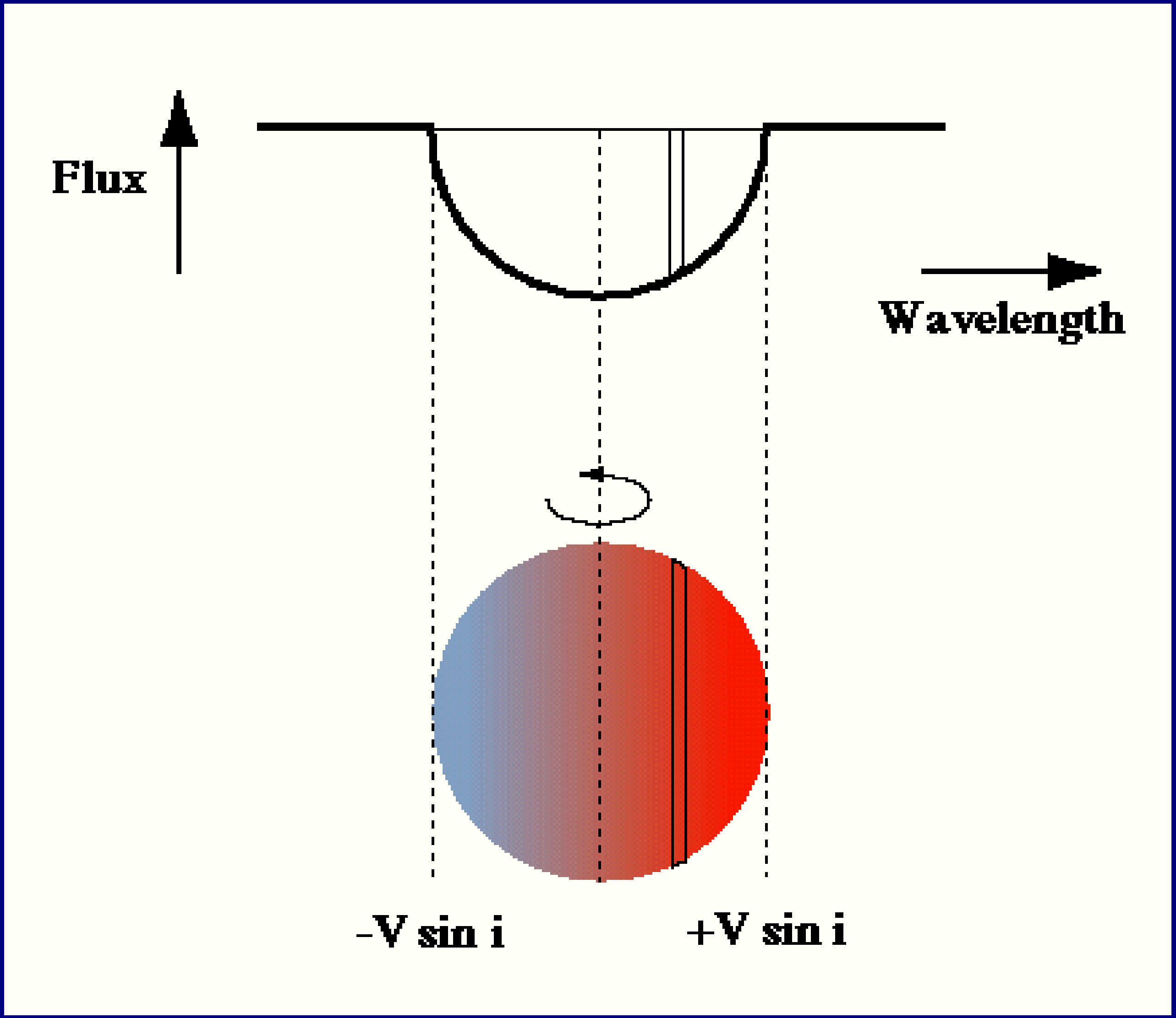
Rotational broadening: Each part of a star's surface has its own Doppler shift. When we see all the light together we see a *broad* line.

observer on the right

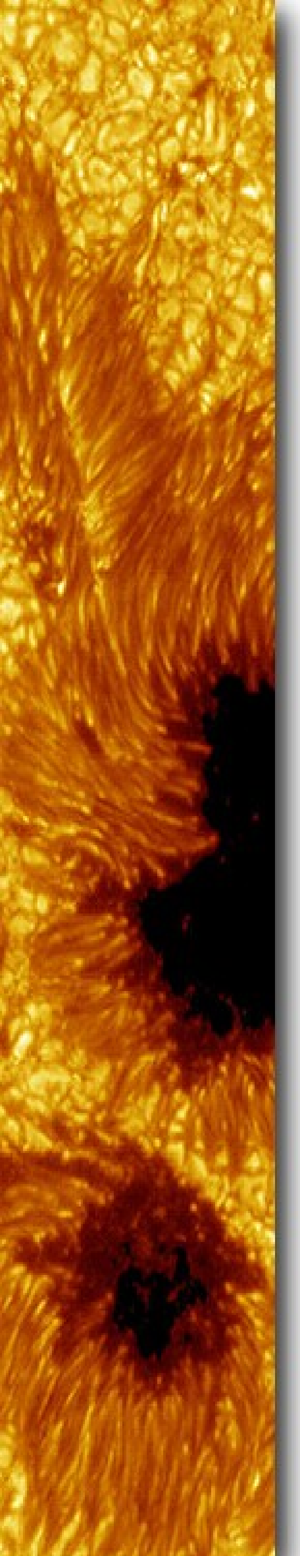


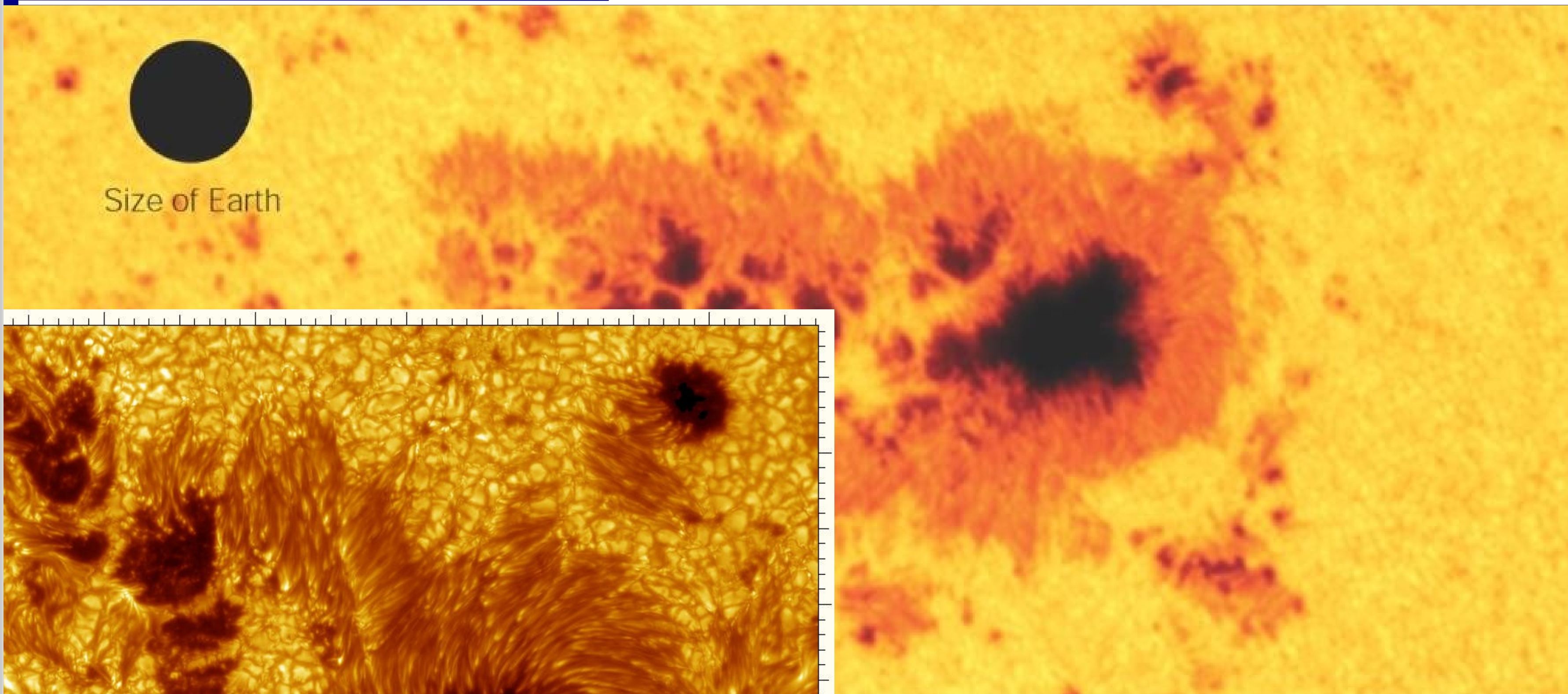
Important: we don't see the surface of the star as anything but a **point of light**; we don't see individual parts of the surface.

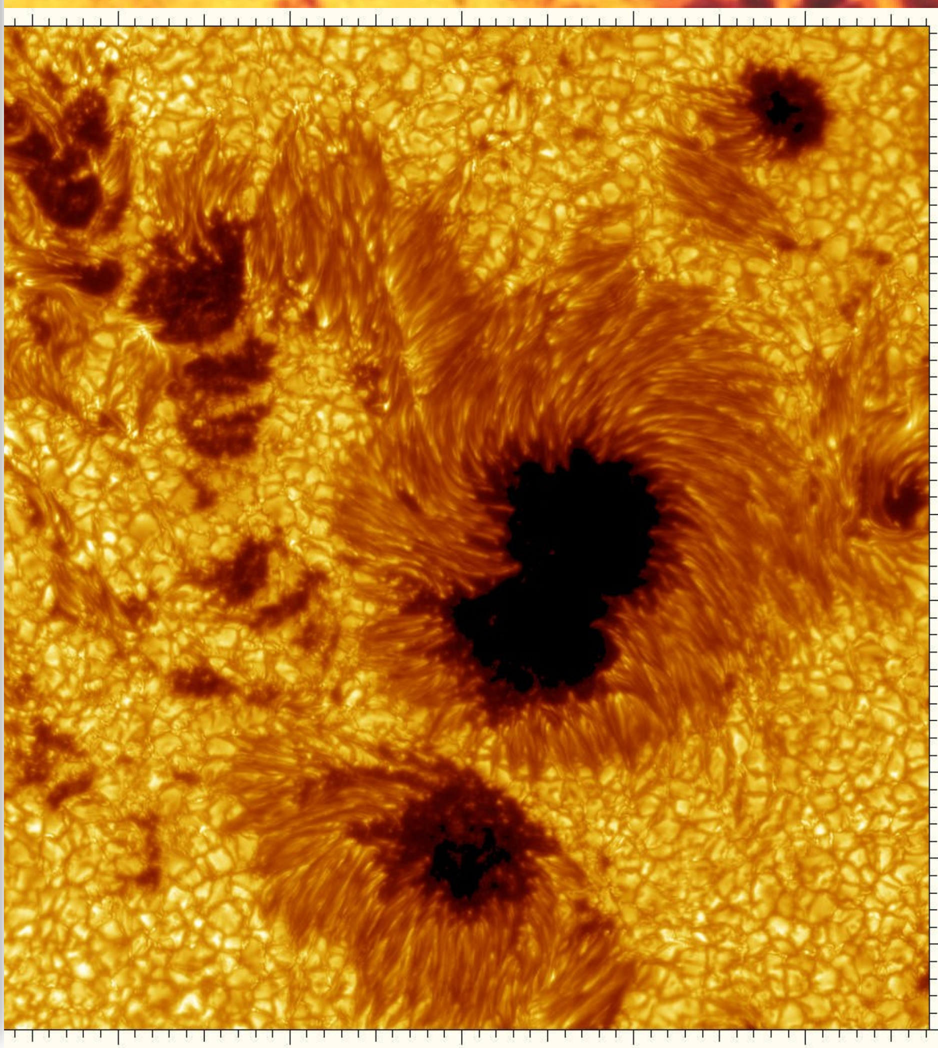
Rotational Broadening of Photospheric Absorption Lines



Sun Spots



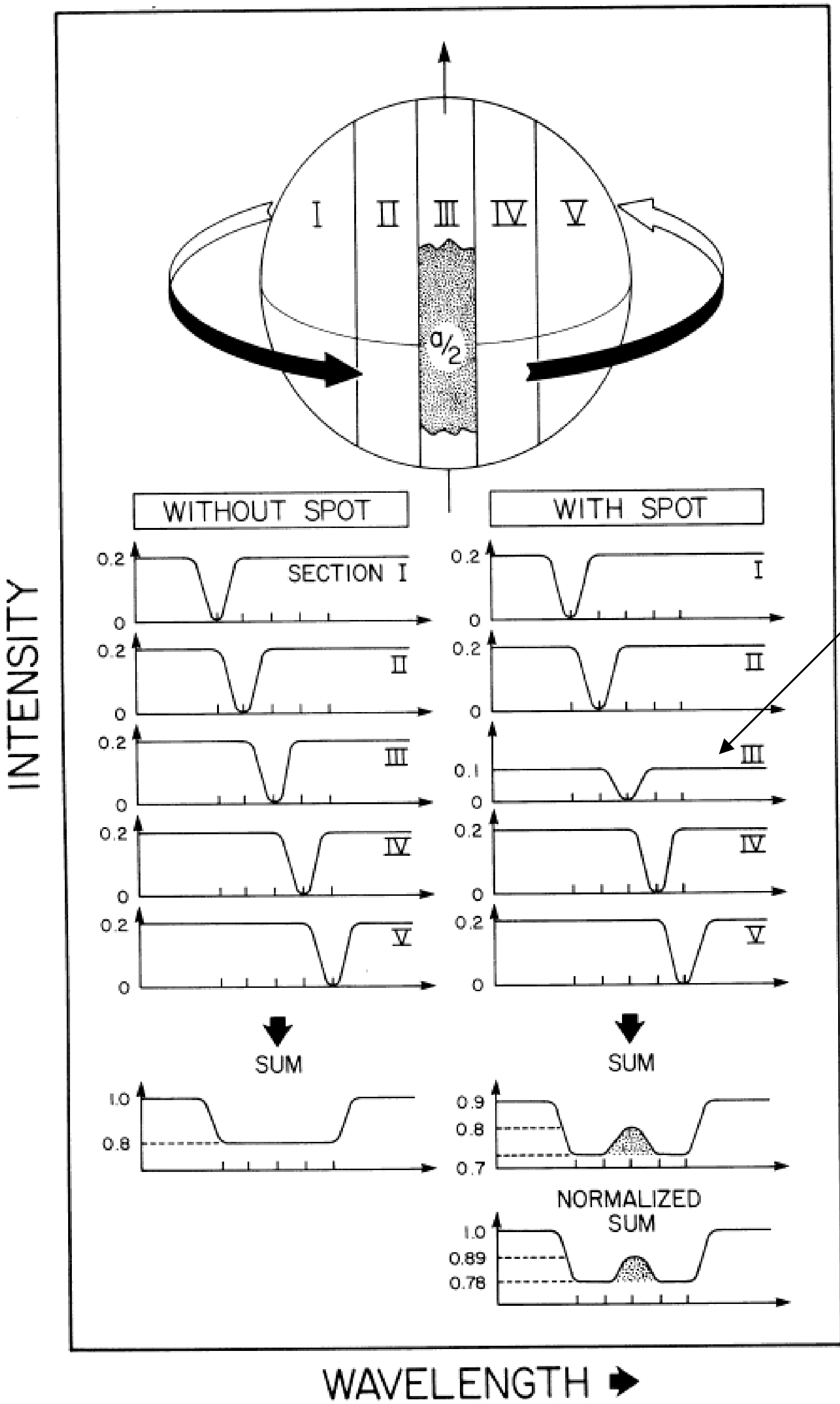




Cooler regions of the photosphere (T ≈ 4200 K).

and

Cool regions on the stellar surface radiate lower continuum flux as compared to the other regions



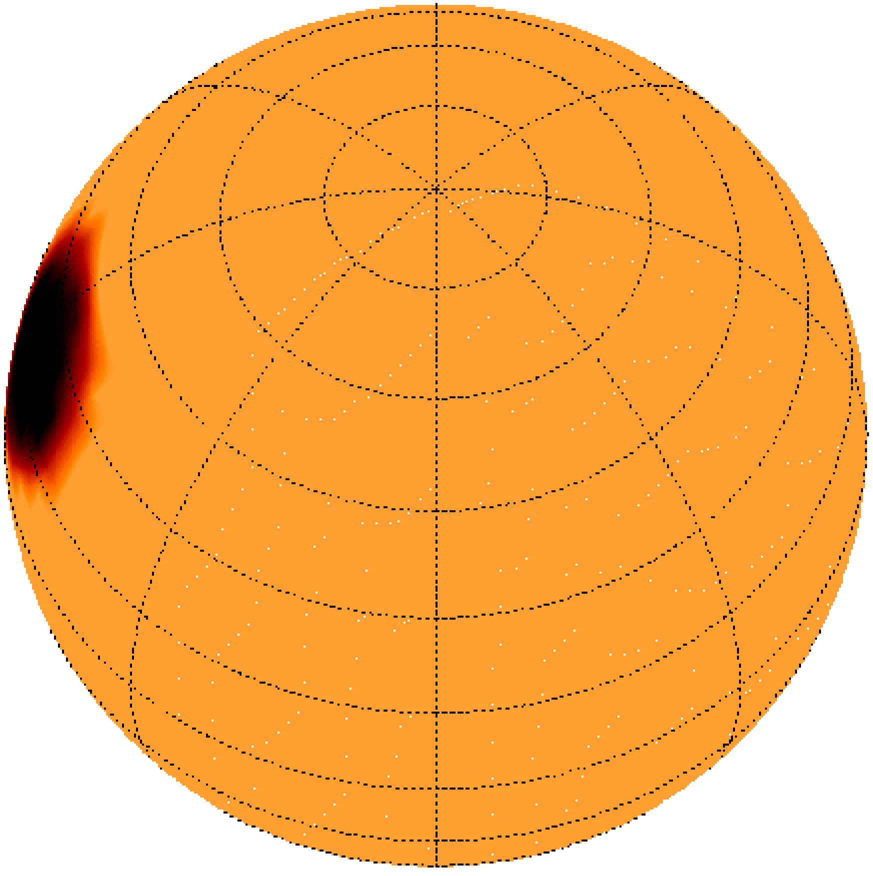
Doppler Imaging from Vogt & Penrod 1983

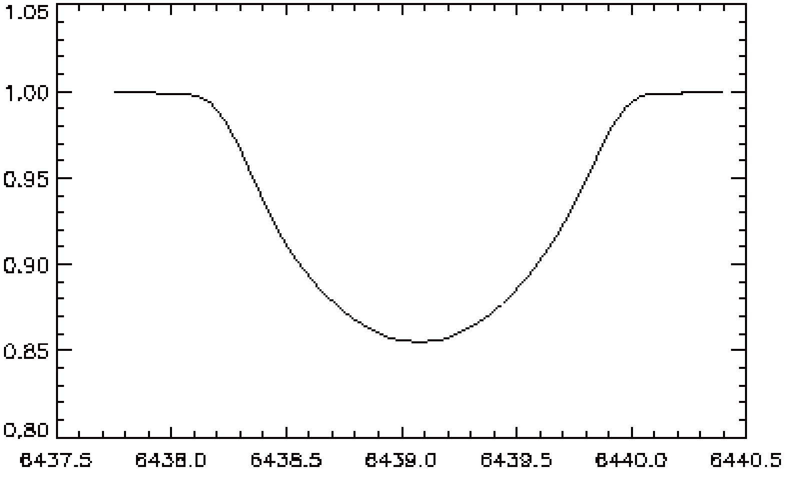
lower continuum

As a spot moves across the star the line profile changes. From an observed line profile, one can construct an image of the surface of the star. This technique has been applied to many different types of stars.

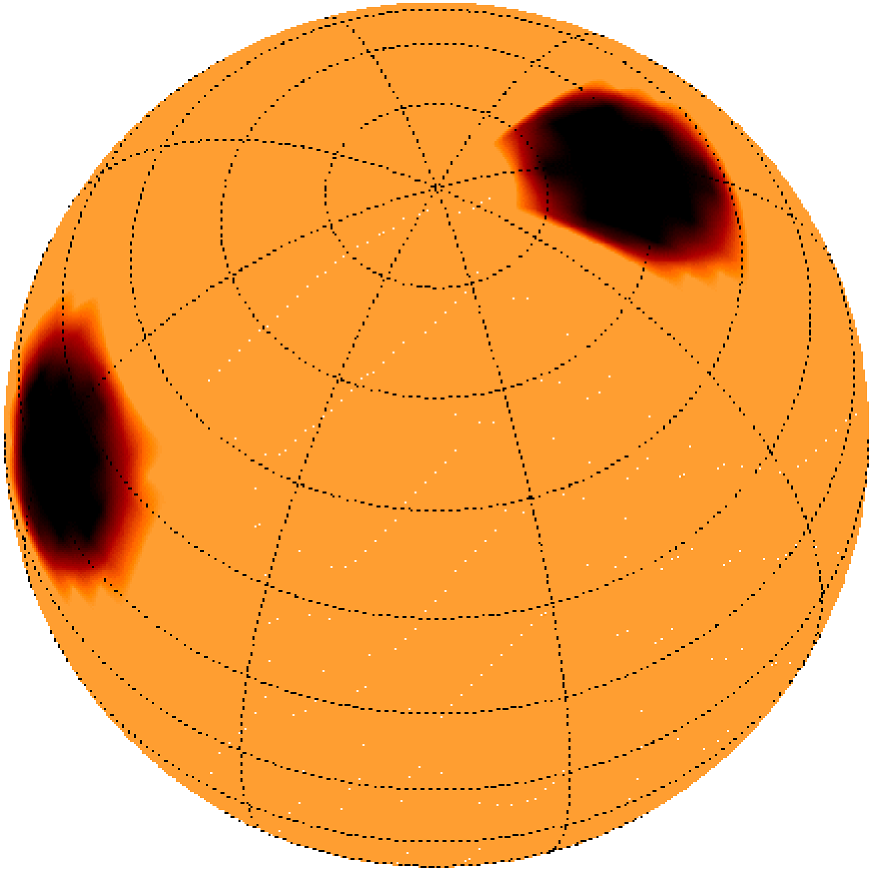
Doppler imaging$_1$

- Missing flux from spots produce line profile deformations
- 'bumps' move from blue to red wing of the profile due to the 'Doppler' effect.
- Position of spots correspond to spot longitudes

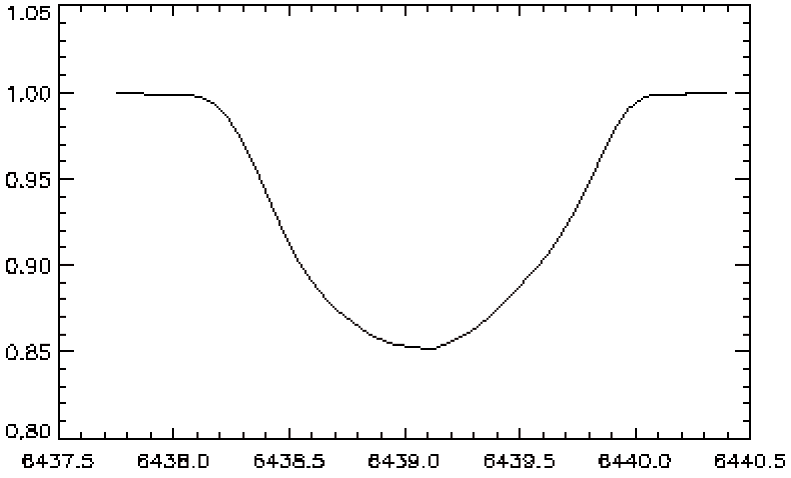




Doppler imaging$_2$



- Speed of spots give indication of the latitude (more uncertain than the longitude)
- 'bumps' from high latitude spots start out somewhere in the middle of the line wing, low latitude spots at the line shoulder



Potsdam im Oktober 2003, M. Weber
http://www.aip.de/groups/activity

Doppler imaging: math

$$F_\lambda(\phi) = \int_{\text{Fläche}} I(\ X(M), \lambda + \Delta_\lambda, \mu\ )\mu d\sigma$$

$$r_\lambda(\phi) = \frac{F_\lambda}{F_\lambda^{\text{cont}}}$$

$$D(X) \equiv \chi^2 = \sum_{\phi,\lambda} \omega_{\phi\lambda} \frac{(r_\lambda(\phi) - r_\lambda^{\text{beob}}(\phi))^2}{N_\phi N_\lambda}$$

$$\Phi(X) = D(X) + \Lambda \cdot R(X)$$

$$R_T(X) = \int\int \|\nabla X(M)\|^2 d\sigma$$

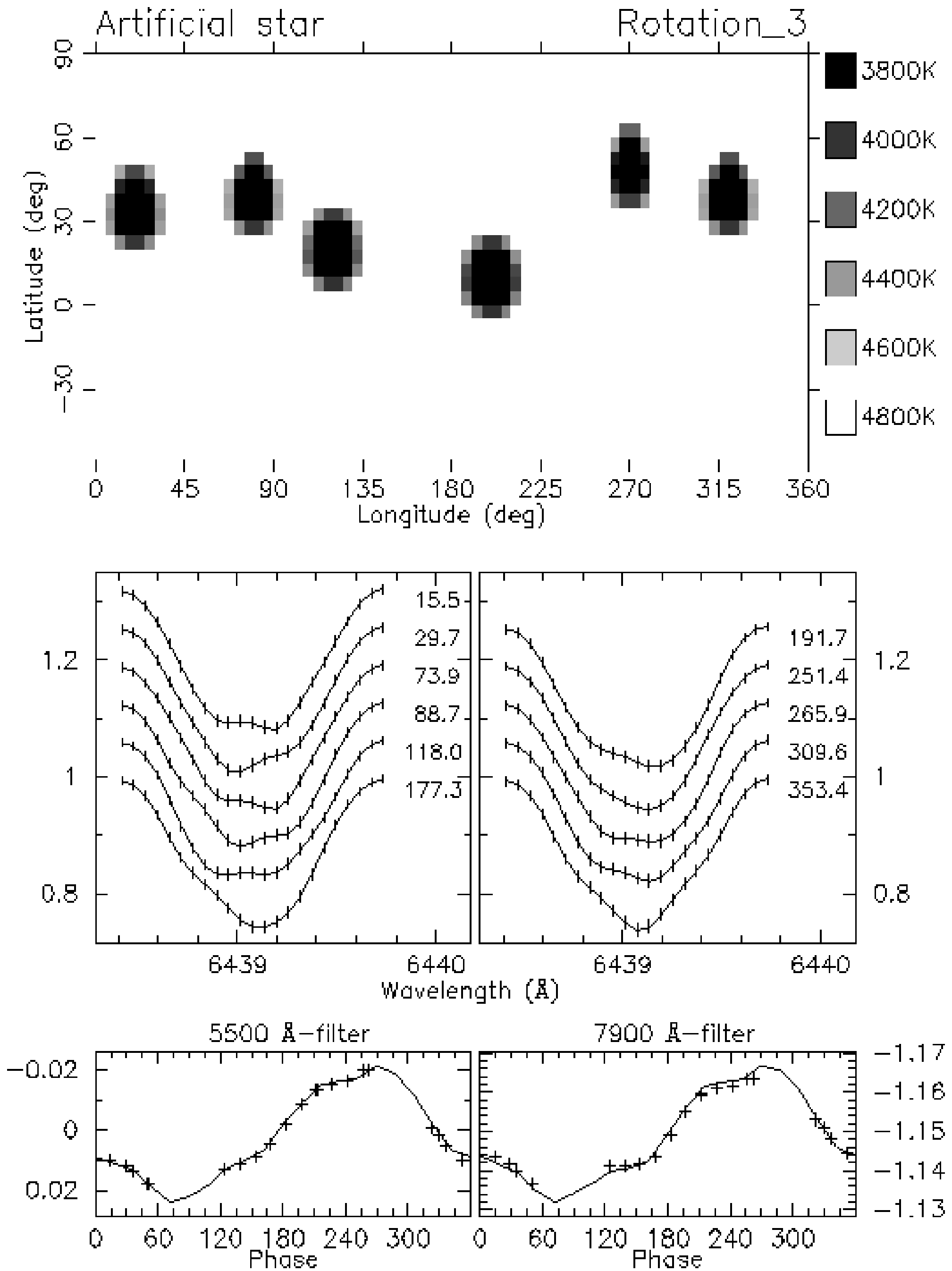
$$R_E(X) = -\int\int X(M) \log X(M) d\sigma$$

X	...	scalar mapping feature (T, Abund, ...)
F	...	Flux
μ	...	direction
r	...	normalized intensity
ω	...	weights
R	...	regularisation function (MEM, Tikhonov)

Potsdam im Oktober 2003, M. Weber
http://www.aip.de/groups/activity

Test with artificial data

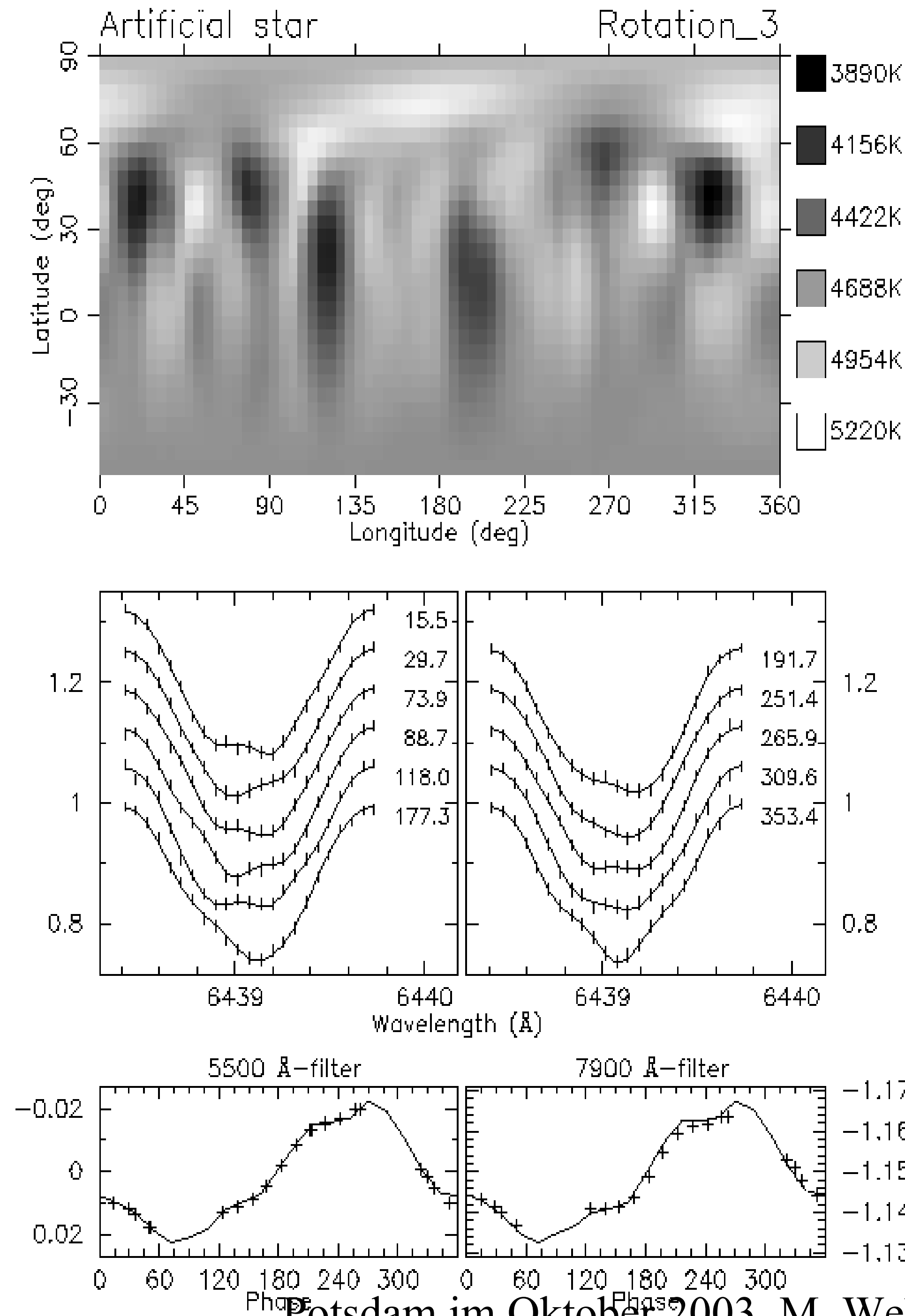
- Circular spots
- modelled after results from HK Lacertae
- S/N=100, vsini=25km/s



Potsdam im Oktober 2003, M. Weber
http://www.aip.de/groups/activity

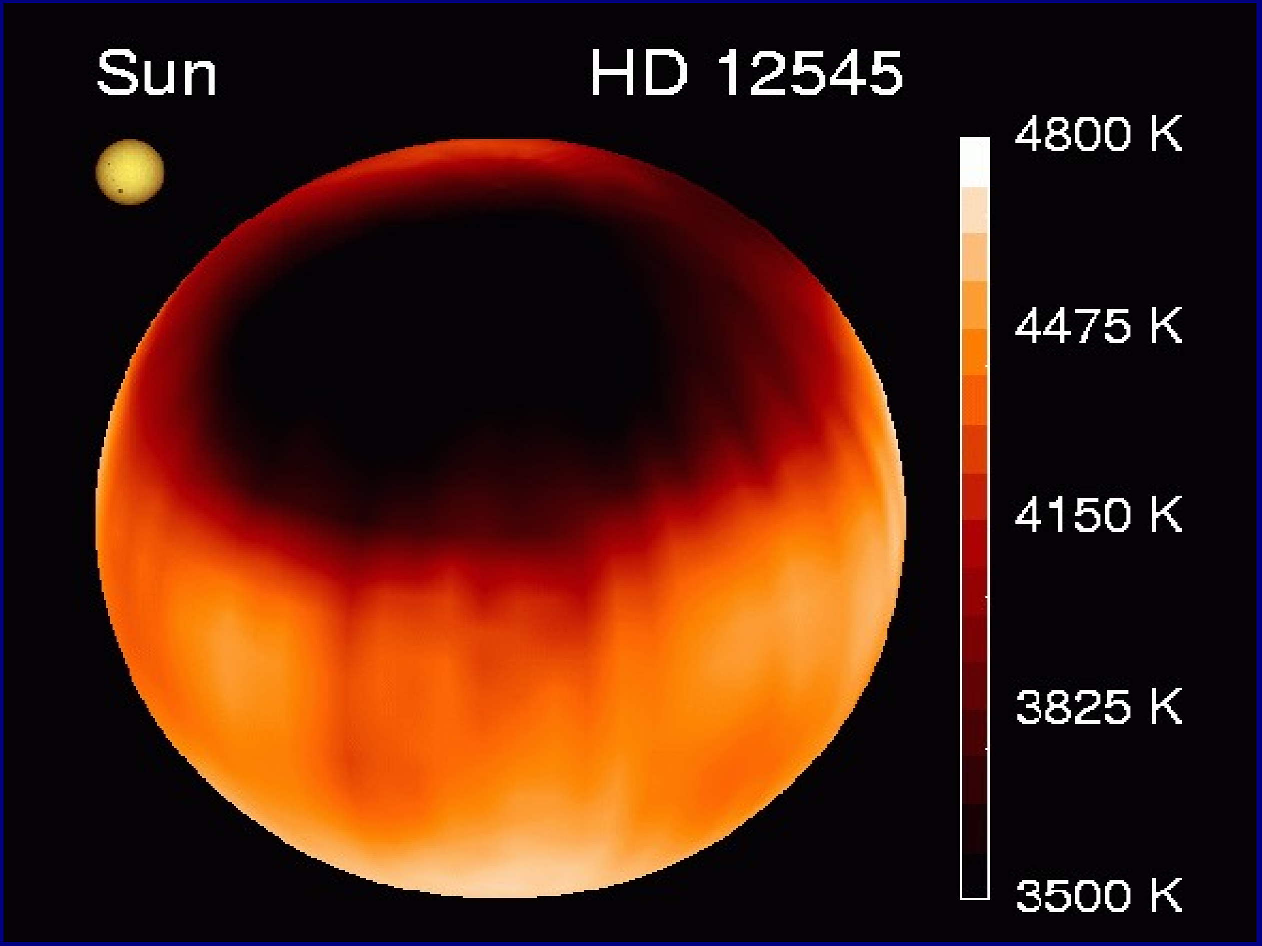
Result from artificial data

- Longitudinal information is well preserved
- Spots appear elongated



Polar spots

- In contrast to the sun, polar spots are frequent on stars



Potsdam im Oktober 2003, M. Weber
http://www.aip.de/groups/activity

Spots on the ZAMS

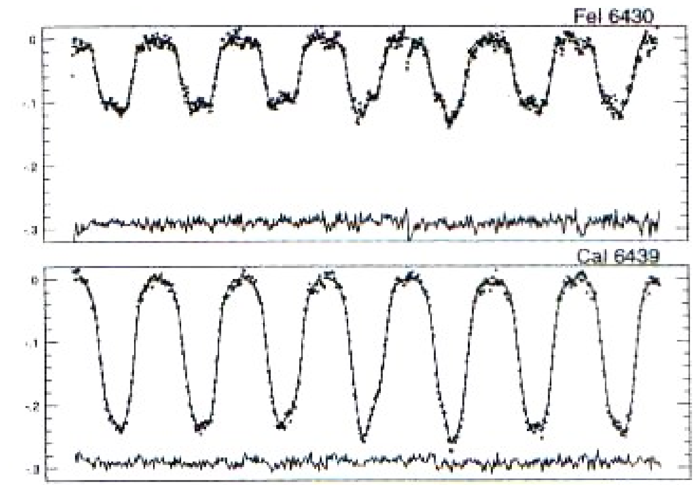


Figure 2. Observed flux profiles (points) and theoretical fits (line) for the Fe I phase-series (top) and Ca I phase-series (bottom) for HII 686. At the bottom of each graph are plotted the residuals of the data from the line fits.

- Two Pleiades dwarfs – K5V, M0
- Vsini=60-70 km/sec
- Periods ~10 hours
- Inclinations ~ 50-60 degrees

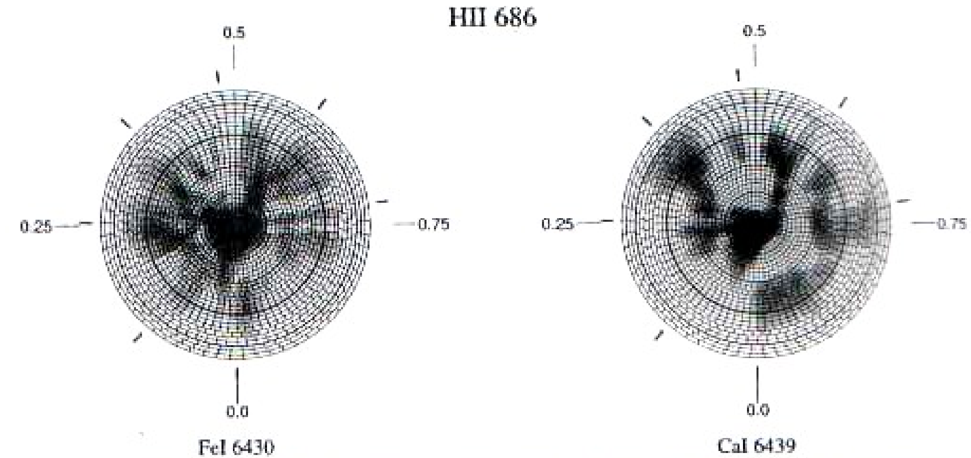
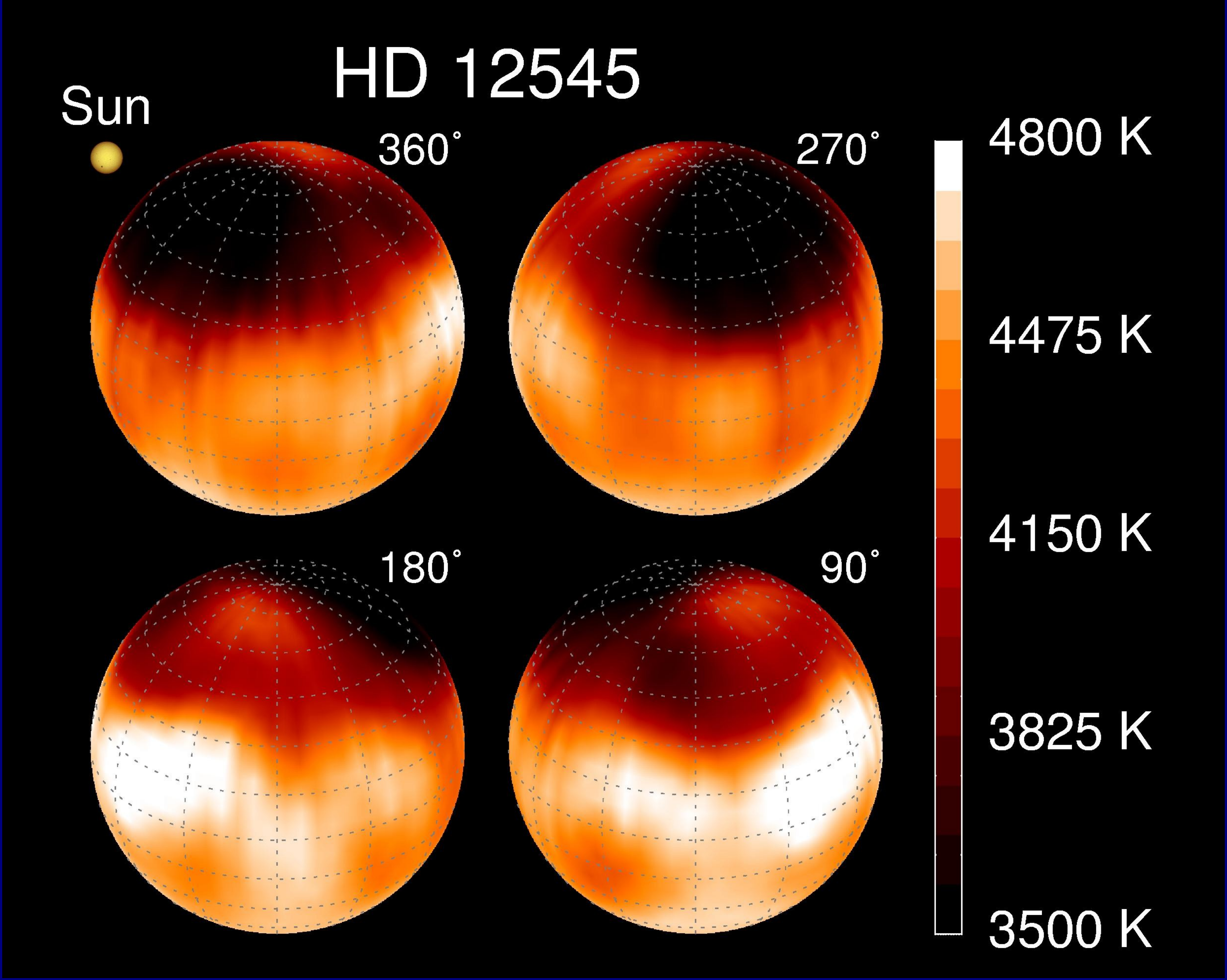


Figure 3. Doppler images of the M0V (ZAMS) star HII 686. These images are flattened polar projections which extend down to a latitude of -45°. The equator is indicated by the bold latitude parallel.

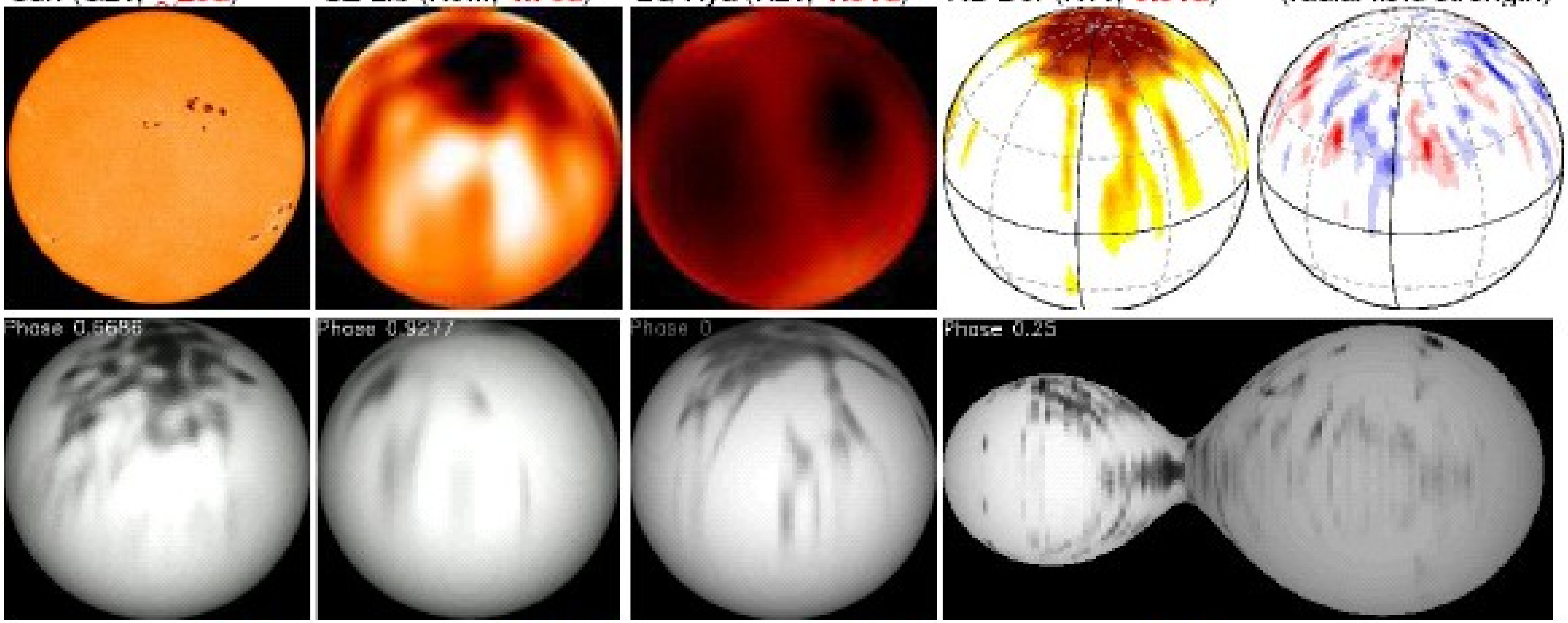
- **Again, dark polar spots**



HD 12545
Sun
360˚
270˚
180˚
90˚
4800 K
4475 K
4150 K
3825 K
3500 K

- How does **surface distribution** of emerging flux depend on stellar rotation?

Sun (G2V, **$\gtrsim$25d**)[1] UZ Lib (K0III, **4.76d**)[3] LQ Hya (K2V, **1.61d**)[2] AB Dor (K1V, **0.51d**)[4] (radial field strength)



He 699 (G2V, **0.49d**)[5] HK Aqr (M1Ve, **0.41d**)[5] BO Mic (K3V, **0.38d**)[5] AE Phe (G1V, **0.36d**)[5]

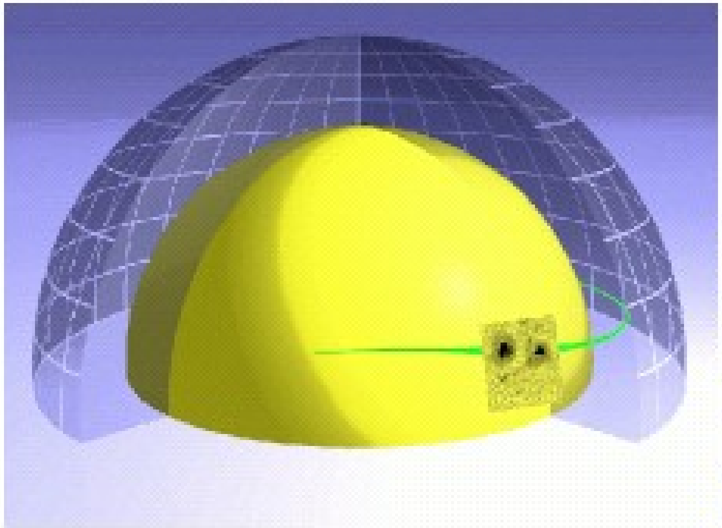
[1]SoHO/NASA; [2]Kovári et al. (2004); [3]Oláh et al. (2002); [4]Donati & Collier Cameron (1997); [5]Barnes et al. (2001a,b, 2004a,b)

- **high-latitude spots** on rapidly rotating stars (e.g. Strassmeier 2002)
- spot coverage up to 40% (O'Neal et al. 2004) ; Sun: $< 0.5\%$

The Solar Paradigm

- strong magnetic fields (flux tubes) originate from **bottom of convection zone** (e.g. van Ballegooijen 1982; Moreno-Insertis 1986)

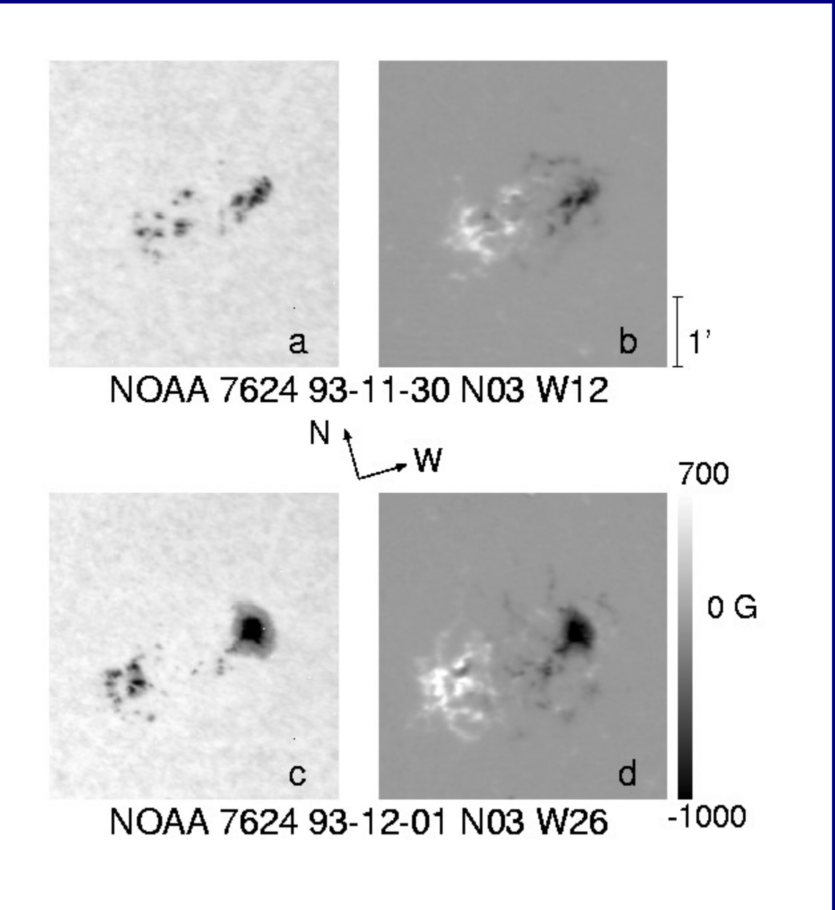
- basic model:
  - field amplification in tachocline
  - storage at interface to radiative core
  - beyond critical field strength onset of instability
  - flux loops rising through convection zone
  - emergence at stellar surface
  - disconnection from sub-surface roots
  - dispersal and transport with large-scale flow

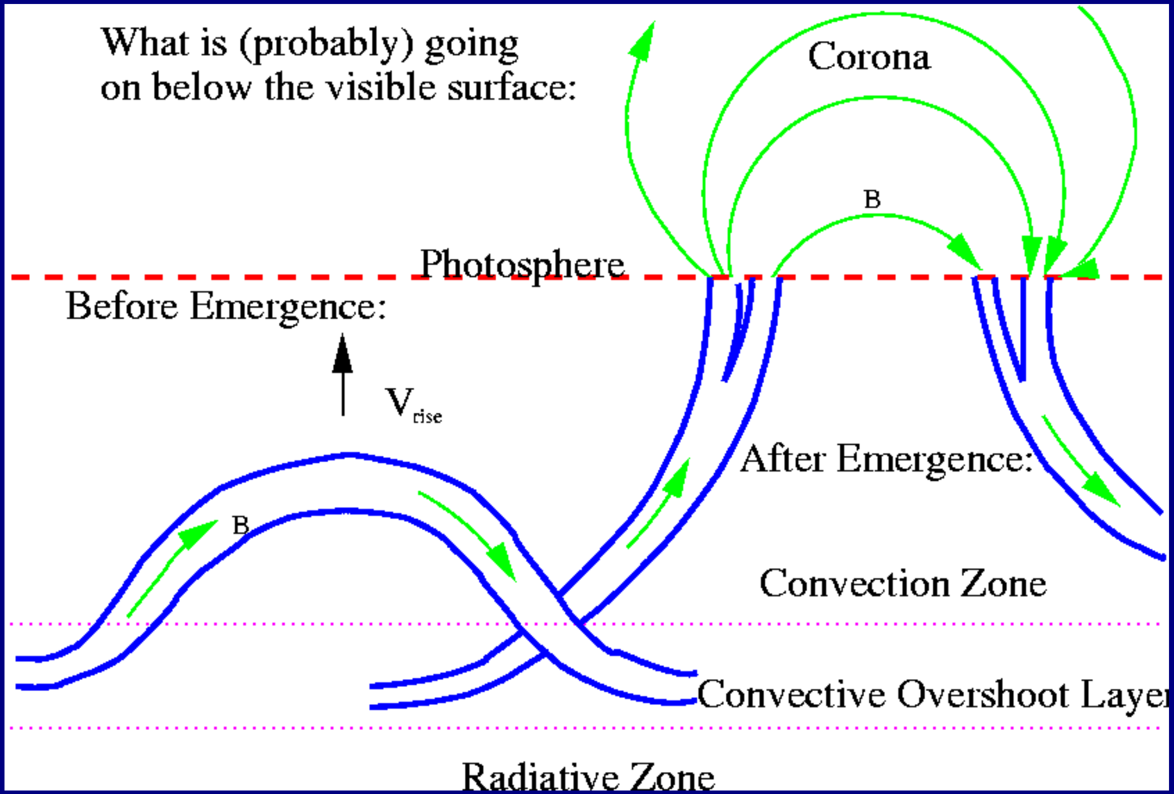


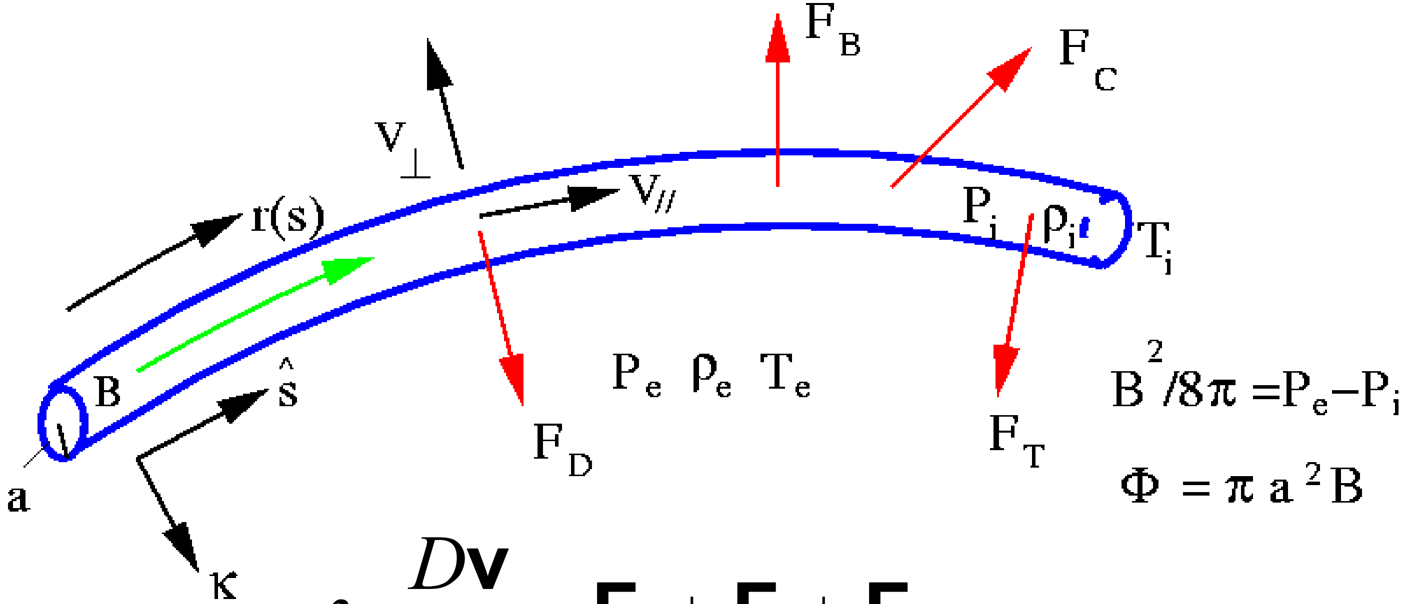
Caligari et al. (1995)

- predictions in agreement with emergence latitudes, tilt angles, proper motions of sunspot groups (e.g. D'Silva & Choudhuri 1993; Fan et al. 1994; Caligari et al. 1995)

hmi.stanford.edu/TeamMeetings/Feb_2006/Proceedings/T3.Fisher/talk-tutorial.ppt
George Fisher







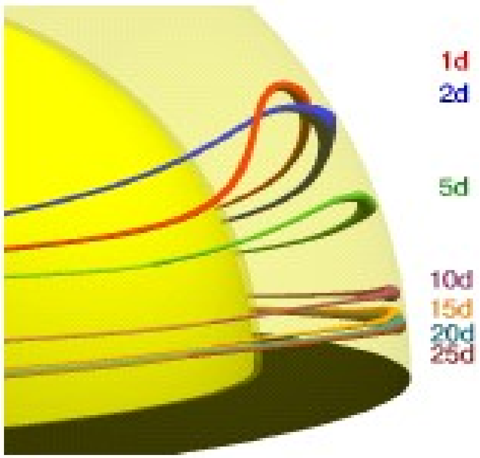
$$\rho_i \frac{D\mathbf{v}}{Dt} = \mathbf{F_b} + \mathbf{F_t} + \mathbf{F_c}\ .$$

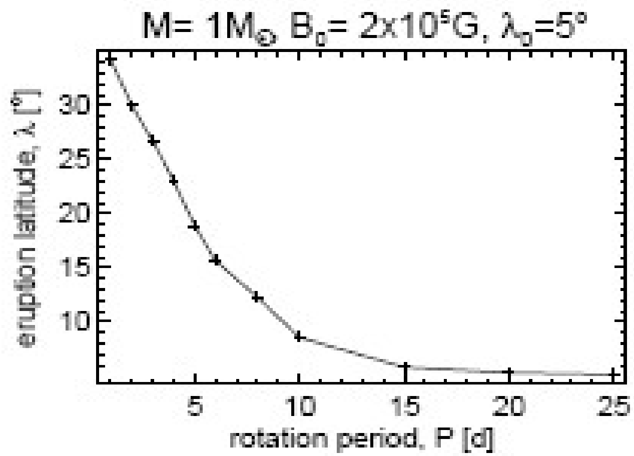
$$\mathbf{F_b} = g(\rho_e - \rho_i)\hat{\mathbf{r}}$$

$$\mathbf{F_c} = -2\rho_i \mathbf{\Omega} \times \mathbf{v}$$

$$\mathbf{F_t} = \frac{B^2}{4\pi}\boldsymbol{\kappa}$$

Eruption properties

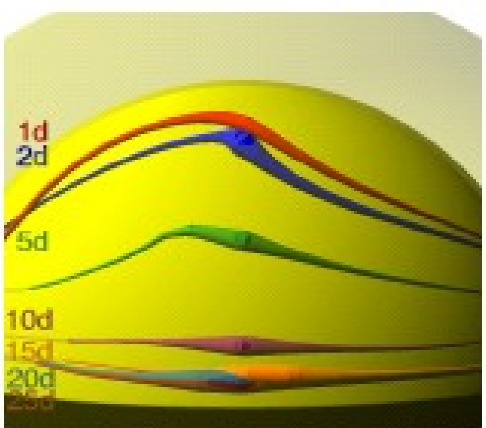


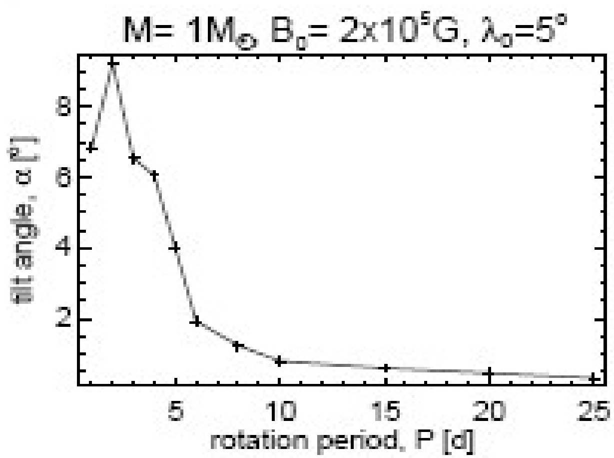


poleward deflection

(e.g. Choudhuri & Gilman 1987)

- rising flux loop expands in longitude → 'cyclonic effect'





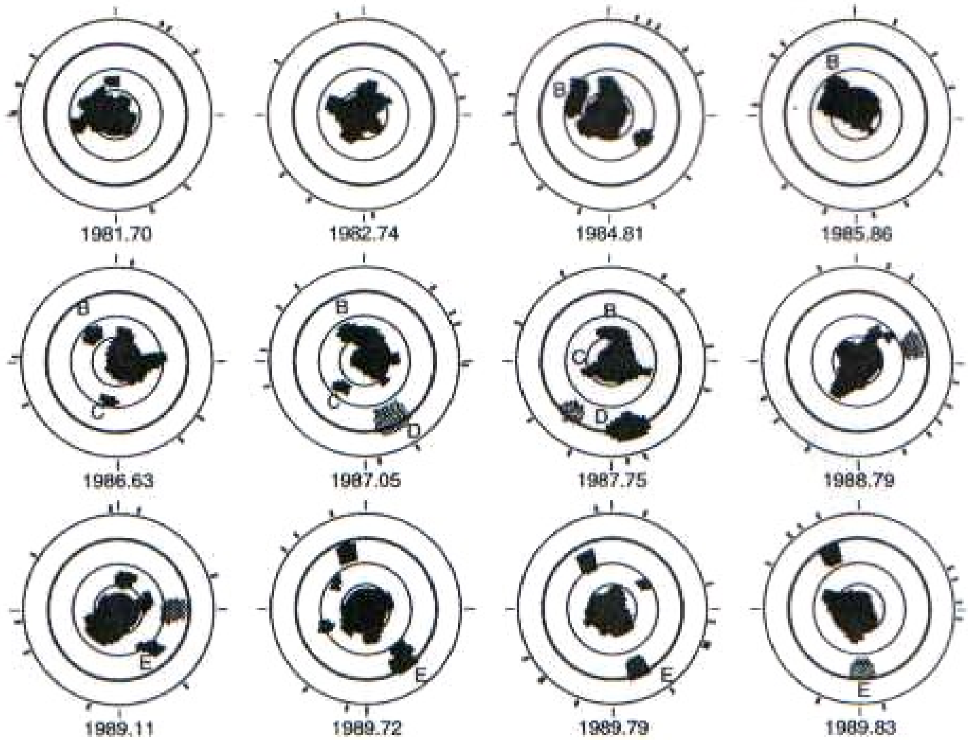
tilted bi-polar spot group

(e.g. D'Silva & Choudhuri 1993)

- effects depend on ratio between magn. buoyancy and Coriolis force

Spots in HR 1099 (Vogt & Hatzes)

- Doppler images of HR 1099 (RS CVn star) from 1981-1989
- Star dominated by a large polar spot
- Smaller spots form in equatorial regions and migrate toward pole
- Spots merge together and may merge into polar spot
- Polar rotation fixed with orbital period
- Equatorial rotation slightly faster
- Some spots persist over years
- Spot patterns reminiscent of solar coronal holes

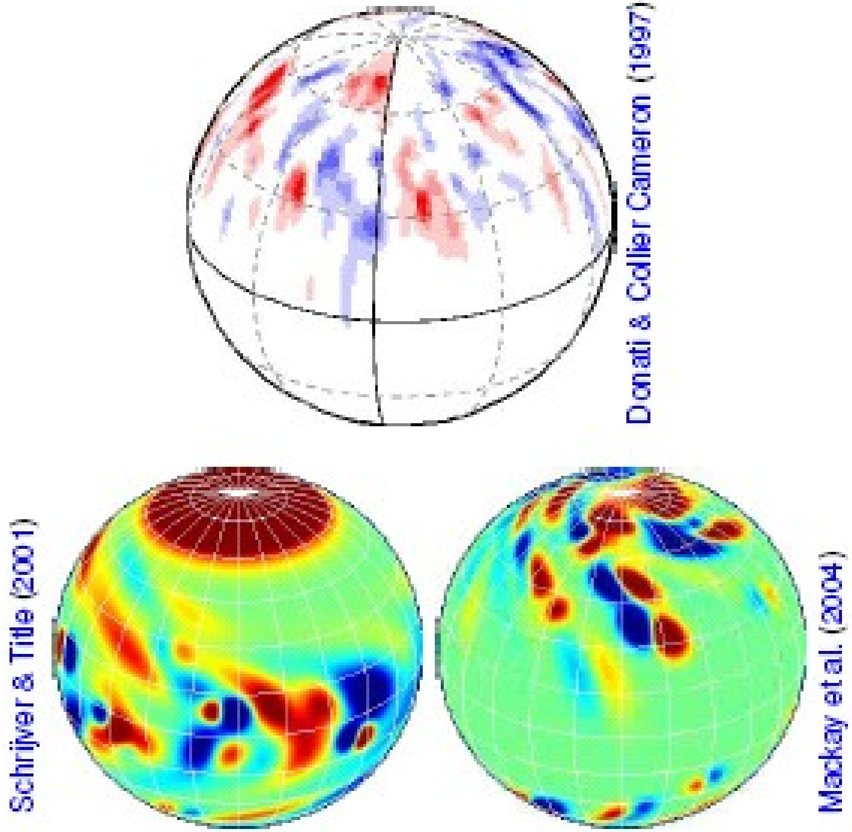


High-latitude spots supported by meridional flows

- combination of pre-eruptive & post-eruptive flux transport to high latitudes

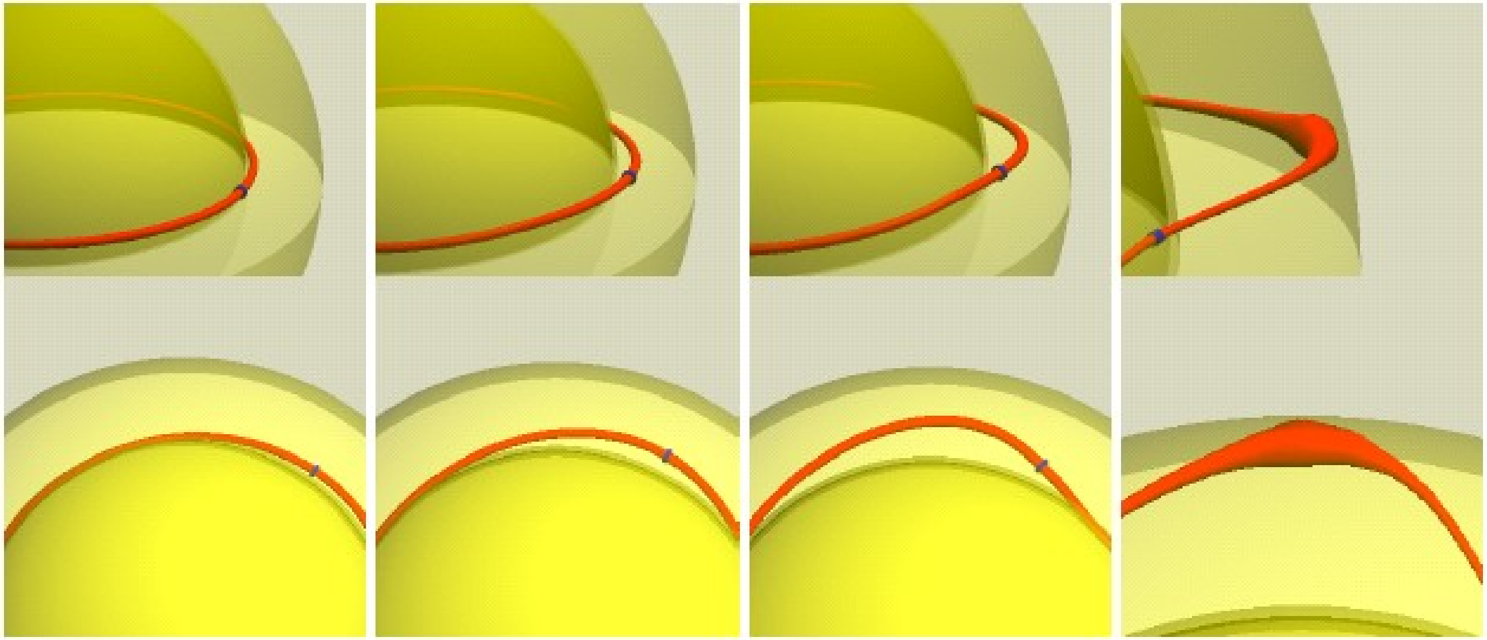
- observation: mixture of polarities at high latitudes (e.g. Donati & Collier Cameron 1997)
  - 30× solar flux emergence → unipolar polar spot (Schrijver & Title 2001)
  - 30× flux emergence, larger latitudinal range, strong meridional flows → mixture of polarities (Mackay et al. 2004)

- strong meridional circulation enhances pre-eruptive poleward deflection (Holzwarth et al. 2006)

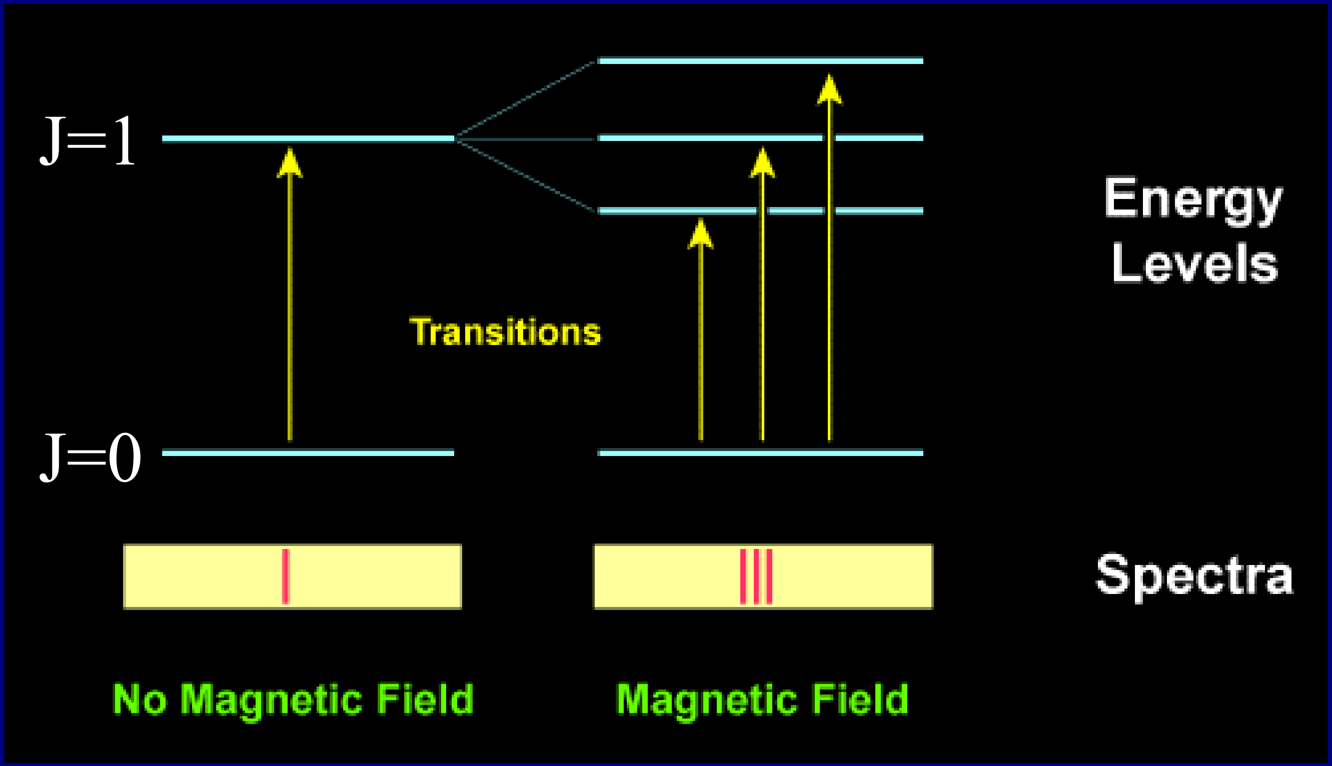


Images courtesy D. Mackay

Eruption of magnetic flux tubes



Measurement of stellar magnetic fields: Zeeman effect



(Zeeman 1896)

broadening (or splitting) of spectral lines: field strength

Polarization of spectral lines: field strength and orientation

extraction of Zeeman signatures: Multi-line techniques

Zeeman-Doppler Imaging

How to reconstruct a stellar vectorial magnetogram?

RESULTS:

giant starspots at high latitude

<u>azimuthal (toroidal)</u> component of the surface field

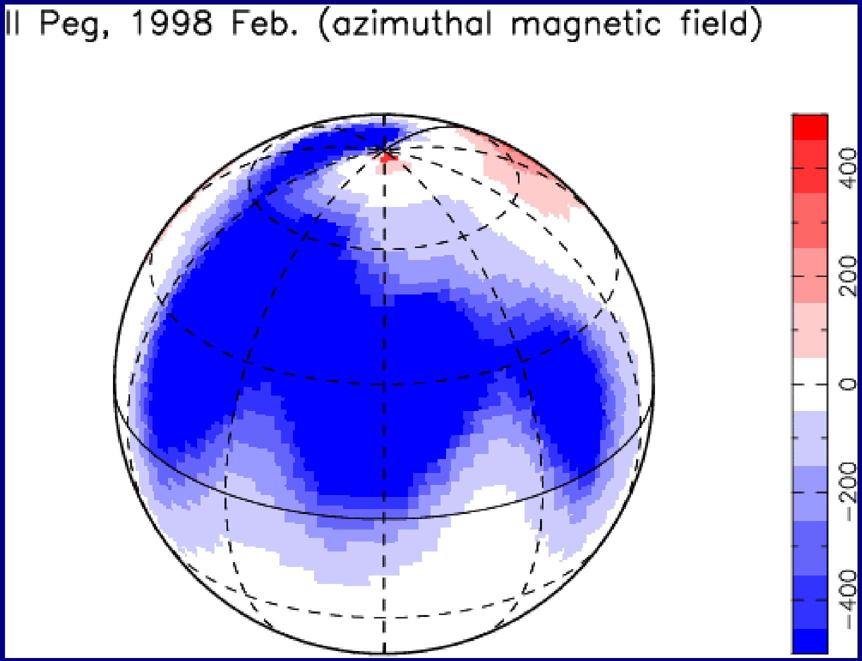
longitude of magnetic regions

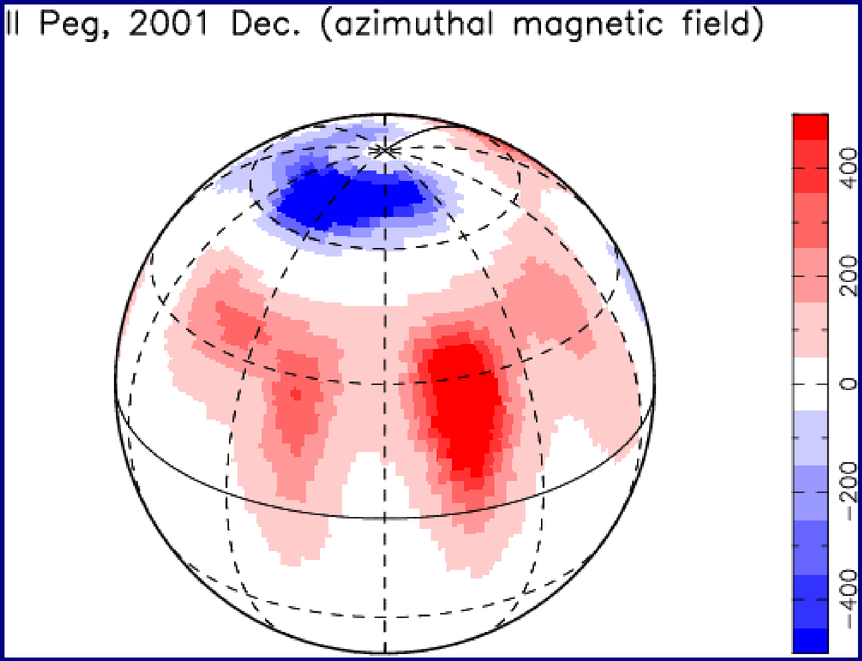
latitude of magnetic regions

. orientation of field lines

Stellar magnetic cycles

Sign reversal of the large-scale toroidal field

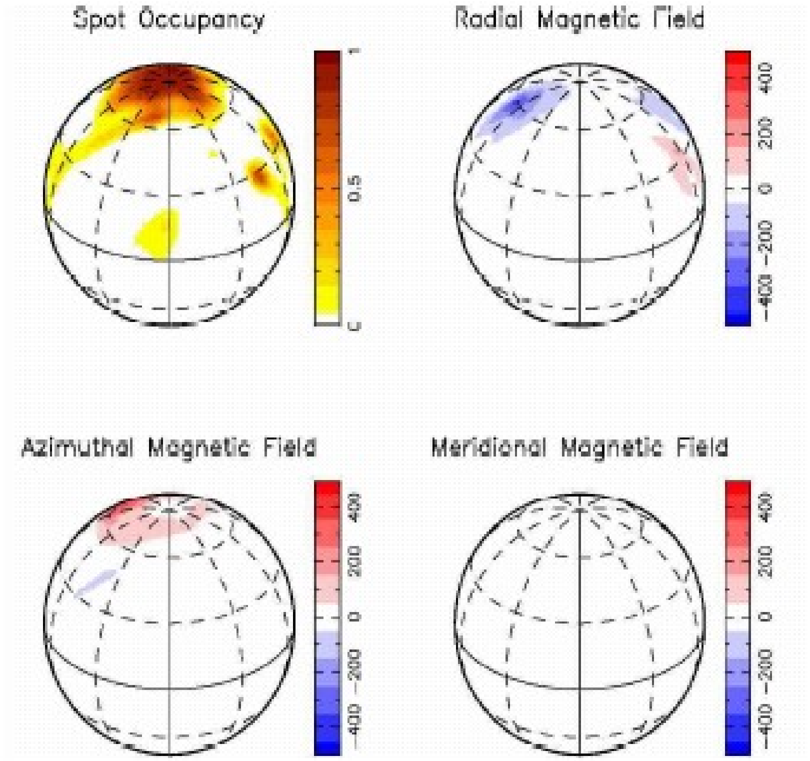




II Peg, Petit et al., in prep.

The photospheric magnetic field

- Spectropolarimetric observations of HD 171488 were obtained at the Anglo-Australian Telescope in circularly polarised light.
- The technique of Zeeman Doppler imaging (Donati et al. 1997, MNRAS, 291, 658) was used to reconstruct the surface brightness and magnetic features.



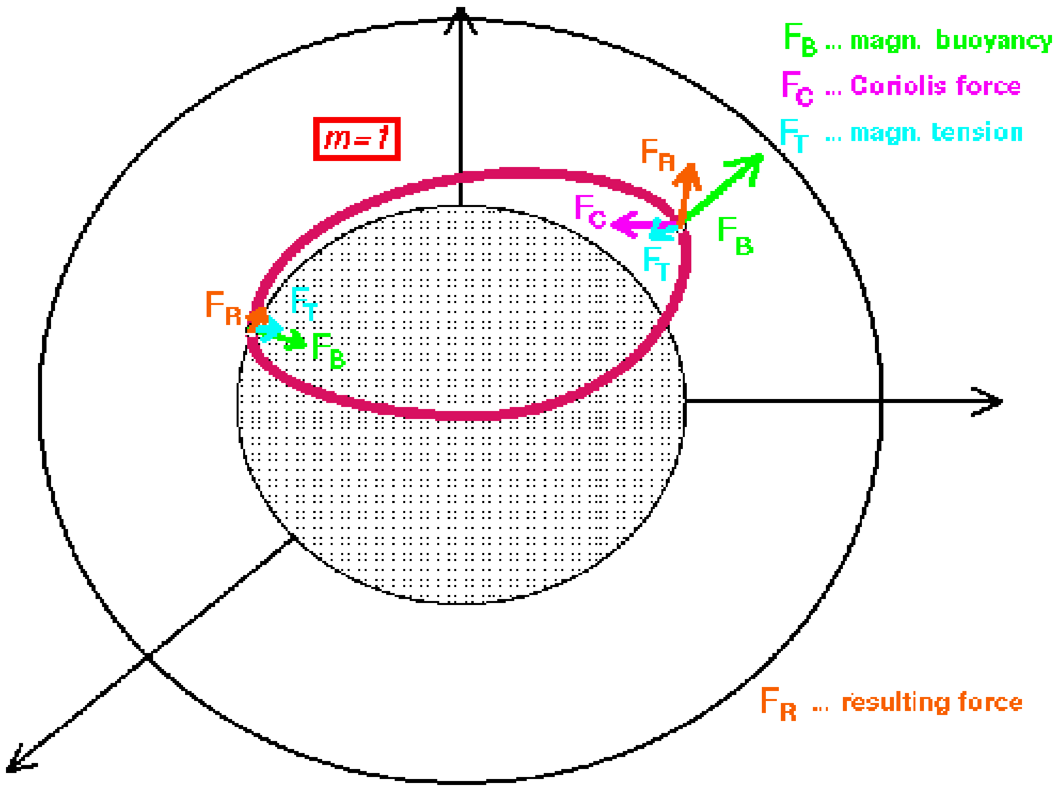
(Marsden et al. 2006, MNRAS, 370, 468)

Institute of Astronomy ETH Zurich

http://www.mpifr-bonn.mpg.de/staff/tpreibis/coronae/contributions/2-09-marsden.pdf

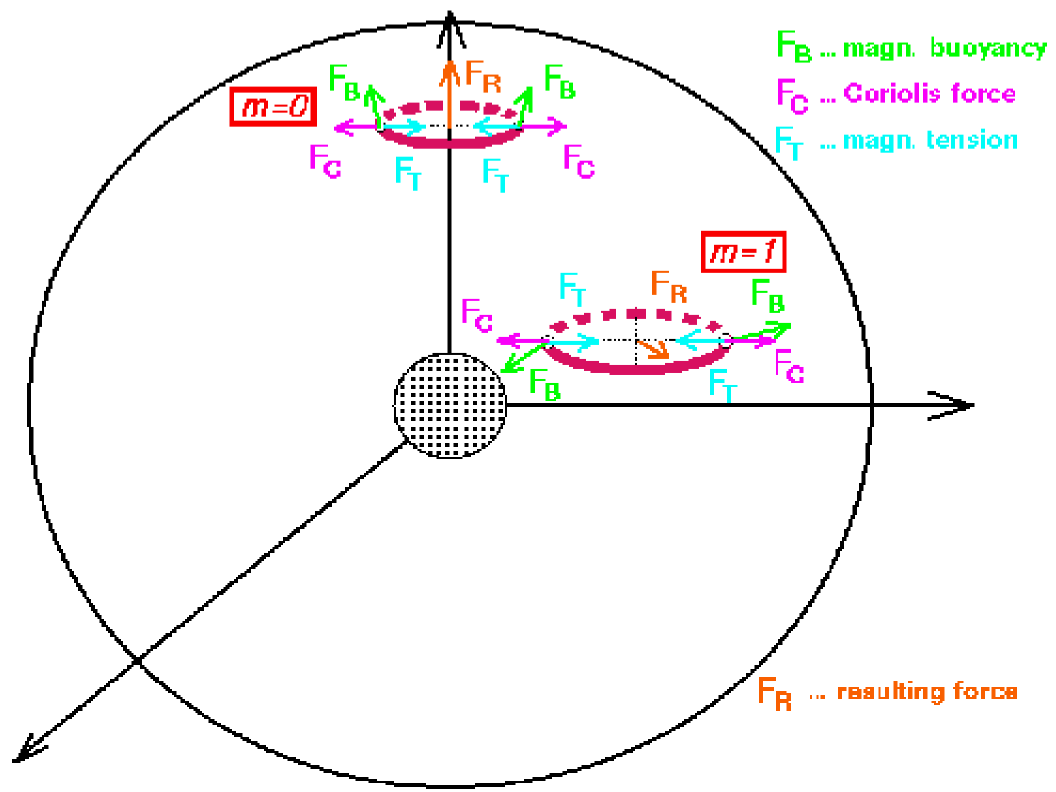
Cause for polar spots 1

- Flux tubes rise to surface
- Are forced to higher latitudes by Coriolis force
- Starspots can appear at higher latitudes than on the sun if core diameter is smaller or rotation rate higher

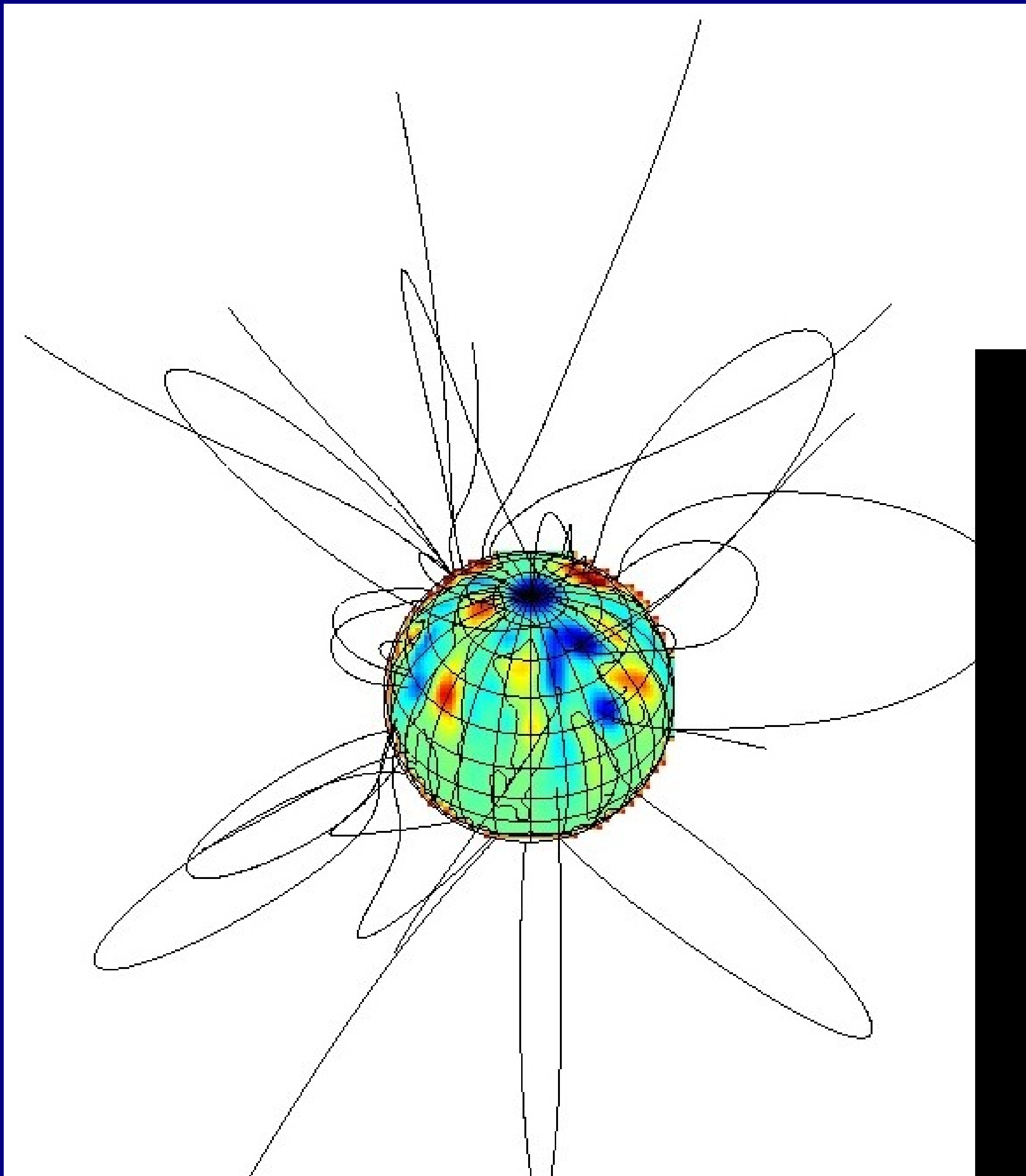


Cause for polar spots 2

- In rapidly-rotating cooler stars the whole flux-tube loop may be caused to rise



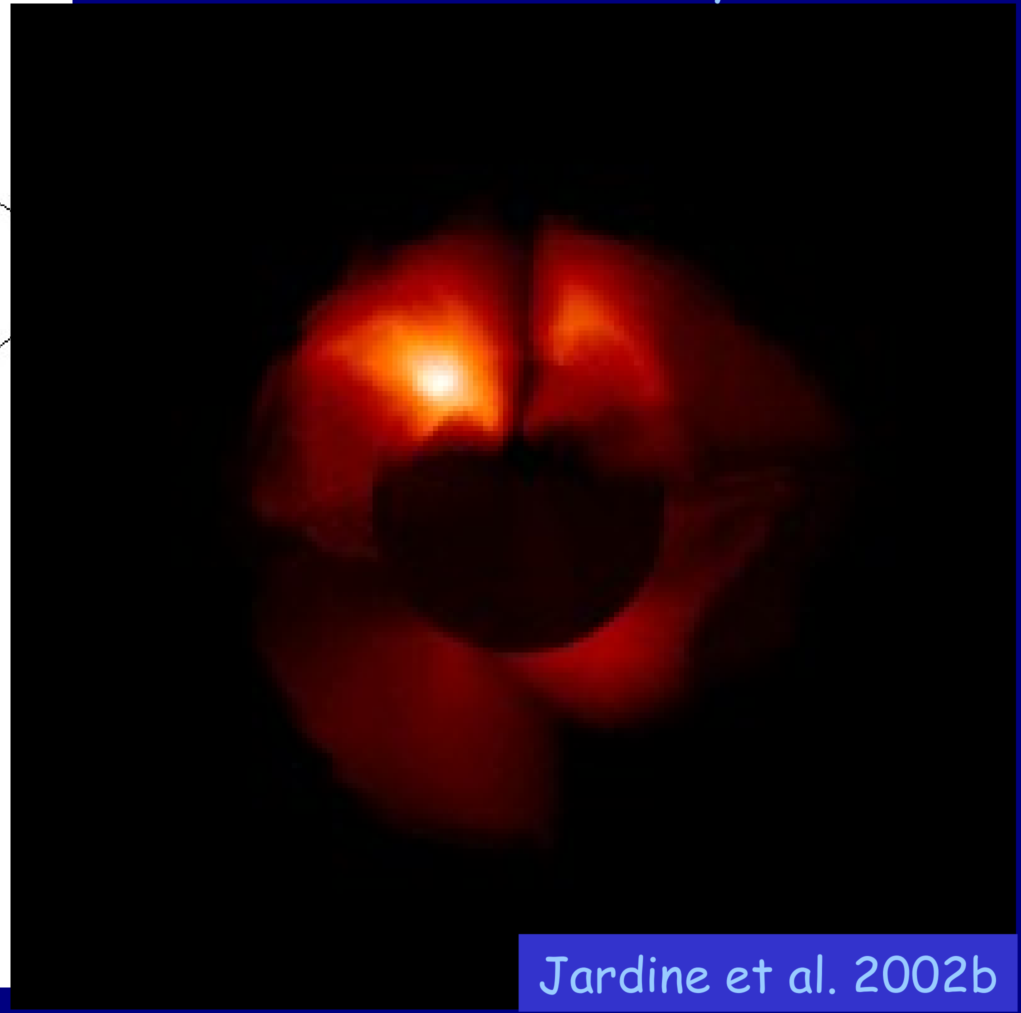
From photosphere to corona



AB Dor, Jardine et al. 2002a

Field extrapolation using ZDI map as boundary conditions (potential field)

Simulated X-ray emission:



Jardine et al. 2002b

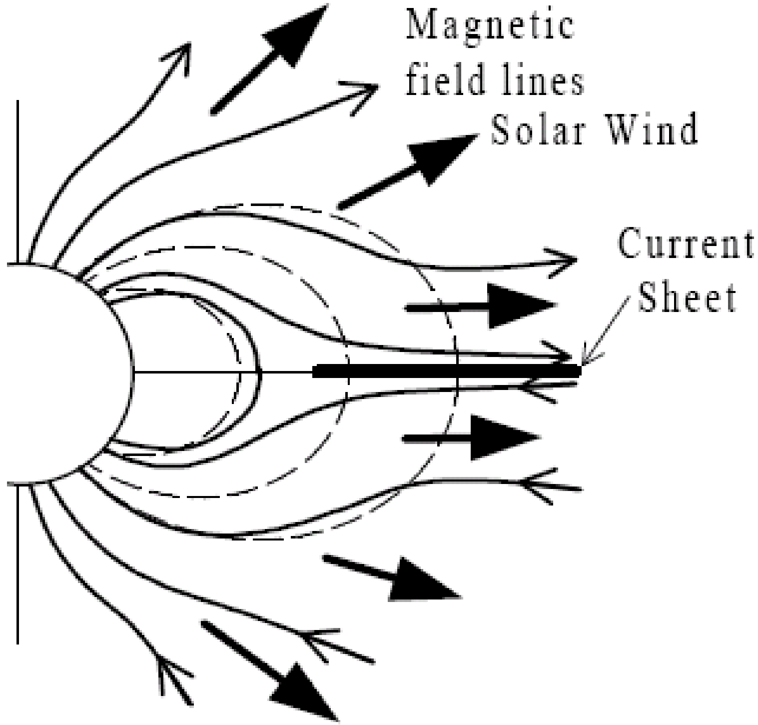
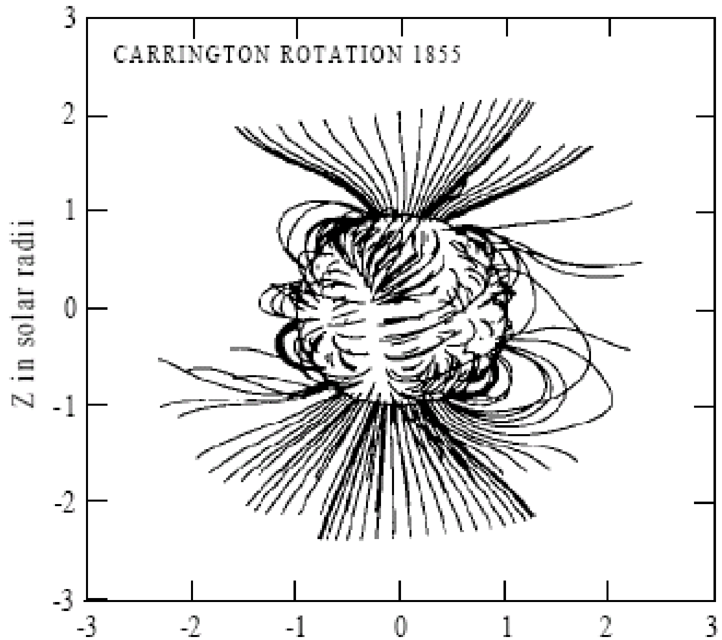


Figure 6. The flow of the solar wind distorts the nominally dipole magnetic field lines as the field is carried away from the corona. Close to the equator, the field lines are stretched out so that opposite polarity field lines are close to each other, separated by a current sheet in the equatorial plane.

http://www.sp.ph.ic.ac.uk/~mkd/AndreHandout.pdf calculations still give a usually good approximation to the coronal structures observed. We have in effect, from Maxwell's equation (or Ampere's law):

$$\nabla \times \mathbf{B} = \frac{1}{\mu_0} \mathbf{j}$$

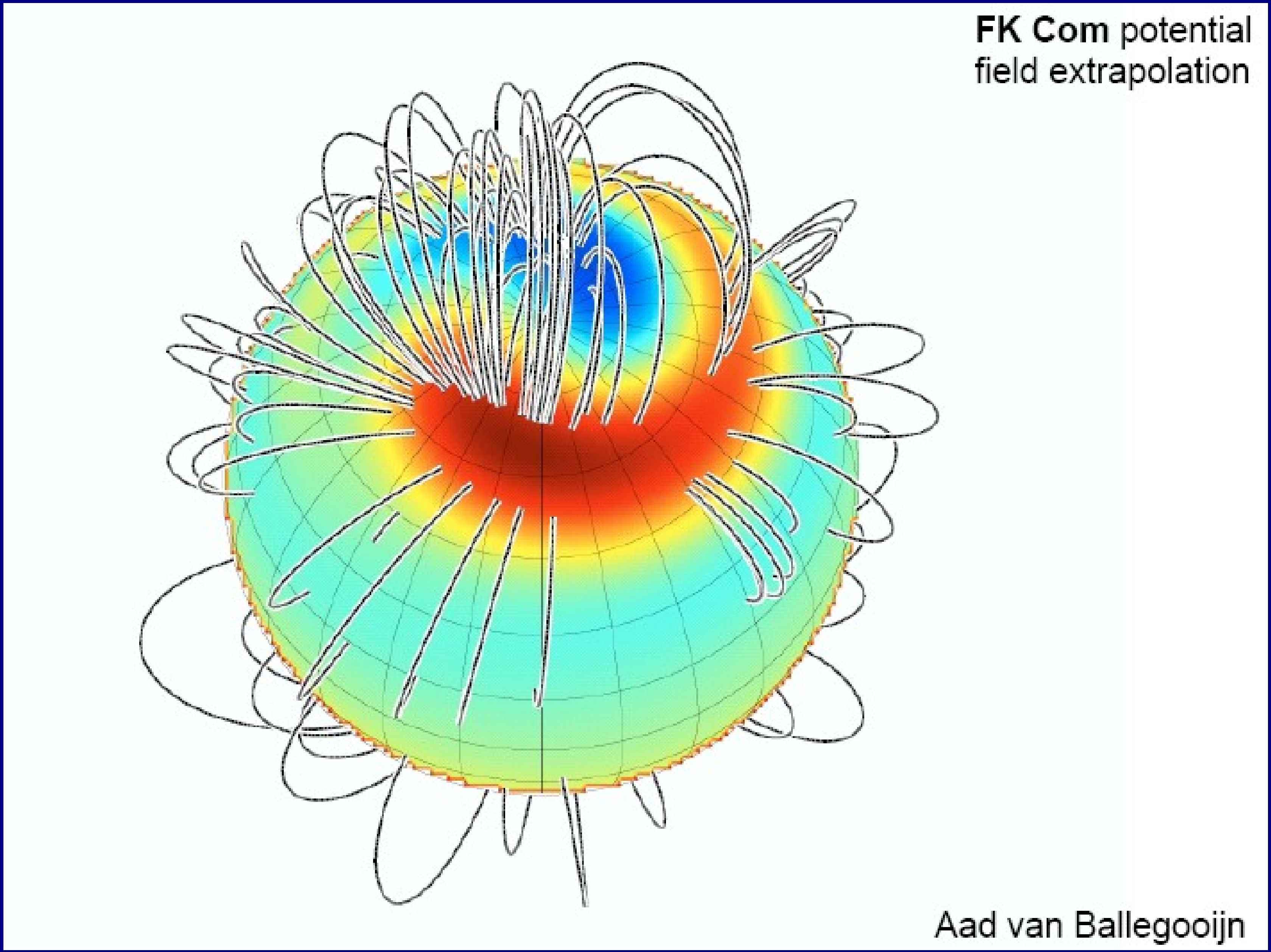
where we neglect the contribution of the displacement current (as the time variations are slow). If there are no currents, $\mathbf{j} = 0$, and the magnetic field is curl-free: $\nabla \times \mathbf{B} = 0$. In this case, as for all scalar functions Φ it is true that $\nabla \times (\nabla \Phi) = 0$, the magnetic field can be derived from a scalar magnetic potential Φ_B, to get $\mathbf{B} = -\nabla \Phi_B$.



Such calculations are routinely made in the following way. The magnetic fields in the photosphere are measured, to high accuracy, but with a relatively low spatial resolution by the Wilcox Solar Observatory, Stanford University, in California. Using these measurements as a boundary condition, together with an outer boundary condition at (usually) 2.5 solar radii, where the magnetic fields that reach this outer boundary (called the source surface) are constrained to be radially oriented, the scalar magnetic potential Φ_B is calculated, using the Laplace equation $\nabla^2 \Phi_B = 0$. From the solution, the magnetic field is computed, together with the

Figure 7. Calculated coronal magnetic field lines at a time in the solar cycle (just before solar minimum) when most of the open magnetic field lines originate near the poles of the Sun and the closed loops are concentrated in the equatorial regions.

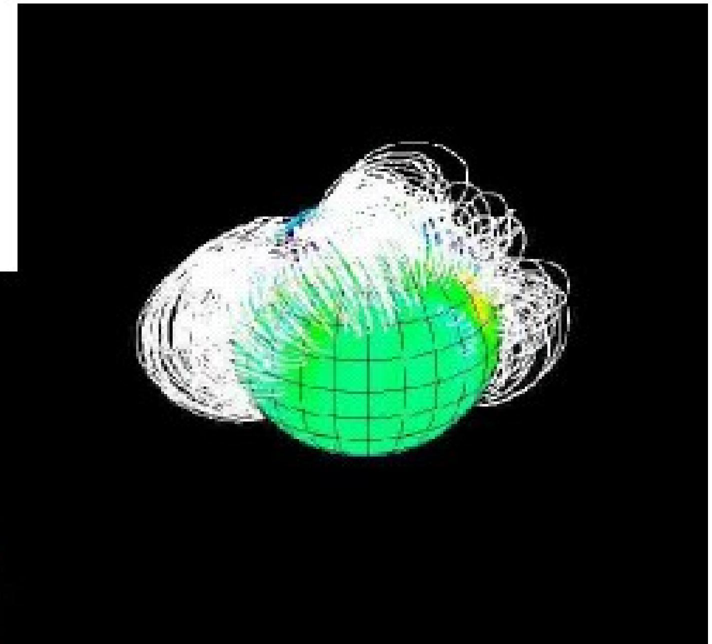
http://www.sp.ph.ic.ac.uk/~mkd/AndreHandout.pdf

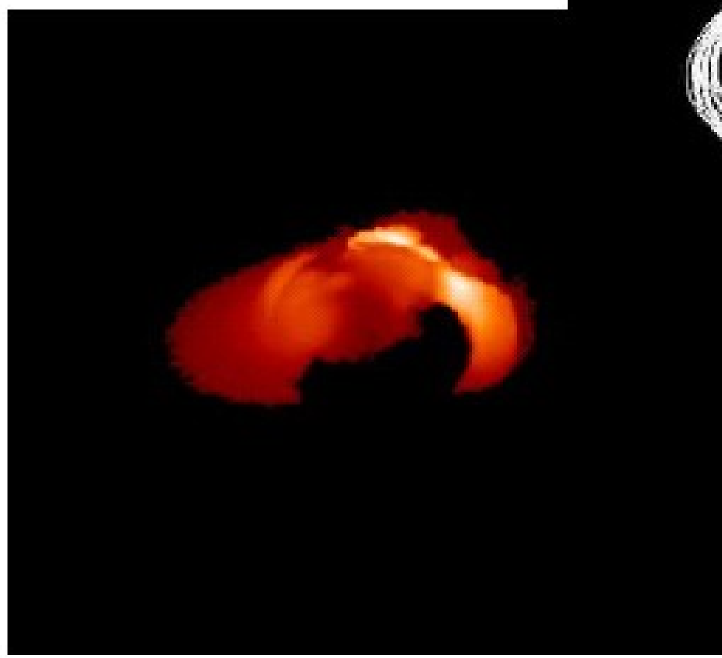

FK Com potential
field extrapolation
Aad van Ballegooijn

Coronal structure

- Using the coronal X-ray modelling technique of Jardine et al. (2002, MNRAS, 336, 1364) we have been able to reconstruct the coronal structure of HD 171488 from the radial magnetic field image.

- HD 171488 should have rotationally modulated X-ray emission.





Institute of Astronomy ETH Zurich

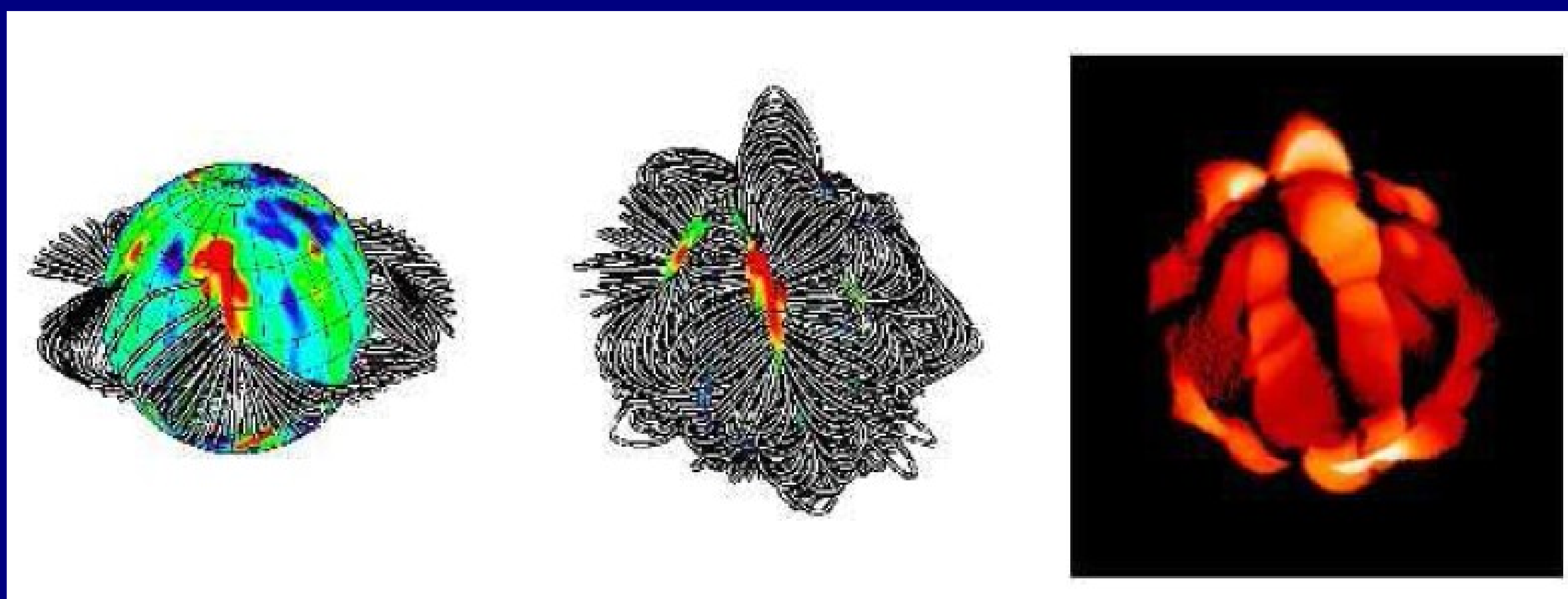
Coronae of Stars and Accretion Disks, Bonn, Germany, 12-13 Dec 2006

http://www.mpifr-bonn.mpg.de/staff/tpreibis/coronae/contributions/2-09-marsden.pdf

T Tauri X-rays arise from a complex reconnecting magnetosphere

Both smaller (<1 R*) and giant (~10 R*) loops are inferred from COUP

Flaccomio et al. 2005   Favata et al. 2005 COUP #6 & 7



Open accreting field lines

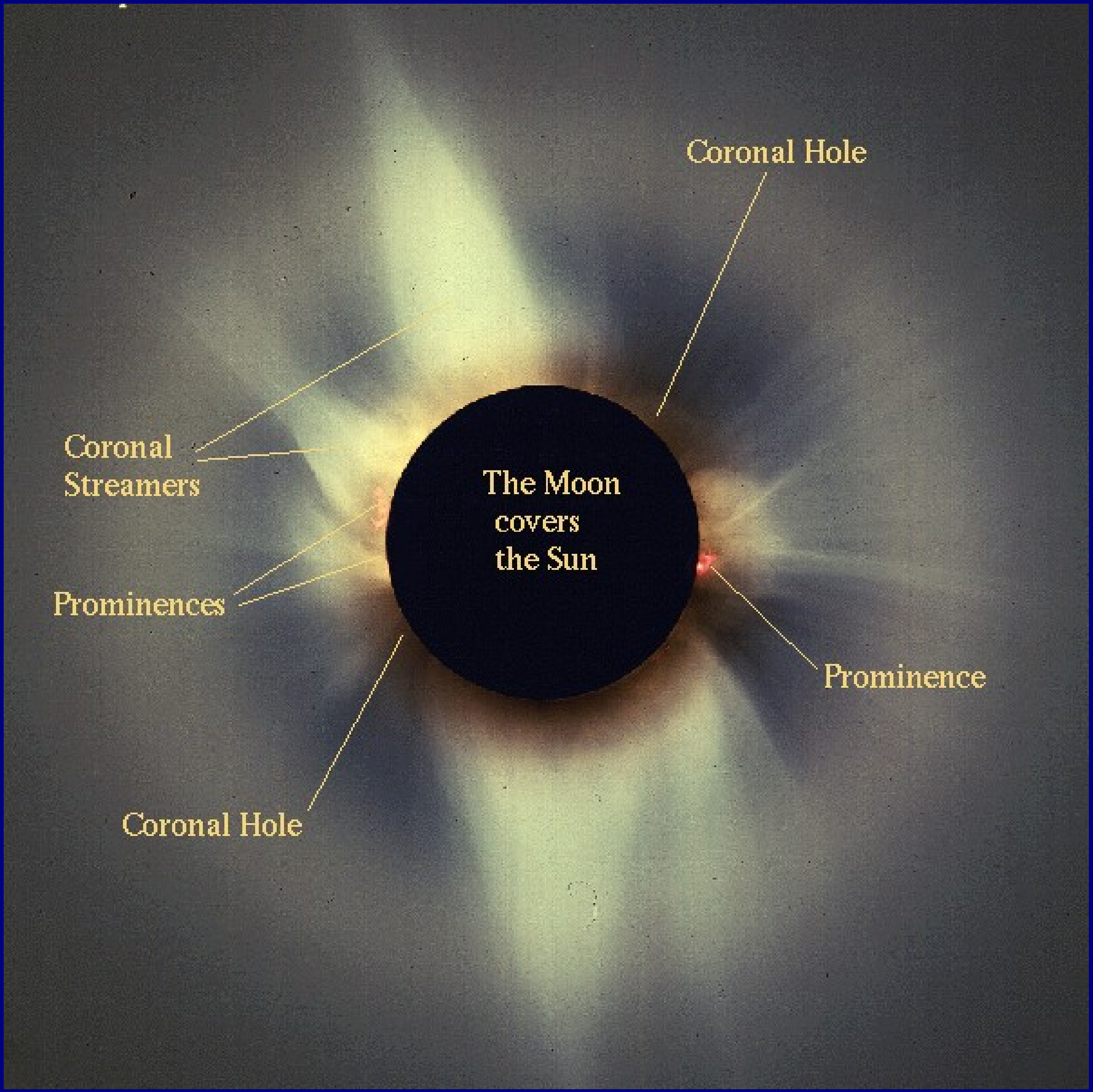
Closed plasma-filled field lines

Resulting X-ray corona (without flares)

Jardine et al. 2006

Mapping streamers...

The Solar Corona in 'White Light'



This is an image of total solar eclipse.

- The radiation are reflection of sunlight by the electrons in the corona.
- The streamers are where *slow* solar wind leave the Sun.
- The coronal holes are where *fast* solar wind leave the Sun.

in the equatorial regions.

It has become also possible now, thanks to very fast supercomputers, to perform a more realistic modeling of coronal structures, without assuming that the corona is current free. In this case, the simulation uses an MHD (magnetohydrodynamics) code. The result of one such calculation is shown in Fig. 8. Note that this figure shows the solar corona near solar minimum activity, when the closed magnetic field lines are mostly close to the solar equator.

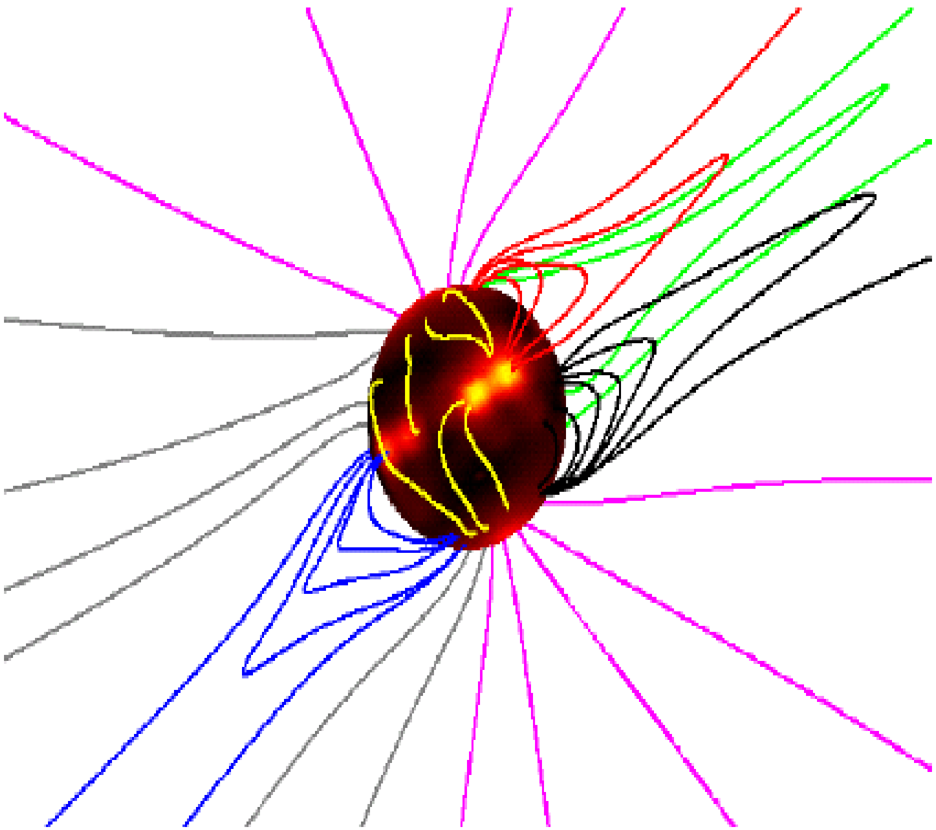
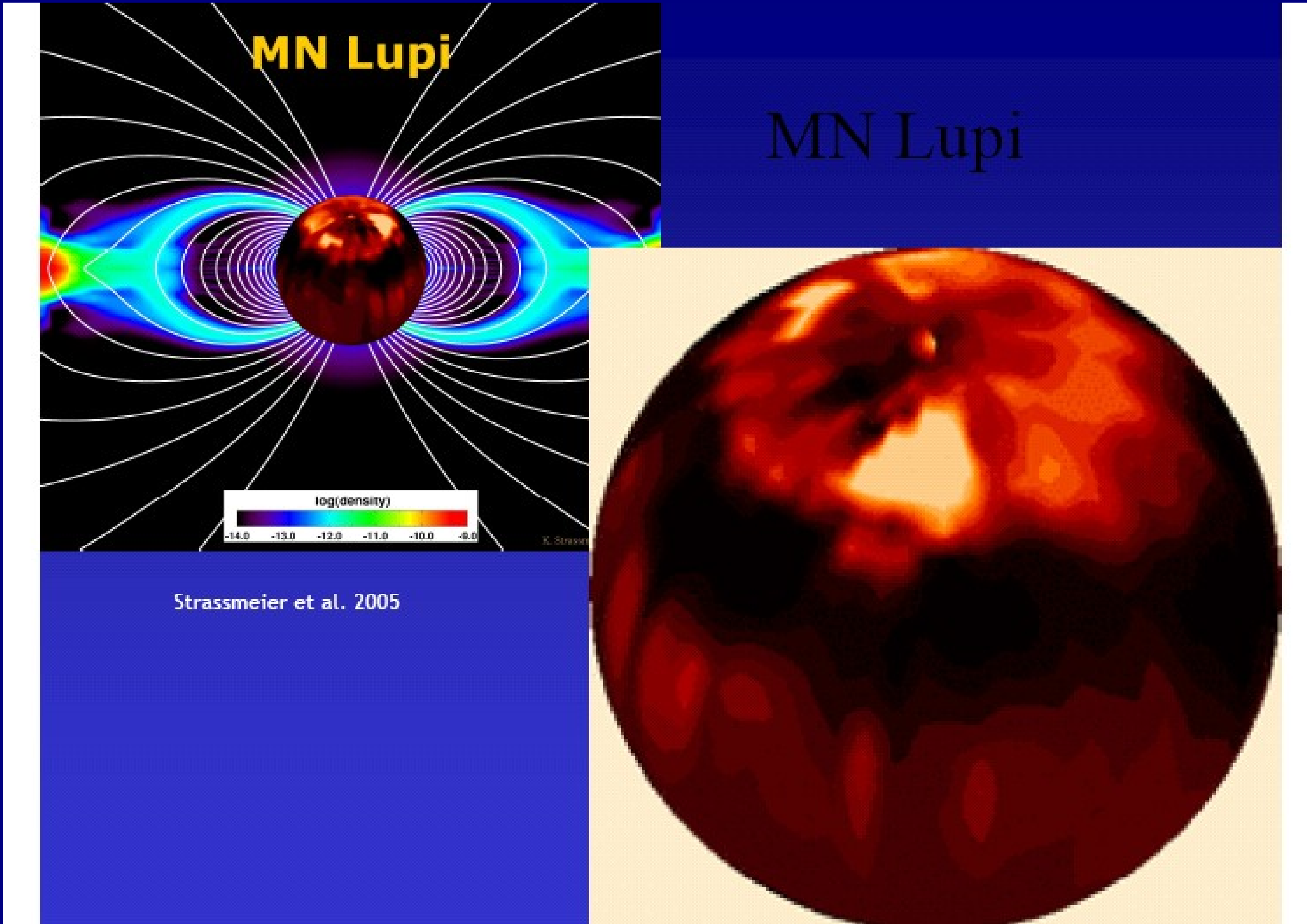


Figure 8. Results of an MHD calculation of coronal magnetic field lines at solar minimum. The open field lines stretch from the polar regions of the corona to lower latitudes, while the near-equatorial loop sustem is stretched out to form the coronal streamers.



http://www.mpifr-bonn.mpg.de/staff/tpreibis/coronae/contributions/3-10-kueker.pdf

Disk Evolution: Equations

Mass conservation: $\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho u) = 0$

Momentum conservation: $\rho \left[\frac{\partial u}{\partial t} + (u \cdot \nabla) u \right] = -\nabla p + f + \nabla \cdot V$

Temperature: $c_V \rho \left[\frac{\partial T}{\partial t} + (u \cdot \nabla) T \right] = -p \nabla \cdot u + \Phi_{visc} + \Phi_{mag}$

Magnetic field: $\frac{\partial B}{\partial t} = \nabla \times \left[u \times B - \eta_t \nabla \times B \right]$

Forces: $f = \rho \nabla \frac{GM}{r} + \frac{1}{4\pi} \nabla \times B \times B$

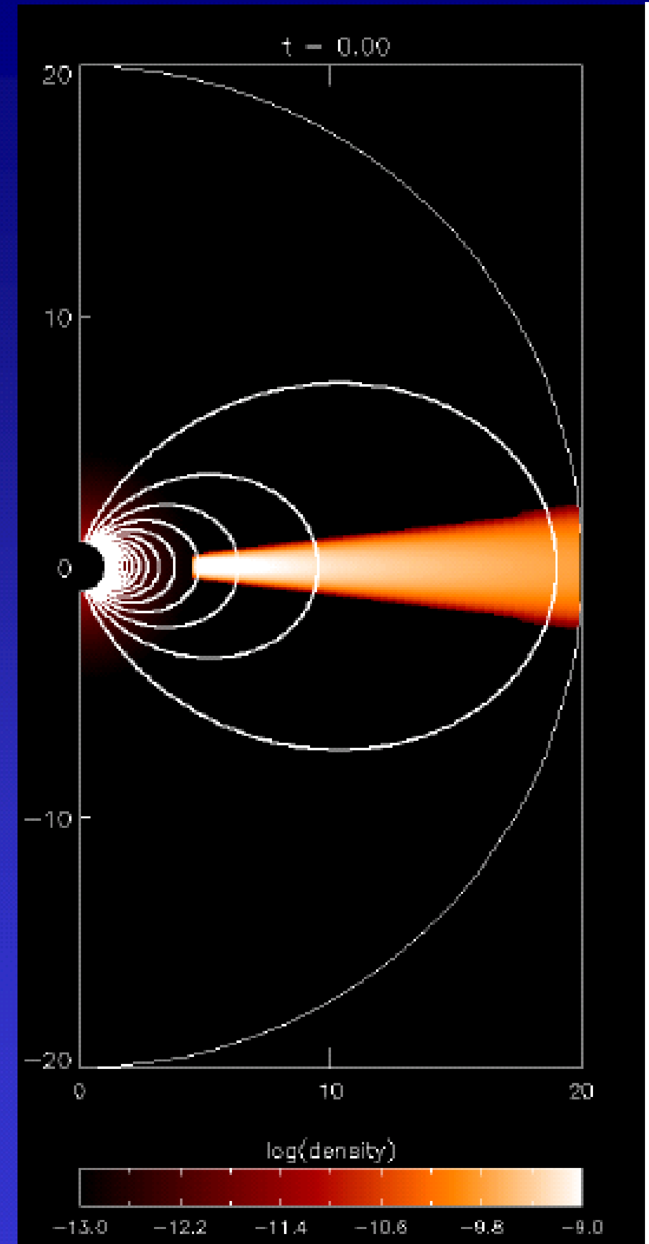
Dissipation: $\Phi_{visc} = (V \cdot \nabla) u$ $\quad \Phi_{mag} = 4\pi \eta_t j^2$

http://www.mpifr-bonn.mpg.de/staff/tpreibis/coronae/contributions/3-10-kueker.pdf

Model setup I

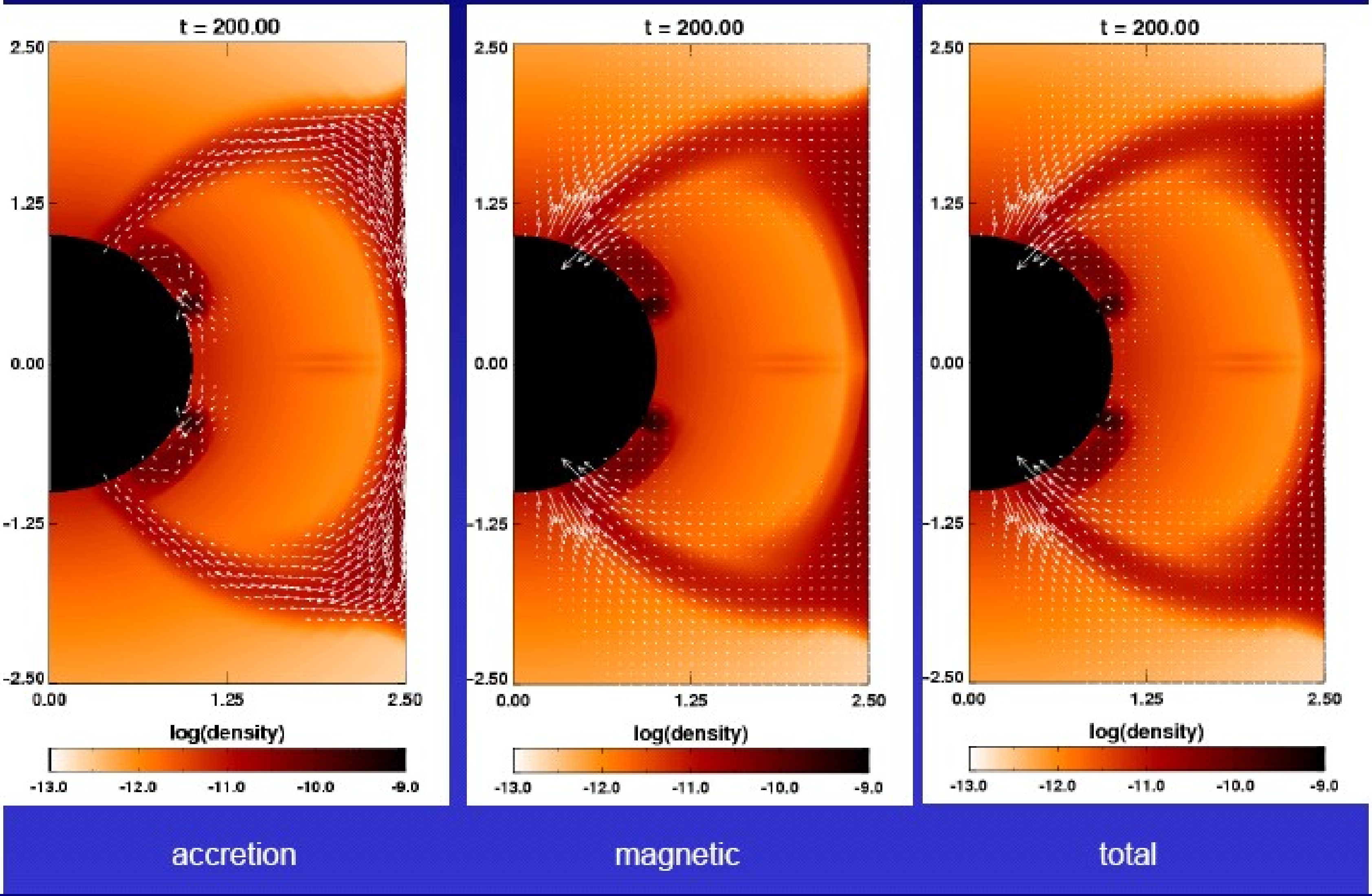
- T Tauri star + accretion disc + magnetic field
- Star:
  - Mass: $M = M_{Sun}$
  - Radius: $R = 3R_{Sun}$
  - Rotation period: $P = 0.1P_K$
  - Corotation radius: $R_{\Omega} = 4.6R_{Star}$
  - Magnetic field: axisymmetric dipole

$$B_0 = 5kG$$

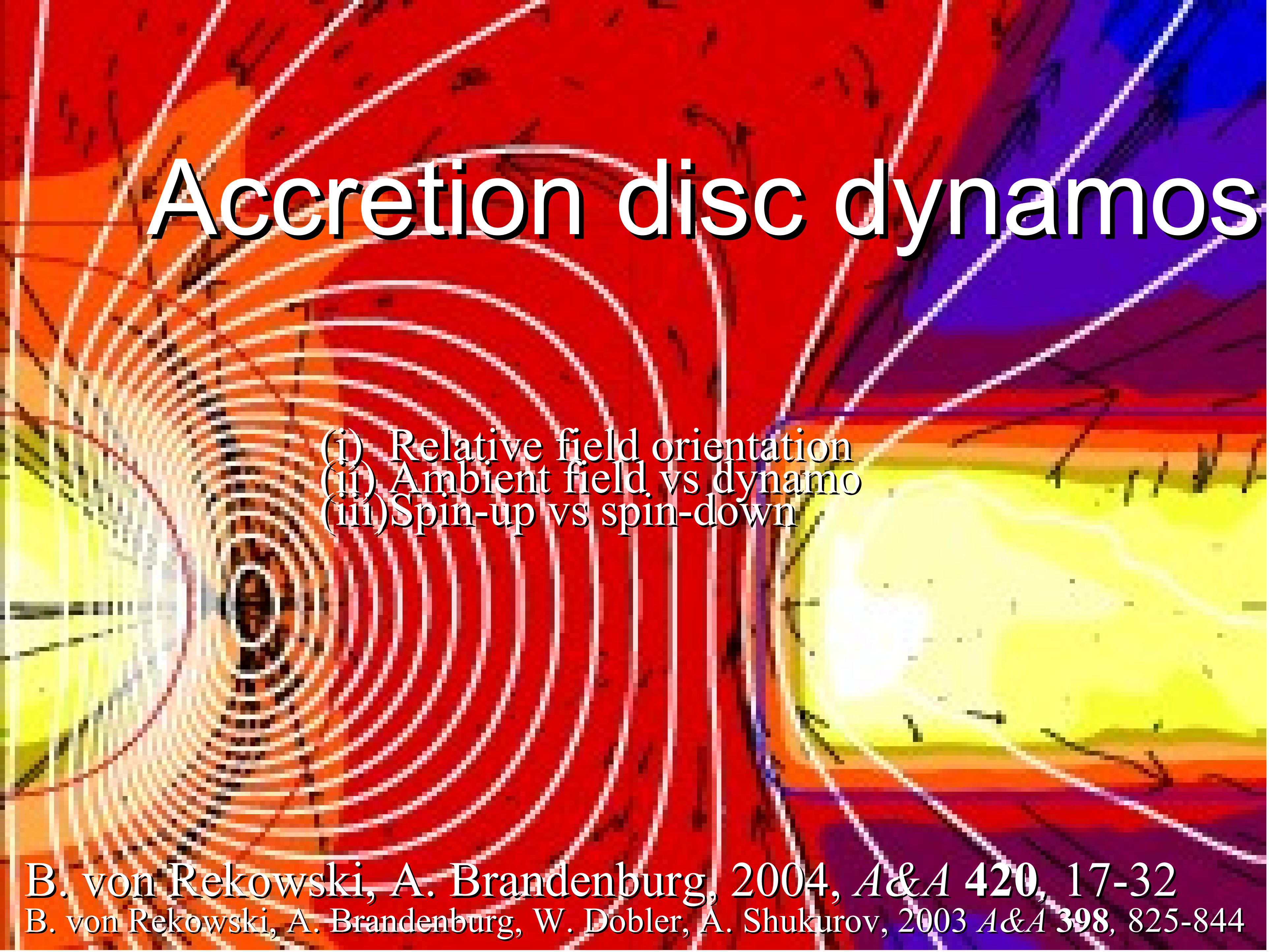


http://www.mpifr-bonn.mpg.de/staff/tpreibis/coronae/contributions/3-10-kueker.pdf

Funnel Flow: Torques



http://www.mpifr-bonn.mpg.de/staff/tpreibis/coronae/contributions/3-10-kueker.pdf



Accretion disc dynamos

(i) Relative field orientation
(ii) Ambient field vs dynamo
(iii) Spin-up vs spin-down

B. von Rekowski, A. Brandenburg, 2004, *A&A* **420**, 17-32

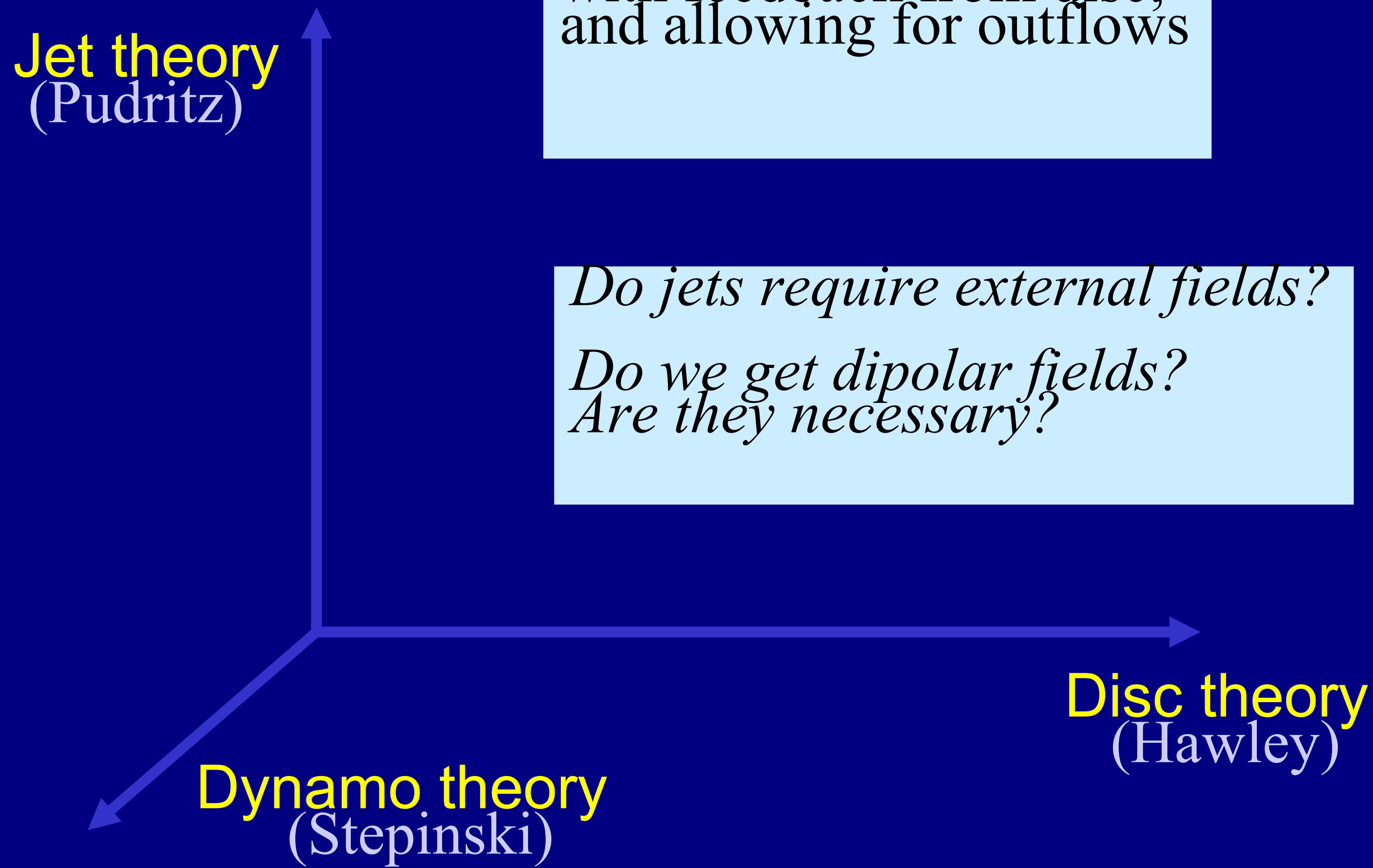
B. von Rekowski, A. Brandenburg, W. Dobler, A. Shukurov, 2003 *A&A* **398**, 825-844

Bridging the gaps: jet-disc-dynamo

Model of disc dynamo,
with feedback from disc,
and allowing for outflows

Do jets require external fields?

Do we get dipolar fields?
Are they necessary?



A. Brandenburg

END