Other Effects on Stellar Structure and Evolution

Stellar Evolution in a Nutshell

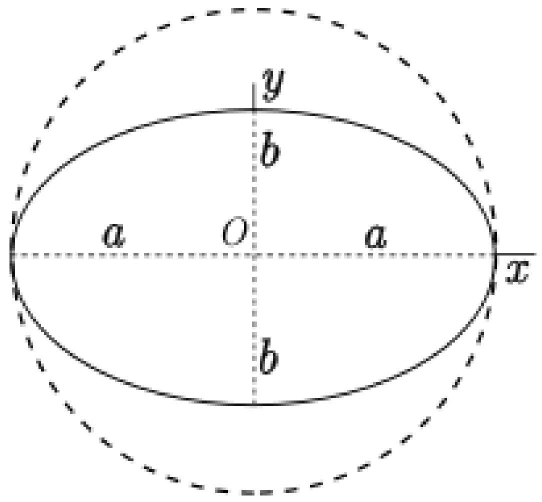
- $M \lesssim 0.5\ \mathrm{M}_\odot \longrightarrow$ fully convective
- $0.5\ \mathrm{M}_\odot \lesssim M \lesssim 2.25\ \mathrm{M}_\odot$
  $\longrightarrow$ RG (H shell fusion) $\longrightarrow$ (He flash) He core fusion + mass loss
  $\longrightarrow$ AGB + CO core fusion + mass loss
  $\longrightarrow$ PN ejection + CO WD ($0.55\ \mathrm{M}_\odot$)
- $2.25\ \mathrm{M}_\odot \lesssim M \lesssim 10.5\ \mathrm{M}_\odot \longrightarrow$ He ignition in ND condition
  - ✓ $M \lesssim 8.5\ \mathrm{M}_\odot \longrightarrow$ CO WD ($< 1.1\ \mathrm{M}_\odot$)
  - ✓ $8.5\ \mathrm{M}_\odot \lesssim M \lesssim 10.5\ \mathrm{M}_\odot \longrightarrow$ electron deg O and Ne core
    $\longrightarrow$ AGB + ONe WD ($[1.1 .. 1.37]\ \mathrm{M}_\odot$)

Iben

Effect of Rotation

Flattening $f = (a - b)/a$
(Ellipticity or oblateness)
↔ density and (balance between gravitation force and centrifugal force)

cf, eccentricity $e = \left(1 - \frac{b^2}{a^2}\right)^{1/2}$
a: semimajor axis; b: semiminor axis
b/a: compression factor; aspect ratio



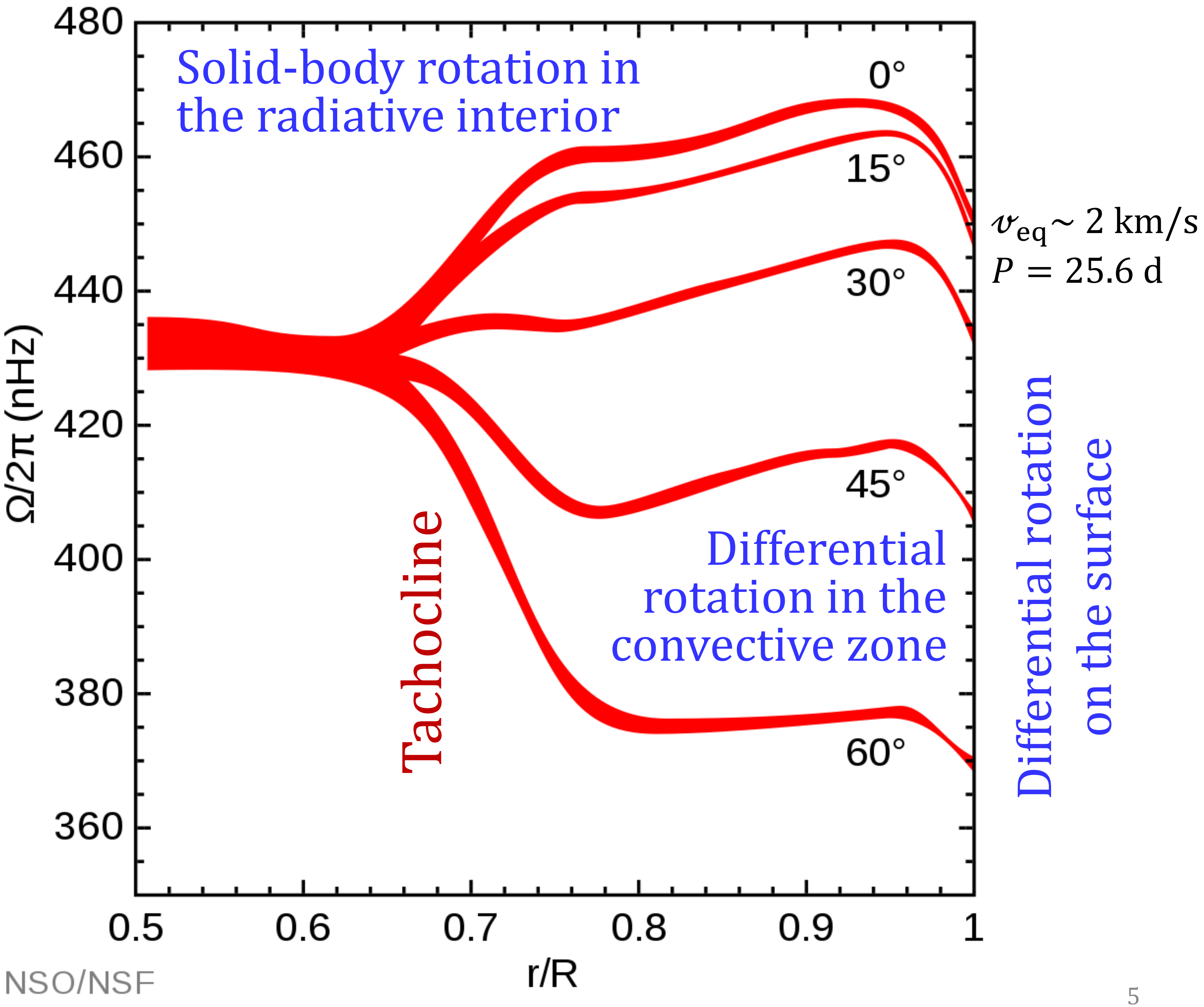
Jupiter: $1/16 \approx 6\%$
Saturn: $1/10$
Sun: $1/100000$
Moon: $1/900$
Earth: $3/1000$ ($D_{\text{eqatorial}}$ 42 km more than D_{polar}; bulge)

Solar Rotation

The Sun rotates slowly, $\approx 2\ \mathrm{km\ s^{-1}}$ @equator ($P \sim 25$ d)

Slower at higher latitudes ($P \sim 34$ d at poles).

Differential rotation in the convective region; rigid rotation in the radiative region ($< 0.7\ R_{\odot}$)



NSO/NSF

Rotation vs Spectral Type

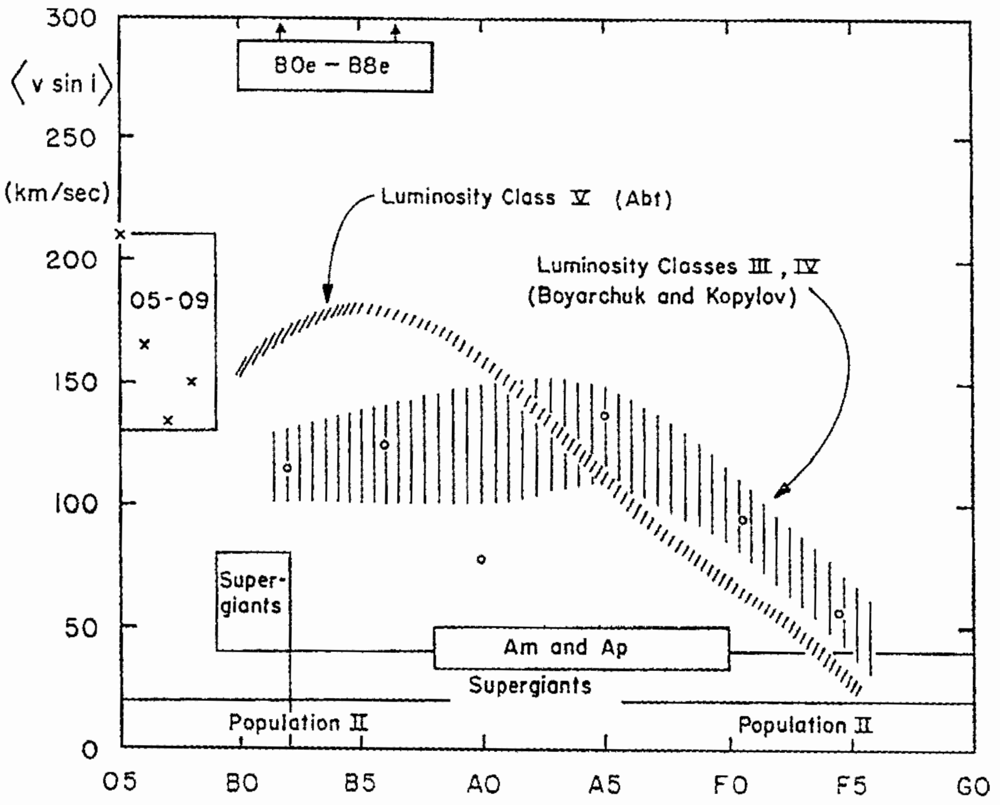


Fig. 3. Projected equatorial velocities, averaged over all possible inclinations, as a function of spectral type. On the main sequence (luminosity class V), early-type stars have rotational velocities that reach and even exceed 200 km/s; these velocities drop to a few km/s for late-type stars, such as the Sun (type G2) (Slettebak [20]; courtesy Gordon & Breach)

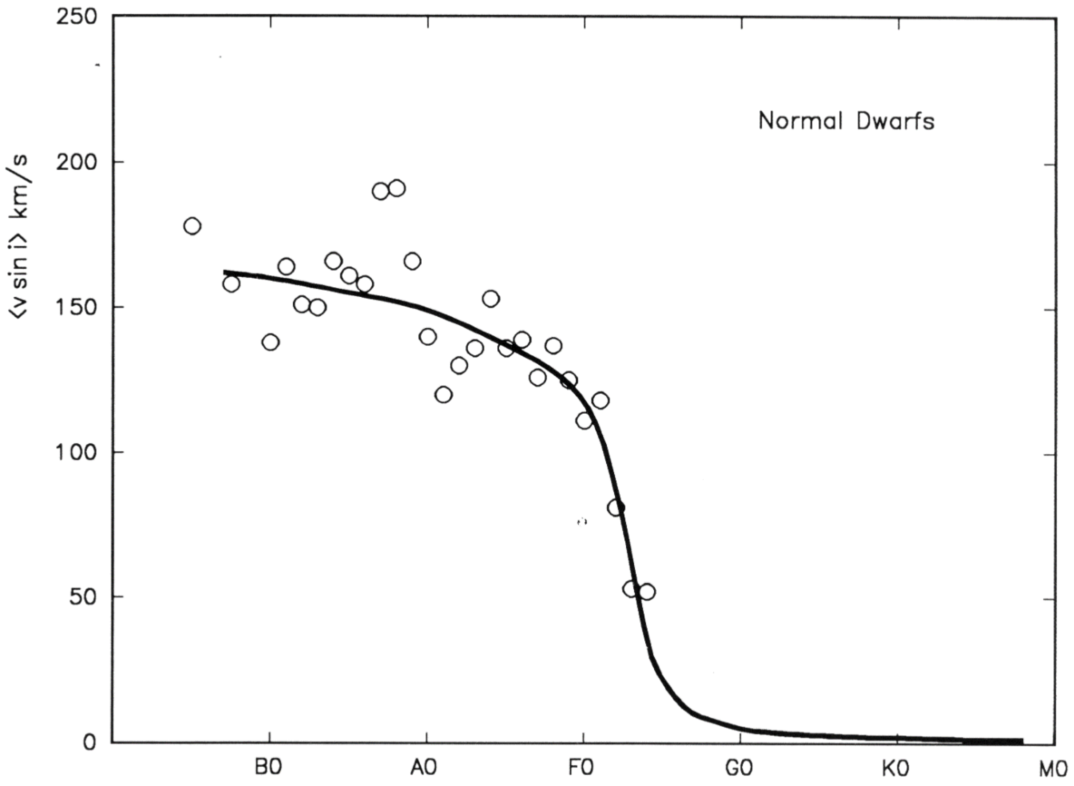
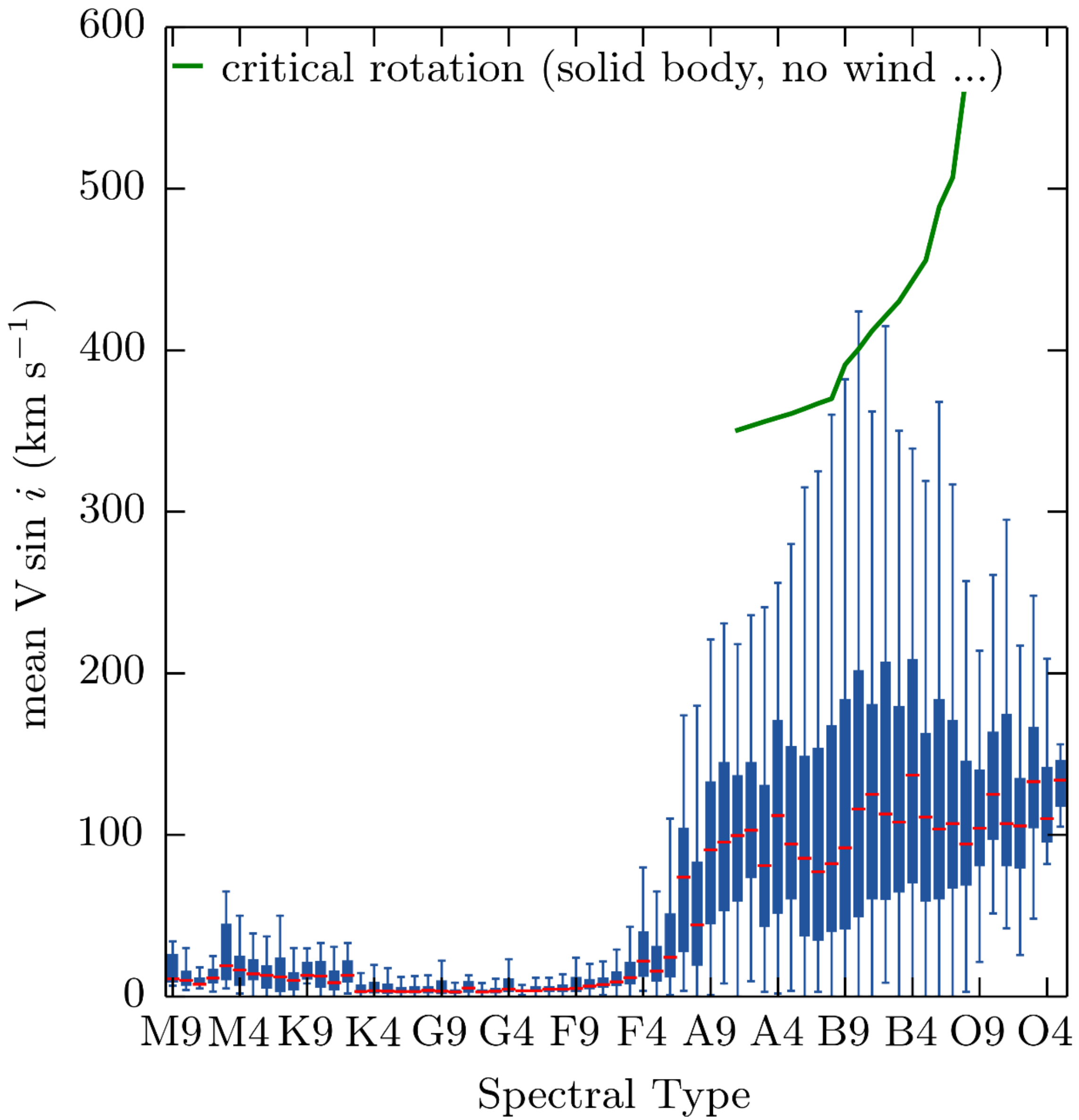


Fig. 17.16. The average rotation rates are shown for spectral intervals as a function of spectral type. (Data are from Uesugi and Fukuda (1982), Soderblom (1983), and Gray (1982b, 1984b).)



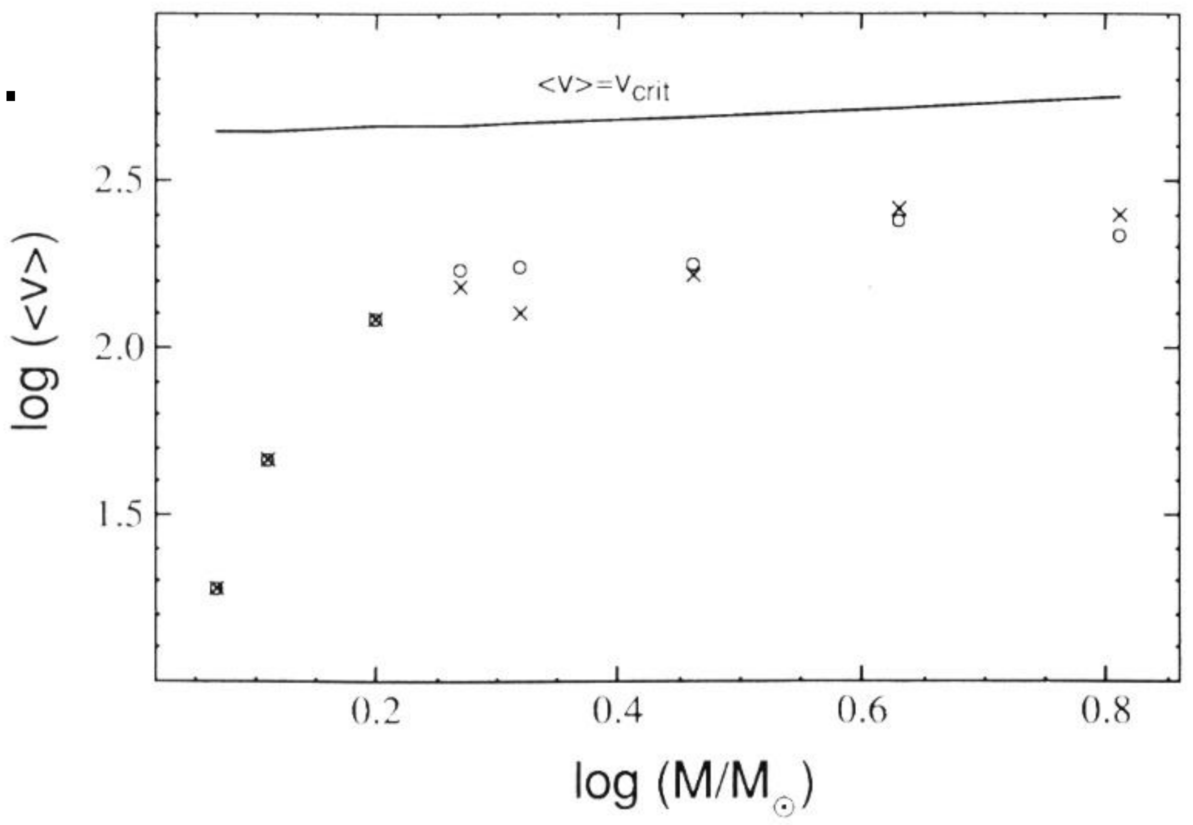
https://aa.oma.be/stellar_rotation

Rotation vs Stellar Mass

- ✓ Massive stars are fast rotators.
- ✓ Rotation declines in the F type (convection? disk?)
- ✓ Low-mass stars spin down quickly early on (disk-star coupling via **B** field), and then experience weak-breaking on the MS due to magnetic breaking and winds.

1.5 $M_\odot$; F0; 6 $L_\odot$

$v_{crit} = \sqrt{GM/R}$



Kawaler (1987)

- ✓ The fastest single rotators, other than remnant objects such as neutron stars, are Be stars; as fast as ~450 km/s, close to break-up speed
- ✓ Mass loss preferentially along the equators
- ✓ Stars no longer spherical
- ✓ Giants and supergiants rotate slowly because of angular momentum conservation.

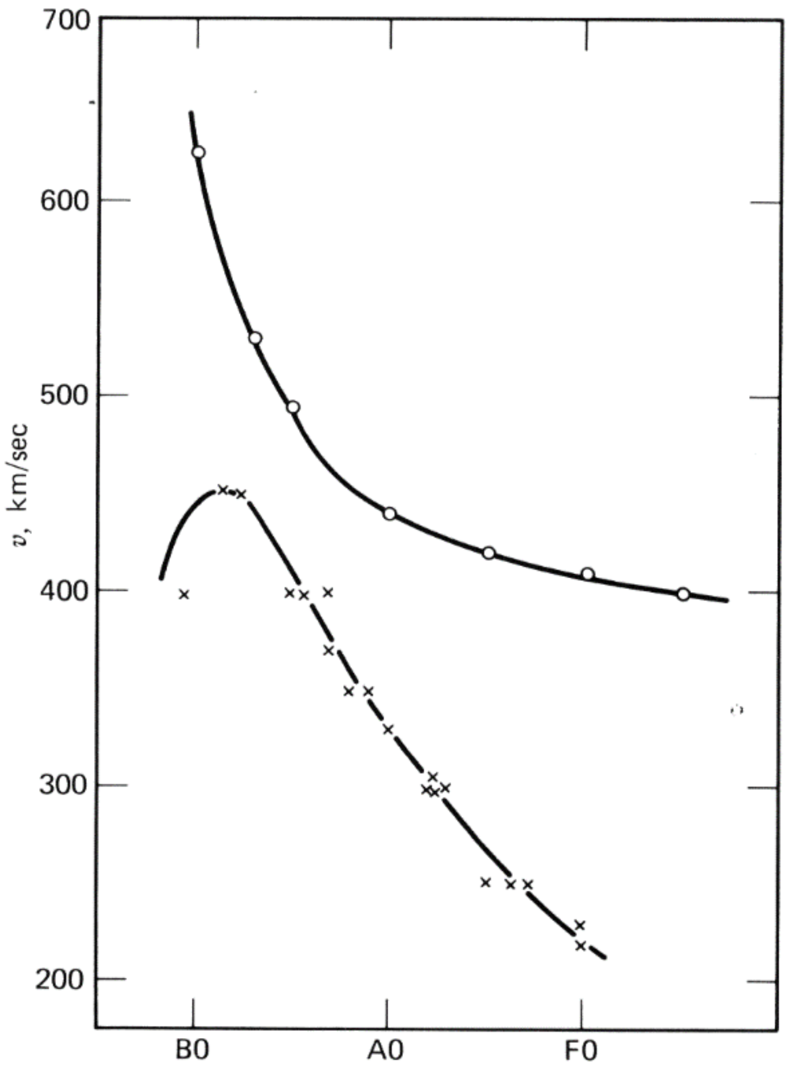


Fig. 17.22. The fastest rotation rates are shown by the ×s. The theoretical break-up velocities (top curve) approach the observed relation most closely in the B-star range. (Data from Slettebak (1966).)

Rotation → star <u>cooler</u> and <u>fainter</u>

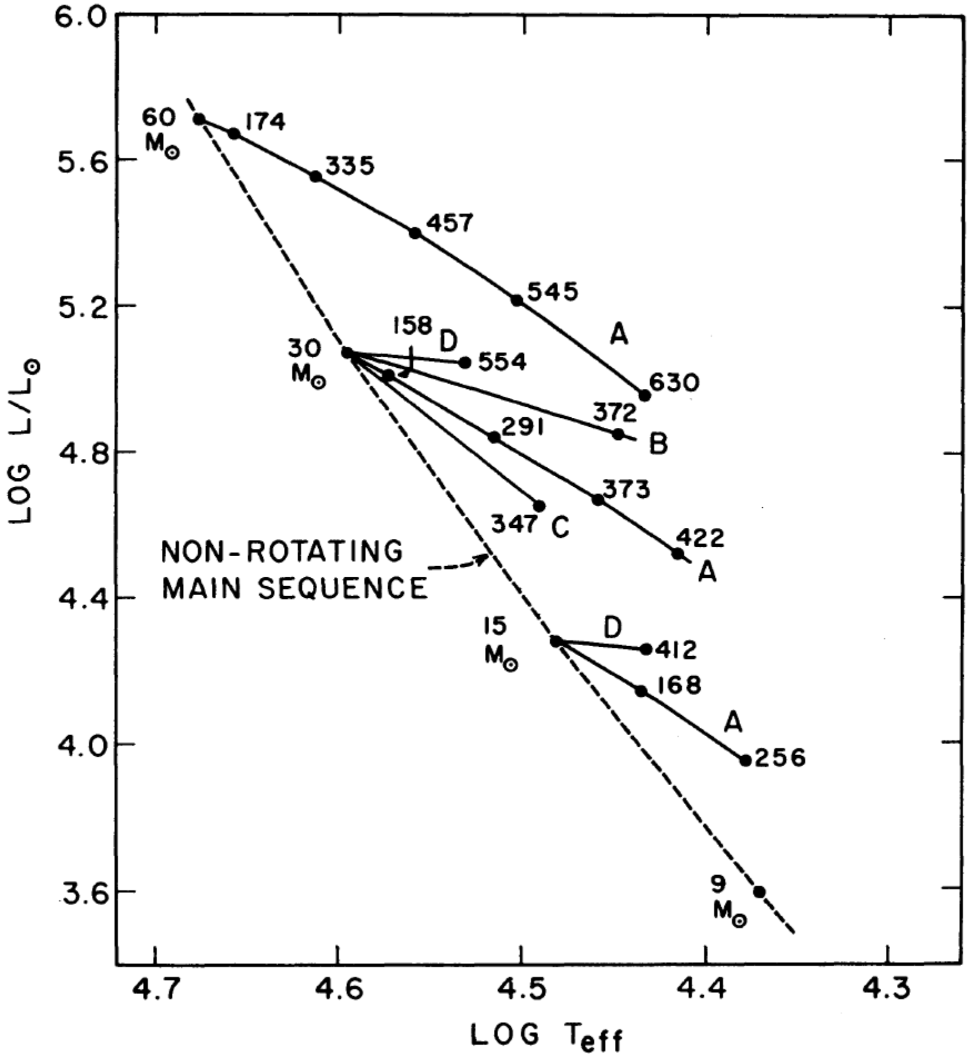


FIG. 2.—Theoretical H-R diagram showing model sequences of increasing angular momentum (*solid curves*). Numbers on curves give calculated velocities at the equator in km sec^{-1}. The distribution of angular momentum for each sequence is indicated by the letter A, B, C, or D.

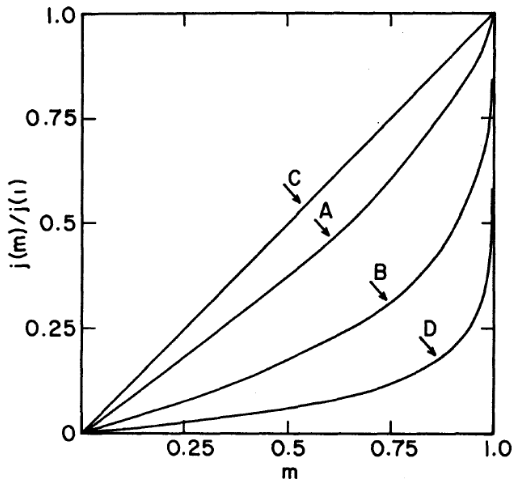


FIG. 1.—Angular momentum per unit mass, as a function of mass fraction interior to a given cylinder about the axis of rotation, for three assumed laws of differential rotation (Cases A, B, and C) and for a uniformly rotating model (Case D) of 30 $\mathfrak{M}_\odot$, log J = 52.73.

D: solid body rotation

<u>Rotation law</u>:

angular momentum distribution $j(m_\varpi)$ as a function of, m_ϖ, the mass fraction interior to the cylinder of radius ϖ about the rotation axis.

Bodenheimer (1971) ApJ, **167**, 153

Rotation
→ line broad
and shallow

Line blending

HR 9024 (OU And)
G1 IIIe

HR 3664 G6 III

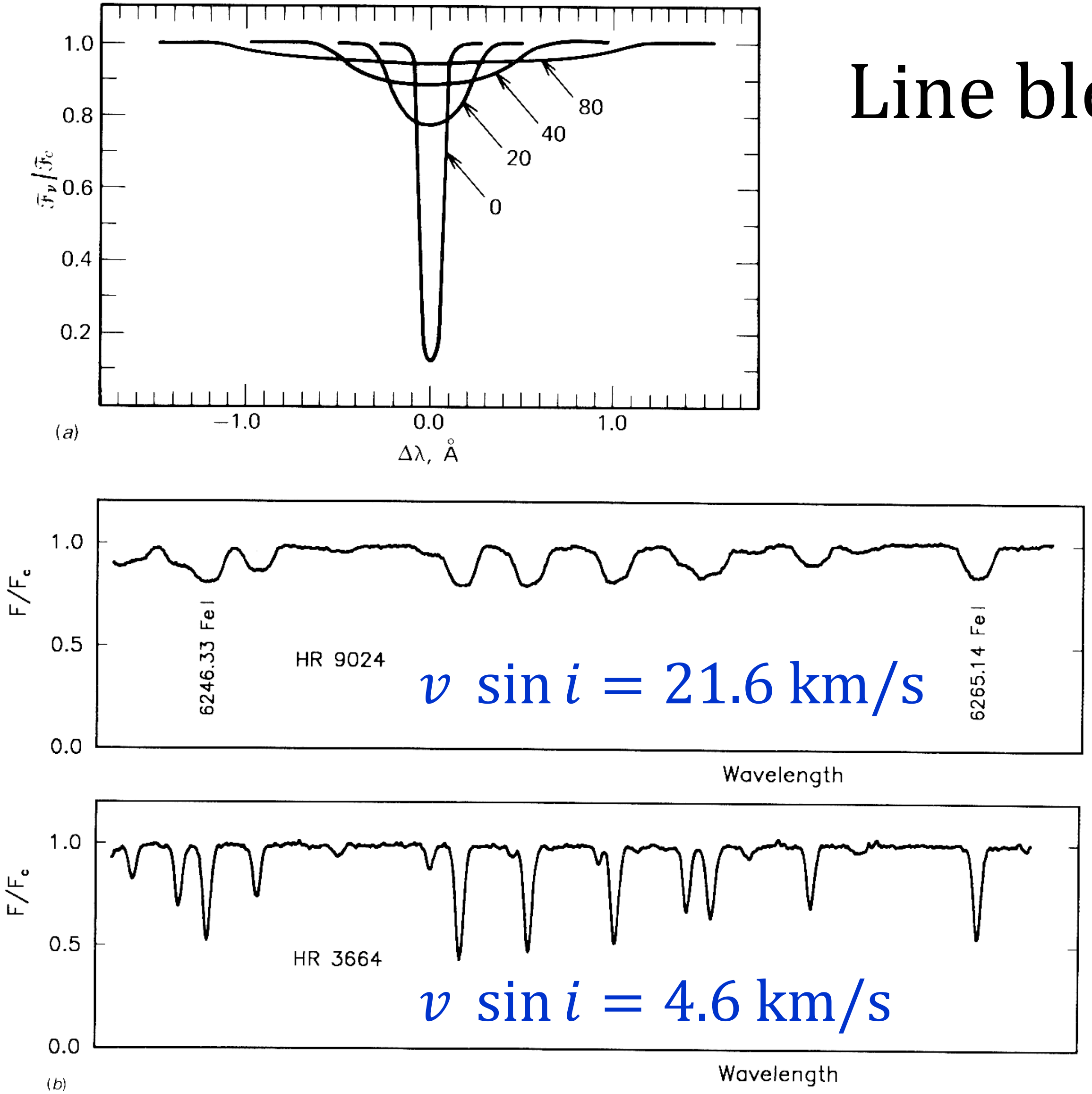


Fig. 17.7. (*a*) Computed profiles illustrate the broadening effect of rotation. The profiles are labeled with $v \sin i$. the wavelength is 4243 Å, and the line has an equivalent width of 100 mÅ. (*b*) These two early-G giants illustrate the Doppler broadening of the line profiles by rotation.

Gray p. 376

MESA Isochrones and Stellar Tracks (MIST)

https://waps.cfa.harvard.edu/MIST/interp_isos.html

PARSEC (CMD3.7 – STEV the OAPd server; Pardova)

http://stev.oapd.inaf.it/cgi-bin/cmd

Effect of Magnetic Field

Stellar Magnetism

Magnetic field may be important in star formation; governing mass (charged and neutral) flow; $\boldsymbol{B}$ usually not important in stars, except in compact objects, such as in WDs or NSs.

Typical field strengths

Earth/Sun ~ 1 G
(sunspots ~kG)
Ap/Bp ~10^3 G
White dwarfs ~ 10^6 G
Neutron stars ~ 10^{12} G
Magnetars ~ 10^{15} G (10^{11} teslas)

So stellar magnetism may be important only at the beginning and at the end of a star's life.

Some chemically peculiar (CP) stars, usually hot MS stars (~10%, Ap and Bp stars), with B field in the outer layer to stratify specific elements in the atmospheres (Ap/Bp stars), e.g., He, N, and O to diffuse and settle into deeper layers, while others, e.g., Mn (Manganese 錳), Sr (Strontium 鍶), Y (Yttrium 釔), Zr (Zirconium 鋯) are radially "levitated" to the surface → spectral peculiarities.

The bulk chemical composition of the entire star remains normal = that of ISM

Some CP stars have no strong field (Am stars).

THE ASTROPHYSICAL JOURNAL, Vol. 160, May 1970

DIFFUSION PROCESSES IN PECULIAR A STARS

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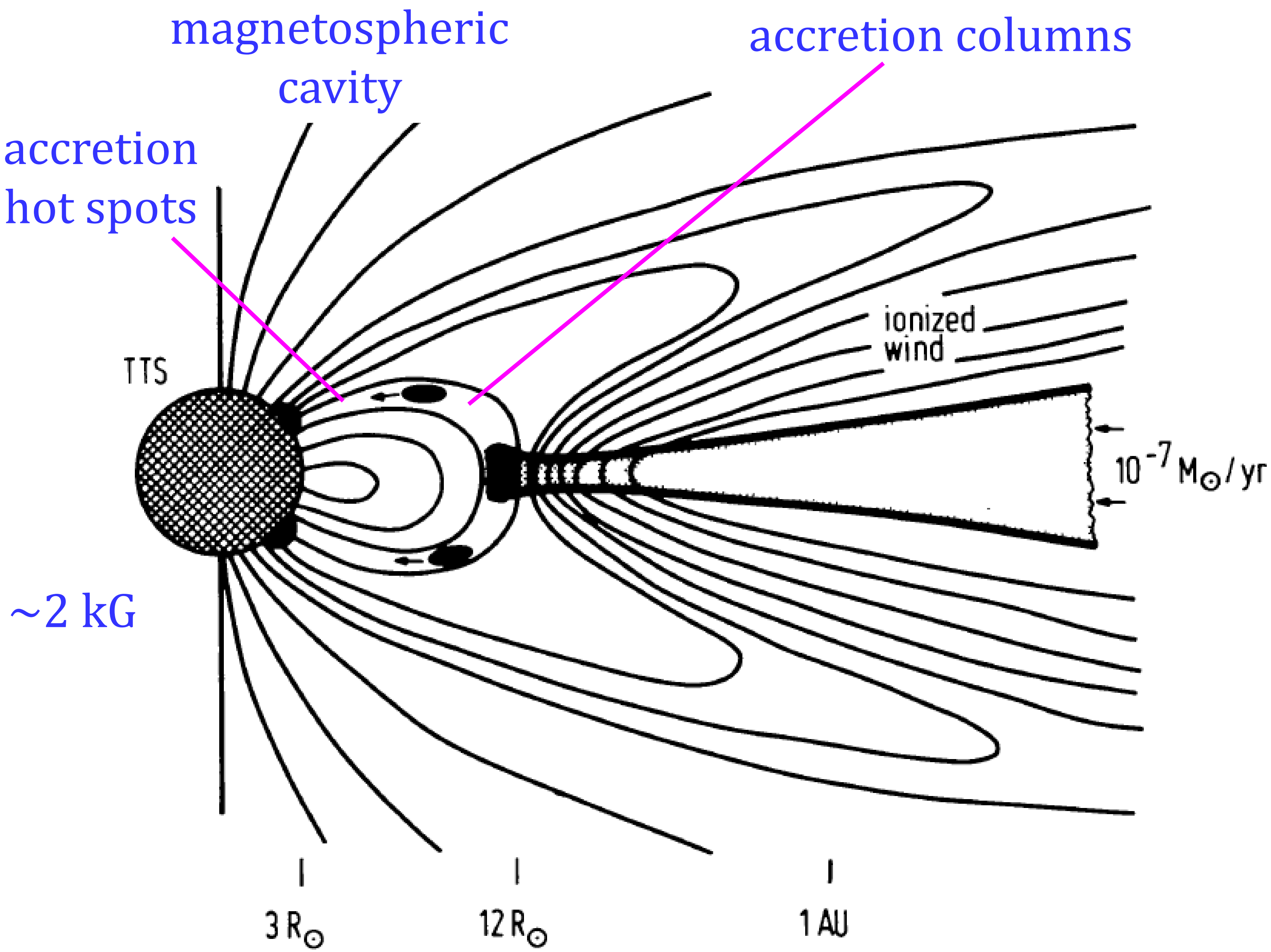
Hale Observatories, Carnegie Institution of Washington,
California Institute of Technology
Received 1969 September 19

ABSTRACT

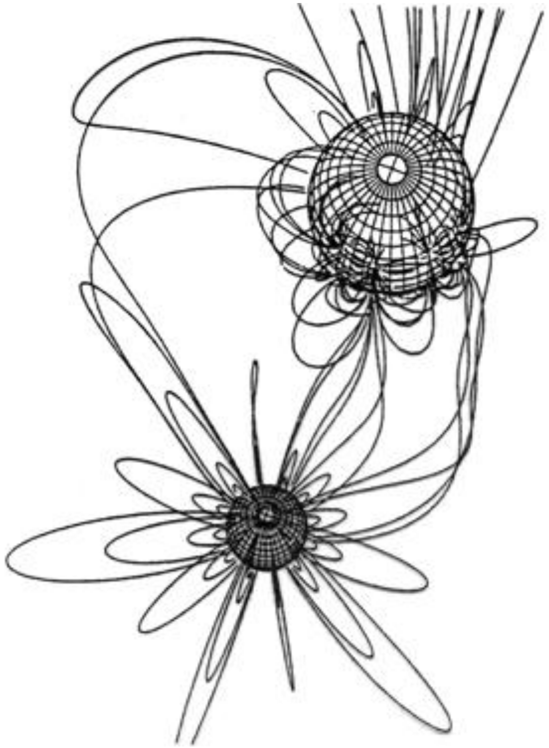
It is suggested that diffusion processes are responsible for most of the peculiar abundances observed in Ap stars. If it is assumed that the atmosphere is stable enough for diffusion processes to be important, gravitational settling leads to the underabundances of He, Ne, and O in the stars where they are observed (that is, with the θ_{eff}, log g they are observed to have). Radiation pressure leads to the overabundances of Mn, Sr, Y, Zr, and the rare earths in the stars where they are observed. Silicon would be expected to be overabundant only if it has wide autoionization features. Phosphorus would be expected to be overabundant in stars with $\theta_{eff} \simeq 0.5$, but is observed to be overabundant in stars with $\theta_{eff} \simeq 0.4$.

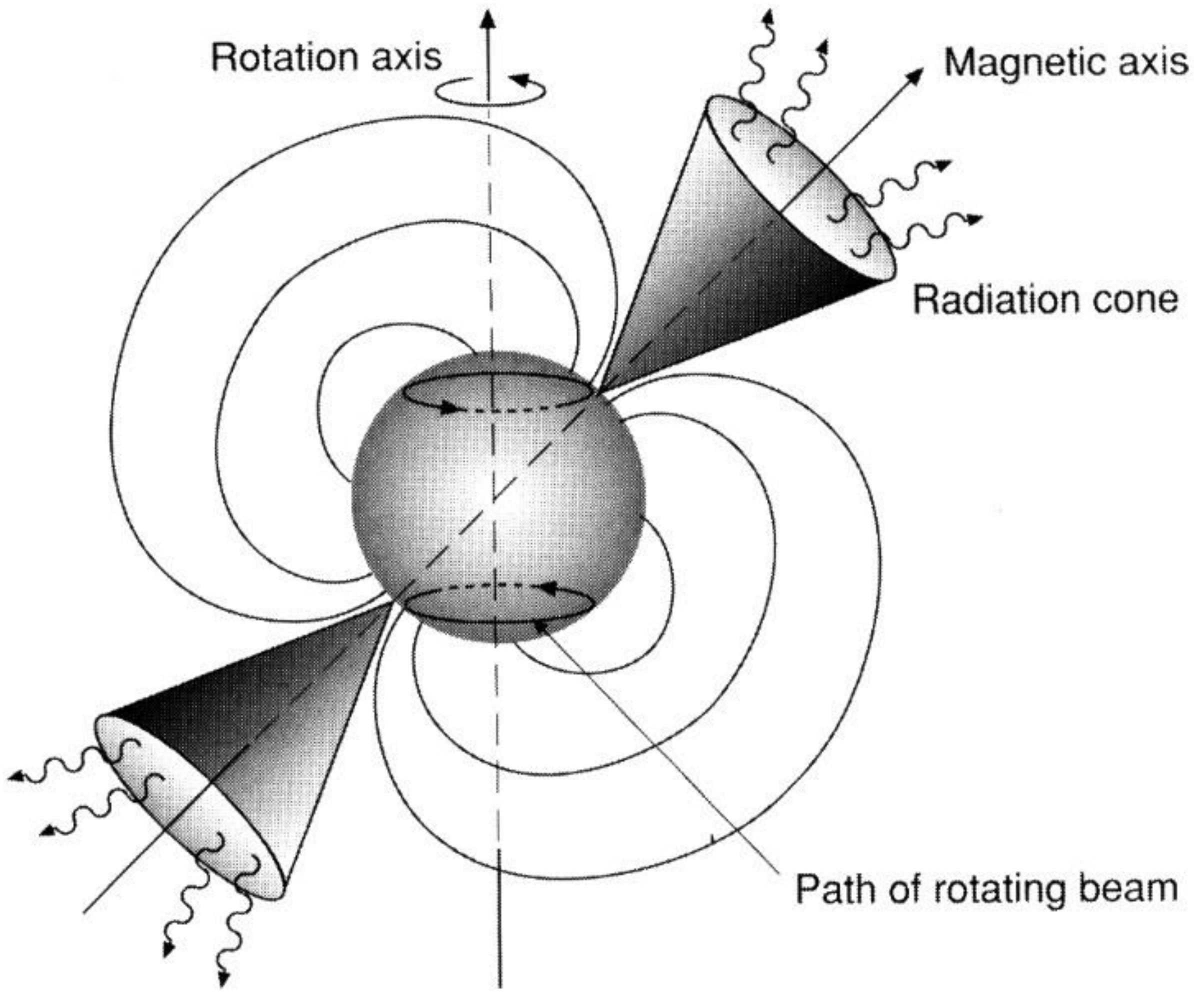
The magnetic fields observed in Ap stars could bring to the atmosphere the stability needed for diffusion processes to be important. They would also guide diffusion into patches leading to the periodic variation of the observed overabundances.



Camenzind 1990

An RS Canum Venaticorum (CVn) binary





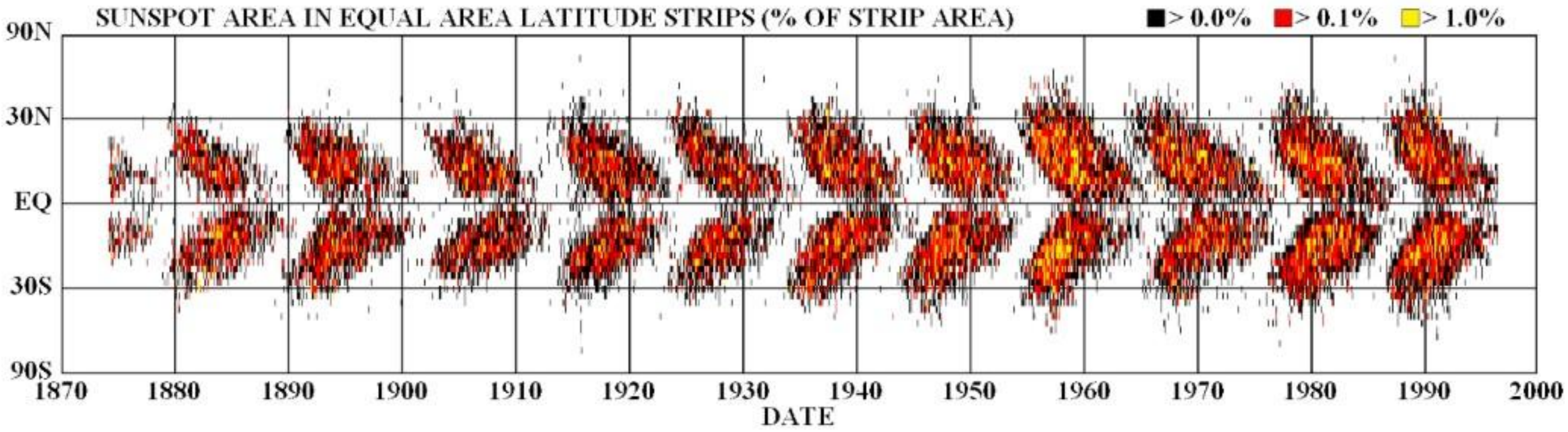
A pulsar is a rapidly rotating neutron star (not pulsating).

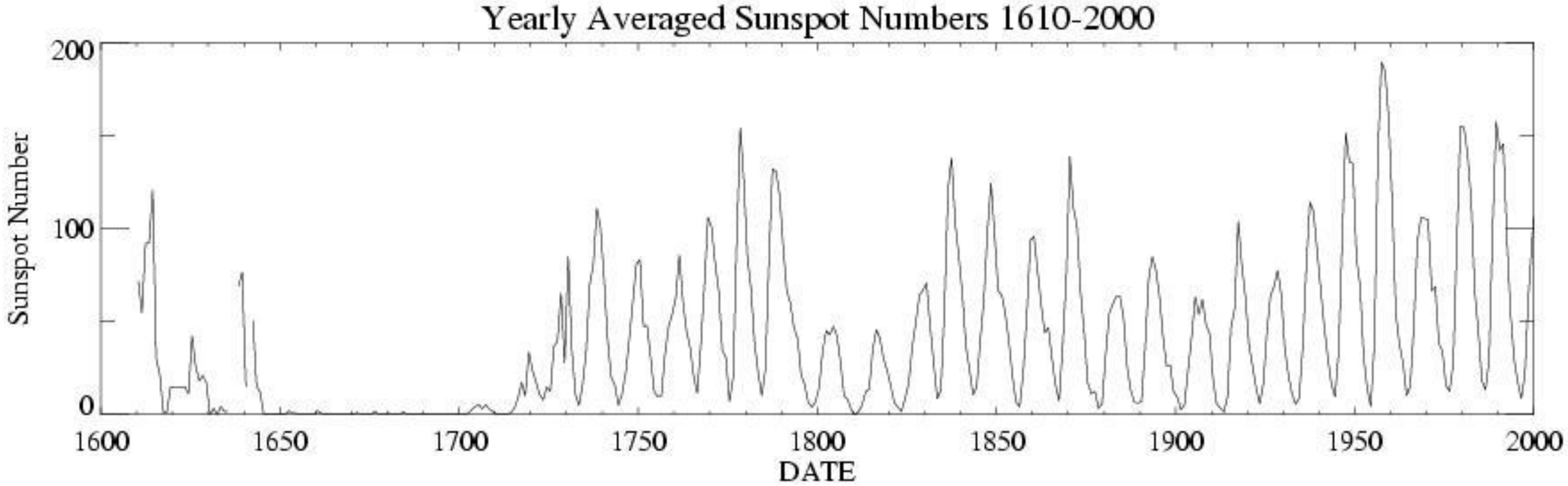
If a star has a weak radial magnetic field B_r , and if the star rotates differentially, B_r is stretched horizontally and will be amplified after a few rounds, $\mathrm{B}_\phi \gg B_r$
→ Spruit dynamo

M dwarfs exhibit rapid, irregular flares, bright in the blue and UV.

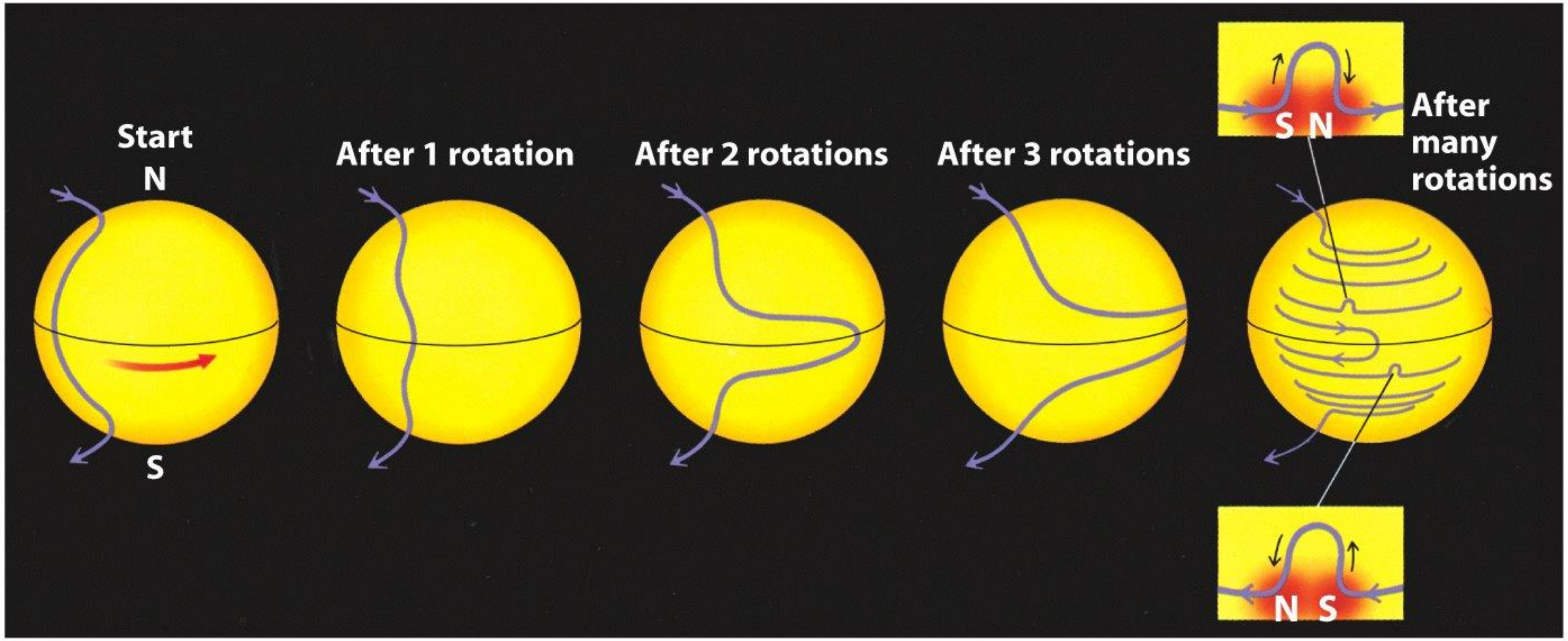
Ultracool dwarfs ($<$ 1000 K) are magnetized, a few kG, and emit radio radiation

Beginning of an 11-year cycle → a few sunspots appear at mid-latitude; progressively more in number and at lower-latitudes.

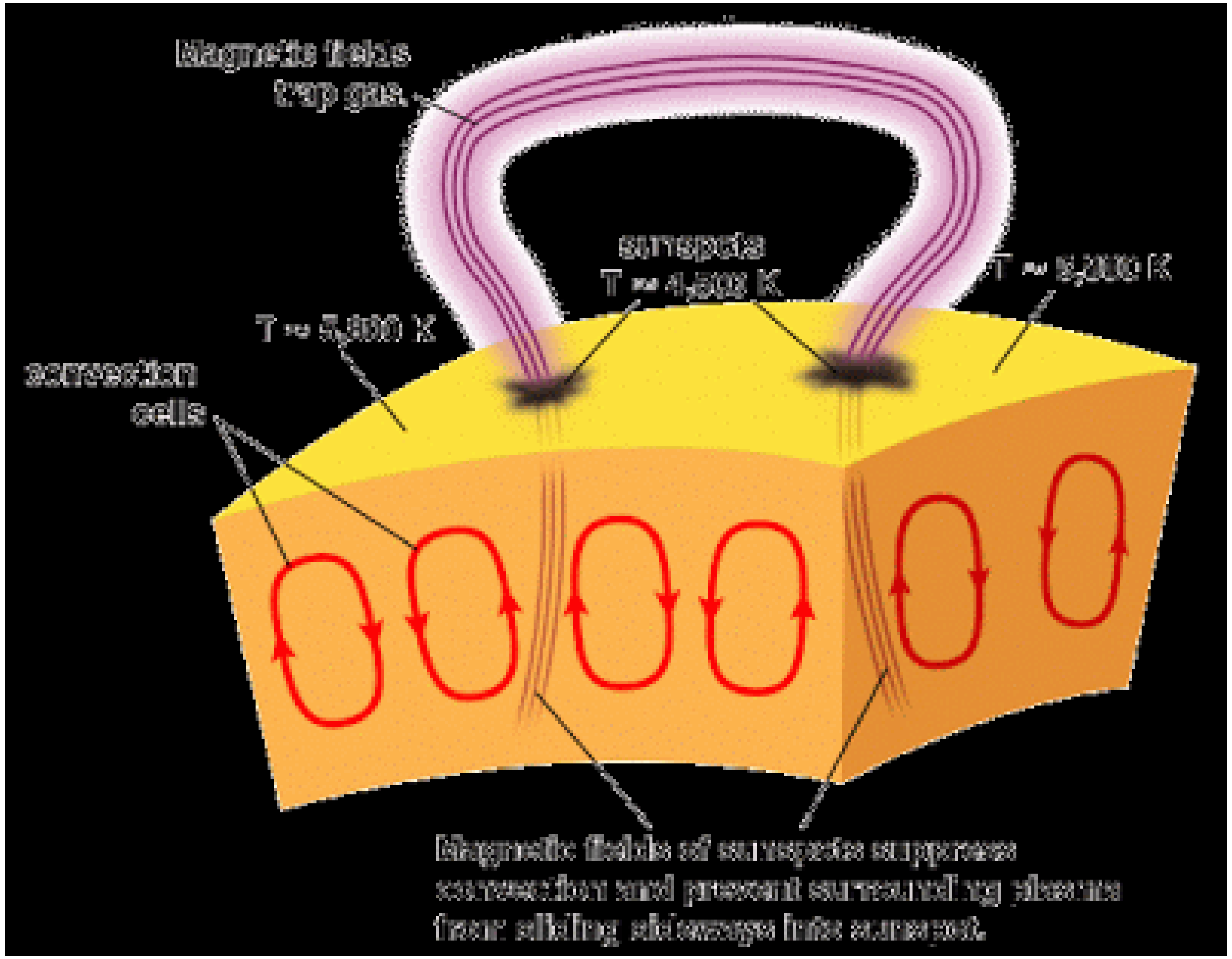


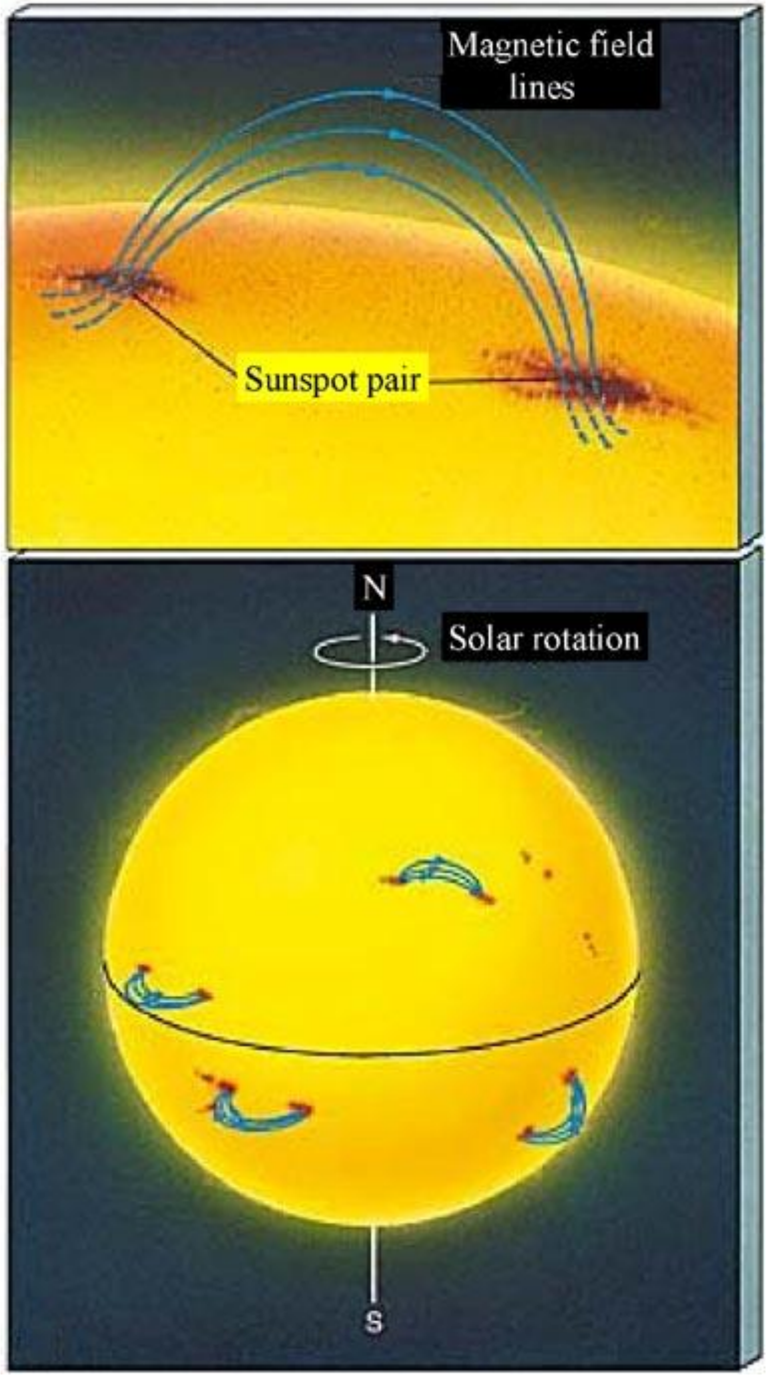


The magnetic field gets increasingly tangled because of the differential rotation. The field breaking through the surface is parallel to the surface and suppresses upward convection → cooler and lower elevation (sunspots)

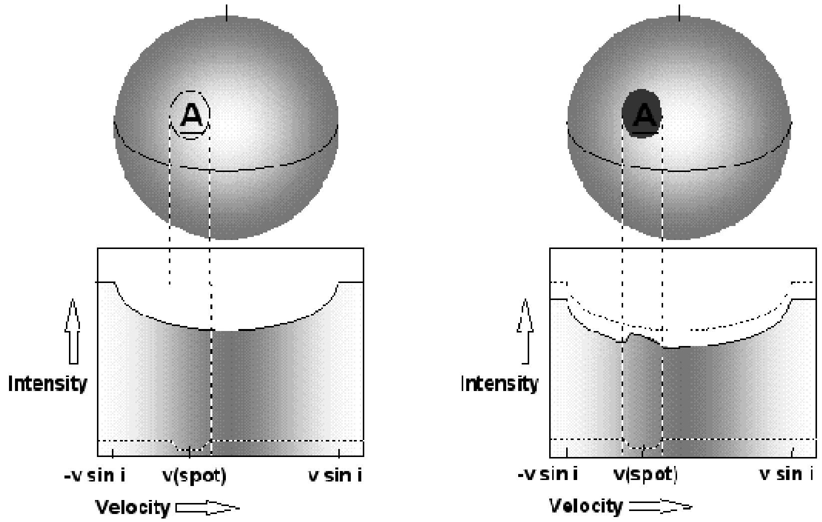


Bobcock’s magnetic dynamo model

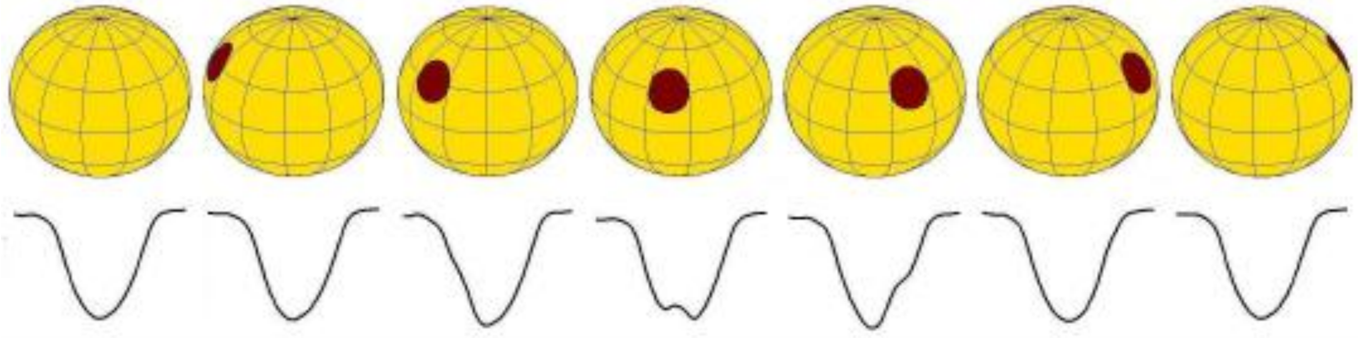

Magnetic fields trap gas.
sunspots
T ≈ 4,500 K
T ≈ 5,800 K
convection cells
Magnetic fields of sunspots suppress convection and prevent surrounding plasma from sliding sideways into sunspot.

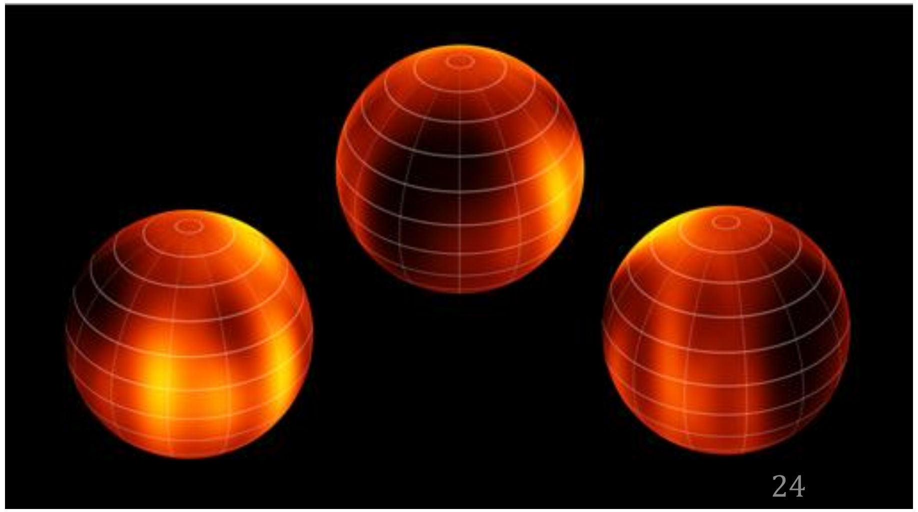

Magnetic field lines
Sunspot pair
N
Solar rotation
S

Surface inhomogeneity (T fluctuations, composition variations, B fields, activity) → distortion across spectral lines as the star rotates

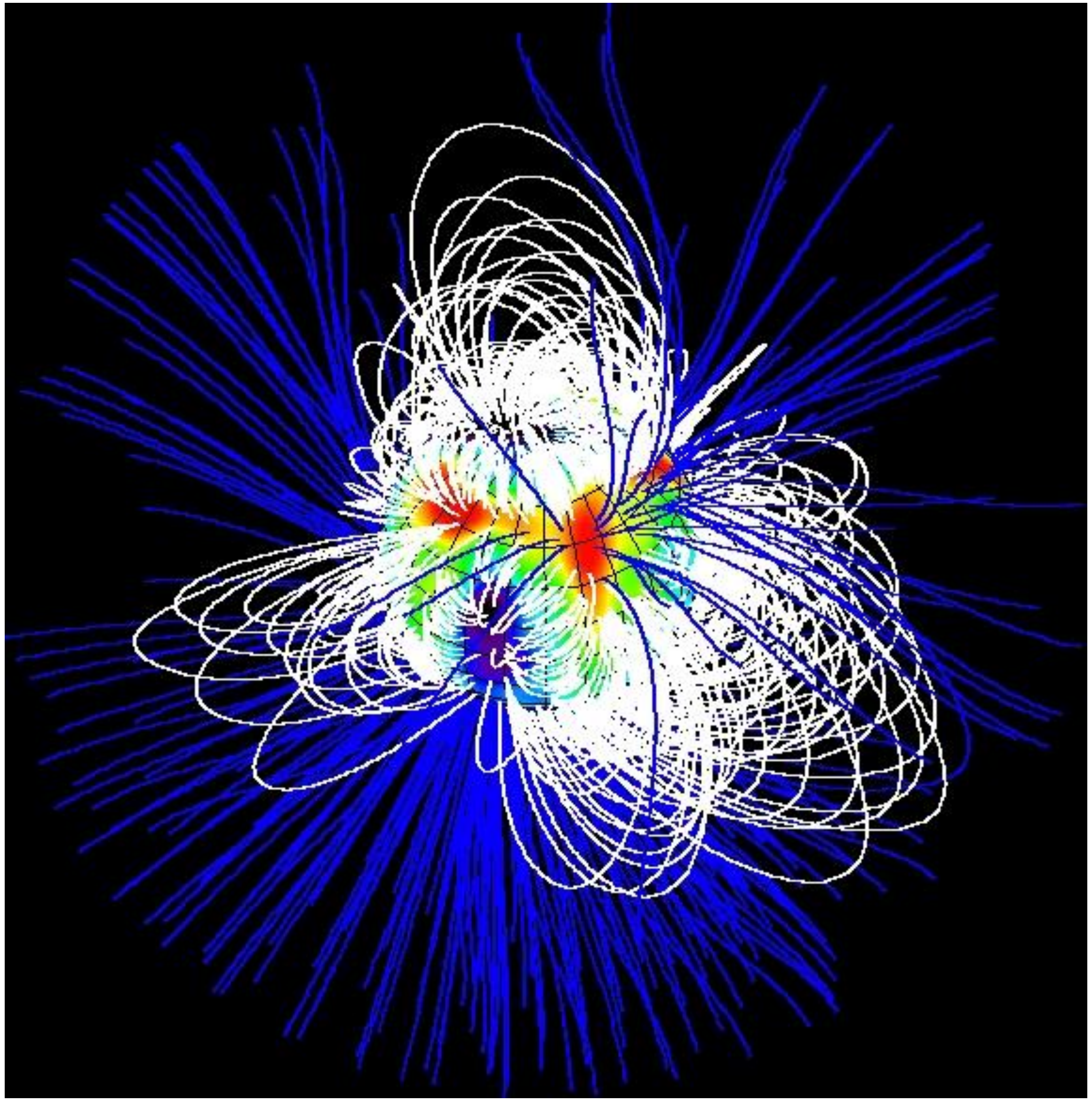


Diagnosed by brightness variations due to starspots, or by **Doppler imaging**





The BD Luhman 16b by the VLT



Surface magnetic field of SU Aur (a young star of T Tauri type), reconstructed by Zeeman-Doppler imaging

Effect of Binarity

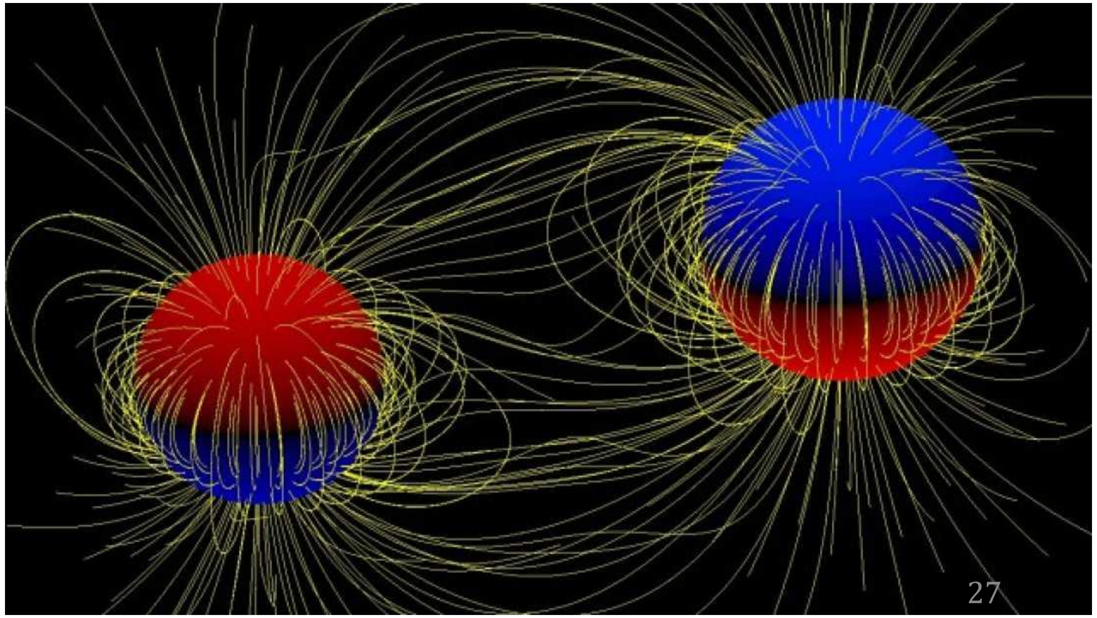
Binary Stars

The binary fraction of young stars comparable to that of MS stars.

Star formation = Binary formation = Cluster formation

One of the solutions (alternative: a disk and planets) to the angular momentum problem during SF

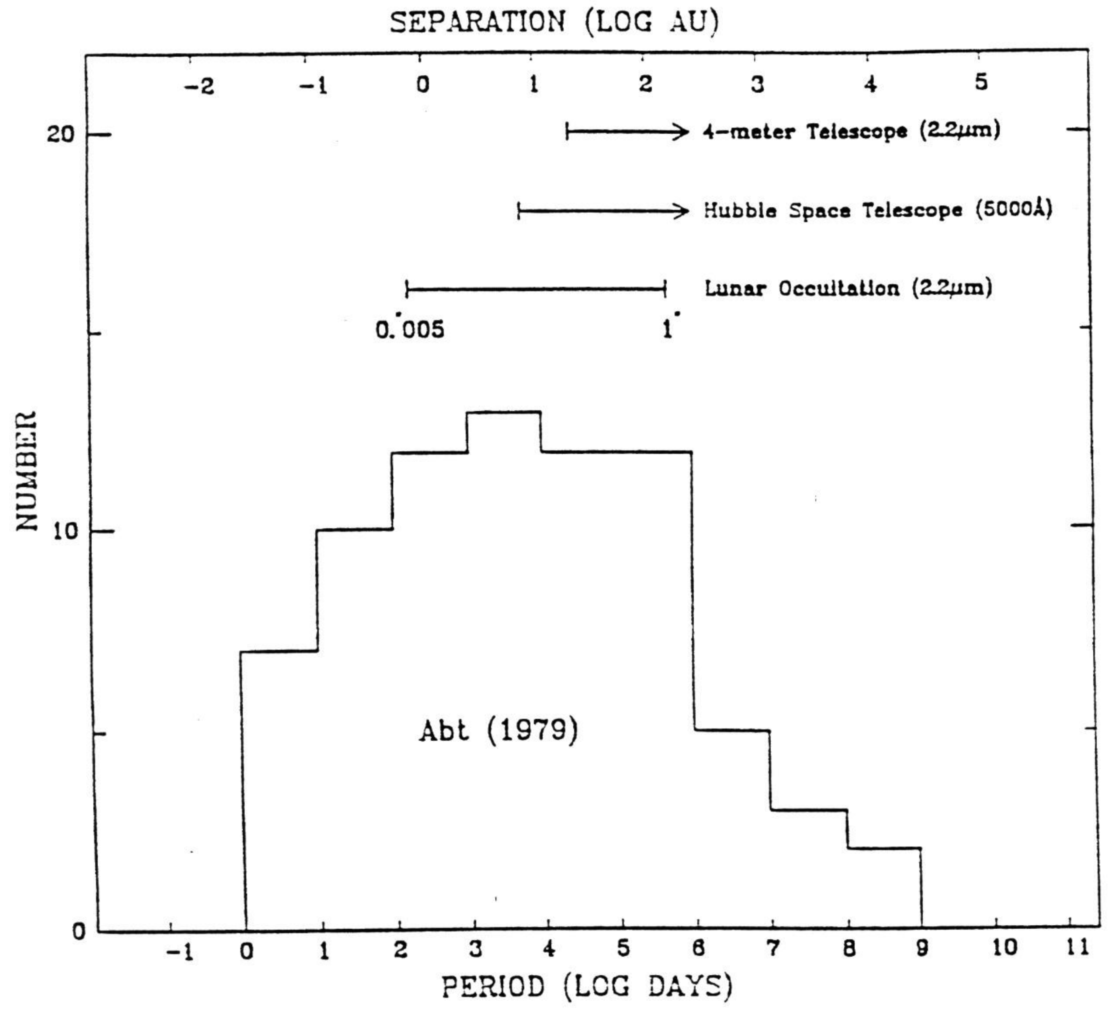
Intricate magnetic interaction between binary components



Solar-type stars,
(singles):(doubles):(triples):(quadrupoles)=42:46:9:2
(Abt & Levy 1976)

A smooth period distribution peaking ~14 yrs

Mass ratio
→ fission (for close pairs), and
→ separate protostellar contraction (for wide pairs)



Close binaries → mass and momentum exchanges

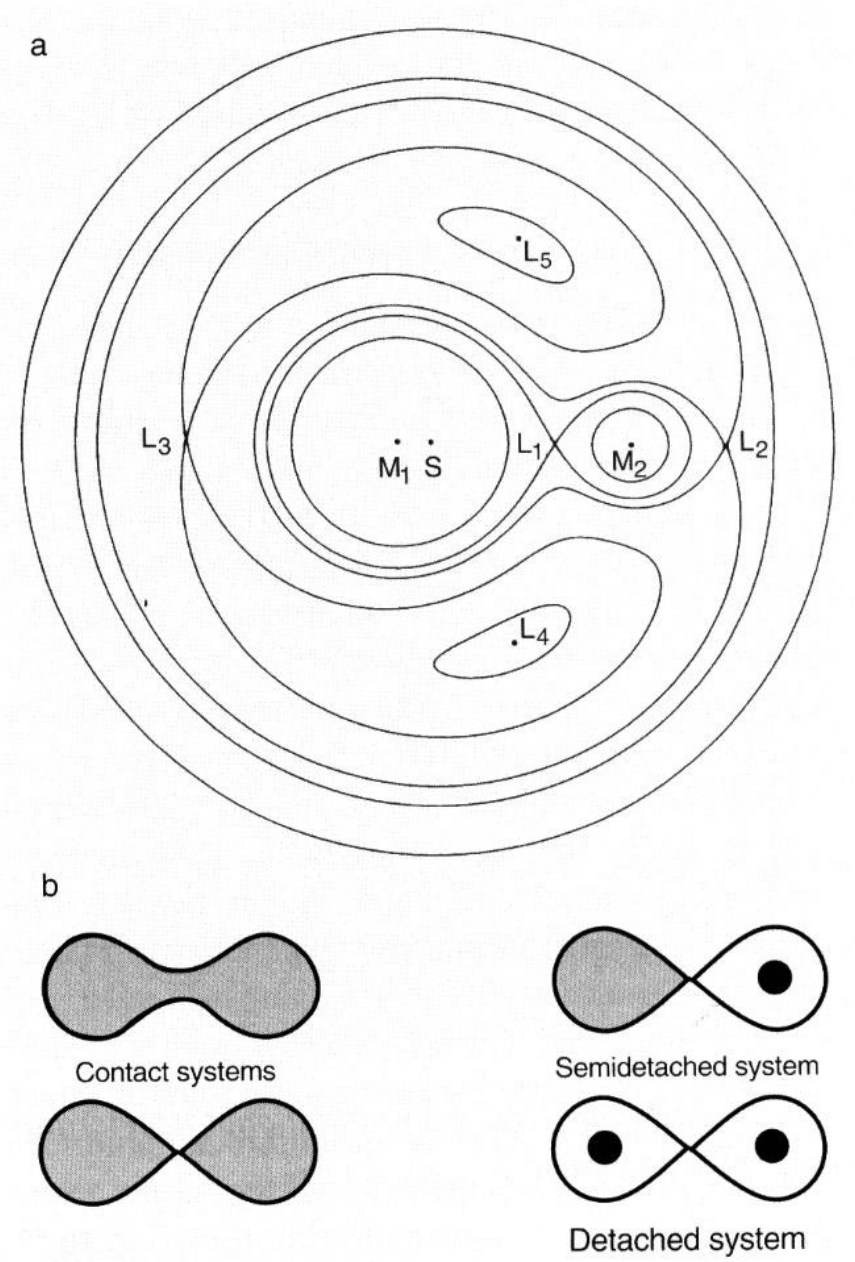
Originally more massive component as the primary

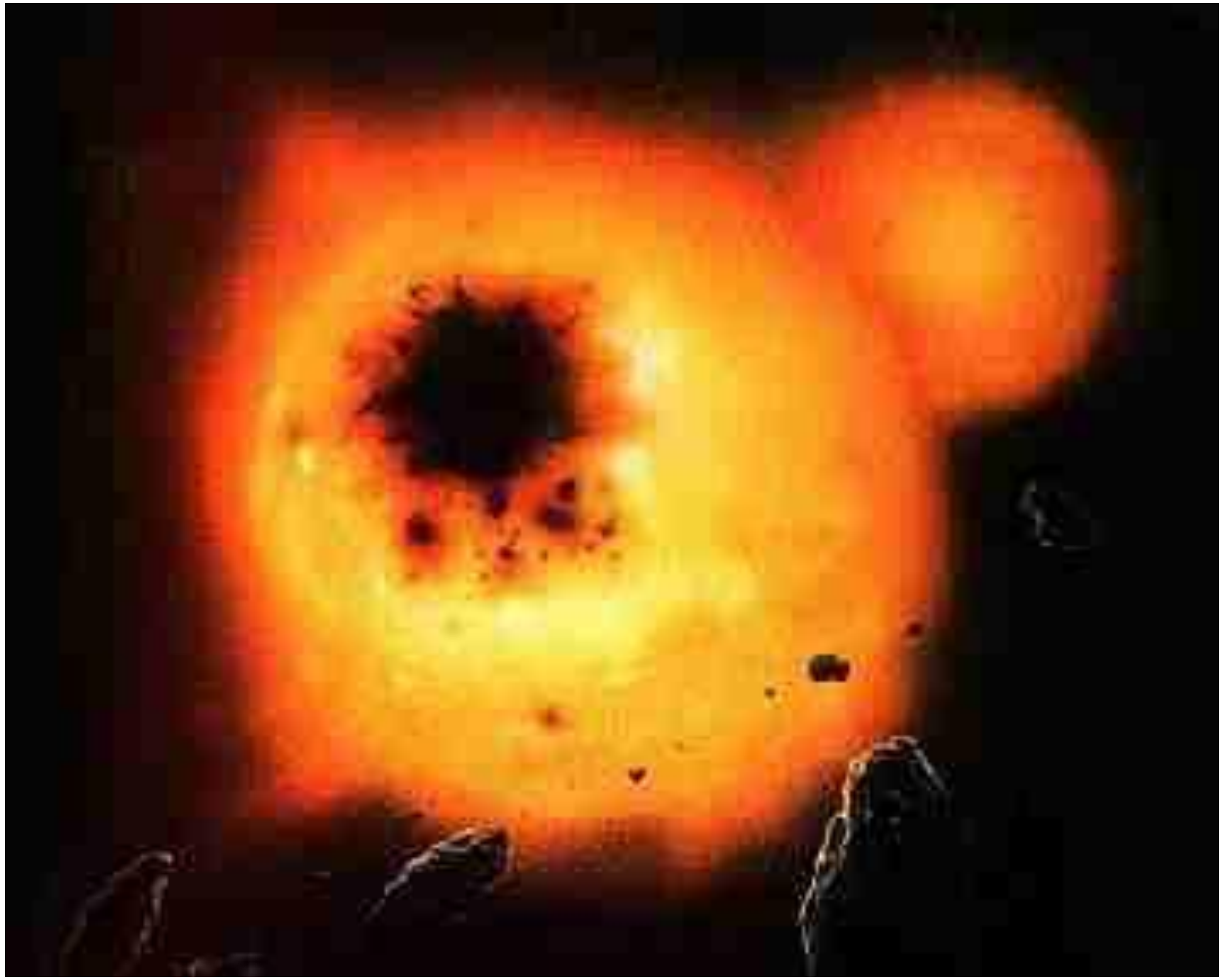
Strong tidal forces
→ orbit/spin synchronization

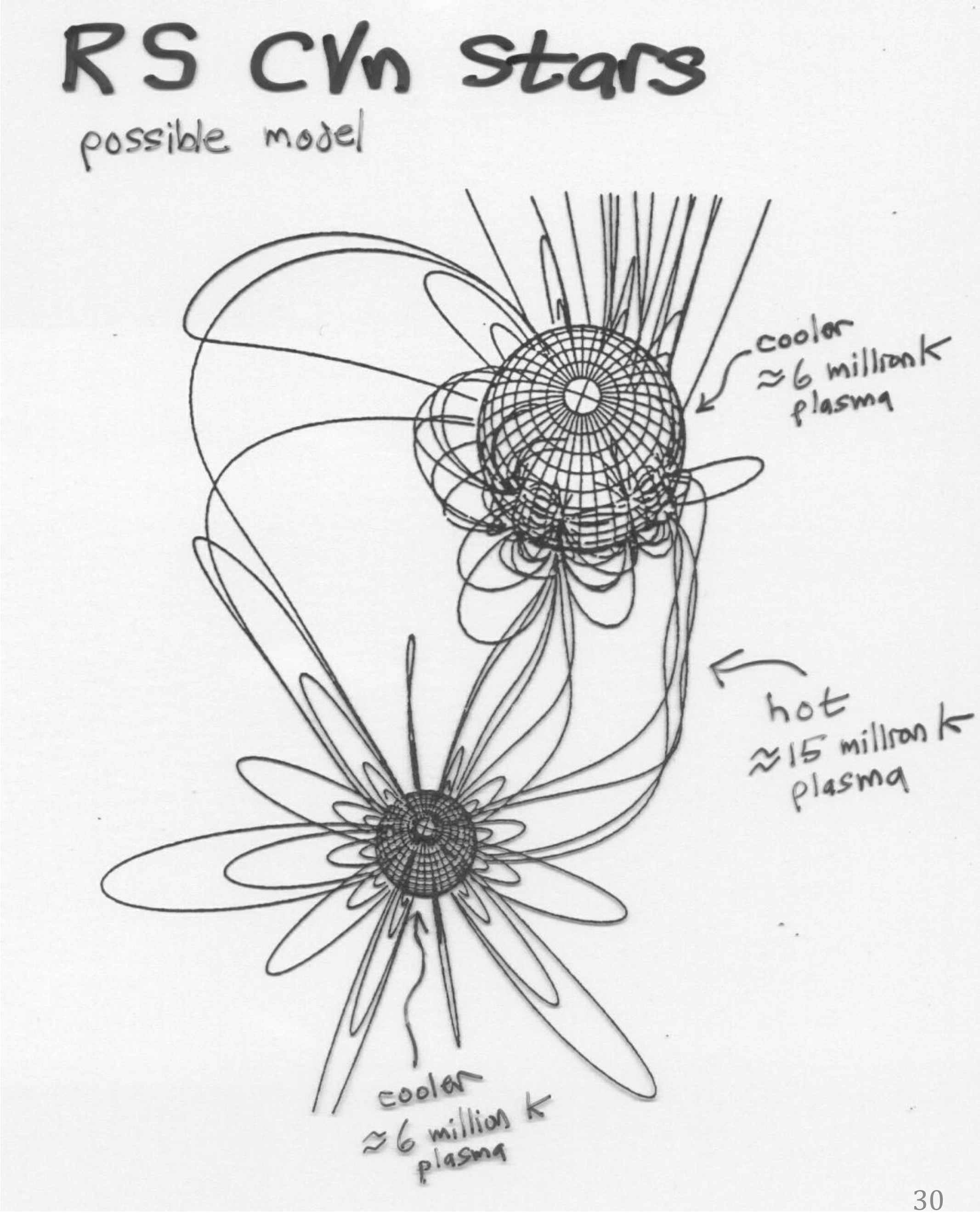
Detached, semi-detached, contact systems

Some with common envelopes

Numerous high-energy phenomena







RS CVn stars: eruptive variables and close binary systems

Effect of Mass Loss

Mass Loss

Every star loses mass in every stage of evolution.

$$\frac{1}{2}mv_{esc}^2 = \frac{GMm}{R}$$

i.e., due to kinetic energy of gas at the stellar surface.

Alternatively, there could be mechanisms to accelerate the particles, e.g., coronal winds (stars with surface convection → acoustic waves, like the Sun), radiative winds (photon momentum), line-driven (continuum-driven, dust-driven) winds, rotation-driven (pulsation-driven) winds.

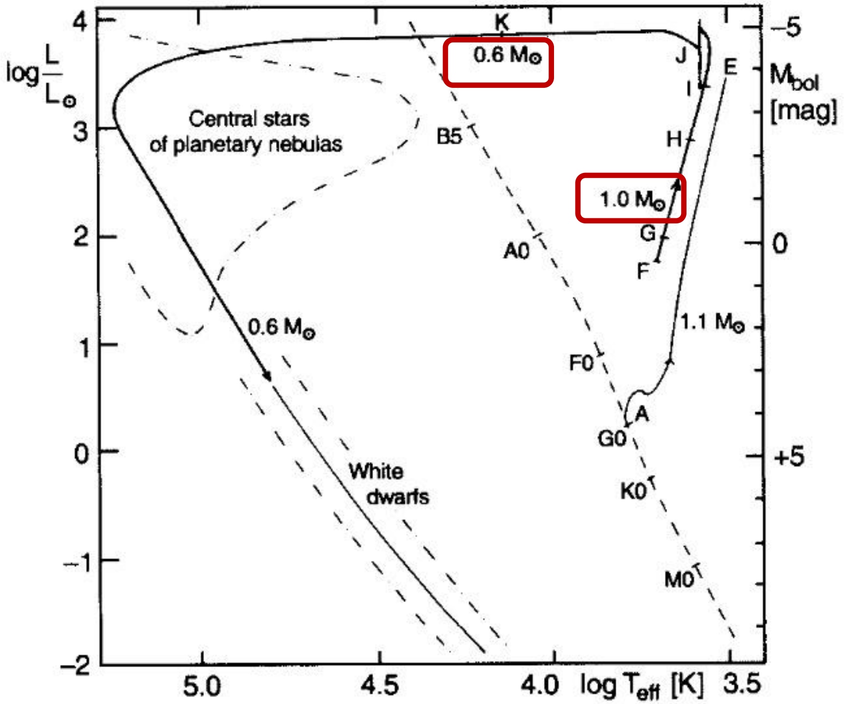


Fig. 8.8. The evolutionary paths in the Hertzsprung–Russell diagram of Population I stars having 1.0 $\mathcal{M}_\odot$ and 1.1 $\mathcal{M}_\odot$, from central hydrogen burning (A) to the helium flash (E), without taking mass losses into account. After A. V. Sweigart and P. G. Gross (1978). The ejection of a mass of 0.1 $\mathcal{M}_\odot$ during the helium flash was assumed. The further evolution of the star of 1.0 $\mathcal{M}_\odot$ was calculated taking the mass loss according to (7.105) into account, after D. Schönberner (1979). F → G: the asymptotic giant branch; only one of the thermal pulses (helium flashes) which occur after I is drawn in, at J. The mass loss becomes important at H and leads to a final mass of 0.6 $\mathcal{M}_\odot$, which is reached at K

Mass loss (Reimers 1975)

$$\dot{M} \approx 4 \times 10^{-13} \frac{L/L_\odot}{(g/g_\odot)\ (R/R_\odot)} \ [\mathrm{M_\odot\ yr^{-1}}]$$

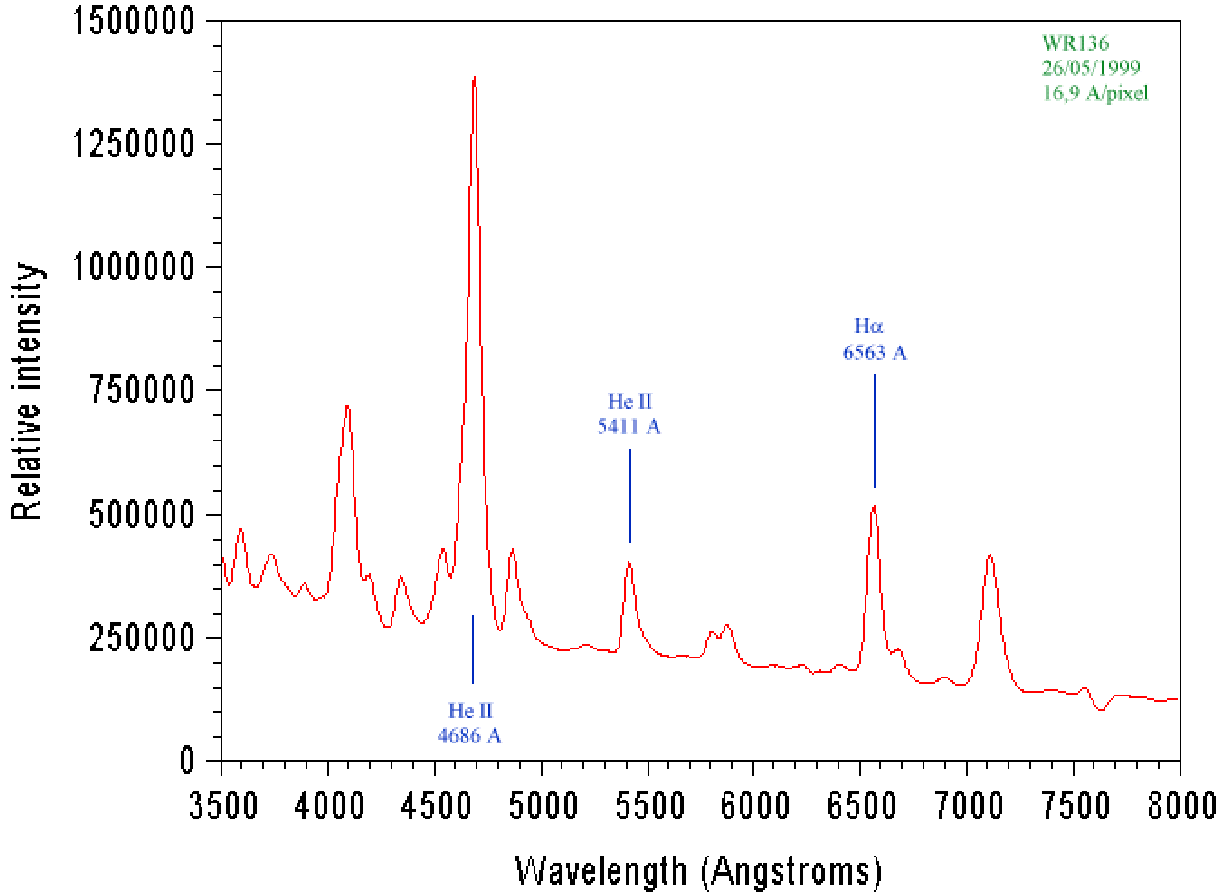
$$g = GM/R^2$$

Sun now $\dot{M} \approx 2 \times 10^{-14}\ \mathrm{M_\odot\ yr^{-1}}$

Cool supergiants $\dot{M} \approx 10^{-7} - 10^{-5}\ \mathrm{M_\odot\ yr^{-1}}$

Metal-rich → mass loss ↑

Unsöld



Spectrum of a Wolf-Rayet star

WR stars

$T_{eff} \sim 25,000$ to $50,000$ K

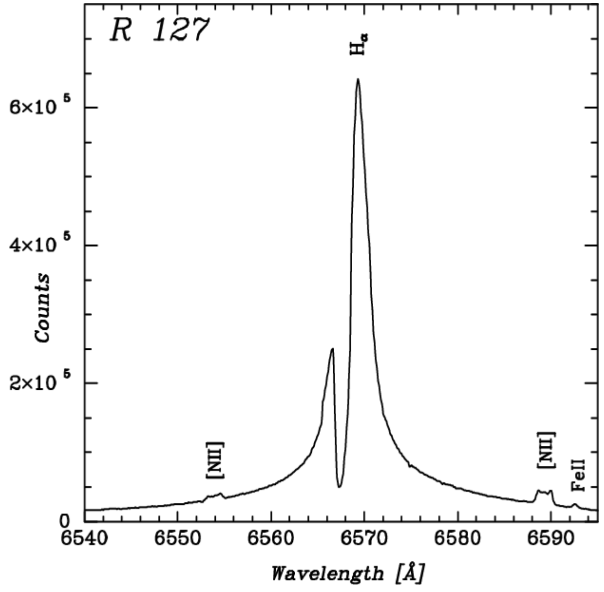
Evolved massive ($\gtrsim 20 M_\odot$) stars

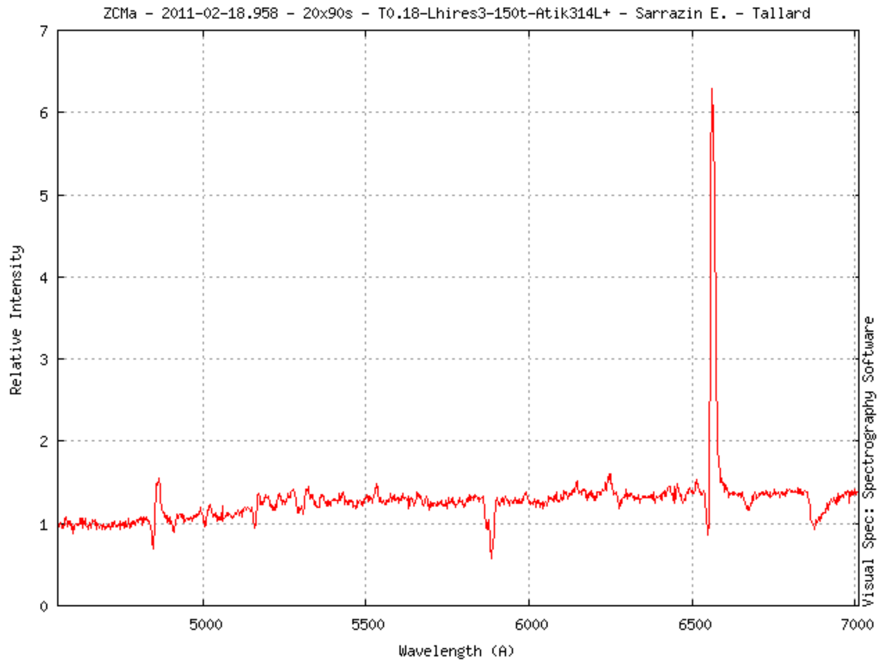
Wind ~ 2000 km s^{-1}

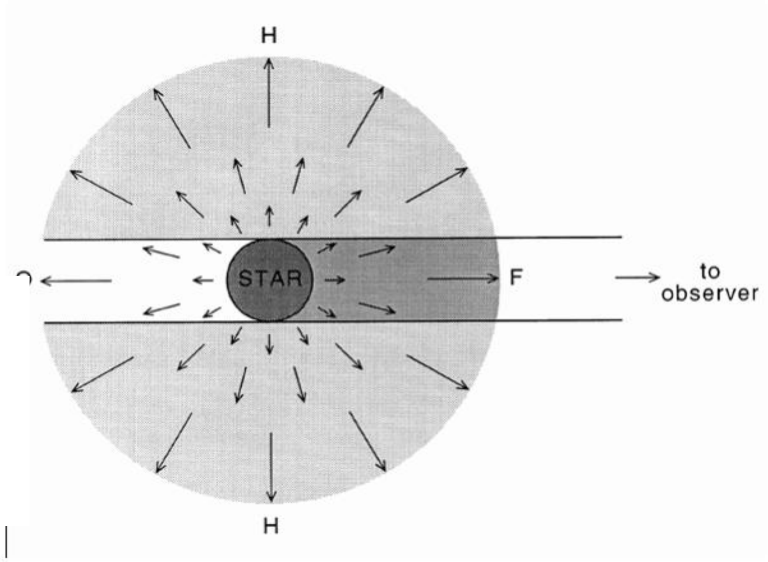
$\dot{m} \sim 10^{-5} M_\odot \, yr^{-1}$

O ($\rightarrow$ WN) $\rightarrow$ LBV $\rightarrow$ WN / WC

$\rightarrow$ SN Ib,c







P Cygni profile of a spectral line --- a blue-shifted absorption superimposed on an emission line → **mass loss** (cool gas toward us)

Lamers and Cassinelli, *Introduction to Stellar Winds*, Cambridge, 1999

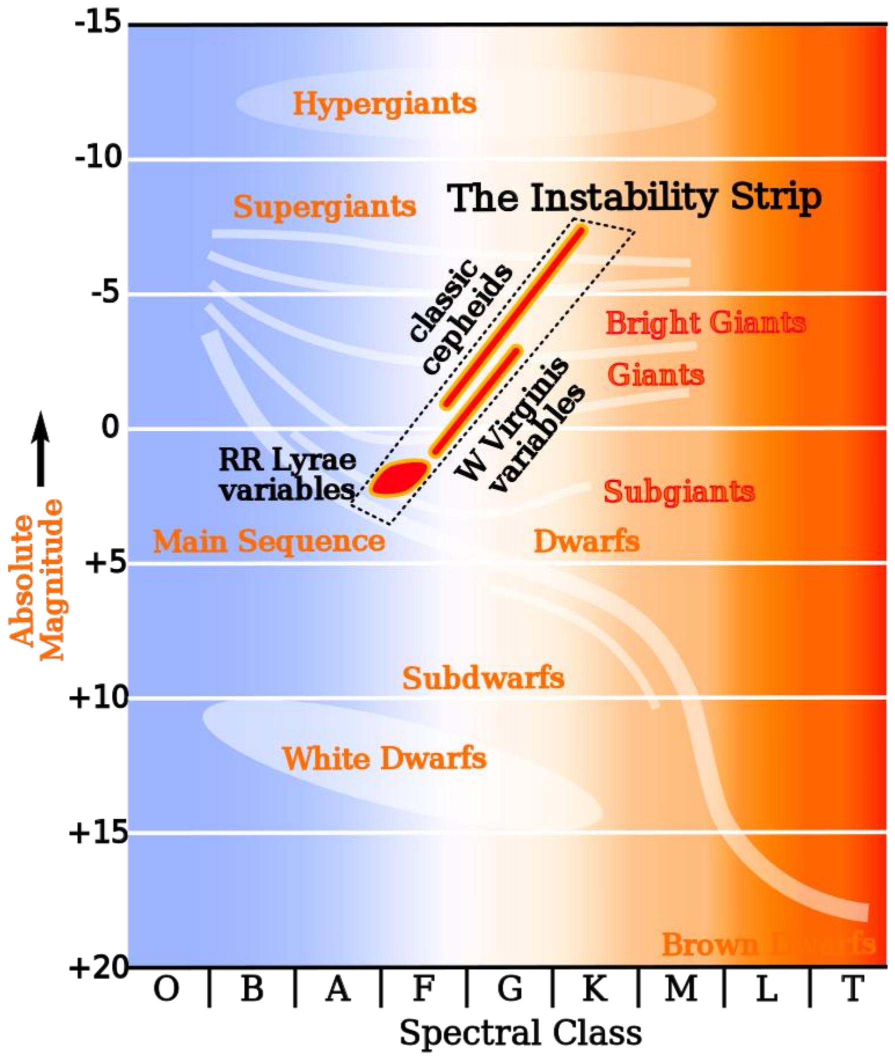
Stellar Variability

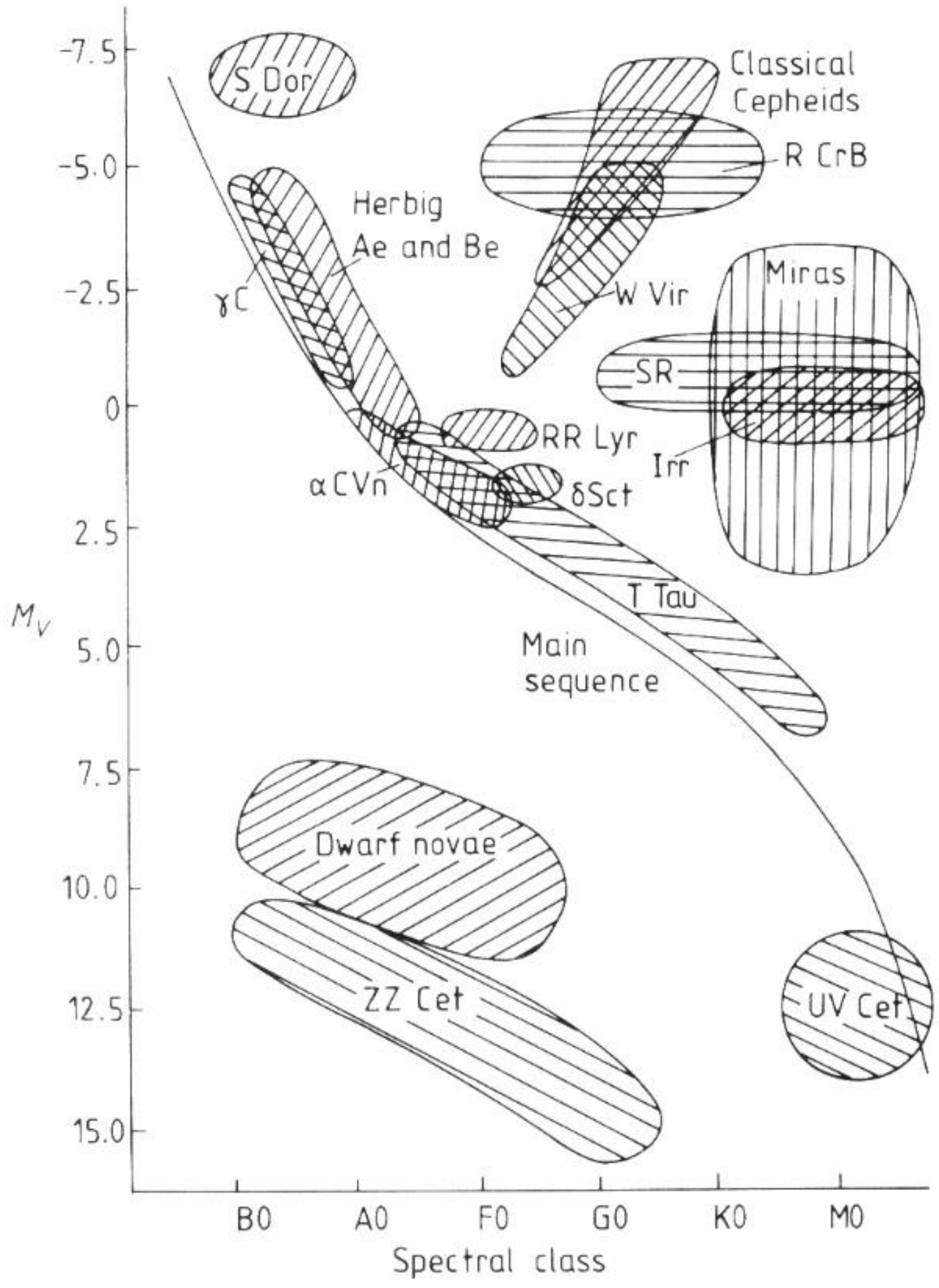
Every star varies in brightness.

The solar constant
The flux density of the solar irradiance at 1 au, including all frequencies

An average value; not a physical constant; it varies

1.361 kW/m^2 at solar minimum; 0.1% greater at solar maximum





S Dor
Classical Cepheids
R CrB
Herbig Ae and Be
γC
W Vir
Miras
SR
Irr
RR Lyr
αCVn
δSct
T Tau
Main sequence
Dwarf novae
ZZ Cet
UV Cet
M_V
-7.5
-5.0
-2.5
0
2.5
5.0
7.5
10.0
12.5
15.0
B0
A0
F0
G0
K0
M0
Spectral class

Kitchin

<u>**Intrinsic variability**</u> *physical*

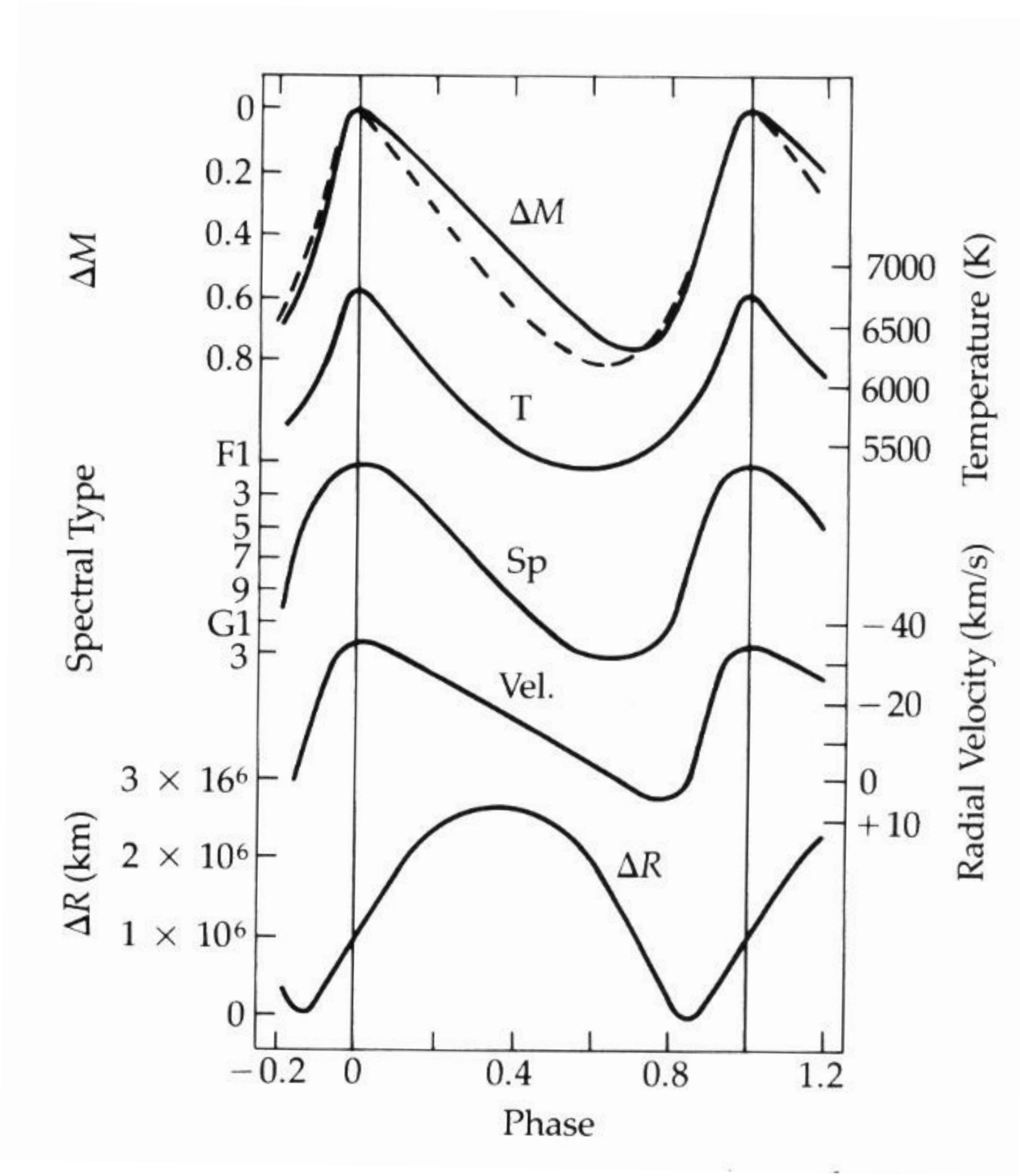
- ✓ Pulsating (RR Lyr; Cepheids, RV Tau; Mira; δ Scu; ZZ Ceti)
- ✓ Rotational (magnetic, spotted)
- ✓ Eruptive (novae, SNe, CVs, X-ray binaries; symbiotic; flare)

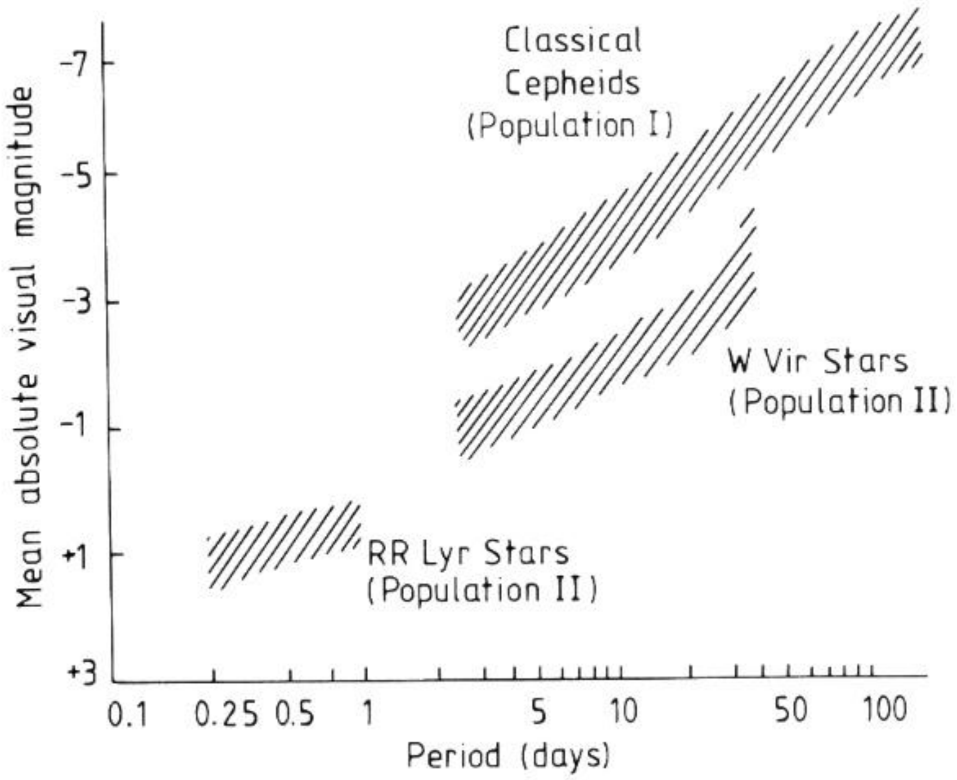
<u>**Extrinsic variability**</u> *non-physical*

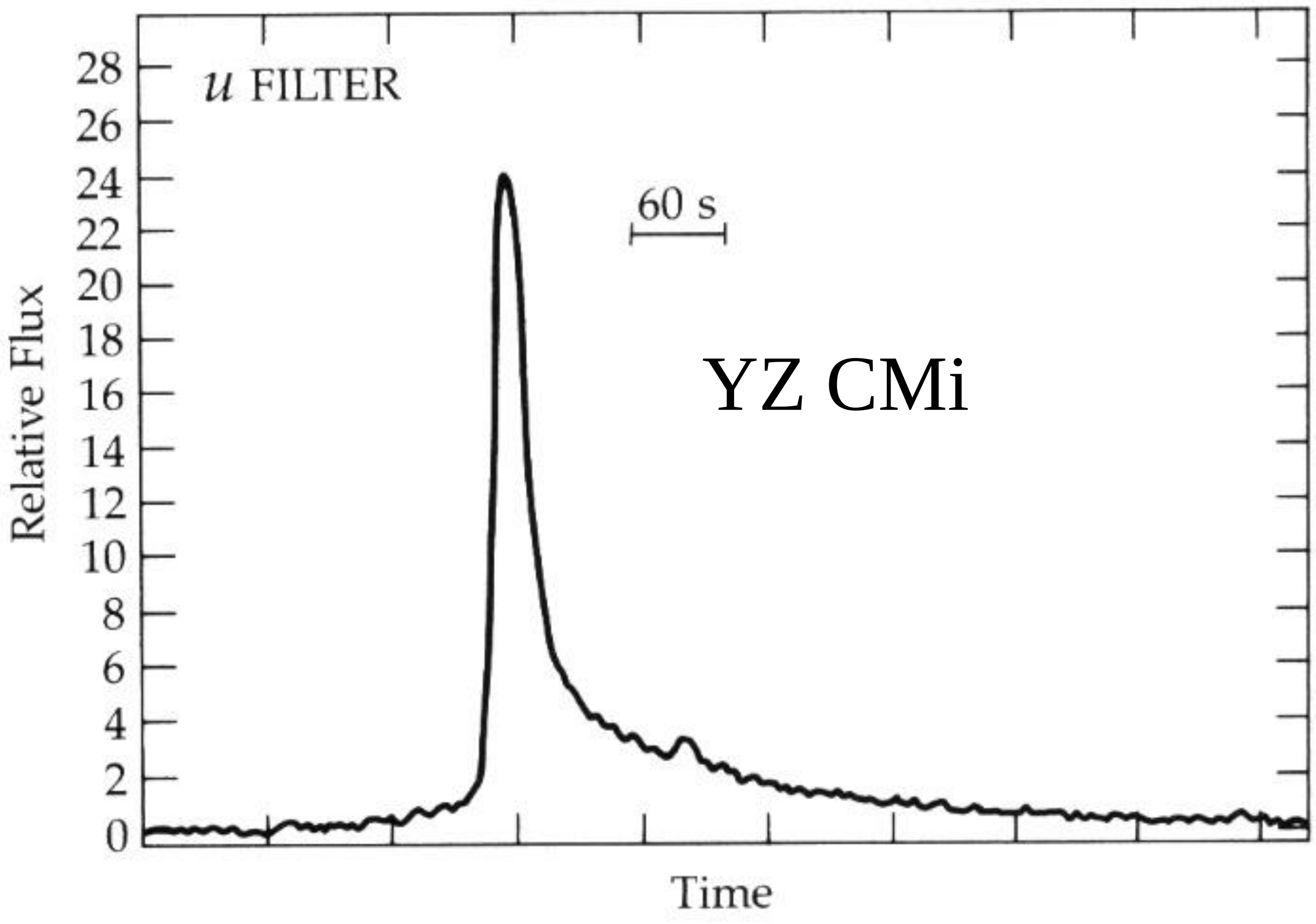
- ✓ Eclipsing (by stars, planets, dust clumps; EA; EB; EW)
- ✓ Gravitational microlensing

Some young variability (Orion var., T Tauri stars, Be stars) could have more than one mechanism.

Period-luminosity relation for pulsating variables

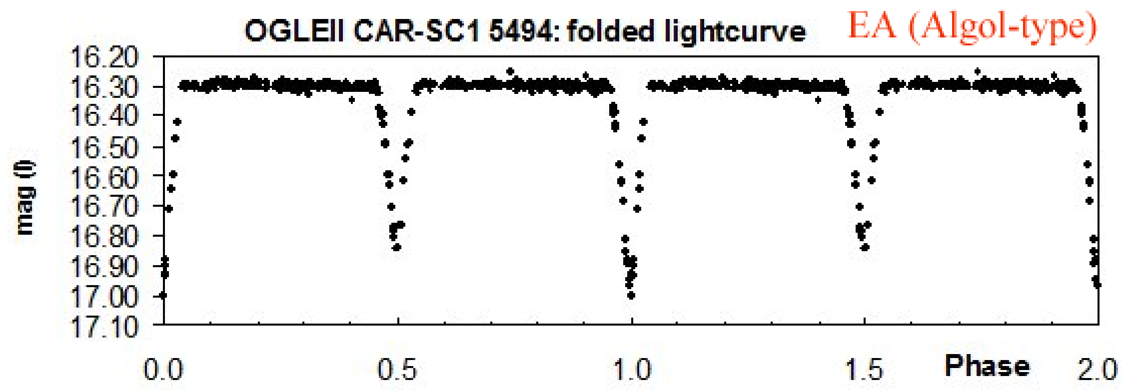


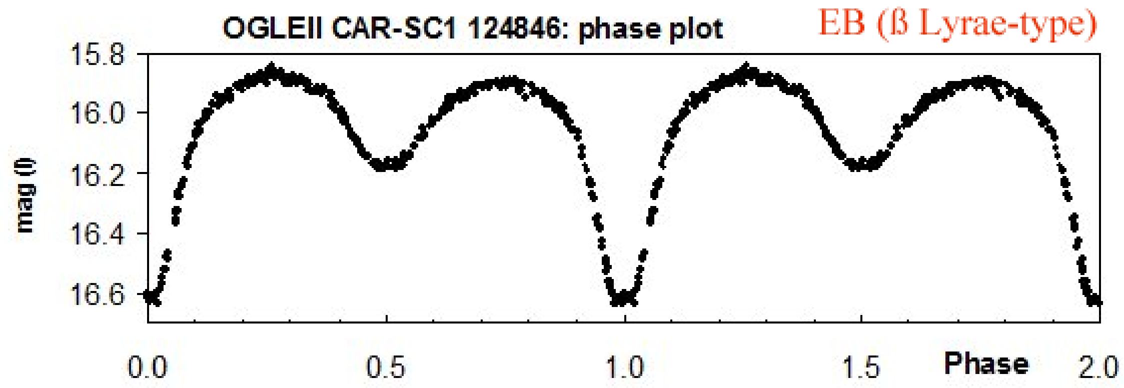


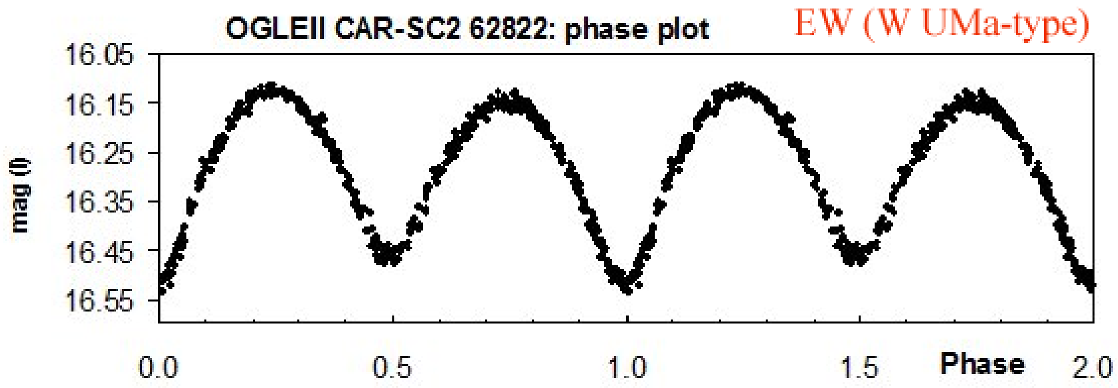


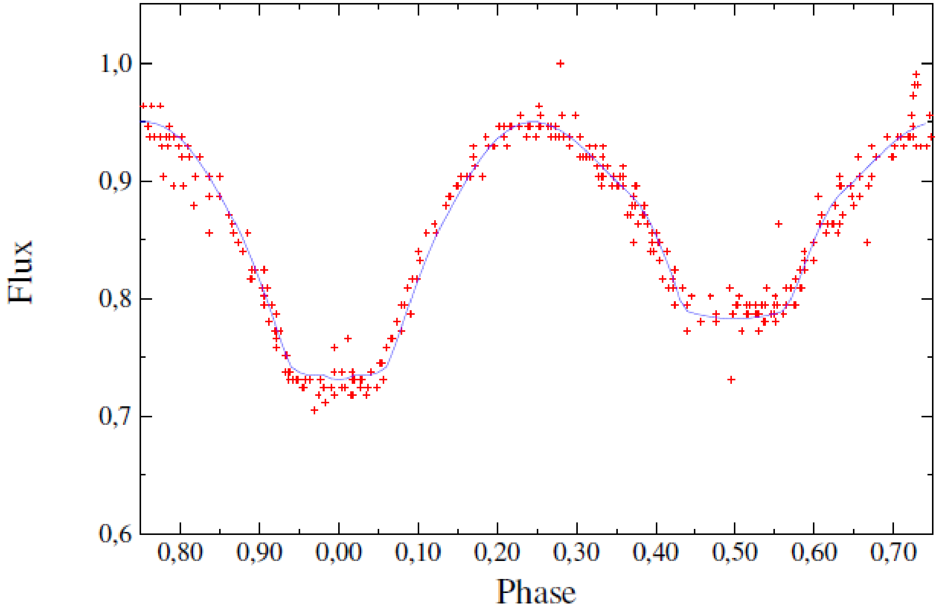
A stellar flare from an M dwarf

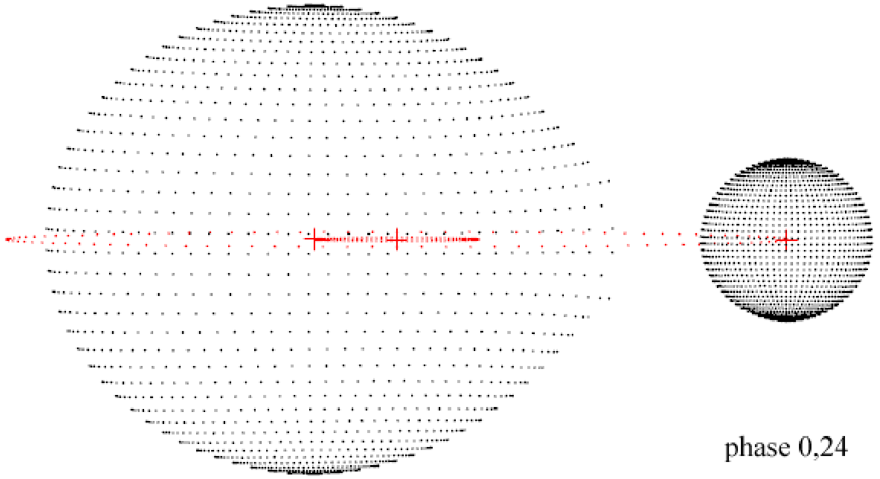
Moffett (1974)











https://vs-compas.belastro.net/bulletin/issue/2/p6

Other Main Sequences

Kippenhahn & Wright
Chap. 23

Compared to H-MS,

He-MS: $R \downarrow$ but $L \uparrow\uparrow$

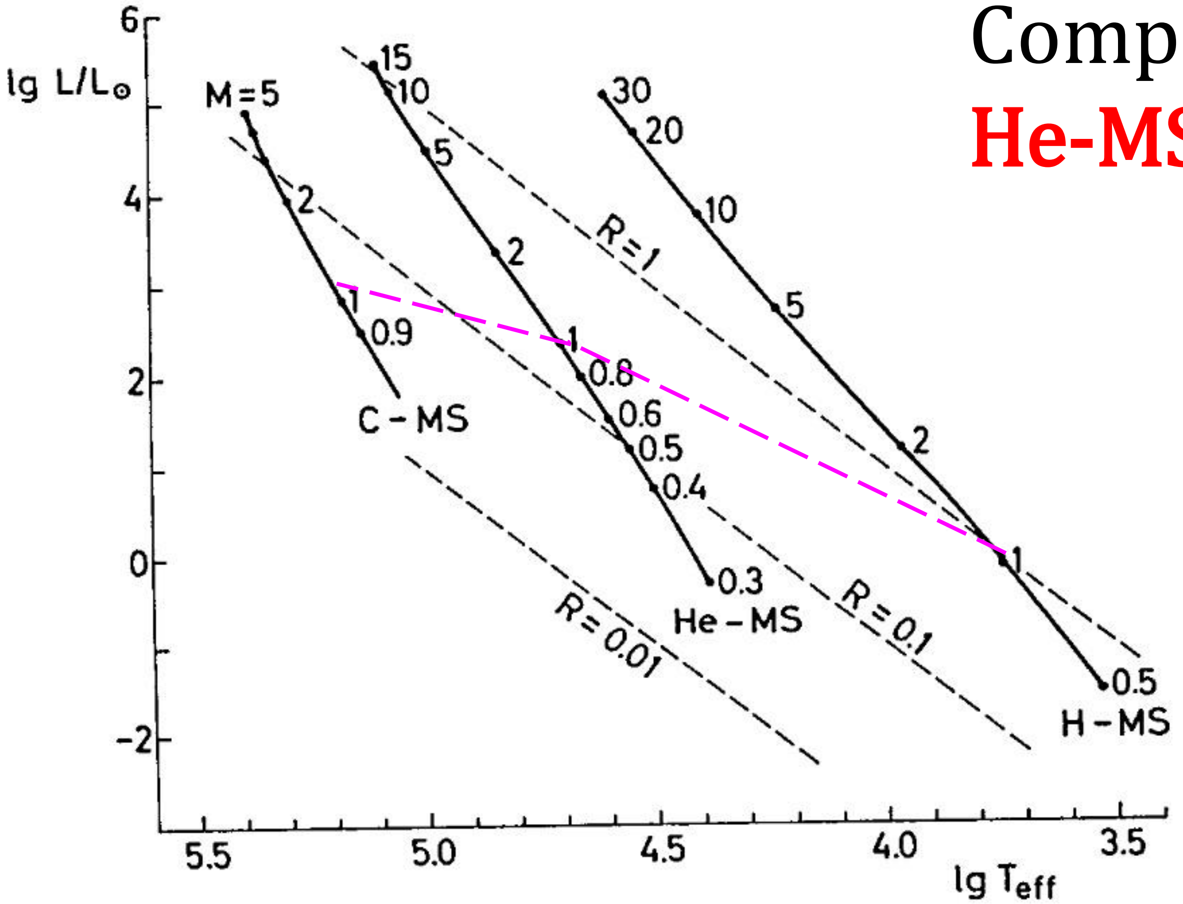


Fig. 23.1. In the Hertzsprung–Russell diagram the solid lines show the normal hydrogen main sequence (H-MS; $X_H = 0.685$, $X_{He} = 0.294$), the helium main sequence (He-MS; $X_H = 0$, $X_{He} = 0.979$) and the carbon main sequence (C-MS; $X_H = X_{He} = 0$, $X_C = X_O = 0.497$). The labels along the sequences give stellar masses M (in units of $M_\odot$). Three lines of constant stellar radius (R in units of $R_\odot$) are plotted (*dashed*)

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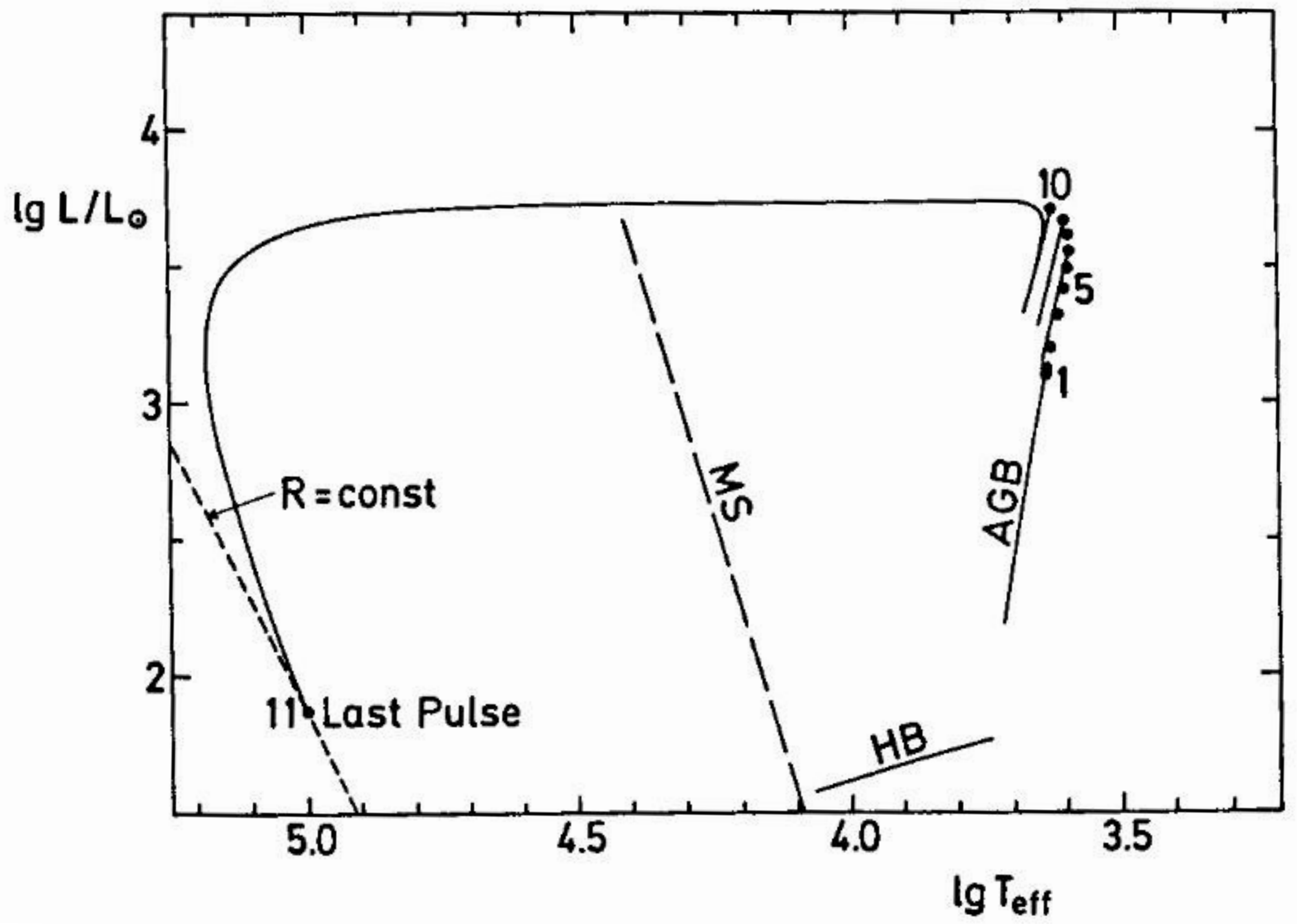
lg L/L⊙
4
3
2
10
5
1
R = const
MS
AGB
11 Last Pulse
HB
5.0
4.5
4.0
3.5
lg Teff