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SPACE WEATHER ON EXTRASOLAR PLANETARY SYSTEMS

Contents

- Space Weather, Space Climate
- Habitability
- Stellar variability
- Stellar activity cycles
- Maunder Minimum?
- M dwarfs
- Case studies of exoplanets

Literature

- Many textbooks
- Reviews e.g.
  - Hanslmeier, A., The Sun and Space Weather, Springer 2002, 2008
  - Hanslmeier, A., Habitability and Cosmic Catastrophes, Springer, 2009
  - Hanslmeier, A., Water in the Universe, Springer, 2011
  - Vazquez, M., Hanslmeier, A., UV Radiation in the Solar System, Kluwer, 2005

Space Weather / Space Climate

- Space weather:
  - All that affects a planet space
    - Atmosphere
    - Surface
    - Magnetosphere
    - Space near a planet
- Space climate
  - similar

Short timescale
Hours, days, weeks, months,...

General: time < period of revolution

Long timescale
Timescale >>period of revolution

Drivers...

- Main drivers:
  - Stellar activity
  - Local properties of planetary systems
    - Asteroids
    - Comets
- Planet specification
  - Atmosphere
  - Magnetosphere

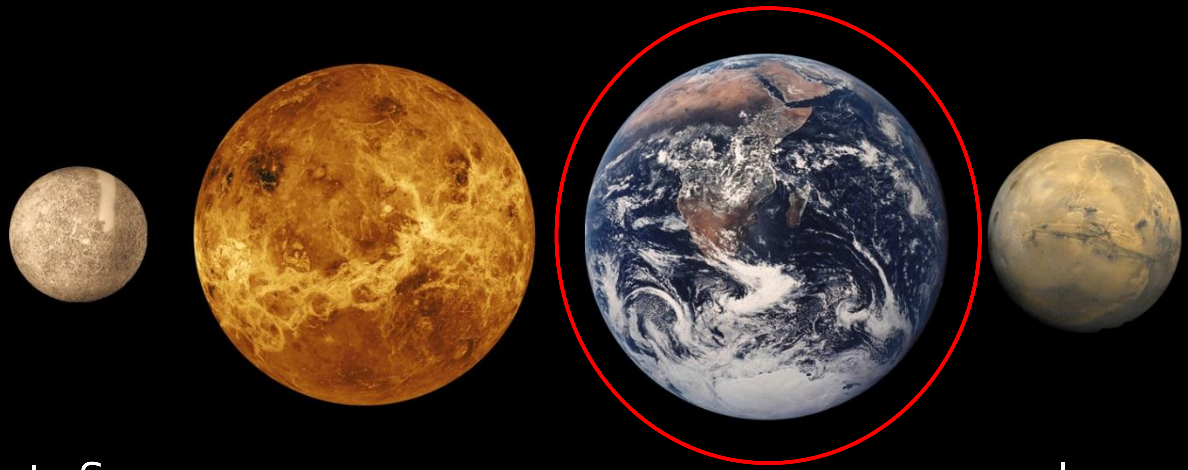
Discussion

- Discuss analogies between space weather and weather
  - What is in common?
  - What are differences?
- Discuss the term climate
  - Hot summer → climate change?
  - Global warming problem?
  - How can be characterize climate?

Habitability

- Space Weather studies → habitability
- Habitable:
  - Water in liquid form
  - Essential for live
    - Solvent
    - Specific chemical and physical properties
- Planet must have been able to keep its water
  - Problem: Venus, Mars

Space Weather - Water



Too close to Sun

Water lost due
to increasing solar
luminosity

Low surface pressure

Discussion

- How does the definition of habitability depend on our knowledge about evolution of life?
  - Life based on carbon
  - Life based on other elements like Si, P,…
- Try to give some arguments why it is highly probable that life depends on
  - Carbon
  - Water

Planets

- Solar system
  - 8 planets
  - Dwarf planets
  - Satellites of planets
- Stars
  - More than 500 planets detected
  - Many systems: multiple planets
  - Planets around stars quite common!

Extrasolar Planets

- Habitable Zones
  - Circumstellar HZ

53% of known system HZ
HZ around gas giants?
Galactic HZ

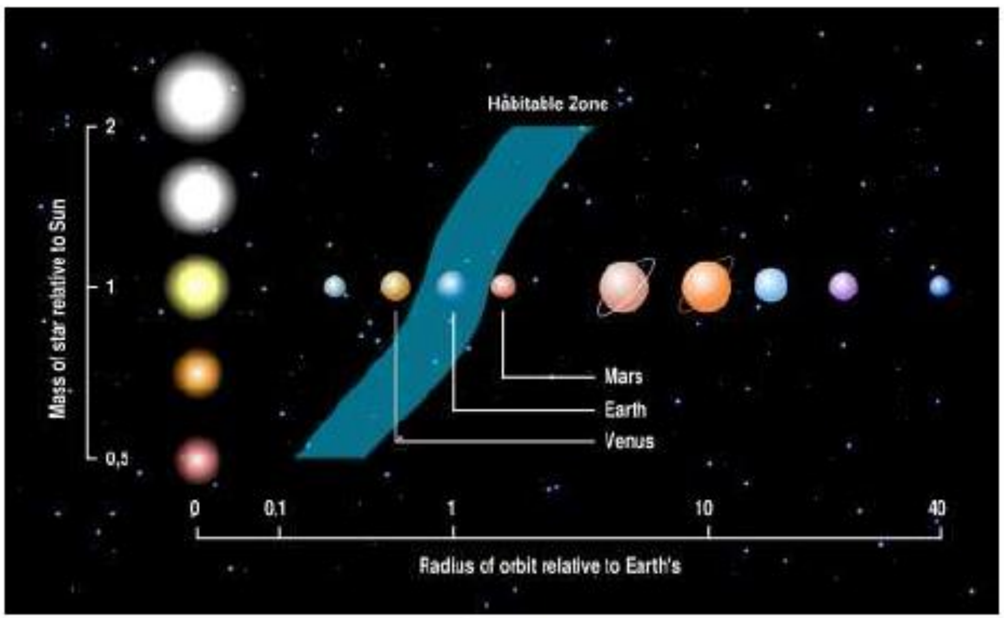


Figure 1.1: The location of the habitable zone for different masses of the central stars (left). Note that the abscissa is in logarithmic units. The solar system (at 1 solar mass) is given at the center.

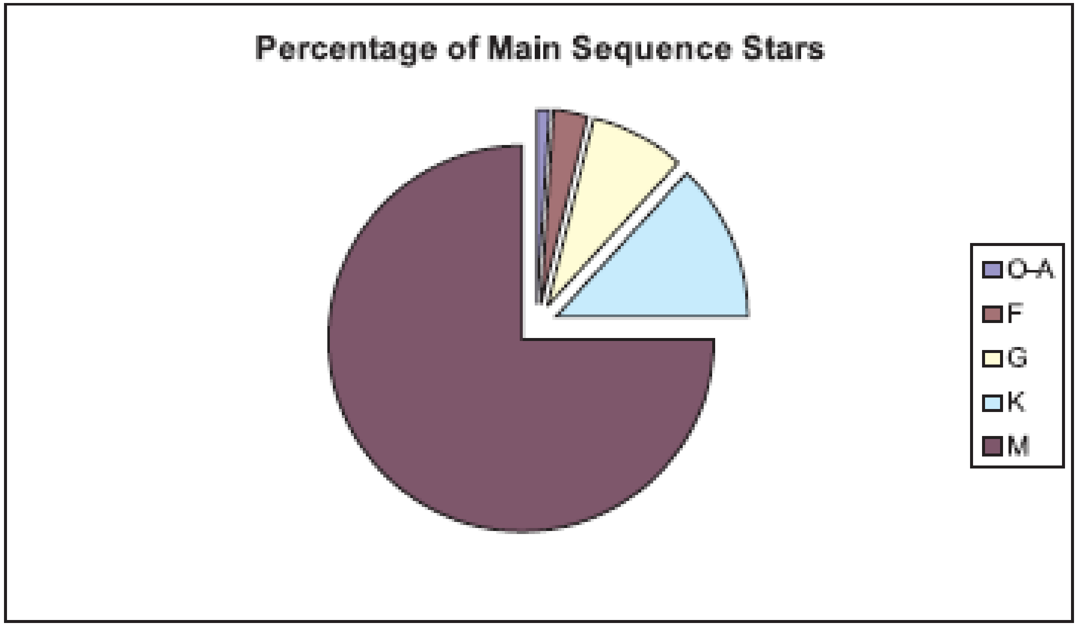
$$d = \sqrt{\frac{L_*}{L_\odot}}$$

Center of a circumstellar HZ
$2\,L_o \rightarrow d = 1{,}41$
$0.5\,L_o \rightarrow d = 0{,}5$

$$F_{\text{Venus}} \sim 1/(0.7)^2 \sim 2$$

$$F_{\text{Mars}} \sim 1/(1.4)^2 \sim 0.5$$

Host stars of planets

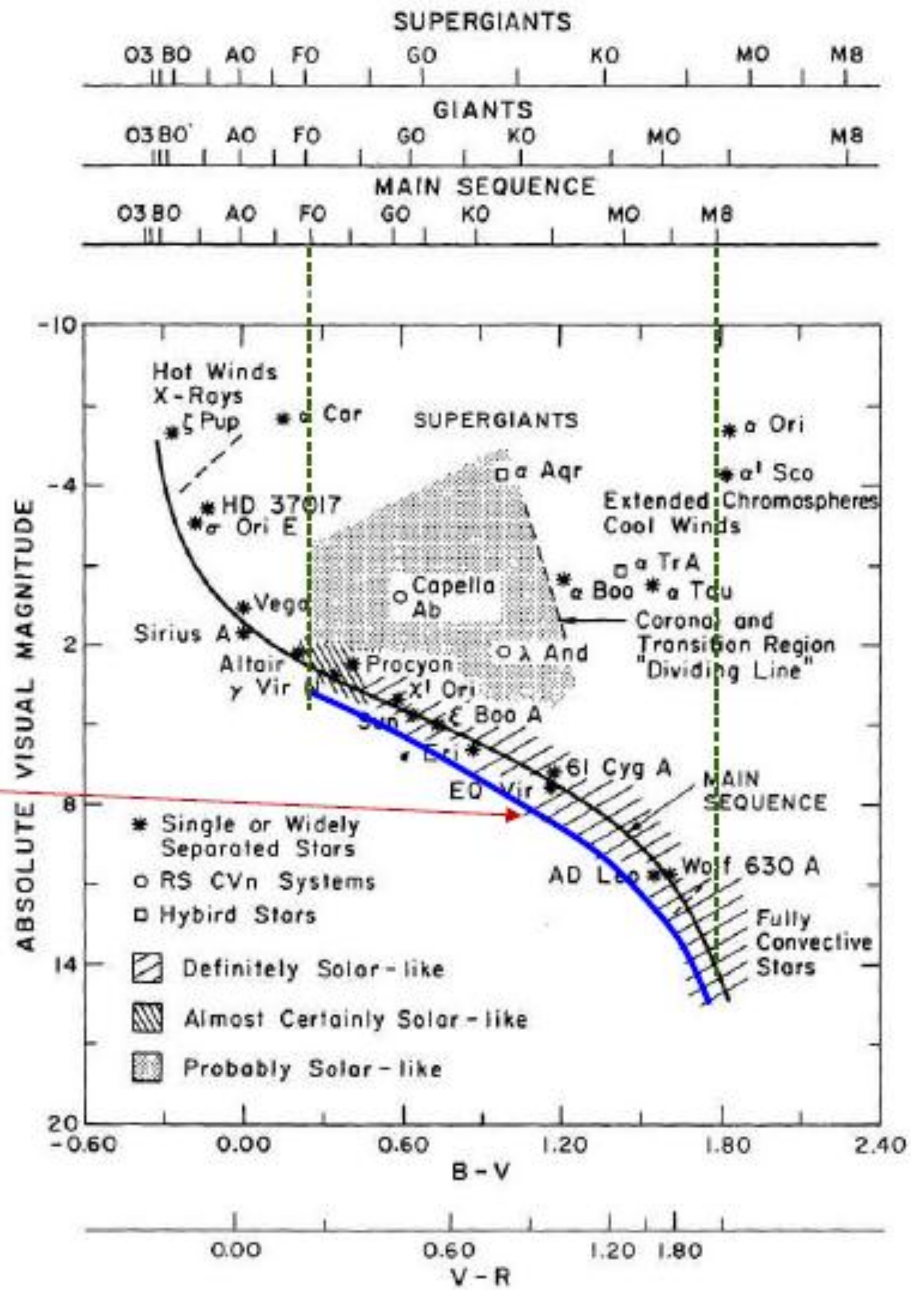


Solar like stars of spectral class G
Only 8% of all M-S stars

$$t_*/t_\odot = (M_*/M_\odot)/(L_*/L_\odot) = (M_*/M_\odot)^{-2.3}$$

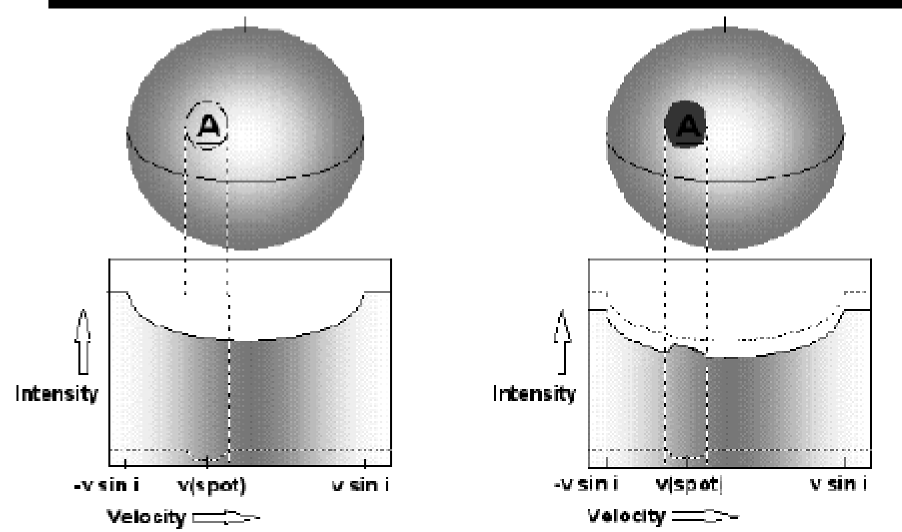
Main sequence lifetime

Stars masses > 2 Mo; M-S lifetime drops below 1 Gyr



Linsky, 1985

Activity on main sequence stars F→ M



Principle of Dopplerimaging

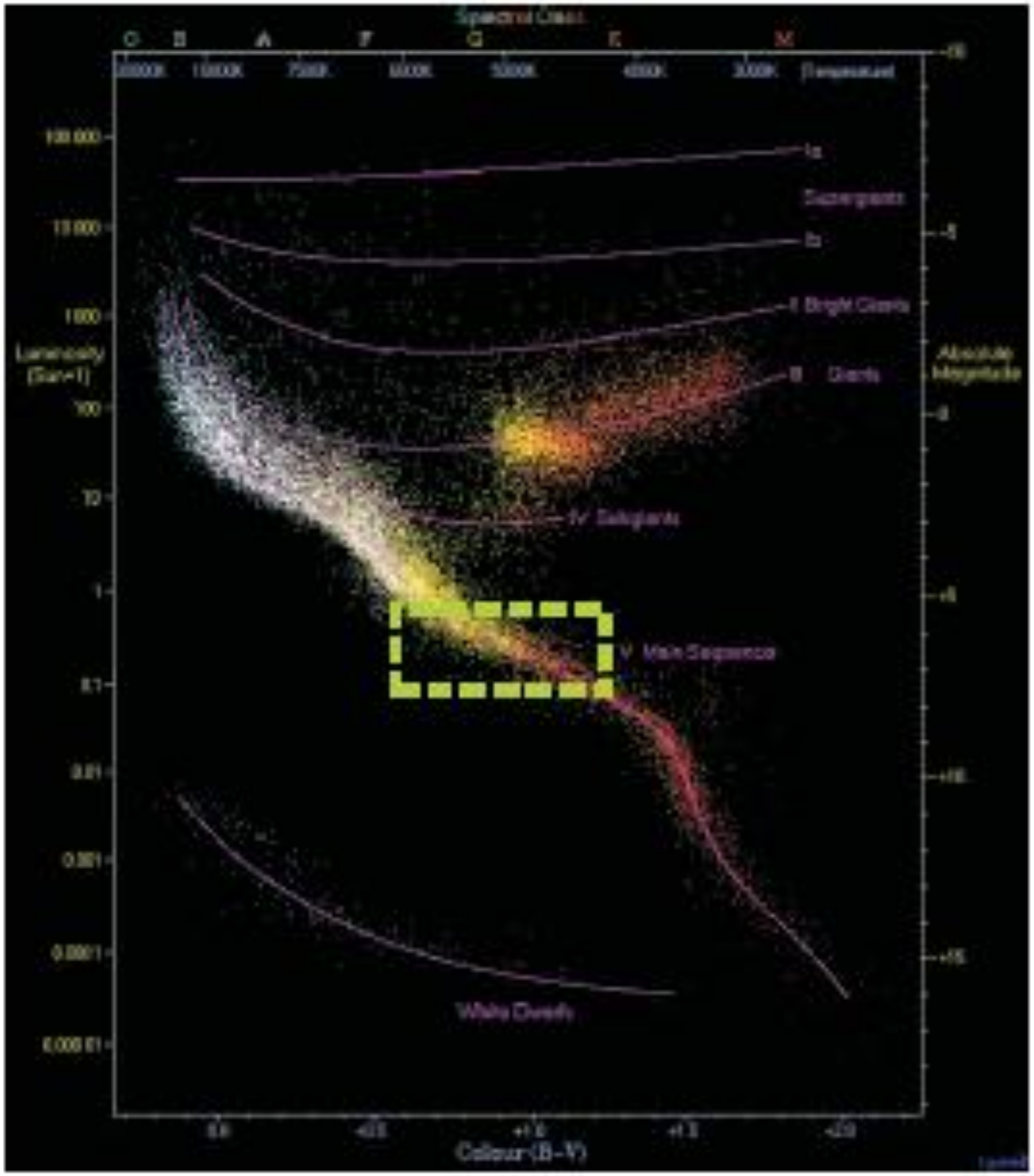


Figure 3.3: The Hertzsprung-Russel diagram. More than 20 000 stars are plotted and the main sequence stars form a diagonal. The region where solar like stars are found that could possibly host habitable pla...

Table 3.4: Habitable zones and some stellar parameters.

Spectral Class	T_{eff} (K)	Life (y)	Abundance %	HZ (AU)
O6V	41 0000	10^6	4×10^{-5}	450-900
B5V	15 400	8×10^7	0,1	20-40
A5V	8200	10^9	0.7	2.6-5.2
F5V	6400	4×10^9	4	1.3-2.5
G5V	5800	2×10^{10}	9	0.7-1.4
K5V	4400	7×10^{10}	14	0.3-0.5
M5V	3200	3×10^{11}	72	0.07-0.15

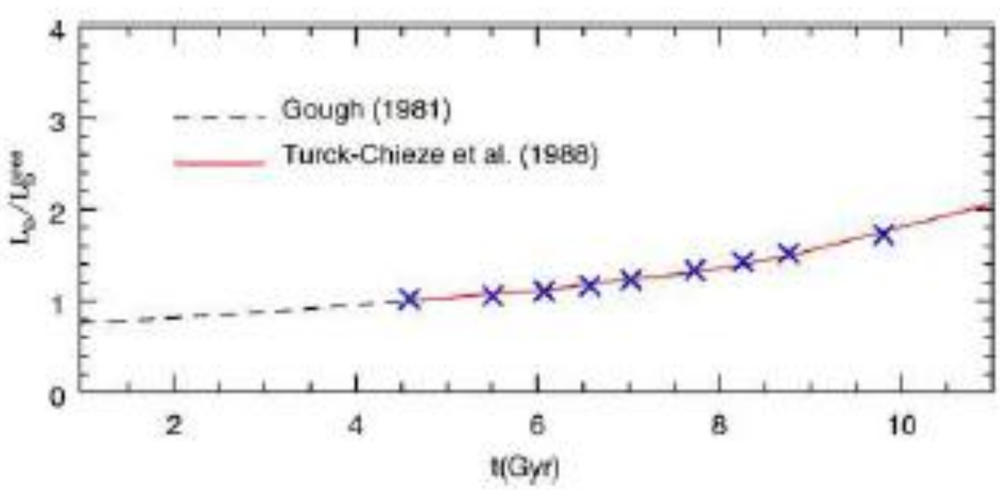


Figure 3.5: The evolution of the solar luminosity.

- Continuously HZ
  - The region in space where a planet remains habitable for a long period of time ~ Gyr
  - Hart, 1979 $r_o/r_i \sim [L(3.5)/L(1.0)]^{1/2}$
  - Inner/outer radius
  - L(t) luminosity after t billion yr.
  - $R_o \sim R_i$ for stars with M~ 0,83 M_o

Discussion

- How long did it take on Earth for life to evolve?
  - 100 million years
  - 200 million years
  - 1 Gyr
- Discuss the effects of space weather on the evolution of life
  - Extinction?
  - Mutation?

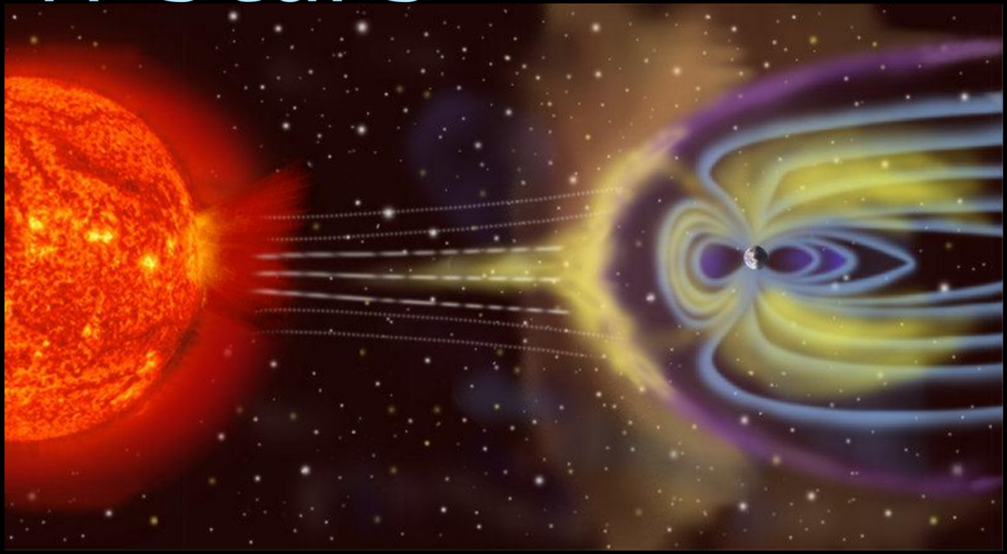
- Effects on the planetary atmospheres
  - Inner edge
  - Outer edge
- Inner Edge:
  - Star too close to planet, UV flux too high, photolysis of water; moist greenhouse effect
- Outer Edge:
  - Formation of CO_2 clouds; cool the planet‘s atmosphere, increase of albedo
- Planets with high CO2 concentration: greenhouse effect, extension of HZ

$$H_2O + h\nu \rightarrow H_2 \uparrow + O$$

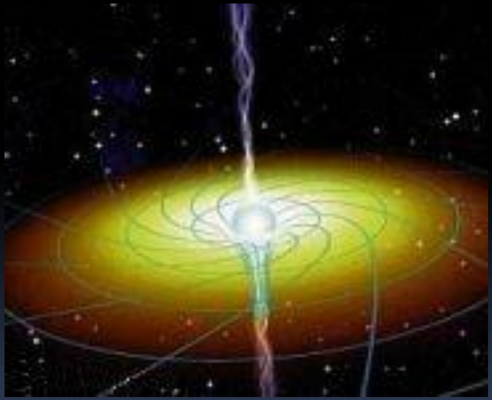
Stellar activity

- Sun as a proxy
  - Flares, CMEs, Solar wind
  - Energies involved
  - Particles, radiation
- Stars
  - Activity could be of
    - Higher amplitudes
    - Higher energy involved
  - Strongly dependend on spectral type

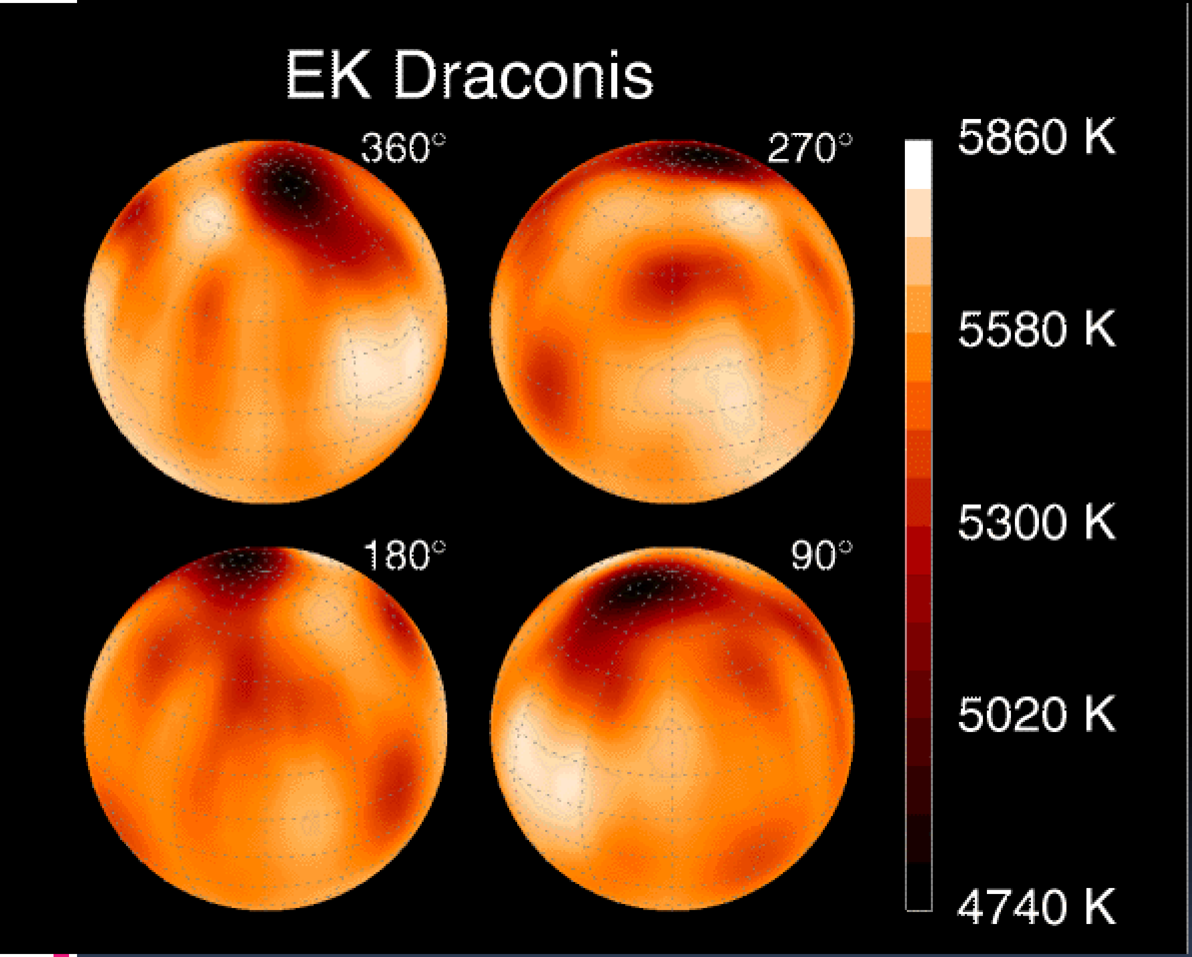
M stars



Solar system



Late type star



EK Dra
Single
G1.5 V
eq velocity 20
rot period: 2.6

Problem of polar spots

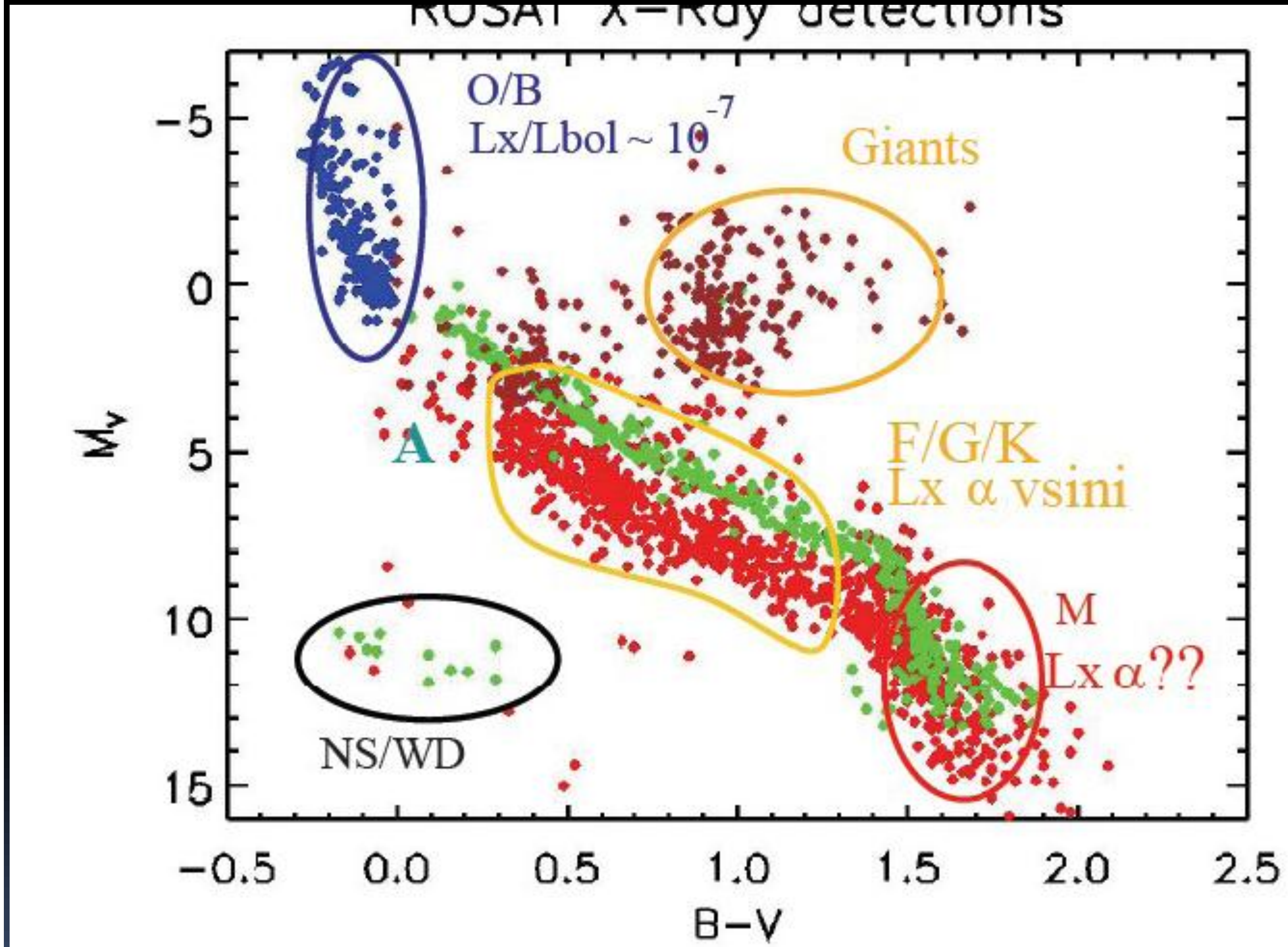
Flux tubes rise to surface

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

Fast rotating stars: polar activity zones
More active

Space climate:
Planets in equatorial plane (?)
Effects smaller (polar outflows…)



Dependence of
Lx on eq veleocity

Discussion

- Discuss the formation of planets
  - Why do planets occur in the equatorial plane of a star?
  - What are the consequences of space weather in the case of rapidly rotating stars?
- Observational aspects
  - How can we determine stellar rotation rates?
  - Discuss Doppler Imaging

X-ray emission

- F→M, cool dwarfs
  - Outer convective zones
  - X-ray sources
  - Heating by dynamo generated magnetic fields
- Very hot stars (O, B) strong X-ray emitters by radiatively driven winds
- Late type giants (<K III) not X-ray sources but possess massive cool winds

Discussion

- X ray emission of a star
  - How can it be measured?
  - Where does the X-ray emission from the Sun come from?
  - Explain the term non thermal emission
- Consider a late type giant
  - What will happen to the rotation rate if the Sun becomes a red giant?
  - Discuss stellar activity of a red giant
  - Why do red giant have strong stellar winds?

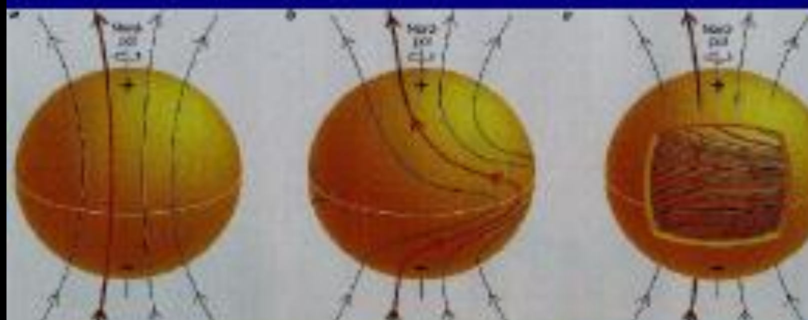
Red dwarfs

- Masses 0.08 – 0.5 M_o
  - Lower mass limit: critical mass for H burning
  - Upper limit M_o stars
- Radii: 0.2 to 0.6 R_o
- T: 2500 – 4000 K
- L: 01, to 8% L_o
- Constitute 80% of the stellar population in the Galaxy

Activity

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"

Solar like stars

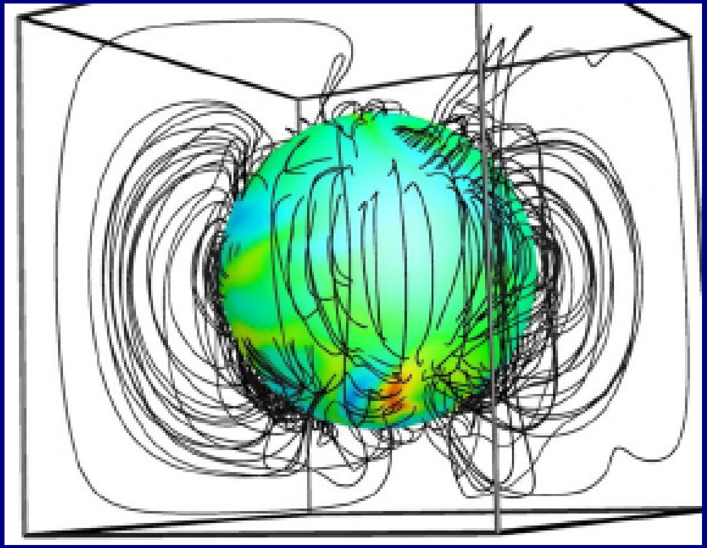
For fully convective M stars

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
- **<u>Coverage uniform over the stellar surface</u>**

- 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):

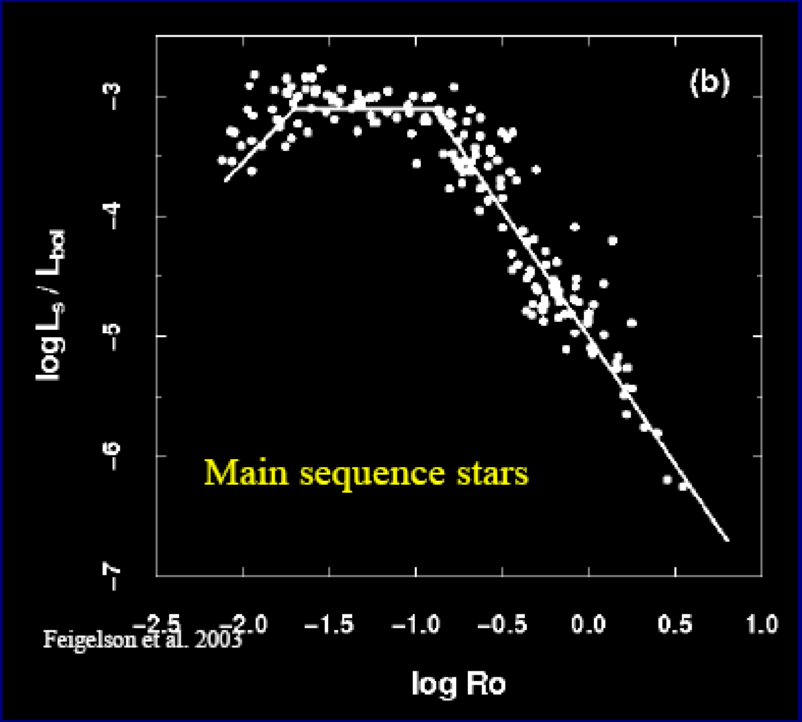
$\alpha-\Omega$ dynamo + **turbulent dynamo**

→ **activity-rotation relation**

→ **small-scale intranetwork fields**

Connection to dynamo theory

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



Feigelson et al. 2003

Prediction for α–Ω dynamo:

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

Dynamo saturation for $Ro \leq 0.1$

Discussion

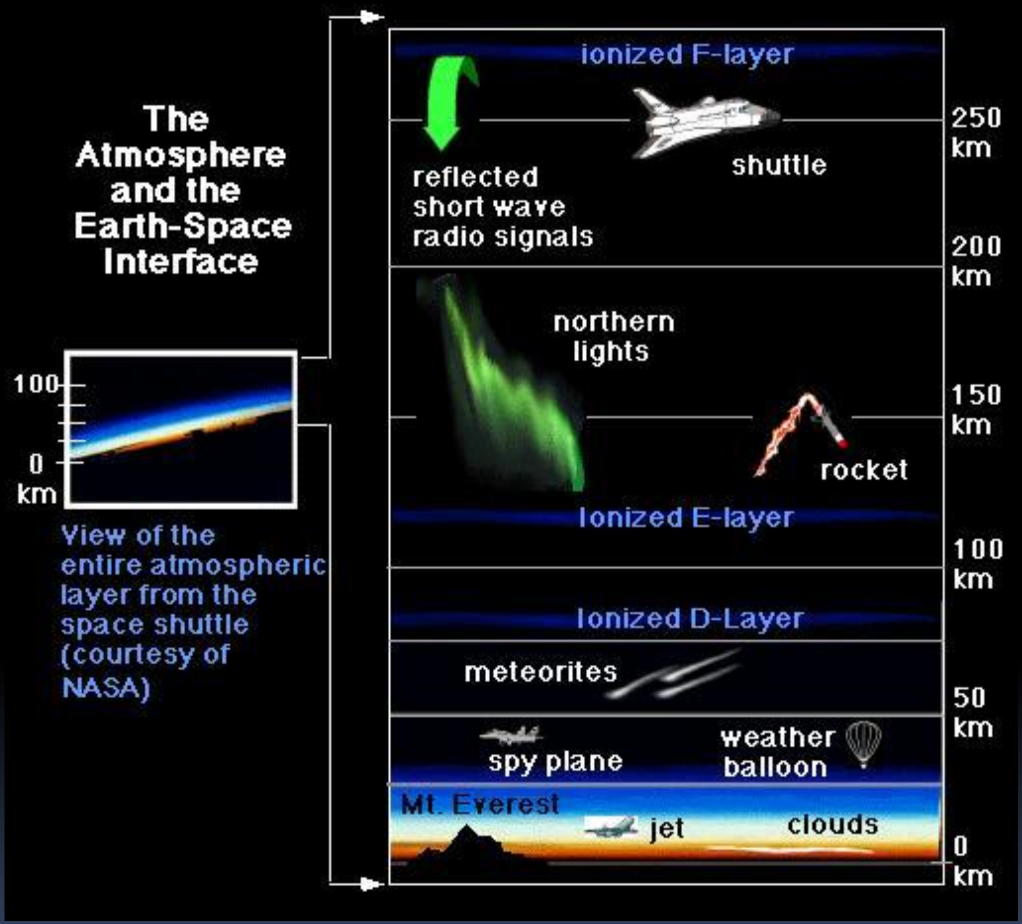
- Consider a nearly fully convective star
  - Why does the Alpha-Omega dynamo mechanism not work?
  - Discuss the role of a turbulent dynamo
  - Discuss the Rossby number of such an object

Influence on planetary atmospheres

- Emission of radiation
  - UV
  - X ray
- Emission of particles
  - Stellar winds
- Cosmic ray modulation
  - Cosmogenic isotopes

Planetary ionospheres
Chemistry in
Stratospheres
Tropospheres

Condensation nuclei


The Atmosphere and the Earth-Space Interface
100
0
km
View of the entire atmospheric layer from the space shuttle (courtesy of NASA)
ionized F-layer
reflected short wave radio signals
shuttle
250 km
200 km
northern lights
rocket
150 km
Ionized E-layer
100 km
Ionized D-Layer
meteorites
50 km
spy plane
weather balloon
Mt. Everest
jet
clouds
0 km

Discussion

- Why does Earth have an Ionosphere?
- What would happen if the Earth has no Magnetosphere?
- How can enhanced short wavelength radiation influence on the atmosphere?

Stellar activity during stellar evolution

- Activity in solar type stars declines with age
  - Related to a loss of angular momentum throughout MS lifetime, Skumanich 1972, Noyes et al. 1984,… Güdel, 1997)
- Young stars
  - High average level of activity
  - Rapid rotation
- Stars as old as the Sun
  - Slower rotation rates
  - Lower activity

Wind density and velocity

- Relevant for planetary atmospheres
- Stellar wind induced thermal escape

$$v_{\mathrm{sw}} = v_* \left(1 + \frac{t}{\tau}\right)^{-0.4},$$

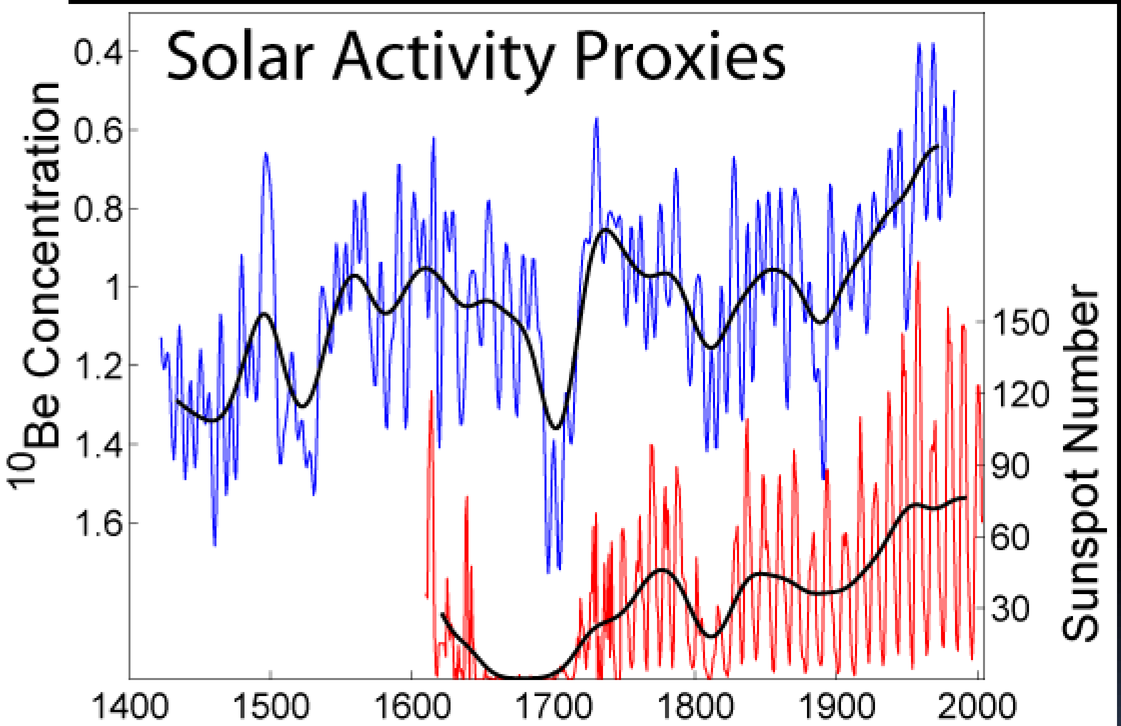
$$n_{\mathrm{sw}}(t) = n_* \left(1 + \frac{t}{\tau}\right)^{-1.86 \pm 0.6}.$$

The proportionality constants are determined by the present day (t = 4.6 Ga) solar wind conditions at 1 AU (Earth orbit: v_{sw} 400 km s^{-1}; n_{sw} 6.5 cm^{-3}) n_* = 1.04 × 105 cm^{-3} and v∗ = 3200 km s^{-1} for the nominal case.
The time constant τ=2.56 × 10^2 Ga according to Newkirk (1980) and t is the time in Ga.

Solar activity cycles

- 11 yr, Schwabe cycle; 9-12 yr
- 22 yr, Hale cycle
- 87 yr, Gleißberg cycle; modulation of Schwabe cycle
- 210 yr, Suess cycle
- 2300 yr, Hallstatt cycle
- Other patterns
  c-14: 105, 131, 232, 385, 504,805, 2241 yr

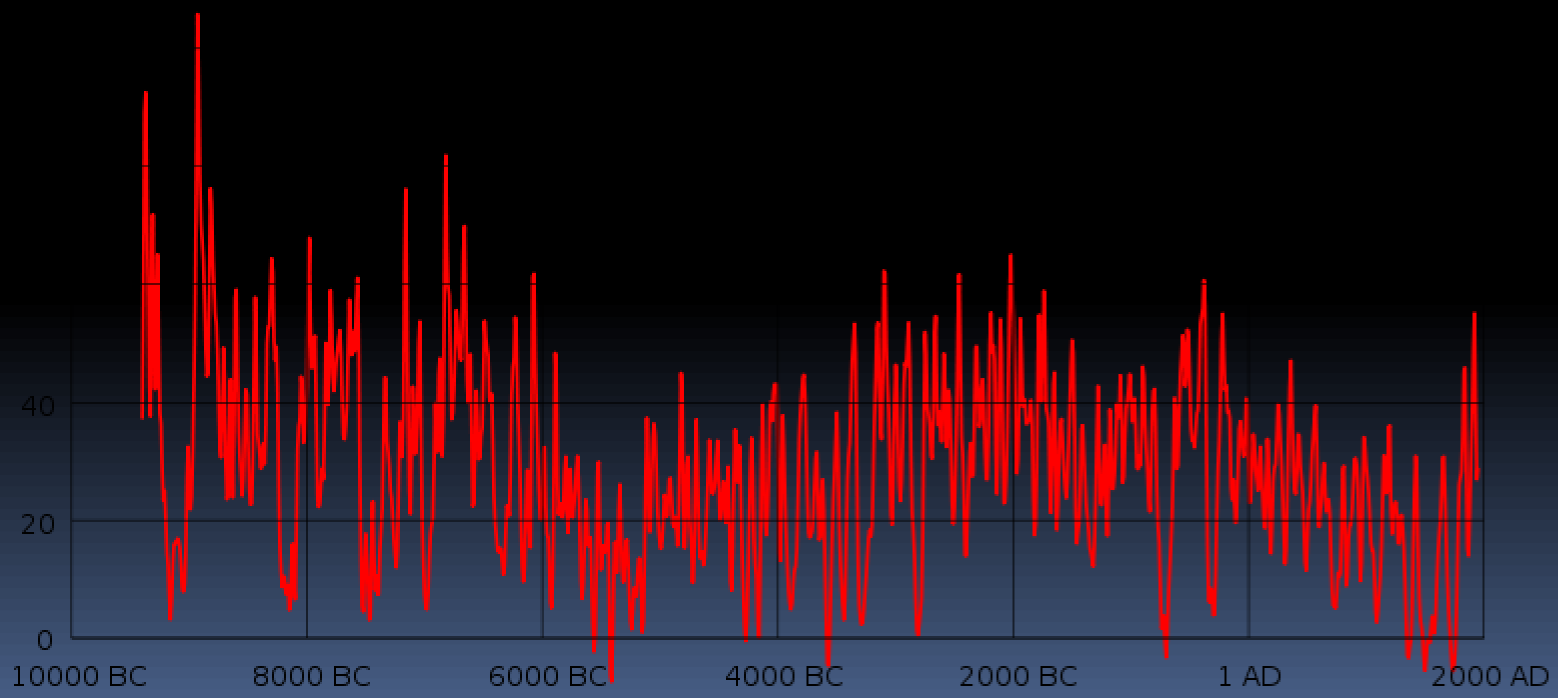
Solar activity proxies



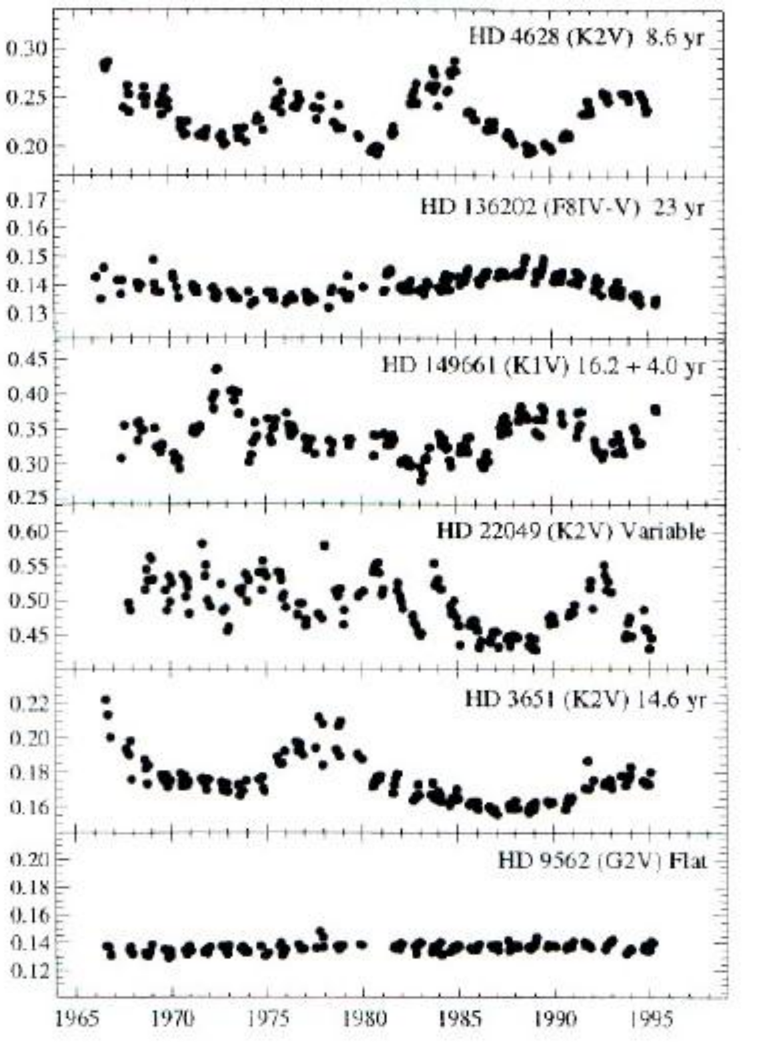
Anticorrelation

Reconstruction of solar activity over last 10 k yr

Solanki, S.K., I.G. Usoskin, B. Kromer, M. Schüssler and J. Beer. 2004. An unusually active Sun during recent decades compared to the previous 11,000 years. Nature, Vol. 431, No. 7012, pp.1084-1087, 28 October 2004.



Stellar activity cycles



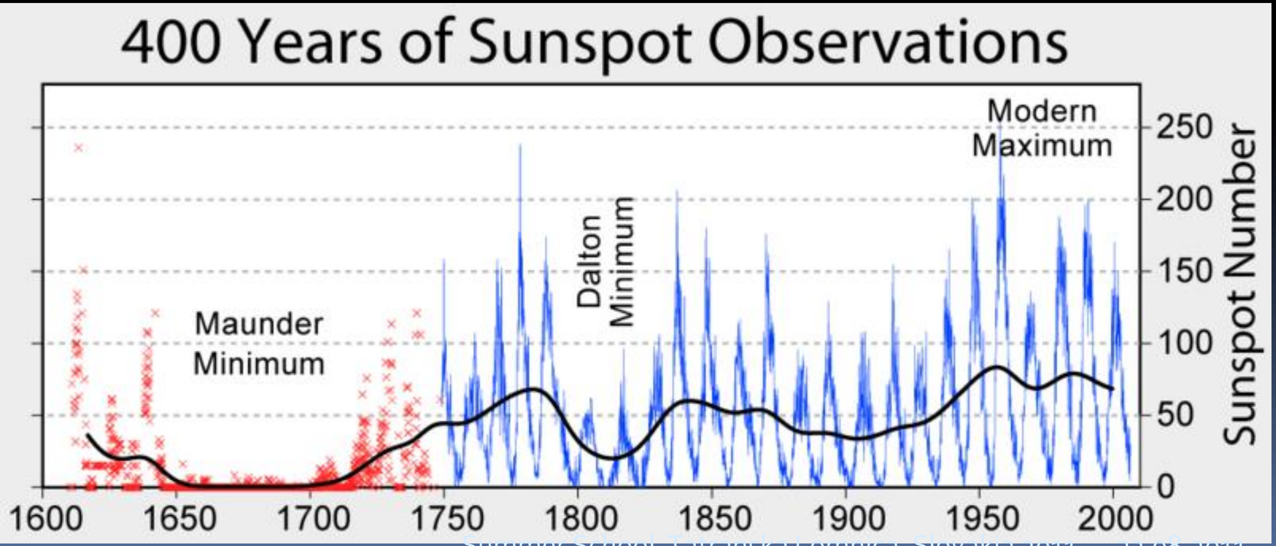
Monitoring chromospheric activity
CaII, H, K

Mt Wilson Survey

Solar variations: <few tenths of a percent
Stellar variability F7… K2

The Maunder Minimum

- J.A.Eddy, 1976 paper in Science.
- Lower than average global temperature
- During 30 yr period only 50 sunspots; modern values 40000-50000



What caused the Maunder Minimum

- Solar irradiance was lower by 1,2 % in 1683
- Solar Rotation rate?
  - Increase?
  - Decrease? (Nesme-Ribes 2%)
- Solar Diameter variation?

Why did the Maunder Minimum occur?

- Solar rotation?
  - Eddy, Gilman, Trotter, 1976: analysed drawings made by Hevelius 1642-1644;
    - equatorial synodic rotation rate was higher by 3-4%
    - Steeper differential rotation
  - Arbanell, Wöhl, 1981; re analysis of Hevelius;
    - Same rotation rate as today
    - Differential rotation steeper
  - Ribes, Nesme Ribes, 1993: Picard, Cassini 1660-1719 observations
    - Decrease of equatorial rotation by 2 %
  - Vaquero et al, 2002; Flamsteed observations
    - Decrease of rotation rate

- Vaquero J.M., Sánchez-bajo F., Gallego M.C. (2002). "A Measure of the Solar Rotation During the Maunder Minimum". *Solar Physics* **207** (2): 219

- Bouvier (1990):
  - Lx X-ray luminosity
  - V equatorial velocity

Total Solar Irradiance for the Maunder Minimum

Date	Rotation Rate (deg per day)	r_0 (arcsec)	Percentage Departures from Modern Irradiance
1683....	14.16 ± 0.10[a]	962.50 ± 0.5[b]	−1.23 ± 0.84
1715....	14.32 ± 0.10[c]	959.63 ± 0.5[d]	−0.37 ± 0.84
1986....	14.42 ± 0.12[e]	959.37 ± 0.28[f]	

Maunder Minimum Ca II H and K Fluxes

Year	Rotation Rate (deg per day)	HK Flux Lowest Estimate	HK Flux Highest Estimate
1683..........	14.16	0.121[a]	0.161[b]
1715..........	14.32	0.122[a]	0.163[b]
Modern......	14.42	0.123[c]	0.164[d]

Mendoza, Blanca
Astrophysical Journal v.483, p.523

Radius variations

- Measurements by solar eclipses

Solar Eclipse Determinations of the Solar Radius[a]

Eclipse Date	$(\Delta R/R) \times 10^4$	Reference
1715 May 3	$+5.4 \pm 2.1^{b}$	Dunham *et al.* 1980
1925 Jan 24	$+6.2 \pm 0.8^{c}$	Dunham *et al.* 1981
1976 Oct 23	-2.4 ± 1.5^{c}	Dunham *et al.* 1980
1979 Feb 26	-0.8 ± 0.9^{c}	Dunham *et al.* 1980
1980 Feb 16	-0.3 ± 0.4^{c}	Dunham *et al.* 1981

- Assuming that

$$\Delta R/R \approx 6 \times 10^{-4}, \qquad |\Delta L/L| \lesssim 5 \times 10^{-3}$$

- Ulrich, 1975: solar variability → change α
- Definition: α=mixing length/pressure scale height
- If this parameter increases, the efficiency of convection increases, R and L increase.
- Problem: luminosity perturbation decreases very slowly, R perturbation decreases more rapidly.

Reynolds Stress and Meridional flow

- Solar convection zone: angular momentum transport
- Turbulent velocity field
  - Fluctuating
  - Axisymmetric (mean) flows

$$v = \langle v \rangle + v'$$

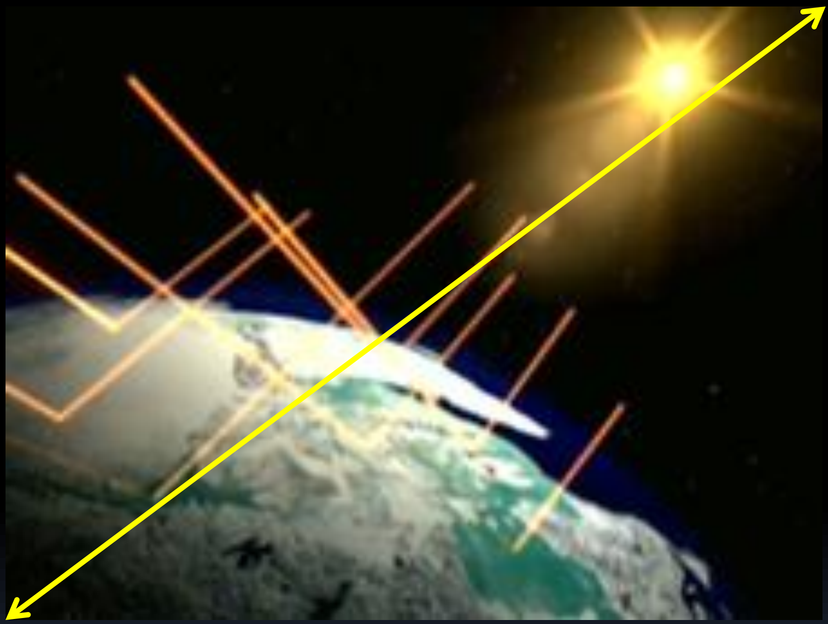
$$\langle F_i \rangle = r \sin\theta \rho \, (\underbrace{\langle v_i' v_\phi' \rangle}_{\text{Reynolds stress}} + \underbrace{\langle v_i \rangle \Omega \, r \sin\theta}_{\text{Meridional flow}})$$

$\mathbf{L} = \mathbf{r} \times \mathbf{p}$

What are the consequences for Earth?

Fluctuations during solar cycle

At present ~ 0.1 %



Earth: 0.1 C T variation

Sun:
Slightly hotter during Maximum
Slightly cooler duirng minimum

Energy balance on Earth

Clouds
Ice
Aerosolos,
oceans
Snow
Ice
Sand…

30% reflected back

Solar energy arriving
At Earth

70% absorbed

Land
Ocean
atmosphere

Greenhouse gases block about 40 percent of outgoing thermal radiation that emanates from Earth

Tidal effects in extrasolar planetary systems

- Affects planets close to host star
- Extreme case: tidal locking
  - slow rotation of planet
  - Always the same side to the star
  - Temperature distribution?
  - Atmosphere?
- Tidal heating
  - Affects on interior

Extrasolar planets: tidal locking

$$t_{\text{lock}} \approx \frac{w a^6 I Q}{3 G M_p^2 k_2 R^5}$$

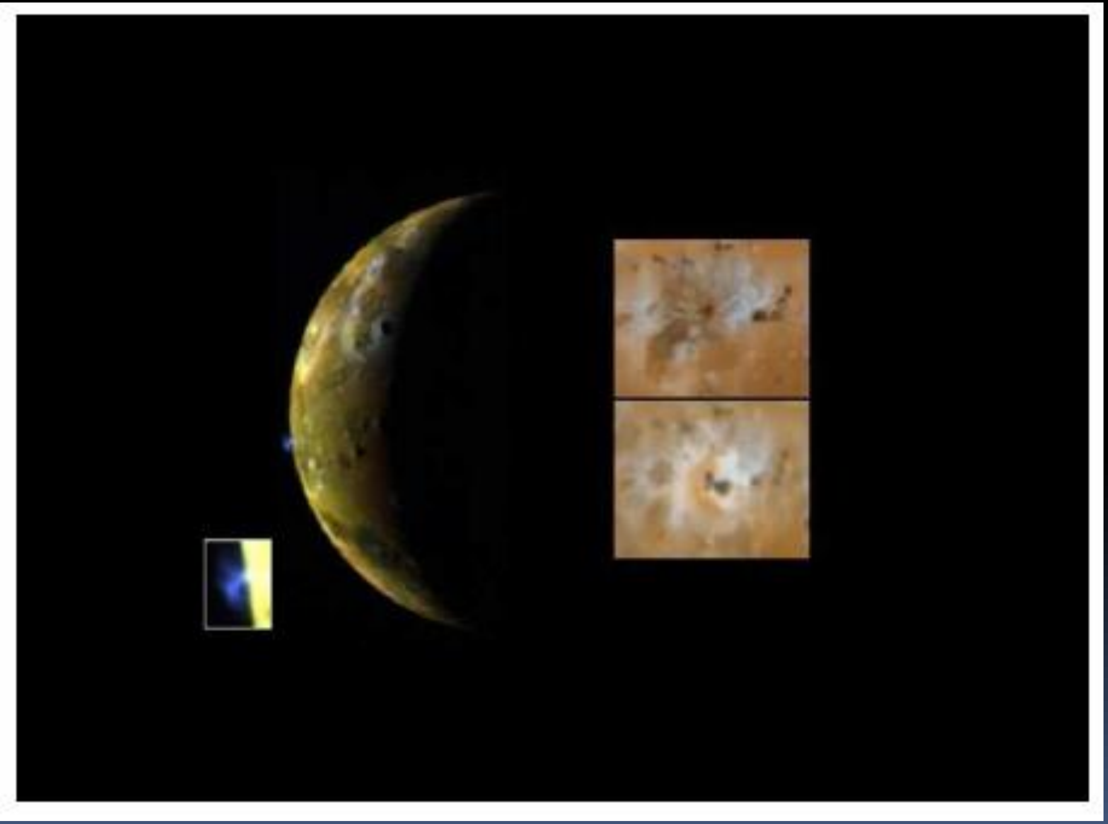
Tidal locking time
R… Radius of planet
Mp.. Mass of planet
I… moment of inertia of the satellite
Q… dissipation function of satellite

$$t_{\text{lock}} \approx 6 \frac{a^6 R \mu}{M_s M_p^2} \times 10^{10} \text{ years},$$

Strong dependence on the semi major axis

Tidal heating

- examples: Io…



Discussion

- What is tidal locking?
  - On what parameters does it depend
  - Would a tidally locked planet have an atmosphere?
- Tidal heating
  - Discuss good cases
  - Tidal heating as energy source

Space climate and impacts

- Solar system
  - SSSBs: comets, asteroids…
  - Can be hazardous to life
  - Earth crossing objects
  - Impacts of comets on Earth → water on Earth
  - Impacts of comets and asteroids on Earth → water + organic compounds on Earth

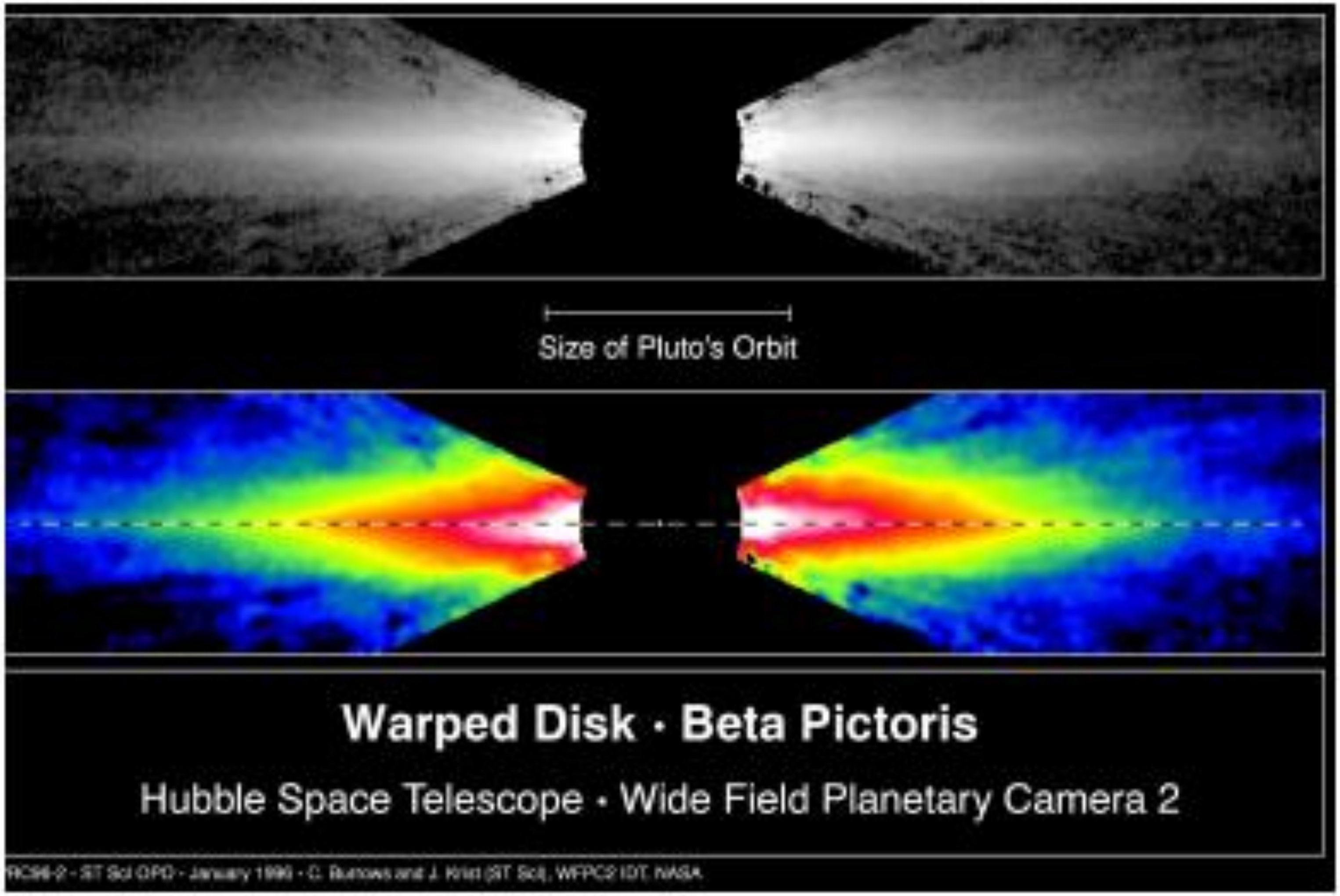


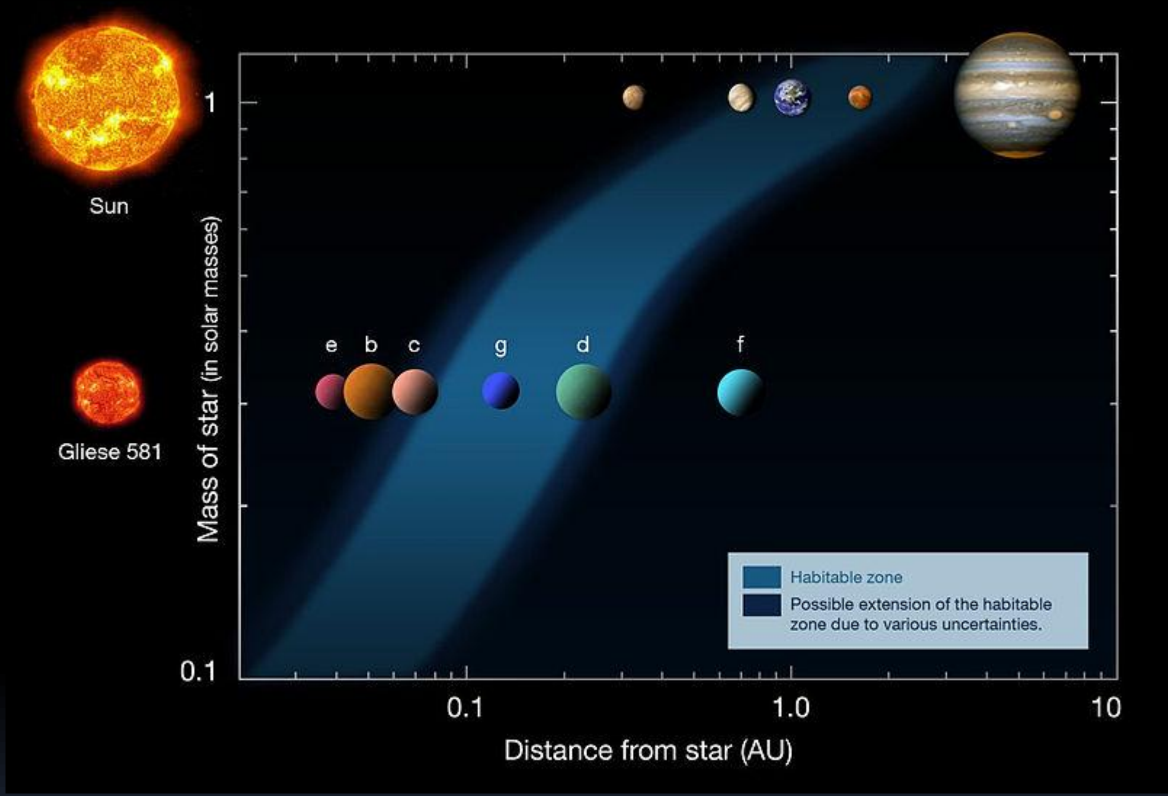
Figure 4.13: The warped dust disk around β Pictoris. The star itself has been occulted artificially.

Impacts in extrasolar planetary systems

- Observable:
  - Immediate EUV-X-ray flash
    - Lasts only for several hours
    - Detection probability extremely low
  - IR afterglow
    - Long lasting
    - Timescale ~ months

Gliese 581

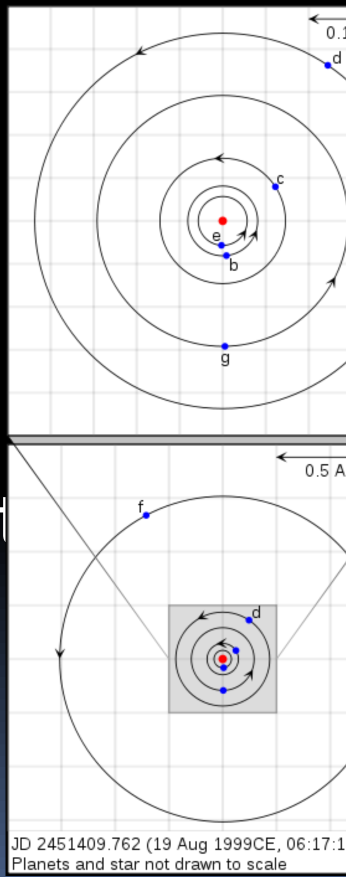
BY Draconis variable ;
Fluctuations 0.5^m
~days to months
 Some of these stars may also have flares, resulting in additional variations of the UV Ceti type



Properties of Gliese 581
0,41 $M_\odot$; 3480 K; 7-11 Gyr
M3V

Gliese 581 c

- Superearth
- Detected 2007
- 5 M_{Earth}, 0.073 AU ,
  - T -3 C if albedo ~ Venus or
  - T ~40 C with albedo ~earth
- Gliese 581 c runaway greenhouse effect
- Gliese 581 d: 0.22 AU, 7 M_{Earth}; in HZ
- Gliese 581 g: 3 M_{Earth}, 0.17 AU



Spaceweather in the Gliese System

- Radiation
  - Flare produce
    - UV
    - X ray

    } 100 – 1000 times
- Strong winds
- Strong luminosity variations

Tidally locked
Orbital period of Gliese 581 g: 36 d

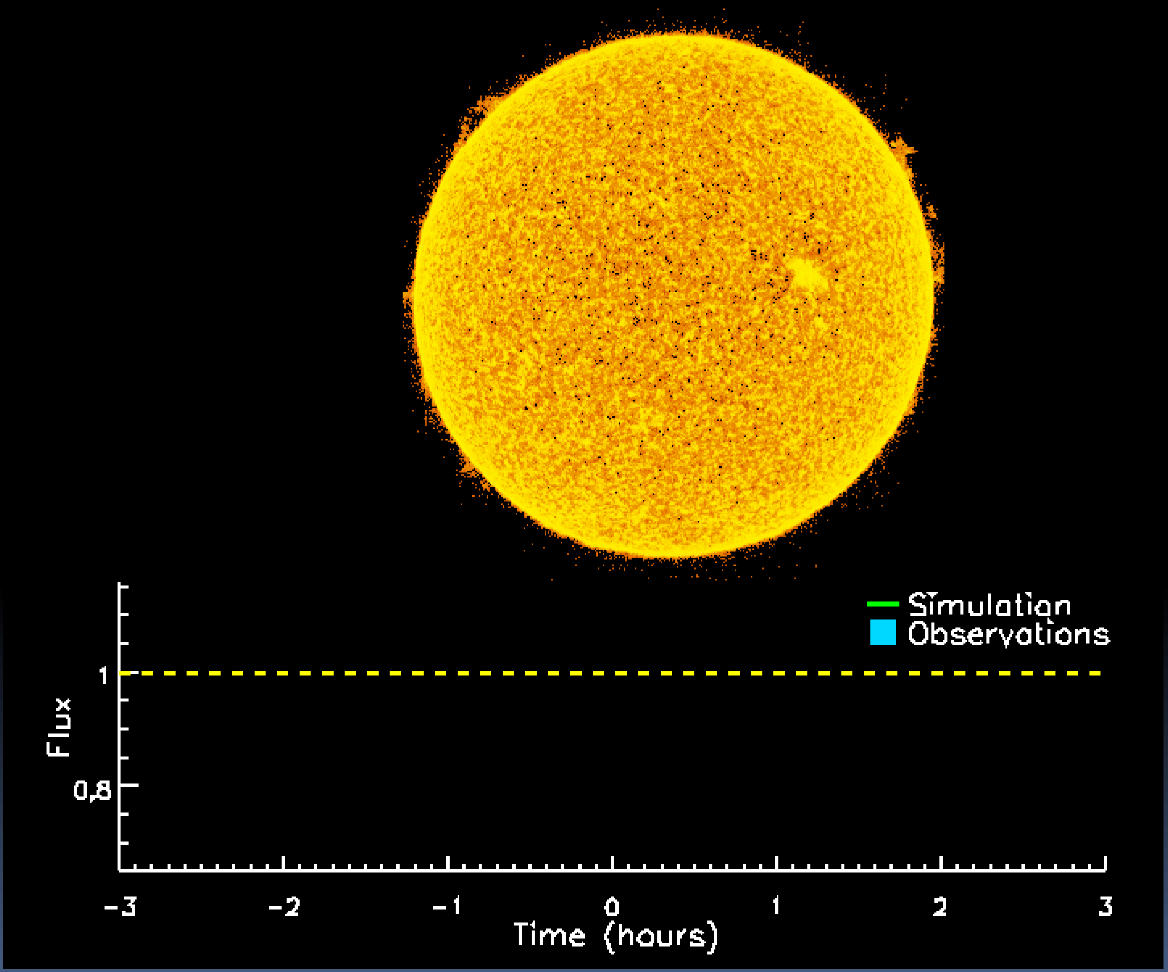
HD 209458 b

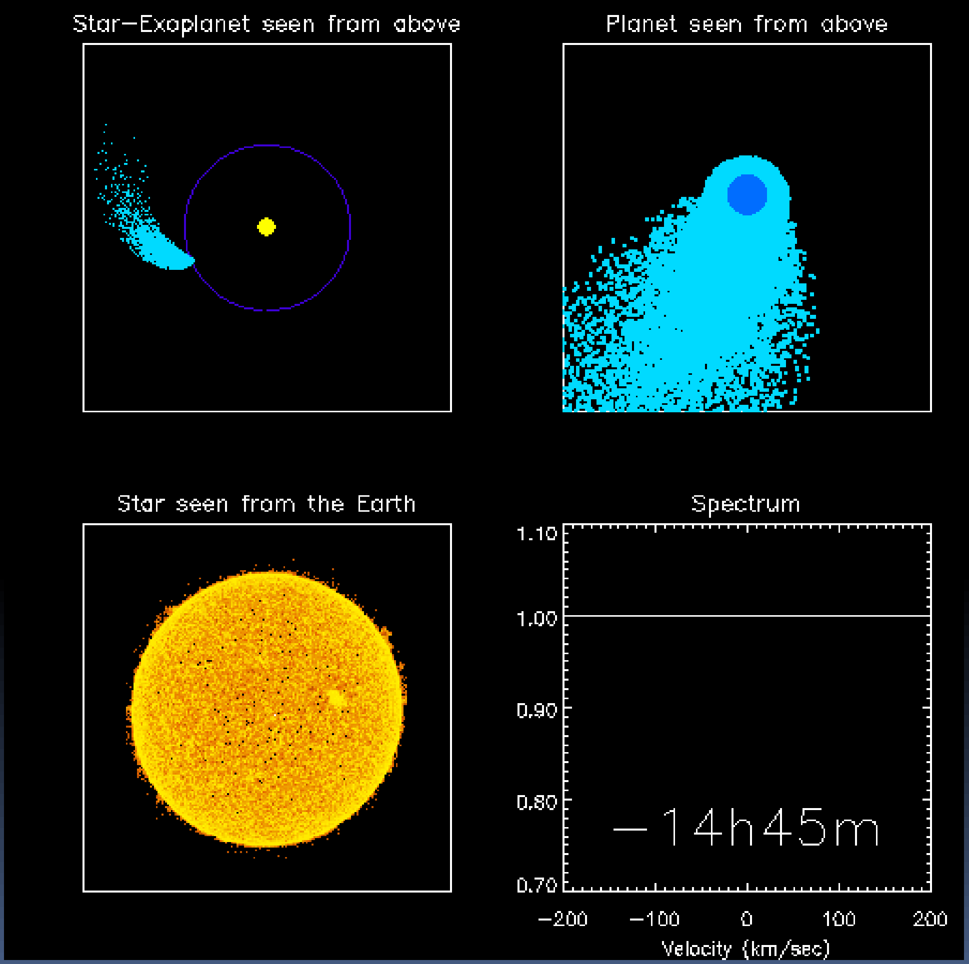
- Diameter: 1.3 R_J.
- Mass: 0.7 M_J, 220 Earth masses.
- Orbit: One-eighth the size of Mercury's orbit around the Sun (7 million kilometres). 3.5 days.
- hot Jupiters .
- First confirmed transiting extrasolar planet.
- Transit: Every 3.5 days, 3 hours in duration. Eclipses 1.5% of the face of the parent star.
- Surface temperature: About 1,000 °C

- THE ATMOSPHERE
- Complex: sodium in the lower atmosphere, evaporating hydrogen detected in upper atmosphere, oxygen and carbon also in the upper atmosphere.
- Extended: During the eclipses the upper atmosphere covers 15% of the face of the parent star.
- H, C, O escape
- amount of hydrogen gas escaping HD 209458b to be at least 10,000 tons per second.
- Hydrogen tail is 200,000 kilometres long.

"The signature of hot hydrogen in the atmosphere of the extrasolar planet HD 209458b"
G.E. Ballester[1], D. K. Sing[1,2] & F. Herbert[1]
[1]University of Arizona, USA [2]Institut d'Astrophysique de Paris, France
Nature, 445, 511-514, 1 Feb. 2007.

- FACTS ABOUT THE PARENT STAR
- Name: HD 209458
- Type: Similar to our Sun
- Distance: 150 light-years from Earth in the constellation of Pegasus
- Brightness: 7th magnitude star
- HISTORY OF HD 209458b
- 2001: Hubble detected the element sodium in the lower part of HD 209458b's atmosphere.
- 2003: Hydrogen in upper atmosphere detected with Hubble. Signs of evaporation.
- 2004: Oxygen and carbon detected in upper atmosphere with Hubble.


Simulation
Observations
1
Flux
0,8
-3
-2
-1
0
1
2
3
Time (hours)


Star−Exoplanet seen from above
Planet seen from above
Star seen from the Earth
Spectrum
1.10
1.00
0.90
0.80
0.70
−14h45m
−200
−100
0
100
200
Velocity (km/sec)

Detection of planetary blow off

- Solar like stars produce far-UV line emissions including the OI (1304 A) and CII (1335 A) multiplets,
- absorption by the planet upper atmosphere should be detectable during transit
- HST observations: detected transit absorption depths of 13+/-4.5% and 7.5+/-3.5% respectively for oxygen and carbon
- Hydrodynamic escape process is what is believed to be at the origin of the formation of the solar wind.
- Blow-off: removed the early atmospheres of Venus, Earth and Mars when the solar UV radiation was much more brighter

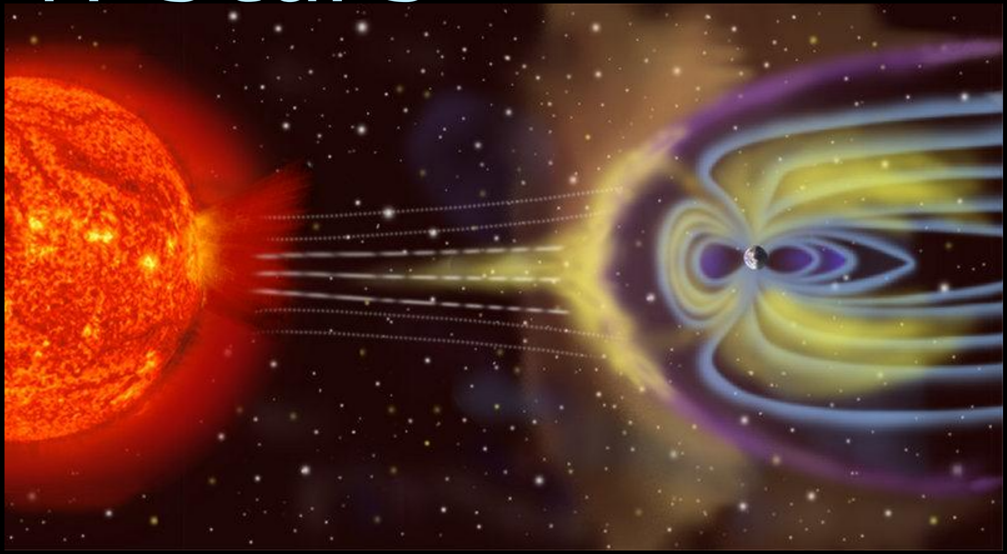
Space weather on extrasolar planets

- Solar system as a proxy
- Consider stars F-M
- M stars: activity restricted to the poles
  - Outflow not in equatorial plane, planets are mainly in equatorial plane
- Important for continuously HZ
- Special effect due to tidal locking and heating
- Blow off: detected on extrasolar planets
- Trigger effects on evolution

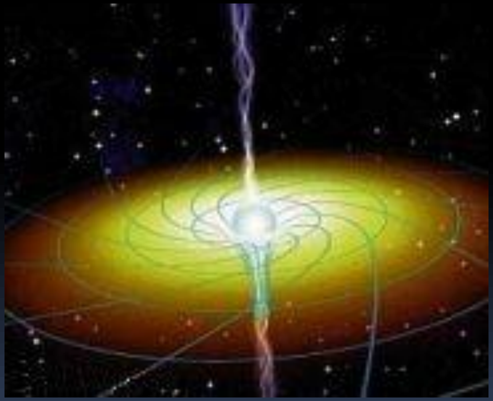
Discussion

- What can we learn from space weather studies in exoplanetary systems?
  - Escape?
  - Water loss?
  - Habitable zone – evolution
- For whioch stars are space weather effects
  - Hazardous to life
  - Trigger evolution
  - Do not trigger evolution

M stars



Solar system



Late type star