

06. Radio Stars

- Which ones?
 - How many?
 - Where?
 - What do we learn?
 - What is expected from forthcoming facilities
-

References:

- Guedel, ARA&, 2002, 40, 217- 261
"Stellar Radio Astronomy: Probing Stellar Atmospheres from Protostars to Giants"
 - Benz & Guedel, ARA&A, 2010, 48, 241-287
"Physical Processes in Magnetically Driven Flares on the Sun, Stars, and Young Stellar Objects"
 - Bastian, Benz & Gary, ARA&A, 1998, 36, 131 – 188
"Radio Emission from Solar Flares"
- Cavallaro, 2017, PhD Thesis
"A Pathway to EMU: the SCORPIO Project"
 - Bietenholz +, 2012, ApJSS, 201, 1
"VLBI for Gravity Probe B. VII. The Evolution of the Radio Structure of IM Pegasi"
 - Zucca + , 2018, arXiv:1804.01025
"Shock location and CME 3D reconstruction of a solar type II radio burst with LOFAR"
-

The Sun and "normal" stars

- What are the emission processes
 - The "excess" of radio emission: quiescent/active state
 - Classification of radio stars
 - Information from observations

 - A few details on special physical processes are given in the appendix (not commented)
-

The Sun and "normal" stars

- What are the emission processes?

BB from the photosphere: in the R-J domain, $S(\nu) \sim \nu^2$. Best seen @ cm and mm wavelengths

Extra emission at cm-dm-m wavelengths, arising from other processes mainly related to B

Flares/bursts are variable processes, more important at \sim m wavelengths

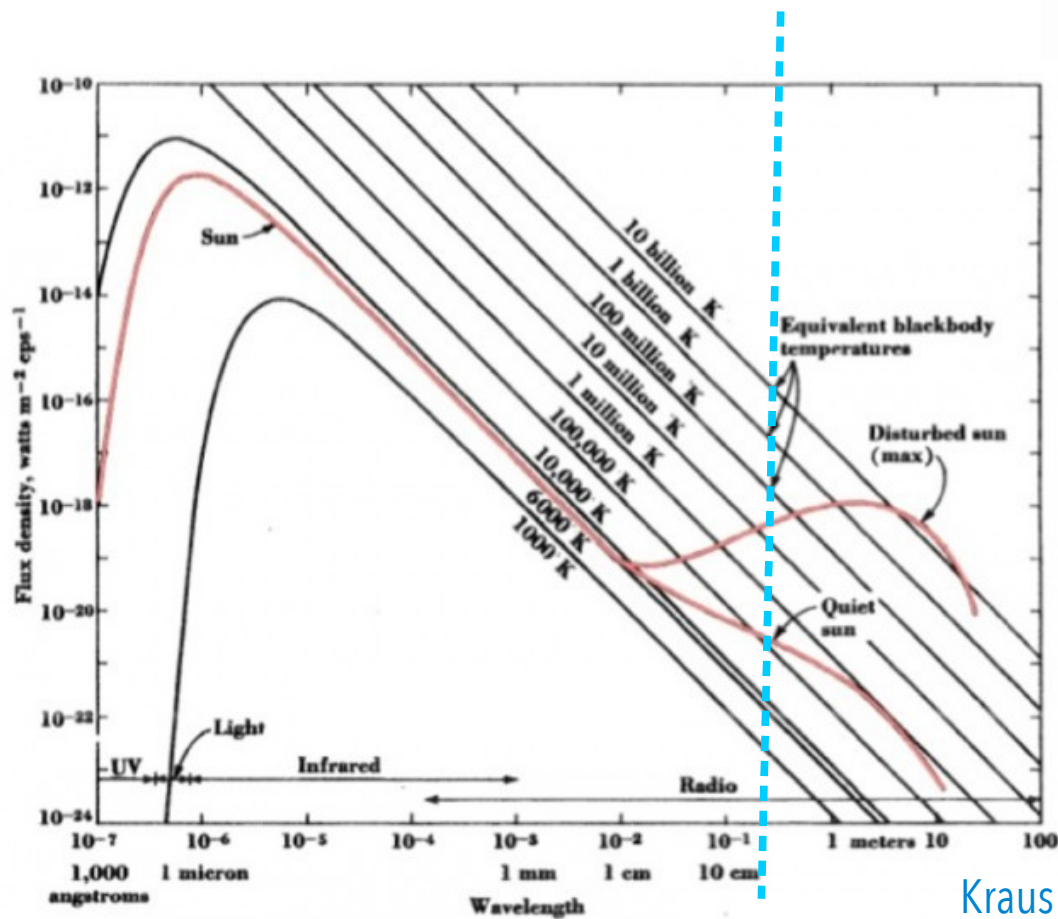
Fast evolution in time and frequency

- Radio and X-ray emissions are correlated, likely to ... == to be refined ==

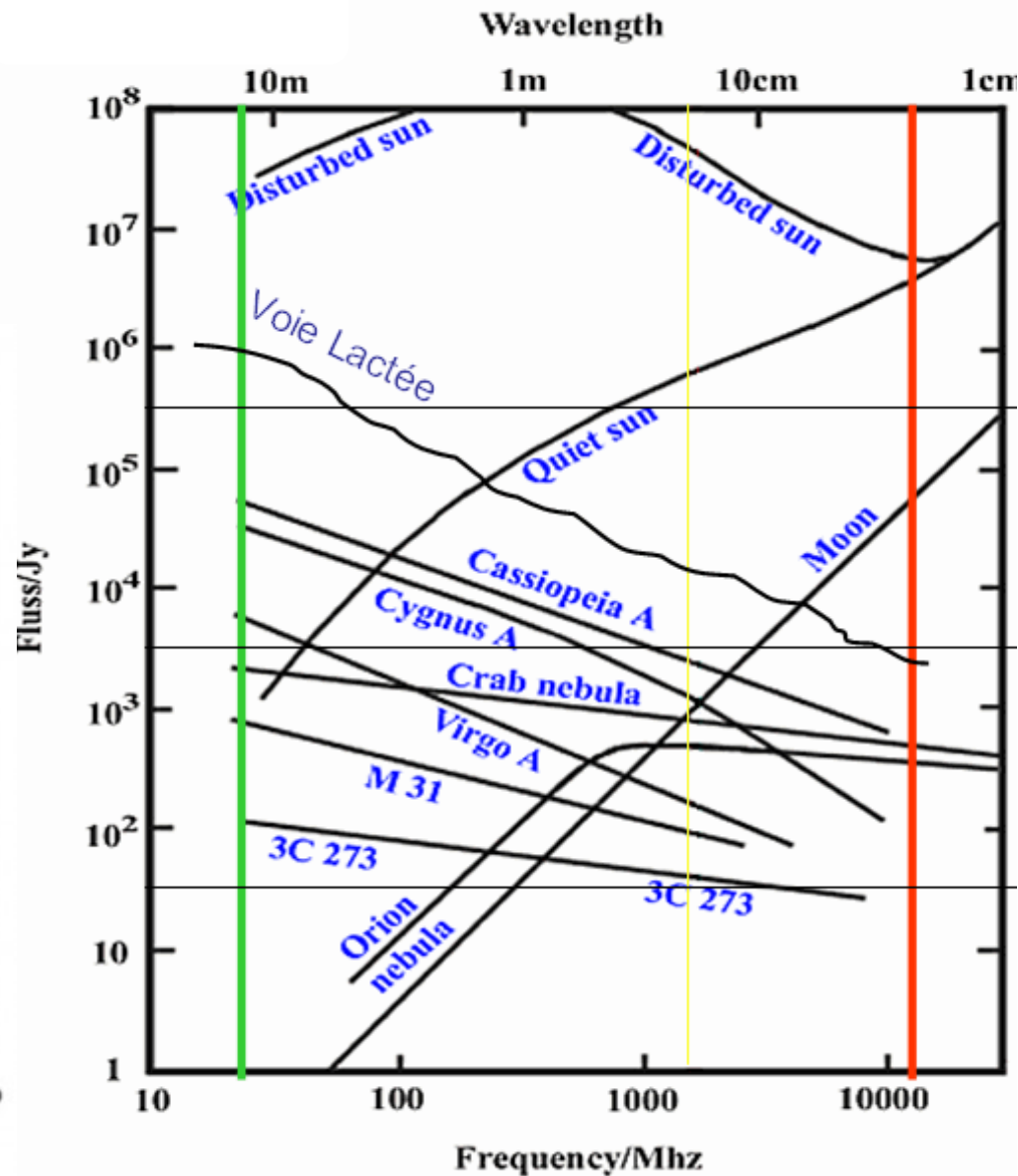
Radio stars: the SUN

- The **SUN**, a strong radio source (which mechanisms?)
550 kJy at 1.4 GHz (Rayleigh - Jeans BB spectrum would imply 2.3 kJy only!)

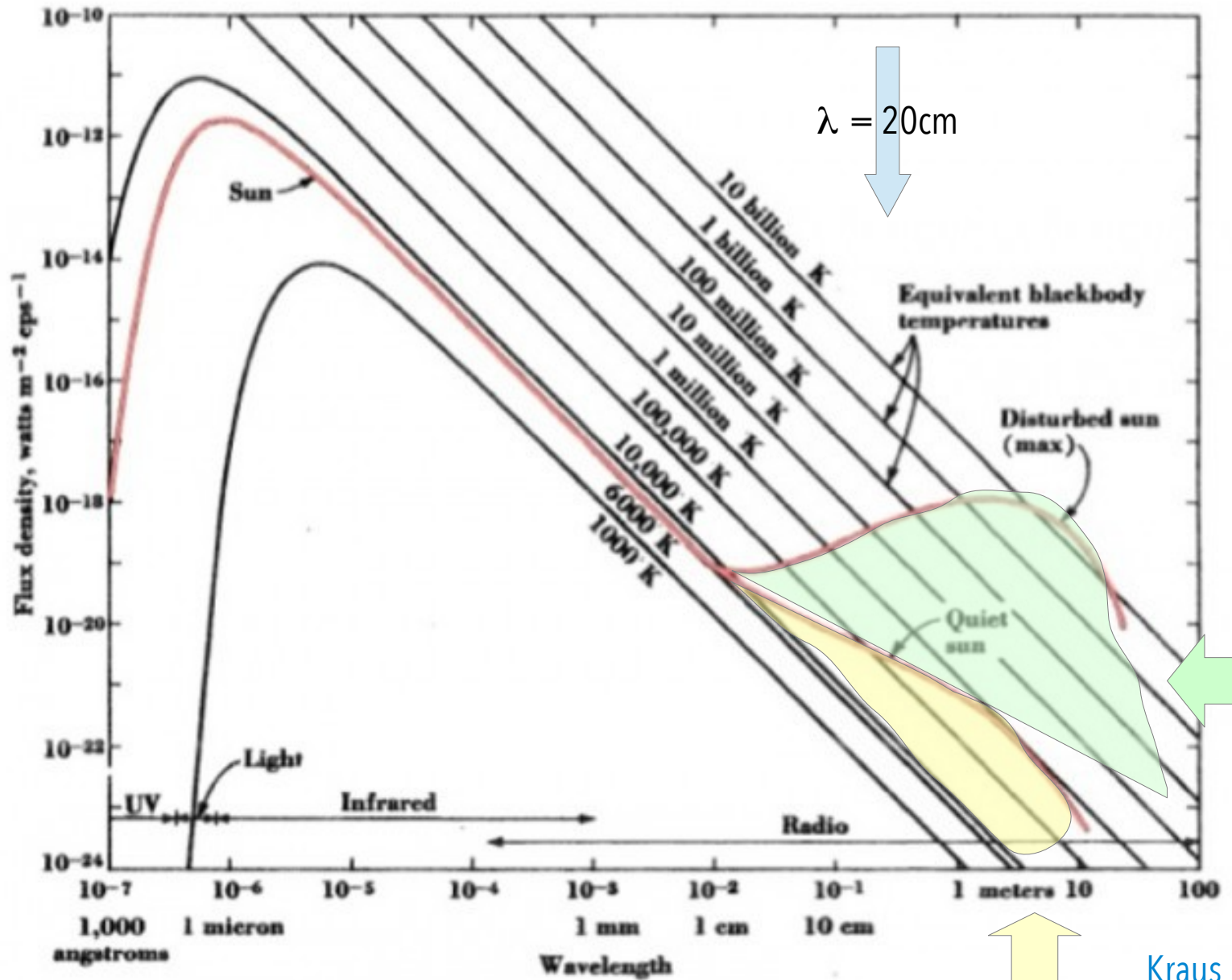
$$S(\nu) = B(\nu, T) \left(\frac{\pi R_0^2}{4\pi D_0^2} \right) \approx 2 \left(\frac{\nu}{c} \right)^2 kT \frac{1}{4} \left(\frac{R_0}{D_0} \right)^2$$



Kraus



- **Additional non-thermal emission** beyond the (thermal) BB



Quiescent emission + stellar activity:

➤ Thermal BB continuum

$$S(\nu) = 2kT_b \left(\frac{\nu}{c} \right)^2 \frac{A}{D^2} \approx 0.1 \left(\frac{T_b}{10^6 \text{ K}} \right) \left(\frac{\nu}{1 \text{ GHz}} \right)^2 \left(\frac{R_*}{10^{11} \text{ cm}} \right)^2 \left(\frac{1 \text{ pc}}{D} \right)^2 \quad [\text{mJy}]$$

Betelgeuse: radius $\sim 900 R_\odot$, $D \sim 220 \text{ pc}$, $T_b \sim 3600 \text{ K}$, is faint at cm wavelengths, better at mm and sub-mm wavelengths!

➤ Stellar activity implies:

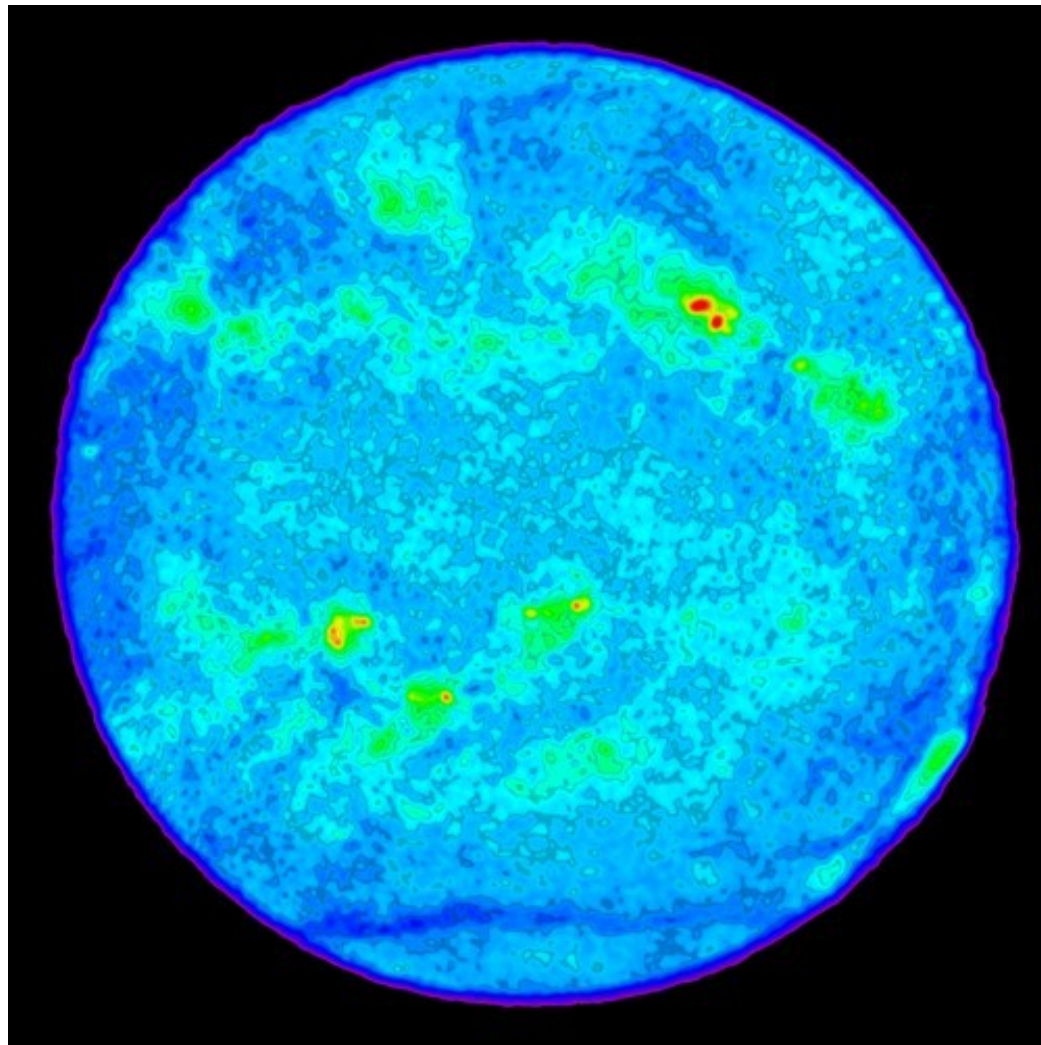
Bremsstrahlung

Gyrosynchrotron (from both thermal & non-thermal plasma)

➤ Coherent emission:

Plasma radiation emitted at ν_p (fundamental &/or 2nd harmonic); T_B up to 10^{18} K , in small bandwidths (local n_e determines ν_p), best observed below 1 GHz ($\nu_p \sim \sqrt{n_e}$, absorption)

Electron cyclotron maser (at the second harmonic of ν_L); T_B up to 10^{20} K , can be used to measure B, 100% polarized



The **full disk of the Sun at 4.6 GHz made with the VLA**. The resolution of the image is 12", or about 8400 km on the surface of the Sun. The brightest features (red) have a temperature of 1 million degrees (the radio T_b measures a true temperature in the Sun's atmosphere) and show where very strong magnetic fields exist in the Sun's atmosphere. An optical image on this day shows sunspots under these features. The green features are not as hot, but show where the Sun's atmosphere is very dense. The disk of the Sun is at a temperature of 30000 degrees, and the dark blue features are cooler yet. The giant slash across the bottom of the disk in this image is a feature called a filament channel, where the Sun's atmosphere is very thin: it marks the boundary of the South Pole of the Sun on this day. Another interesting feature of the radio Sun is that it is bigger than the optical Sun: the solar limb in this image is about 20000 km above the optical limb. **Investigator(s):** Stephen White

Radio stars: putting the SUN @ Prox Cen

- The **SUN**, an apparently strong emitter, is 550 kJy at 1.4 GHz

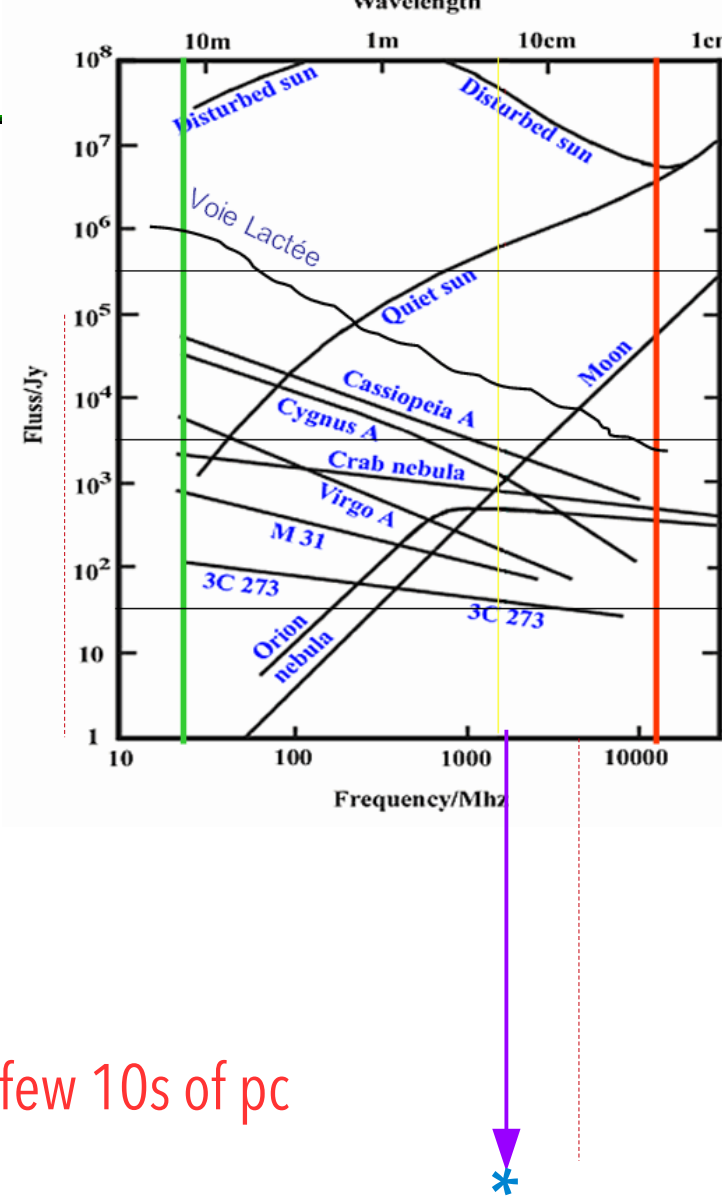
- If located at Prox Cen (1.3 pc) its flux density would be

$$S(\nu)_{\text{PrxCen}} = S_{\text{SUN}} \left(\frac{D_0}{D_{\text{PrxCen}}} \right)^2 = S_{\text{SUN}} \left(\frac{1.5 \times 10^{11} \text{ m}}{1.2 \times 3.08 \times 10^{16} \text{ m}} \right)^2$$

$$= S_{\text{SUN}} (0.41 \times 10^{-5})^2 = S_{\text{SUN}} 1.6 \times 10^{-11} = 9.1 \mu \text{Jy}$$

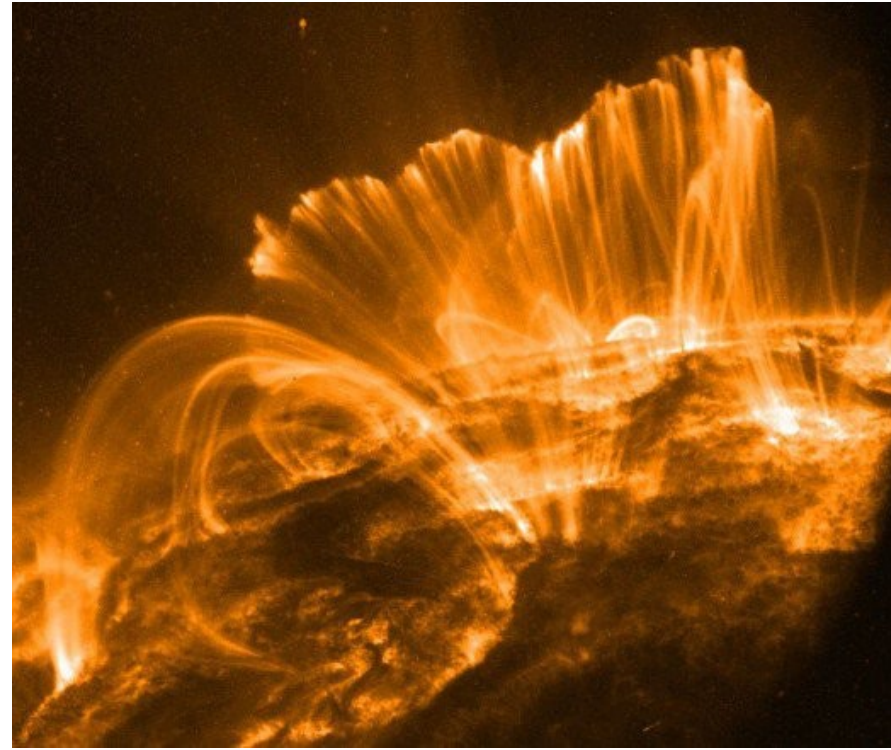
- Only a few "regular" stars will be detected by SKA within a few 10s of pc (see further down for other stars)

- **Additional** (to BB) **emission is much more relevant!**

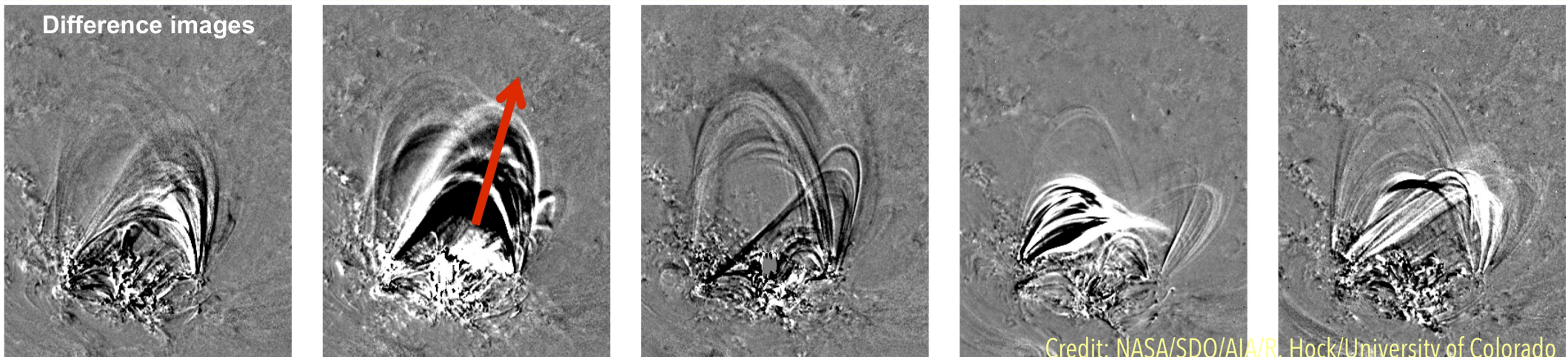
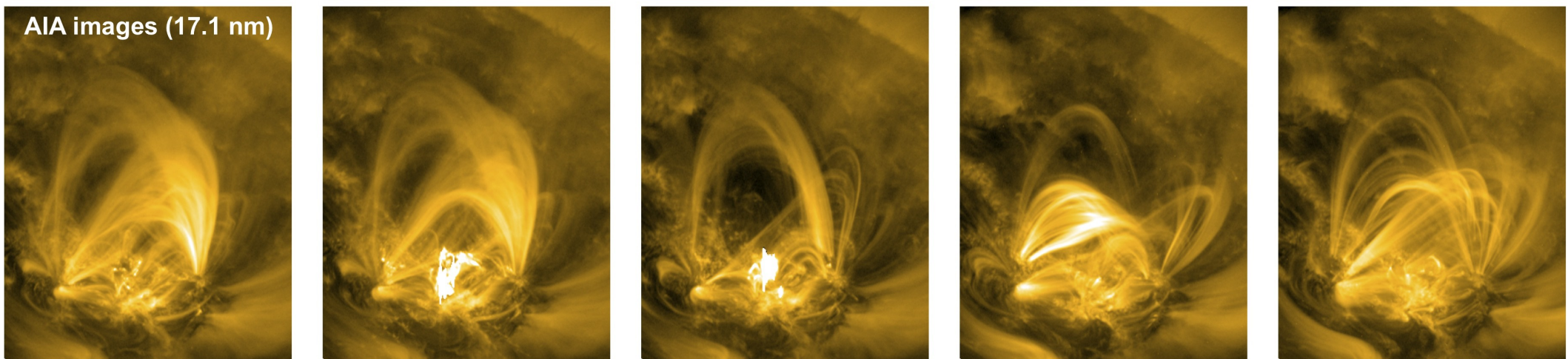
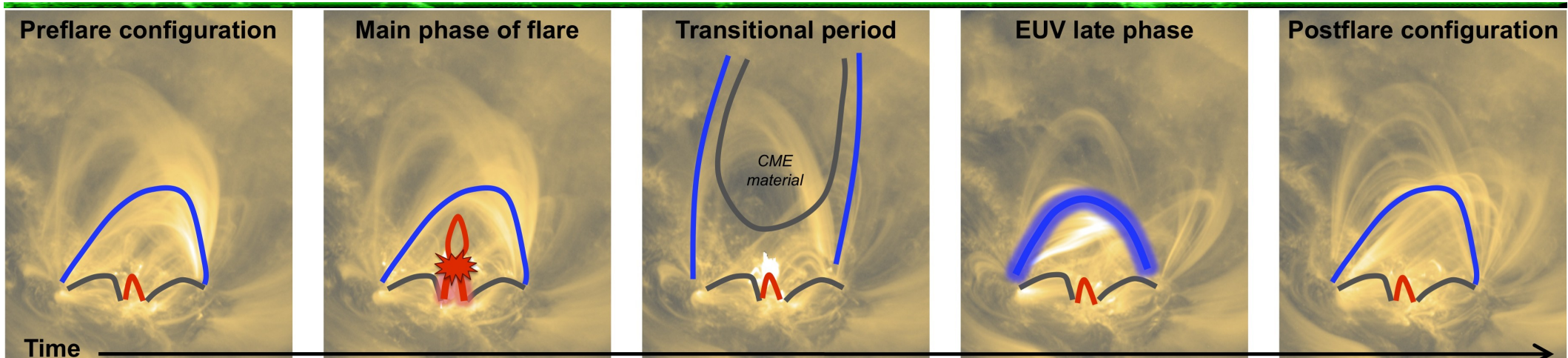


SOLAR FLARES & CORONAL MASS EJECTIONS

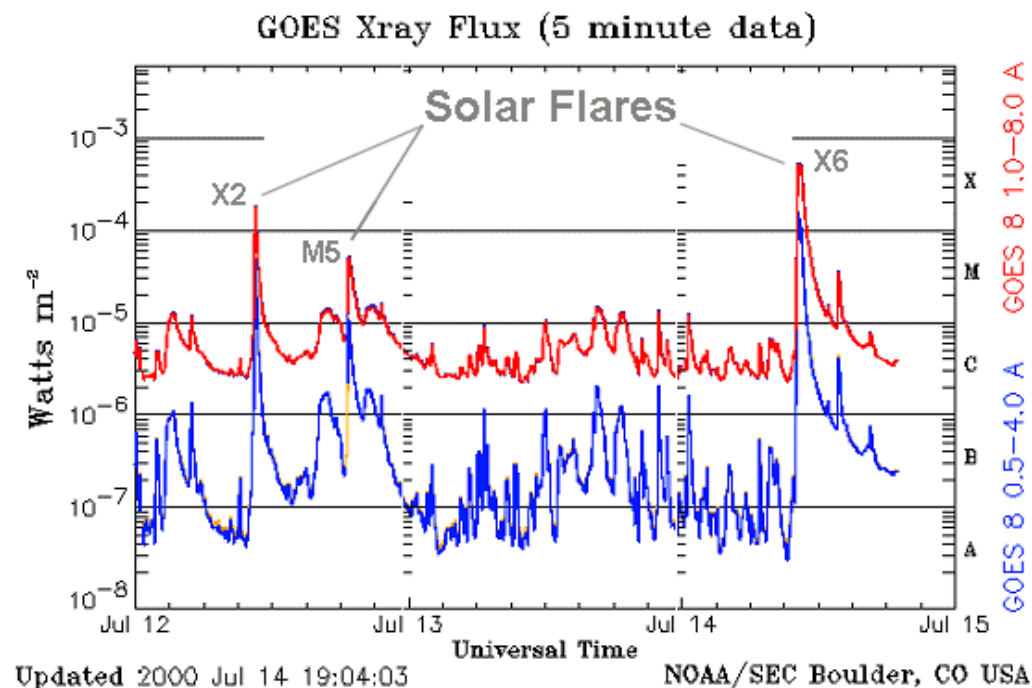
- <https://www.youtube.com/watch?v=TWjtYSRIOUI>
<https://www.youtube.com/watch?v=g9owdmL2UWQ>
- Both phenomena related to magnetic activity in the sun interior, where convective motions stretch, compress, twist & bend field lines
- When these lines "reconnect", there is a release of energy in the form of either Flares or Coronal Mass Ejections (sometimes consequence of a flare)
- Preferred locations at sunspots, and therefore related to solar cycle activity
- Flares eject clouds of electrons, ions, and atoms through the corona of the sun into space. These clouds typically reach Earth a day or two after the event. Radiation instead is released in a sort of a flash, travelling at c (**flare**)



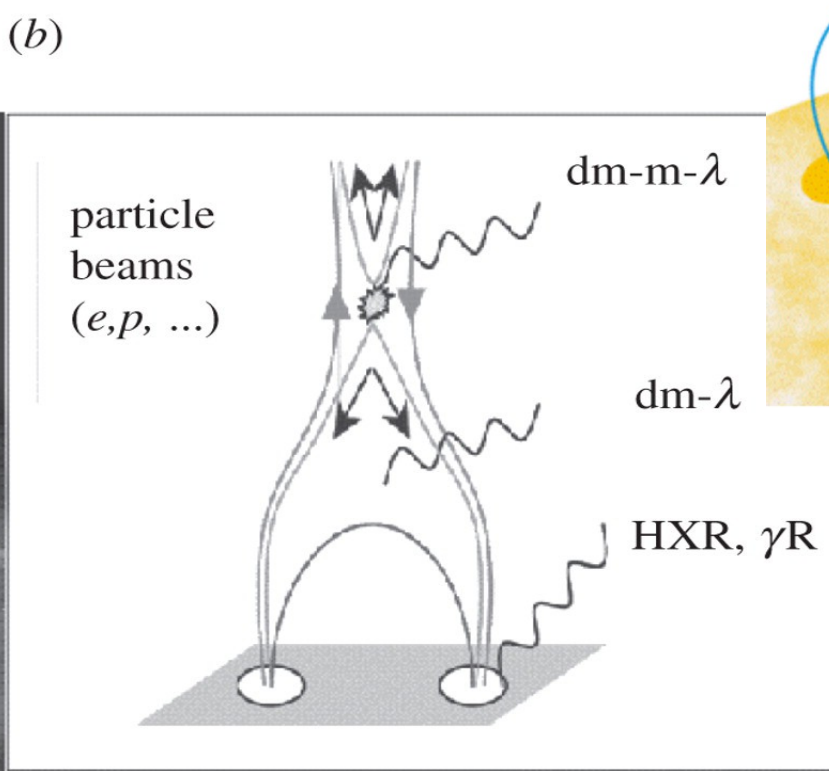
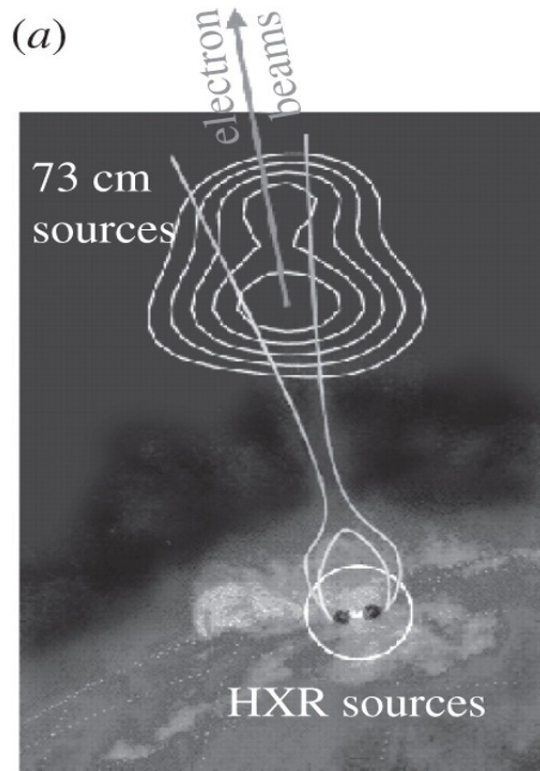
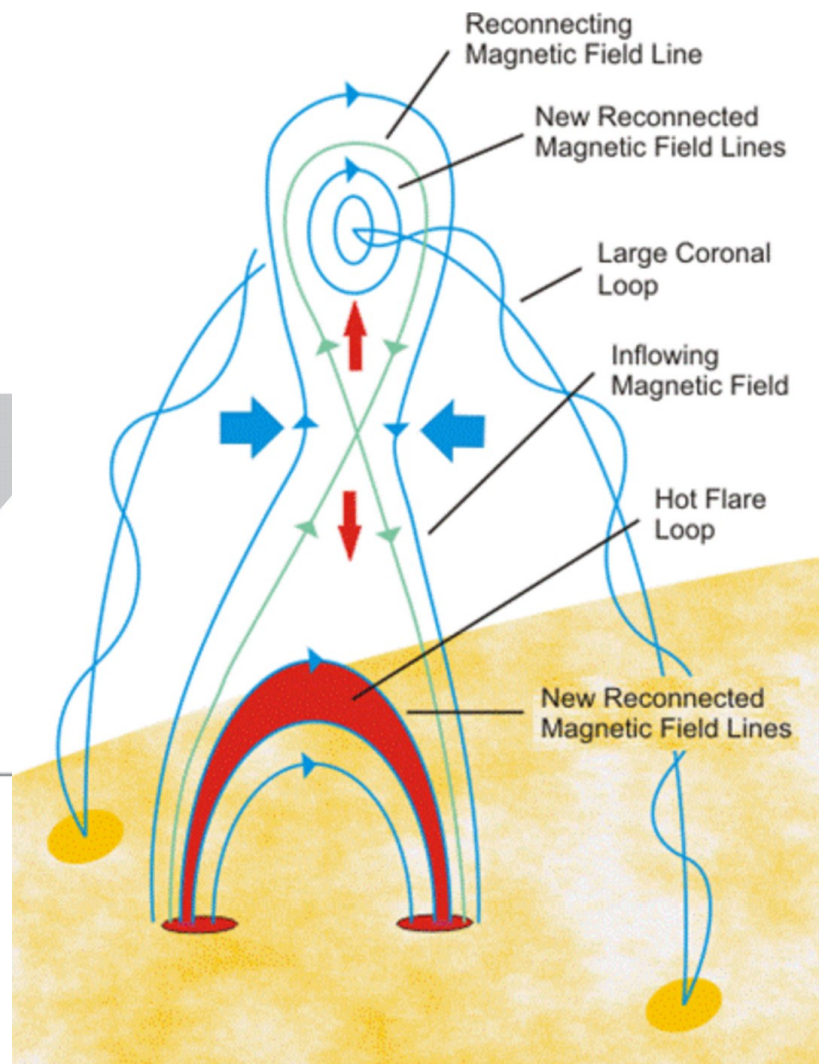
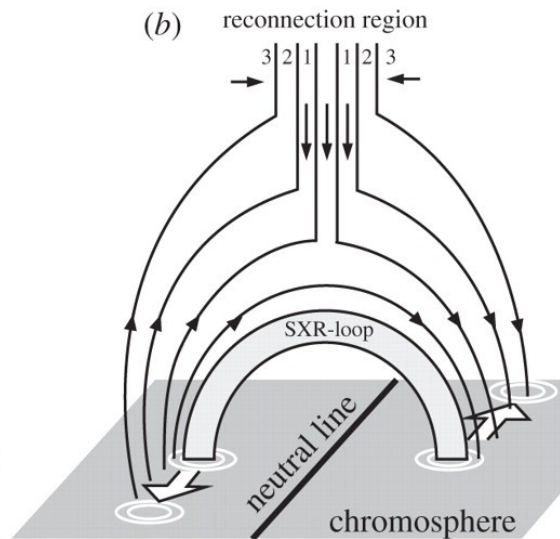
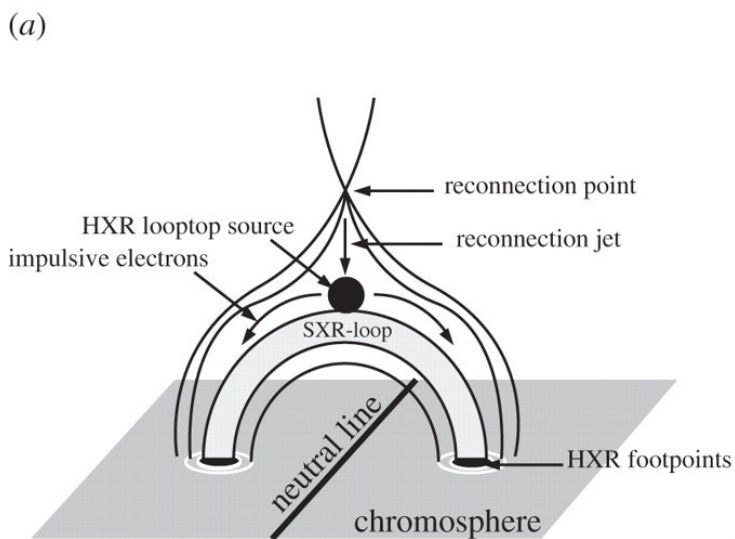
Solar flares & CMEs



- Plasma is heated to $> 10^7$ K
- CR – like electrons & ions are accelerated close to c , non – thermal radiation from radio to the X – and Gamma – Rays
- Magnetic Reconnection is responsible for accelerating charged particles.
- Flares occur in active regions around sunspots: intense magnetic fields connect the solar interior to the corona crossing the photosphere.
- Flares are powered by the sudden (timescales of minutes to tens of minutes) release of magnetic energy stored in the corona.
- The same energy releases may sometimes produce CMEs, although the relation between CMEs and flares is still not well established.



Sun & Radio stars: from flares to radio bursts



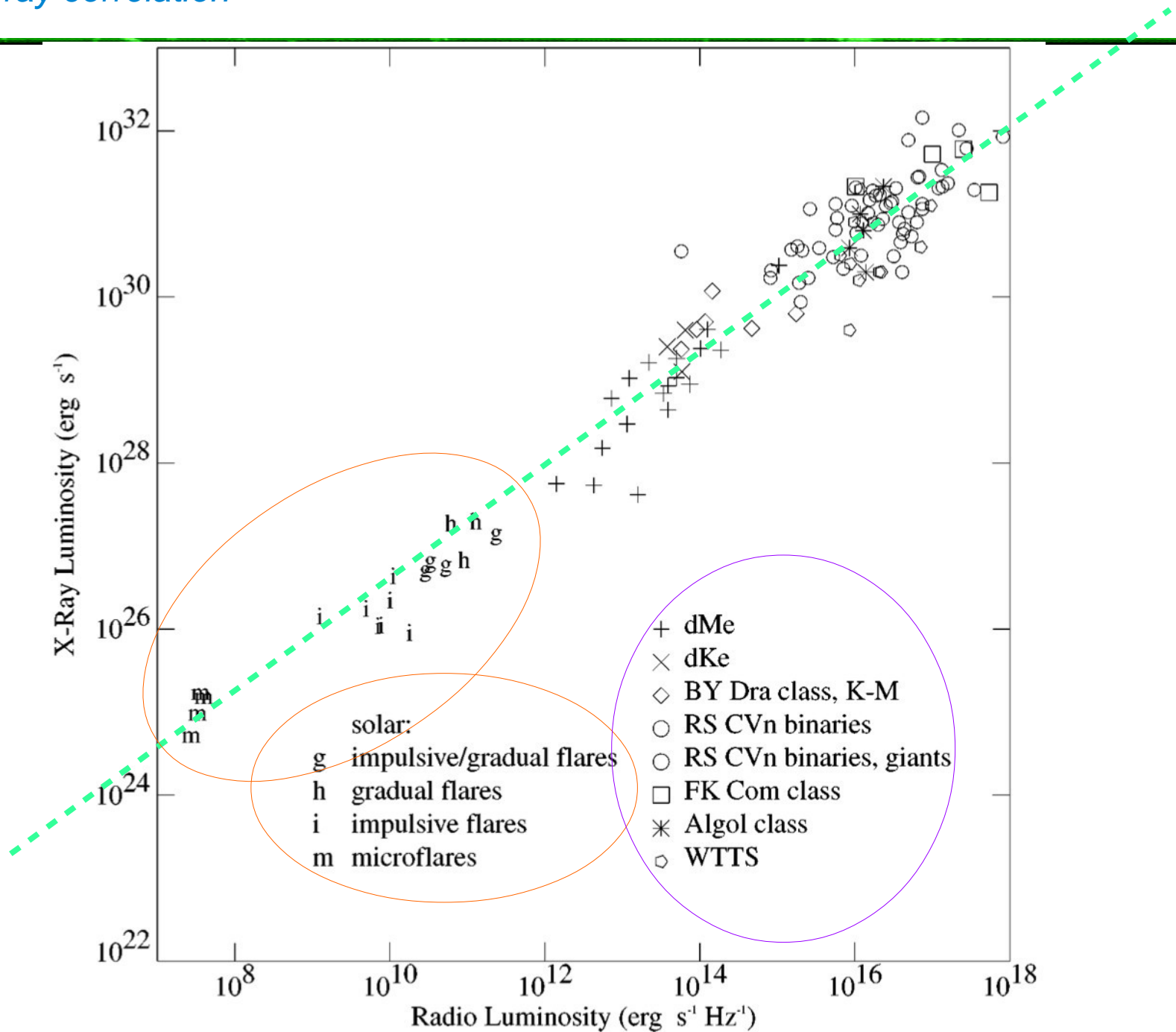
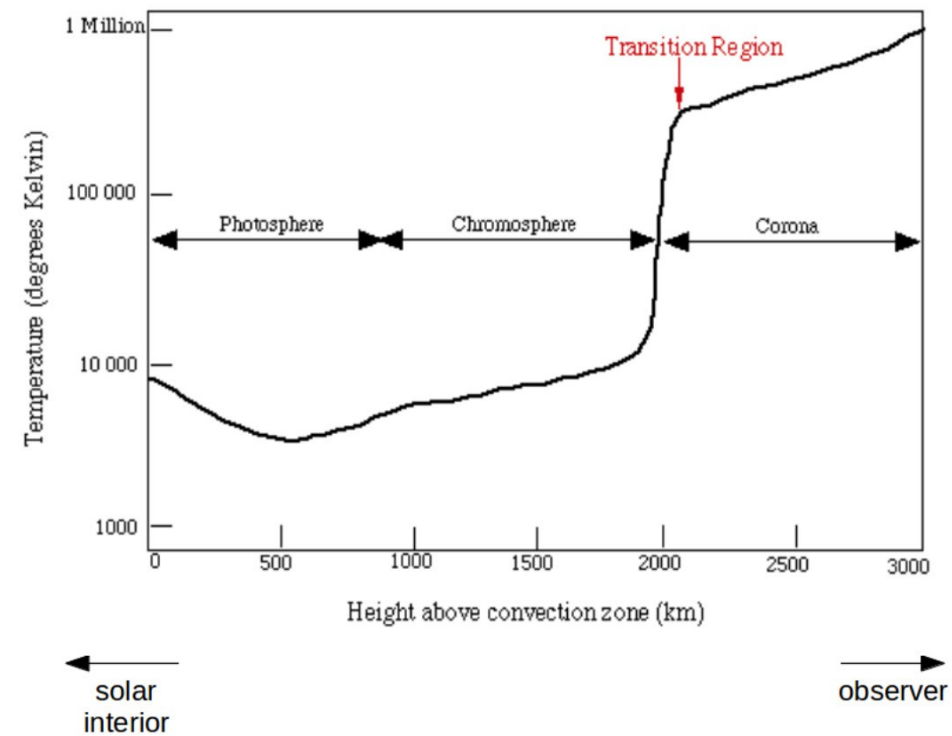
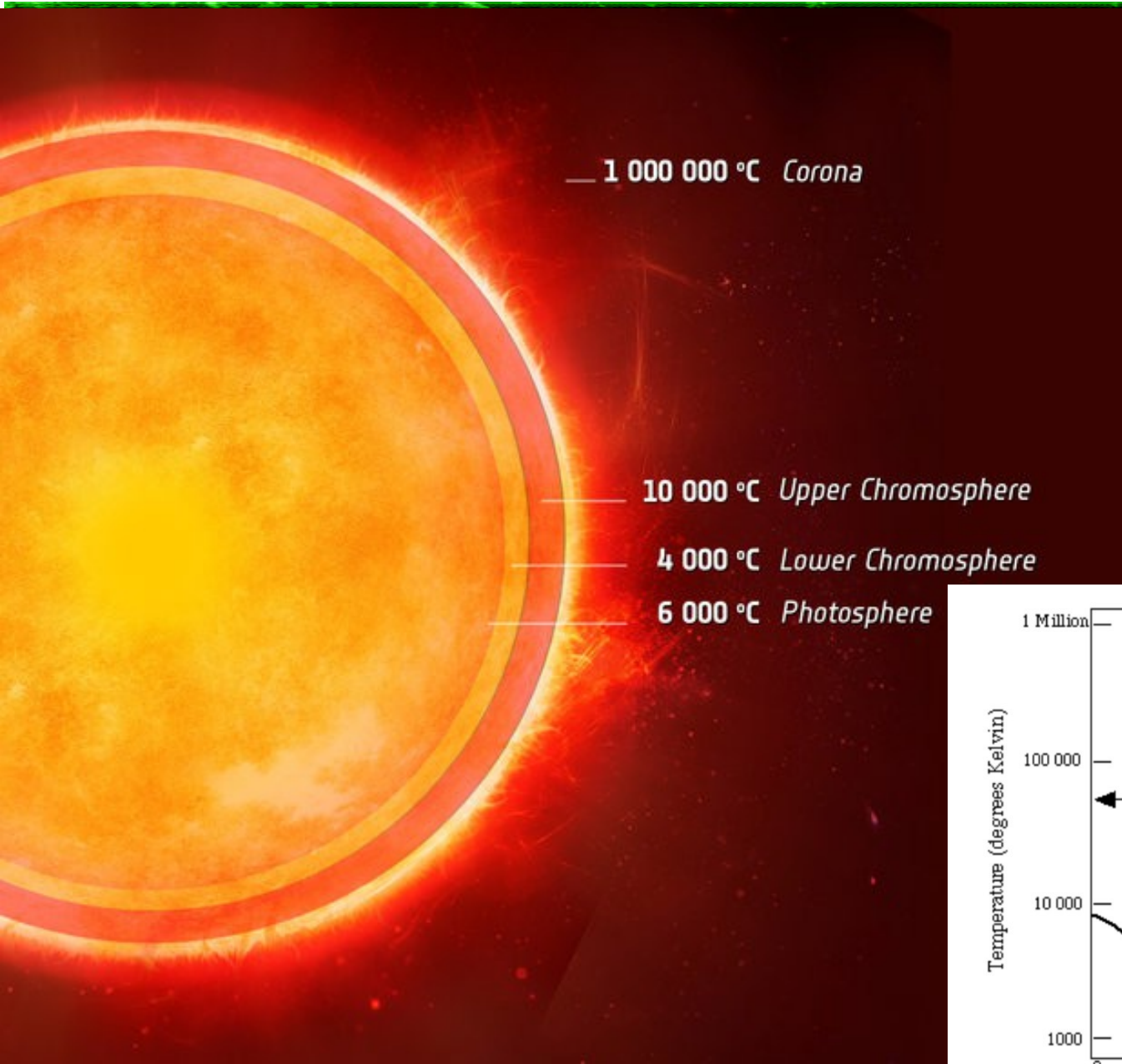


Figure 6 Correlation between quiescent radio and X-ray luminosities of magnetically active stars (*symbols*) and solar flares (*letters*) (after Benz & Güdel 1994).

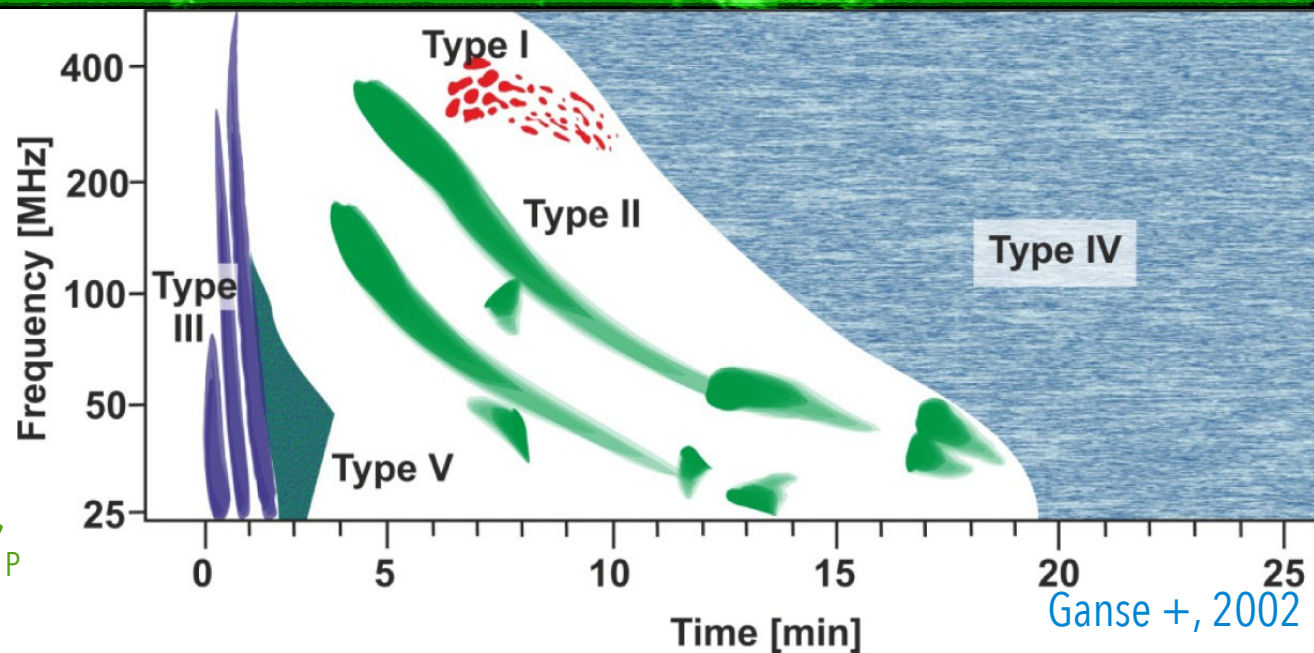
Radio to X – ray correlation



5 classes of **radio bursts**

based on their origin:

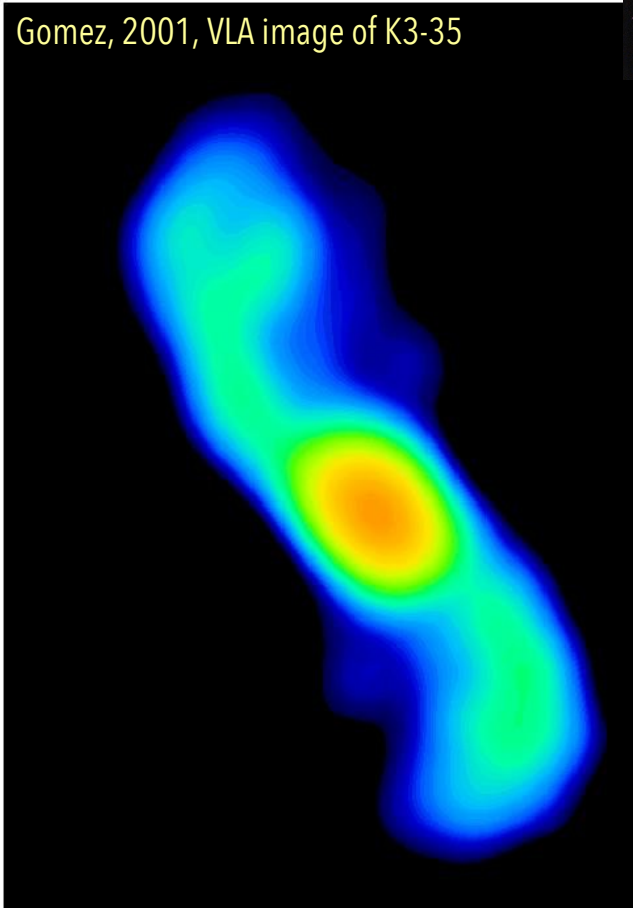
- **Type I**: duration < 1 s, @ $\lambda \sim$ m, many, irregular, series lasting From minutes to several days, at ν_p
- **Type II**: duration \sim several m @ λ m to dam, generated by MHD shock waves propagating through the solar corona, associated with flares & Coronal Mass Ejections
- **Type III**: duration short, 1 GHz to kHz, related to flares, emission from electron beams moving (0.1-0.6c) along field lines (magnetic reconnection)
- **Type IV**: duration hr to days, 20 – 2000 MHz, broadband continua associated with flares
- **Type V**: after a group of type III bursts, with duration of a minute or so. In the type V model source, coherent Čerenkov plasma waves are excited by fast electrons (speed around $1/3$ c) ejected from a flare and oscillating between mirror points in a magnetic trap in the corona



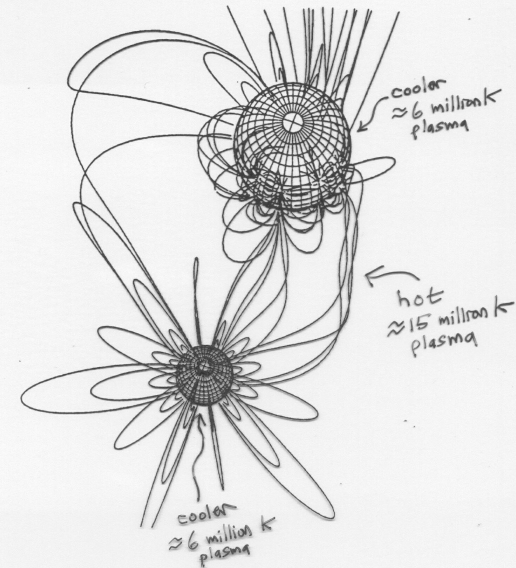
Other (active) radio stars:

- O, B & Wolf – Rayet
- RG & SG
- RS Cvn & Algol:
- Pre – Main Sequence stars (T – Tauri)
- Flare stars:
- LBV stars
- Magnetic & Chemically peculiar stars
- Planetary nebulae:

Gomez, 2001, VLA image of K3-35



RS Cvn stars possible model



Radio stars: the HR diagram

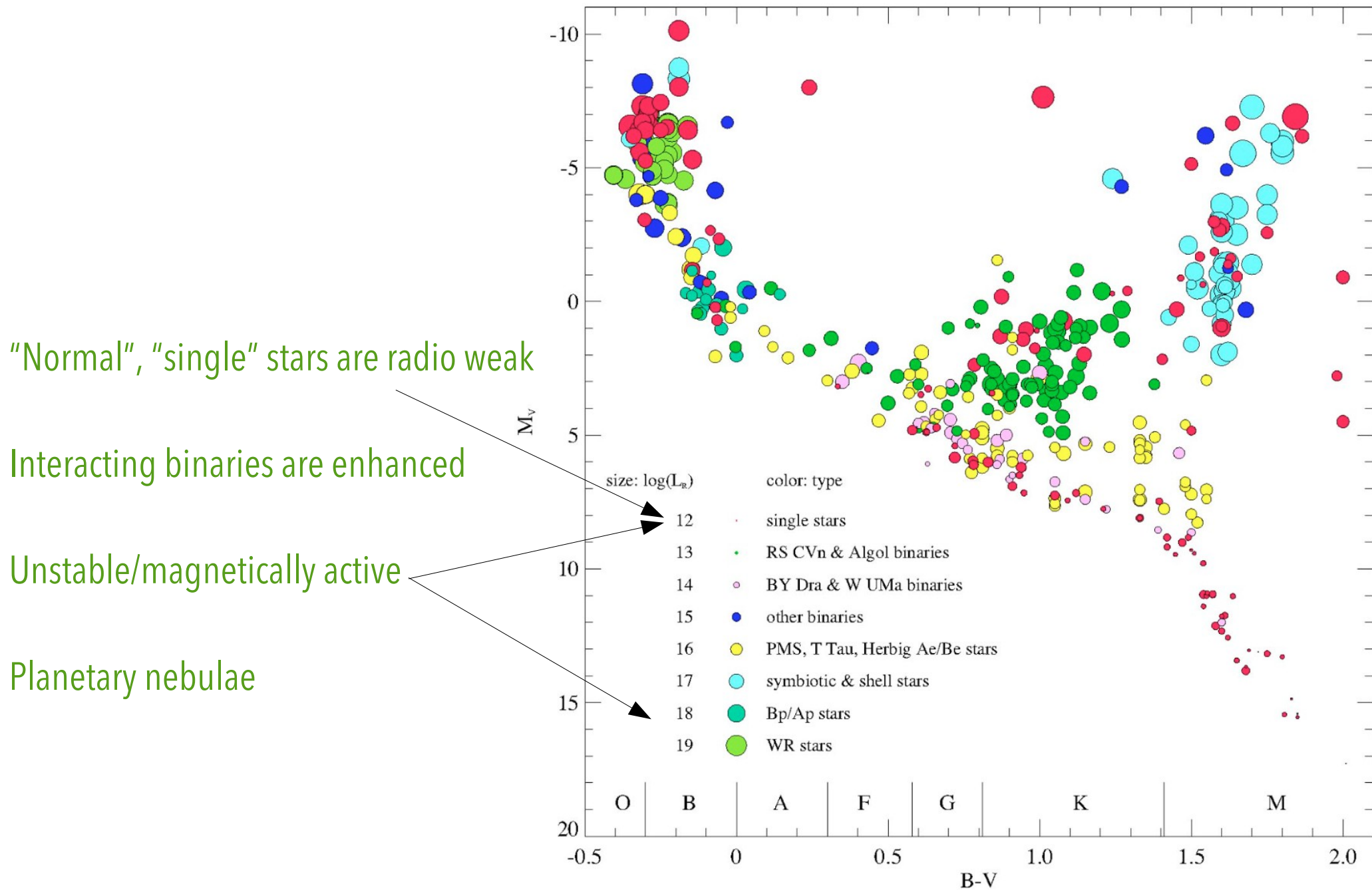


Figure 1 HR diagram showing 440 radio-detected stars.

Radio stars:

O, B & Wolf – Rayet

- High \dot{M} ($10^{-6} M_{\odot}$ and $10^{-5} M_{\odot}$, respectively) via optically thick, fast ($\sim 10^3 \text{ km s}^{-1}$) stellar wind (partially obscuring the optical emission).
- Radio from wind thermal bremsstrahlung: spherically symmetric wind has $n \sim r^{-2}$, $S(\nu) \sim \nu^{0.6}$
- Some also have non-thermal emission from a population of relativistic electrons generated in shocks from the collision of stellar winds in binary systems (WR + O-type \rightarrow symbiotic stars)
- WR stars (late stage of evolution of stars $> 20 M_{\odot}$): outer envelope (H) swept away & internal high T layers are exposed; T from 10^5 to a few in 10^4 and radii 1-20 R_{\odot}

RG & SG

- Cool stars (3000K) but large (several AU), with high mass loss ($10^{-6} M_{\odot}$) rate but slow ($\sim 10 \text{ km s}^{-1}$) wind BB emitters with $S \sim \nu^{-2}$. If there is a massive OB companion which ionizes the wind, $S(\nu) \sim \nu^{0.6-2}$
- Often display maser emission (OH, H_2O , SiO), common in AGB stars

Typical model for OB & WR stars

All have thermal emission. Size dependent on v , optically thick surface at 5 GHz @ 100s of stellar radii. Mass loss correlated with radio luminosity: $\dot{M} \sim (1.2 \pm 0.2) \text{Log } L + C$

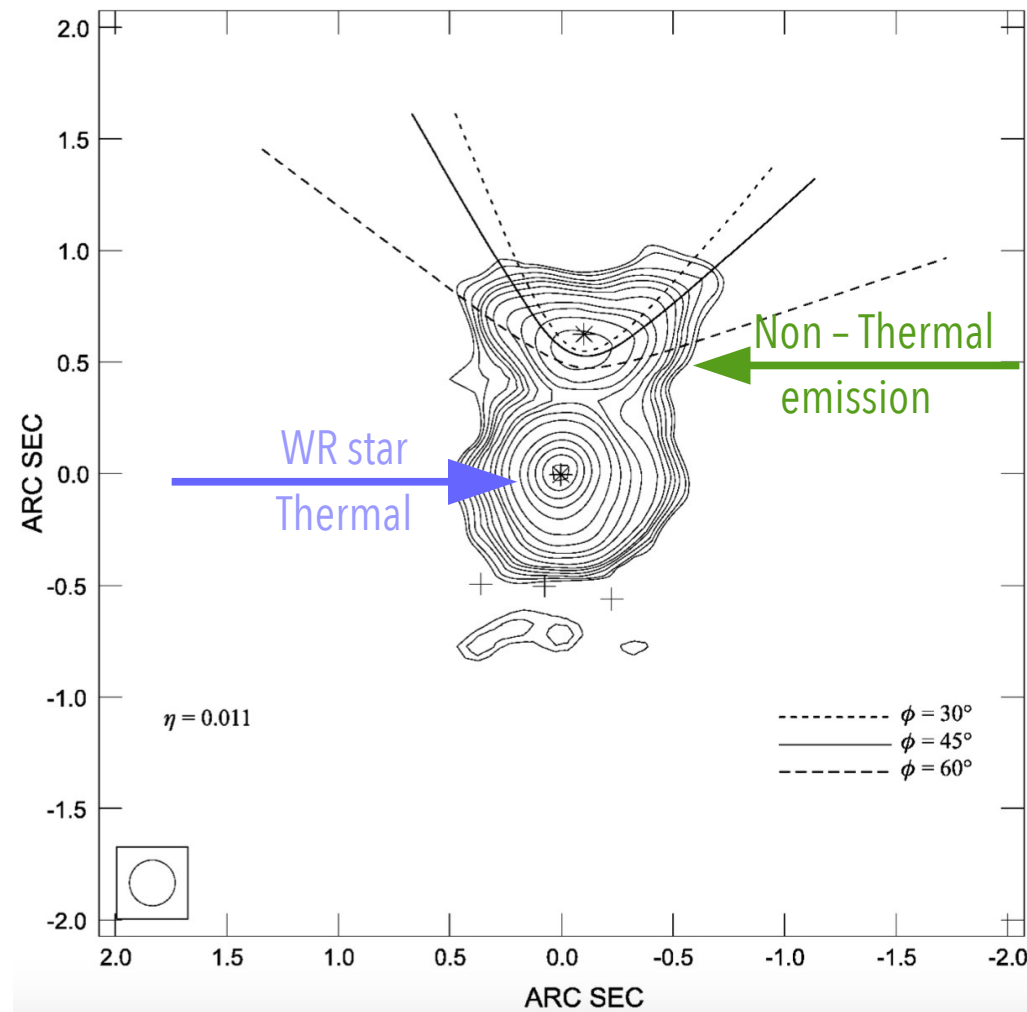
Enhancements when colliding winds in binary systems

Several OB (25%) & WR (50%) stars have synchrotron too, associated with short term variability \Rightarrow B

Given optically thick, also n-t emission must Originate at large distances (100s stellar radii)

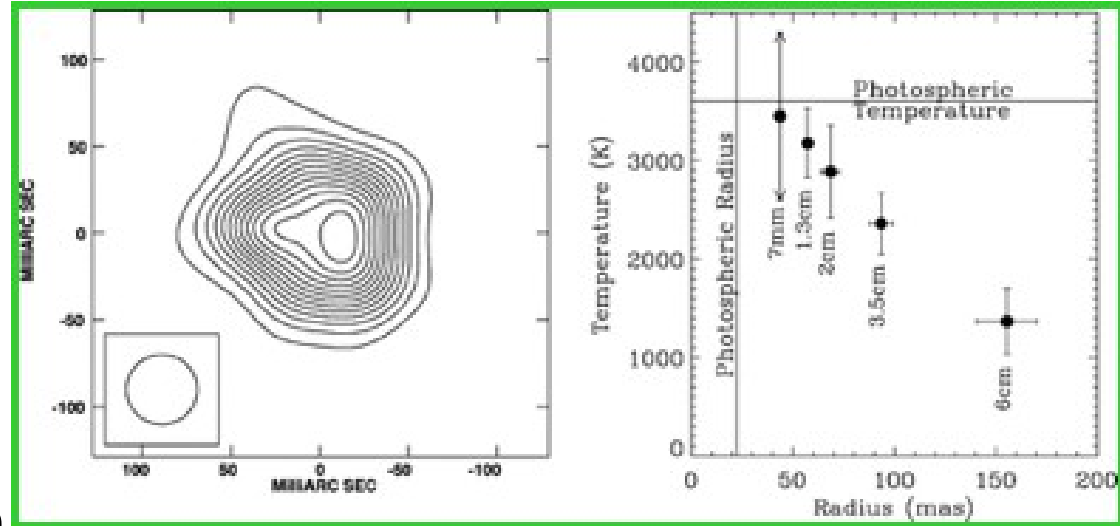
Colliding wind model: OK!

\Rightarrow Most, if not, all n-t sources are binaries & r.emission located between the two stars



Chromosphere emission from cool stars

- Betelgeuse observed at 43 GHz. The radio photosphere is resolved, @ resolution of 40 mas.
- The atmospheric temperature of Betelgeuse as a function of radius, observed at different frequencies. (From Lim et al. 1998)



⚠ warning! Effects on the measure of T are from optical depth

Lim +, 1998: cool, photospheric material is elevated in giant convection cells; dust formation in this environment could then drive Betelgeuse's outflow.

N.B. Filling factor may be a key as well, i.e. only a fraction of the volume is filled with thermal plasma leading to a T underestimate

Active binary systems:

RS CVn & Algol:

- Close detached systems of two late type stars (G + K0 subgiant): **Magnetic reconnection of the two interacting magnetospheres can accelerate particles** – Gyro-synchrotron emission with a flat spectrum for the K0 subgiant
- **Algol** (semi-detached), similar to RS CVn, but the less massive has filled his Roche lobe transferring mass to the more massive and less evolved star (earlier mass transfer in the other direction!)

Pre – Main Sequence stars (T – Tauri)

~1 M_{\odot} , Classical TT: (partially optically thick) **bremsstrahlung emission** from circumstellar matter (debris of the cloud), $S \sim v^{1-2}$ or $S \sim v^{0.6}$ (steady outflow)

WTT (weak lined) **non thermal emission from magnetically active regions**

Flare stars:

MS at low masses exhibiting **chromospheric activity similarly seen in the sun**. Intense flares from the X – Rays to the radio, with correlation between Radio and X – Ray luminosity. X- rays are not produced in the very low mass dwarfs

Both **rotation and field intensity** are essential to determine the entity of the flares

What is relevant for radio stars

VLBI observations of

- radio flares in RS Cvn (& Algol - like stars):

Total radio size \sim binary system size

Compact Core (CC) + Extended Halo (EH)

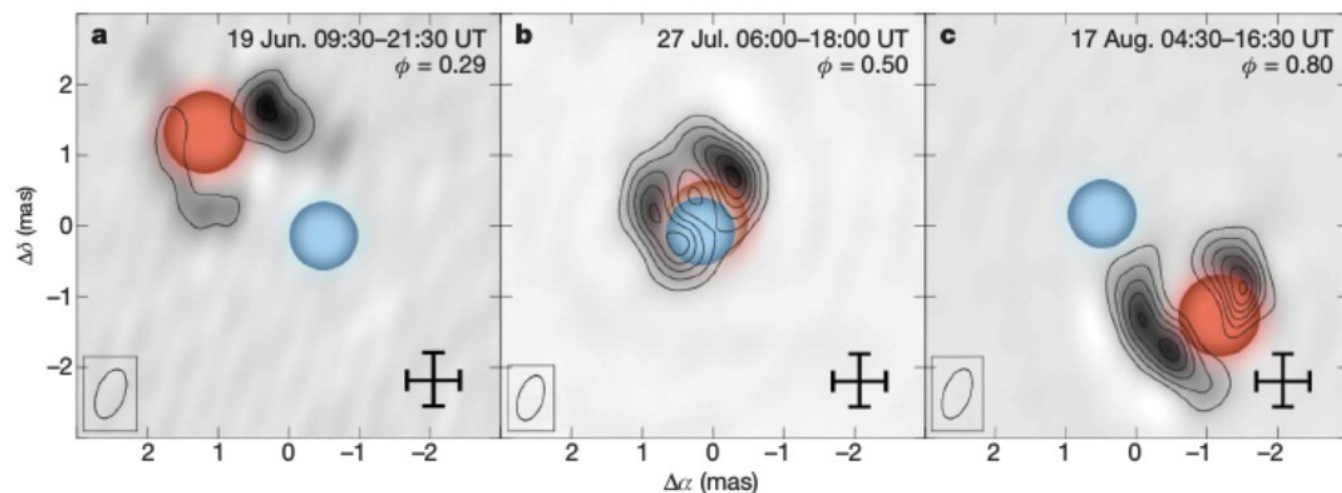
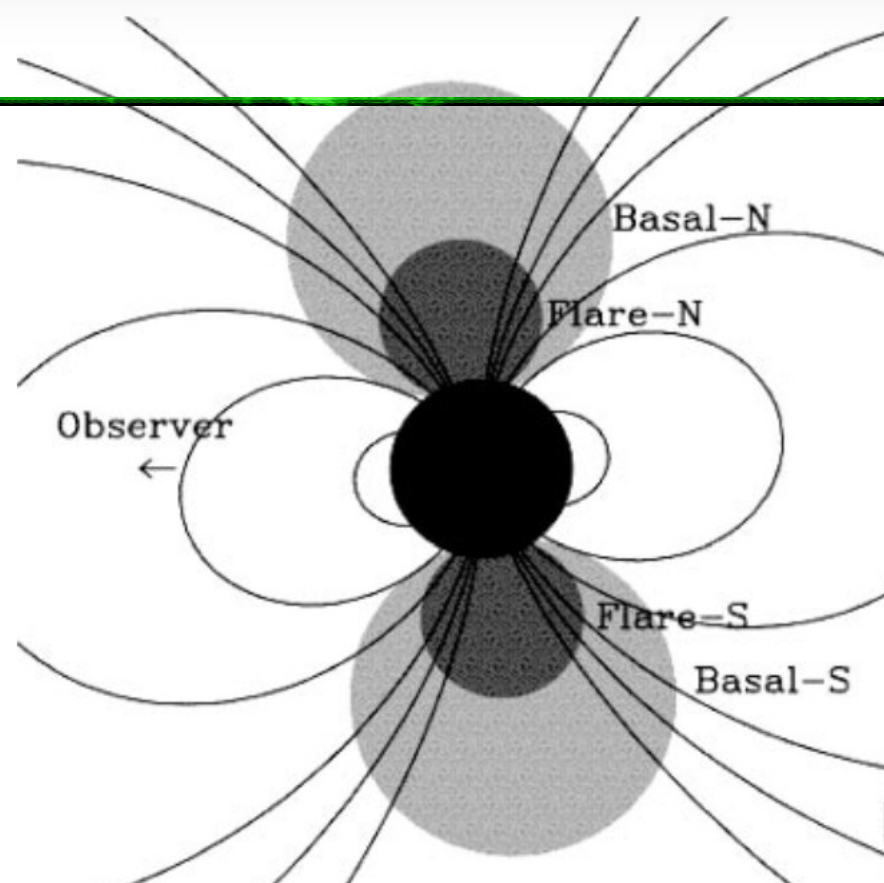
CCs appear flaring sites

EH low level quiescent emission

(decaying electrons from earlier flares?)

- Algol: two opposite, polarized lobes

Common Models: like the one aside, global dipolar structure, similar to van Allen belts



(Peterson et al., 2010) Radio images of Algol at three different orbital phases. Radio emission is localised near the evolved star, pointing towards the main sequence star. The cross shows the position error (also Cavallaro, PhD thesis)

What is relevant for radio stars

CP stars

Emission as a function of ν :

Prediction from model (previous page)

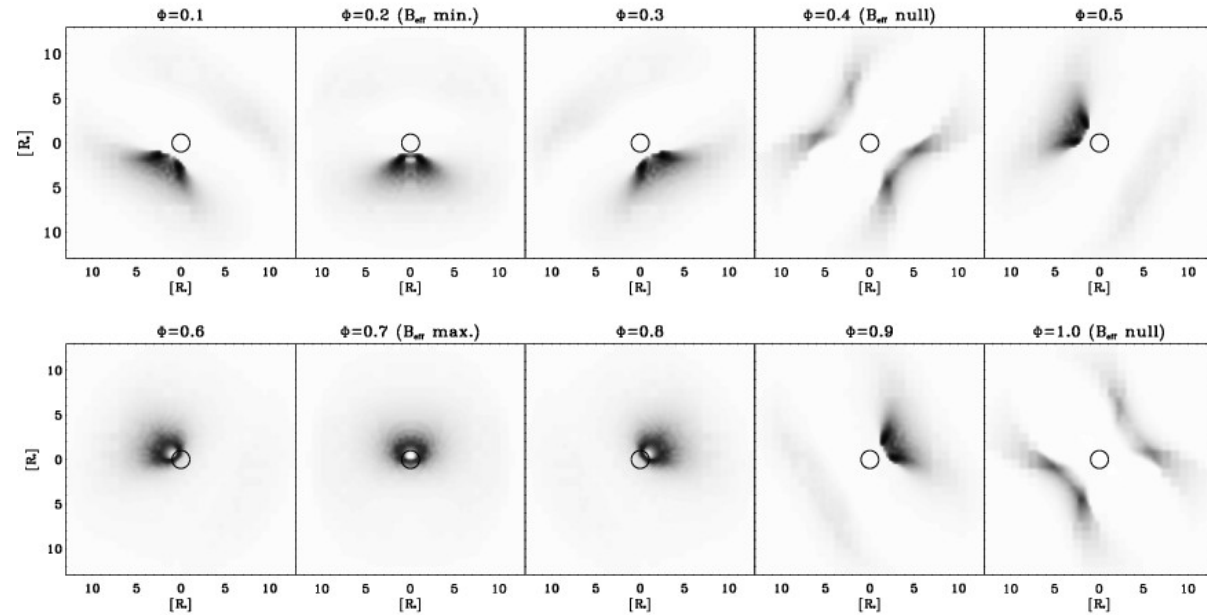
Opacity: determines source size vs

Orbital & rotation periods determines source size and aspect of radio emission

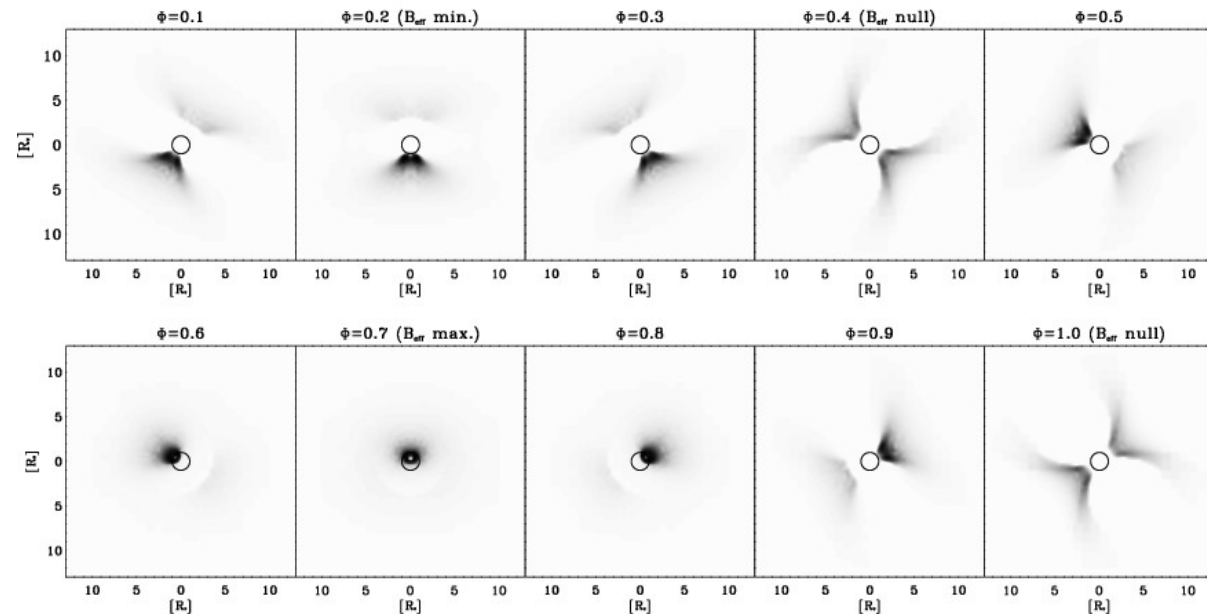
HD 37479 ($i=72^\circ$, $\beta=56^\circ$)

$\nu=5$ GHz

Trigilio +, 2004



$\nu=15$ GHz



VLBI observations of radio flares in RSCVen:

Curvature in a self-absorbed synchrotron radio spectrum: $\Rightarrow B$

$$B \approx 2.9 \cdot 10^{13} v_{\text{peak}}^5 \theta^4 S_{\text{peak}}^{-2} \text{ [G]}$$

Source angular sizes: very small, LBI is necessary

In general,

Measurements have produced $B \sim 10\text{s to } 100\text{s G}$ in CC, a few to 10s G in EH

Summary of B field measurements:

$B \sim 250\text{-}500 \text{ G}$ from the electron cyclotron maser emission

$B \sim 600\text{-}2000 \text{ G}$ in active regions from coronal gyroresonance emission

$B \sim 10\text{-}200 \text{ G}$ from VLBI measurements of large coronal sizes

$B \sim 5 \text{ to } 10\text{s of G}$ for RS CVn halo sources, from a few tens to several hundreds G for the cores

LBV stars ($> 10 M_{\odot}$): high mass loss rate ($10^{-6} M_{\odot} \text{ yr}^{-1} - 10^{-3} M_{\odot} \text{ yr}^{-1}$)
optically thick wind & bremsstrahlung emission $S \sim \nu^{0.6}$ (steady outflow)

Magnetic & Chemically peculiar stars

B or A -type stars in 4 classes:

CP1 (or Am) enhanced abundances of metals

CP2 (or Ap or MCP) strong bipolar magnetic field, slow rotators

These can show radio gyro-synchrotron emission, of non-thermal electrons accelerated in magnetic reconnection, particularly at $\lambda \sim \text{cm}$

CP3 (HgMn), normal magnetic field, even slower rotators, strong Hg & Mn lines

CP4 (He weak), weak He lines

Planetary nebulae: (PNe, $< 8 M_{\odot}$), post-AGB with axi-symmetric mass loss, period of high-mass loss in which hot inner layers ionize the envelope. Emission via bremsstrahlung. Some young PNe also emit non-thermal radiation

- *Microquasars* (see later on!)
- *Pulsars* (see later on!)

What is relevant for radio stars

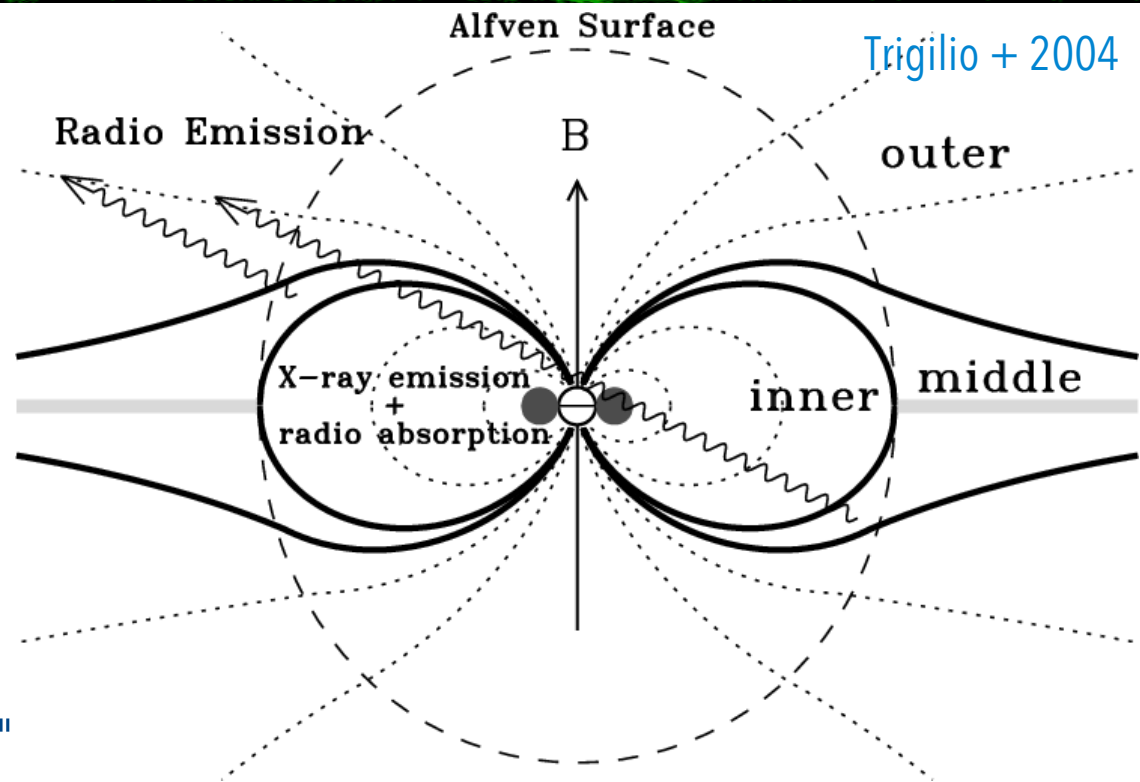
MCP stars (CP2)

Rotation distorts magnetic field lines

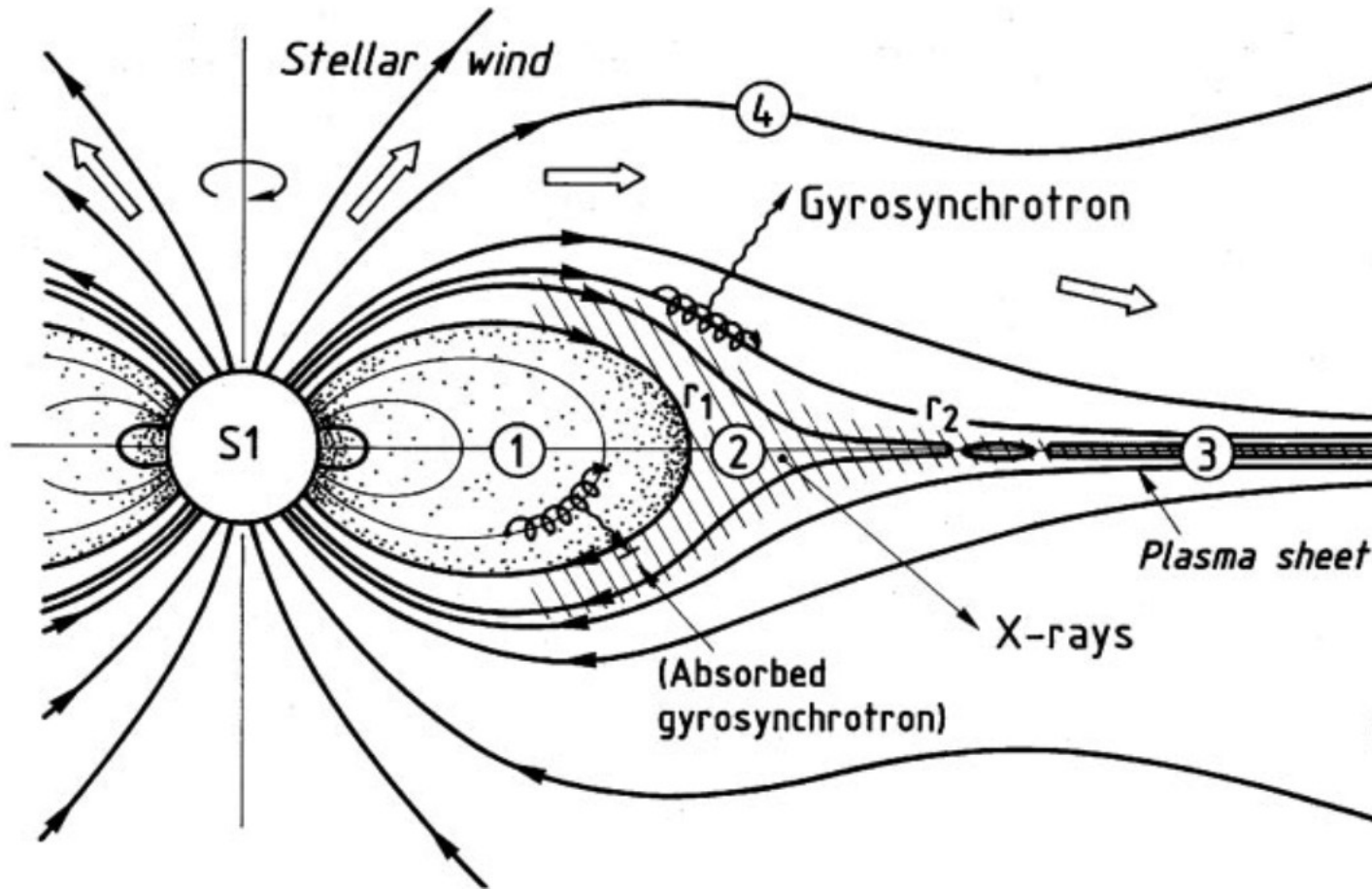
Cross-section of the magnetosphere of MCP stars: dipolar field modified by the stellar wind; inside the Alfvén surface the magnetic pressure exceeds the kinetic pressure of the wind, and the field lines maintain a dipolar geometry.

The largest closed field line defines the "inner" magnetosphere, which confines the stellar wind ("

Here the two stellar wind streams from opposite hemispheres of the stellar surface collide, leading to a shock that produces an enhancement of the temperature of the gas and eventually to X-ray emission. This gas cools and accumulates in the magnetic equatorial plane, forming a torus-like cloud (the two filled circles close to the star). The open magnetic field lines just outside the inner magnetosphere produce current sheets (shaded areas), where the electrons are accelerated up to relativistic energies. They eventually can propagate back toward the stellar surface following the field lines of the "middle" magnetosphere and emit radio radiation by gyrosynchrotron emission process (wave arrows). Hot matter in the inner magnetosphere can absorb the radio radiation. Field lines close to the magnetic poles are open ("outer" magnetosphere), and tend to a radial topology outside the Alfvén surface. Only the wind from the polar caps can escape from the magnetosphere.



Model(s) for large scale magnetic activity in radio stars



Field lines with opposite directions get in touch

Radio star detectability with forthcoming facilities (1)

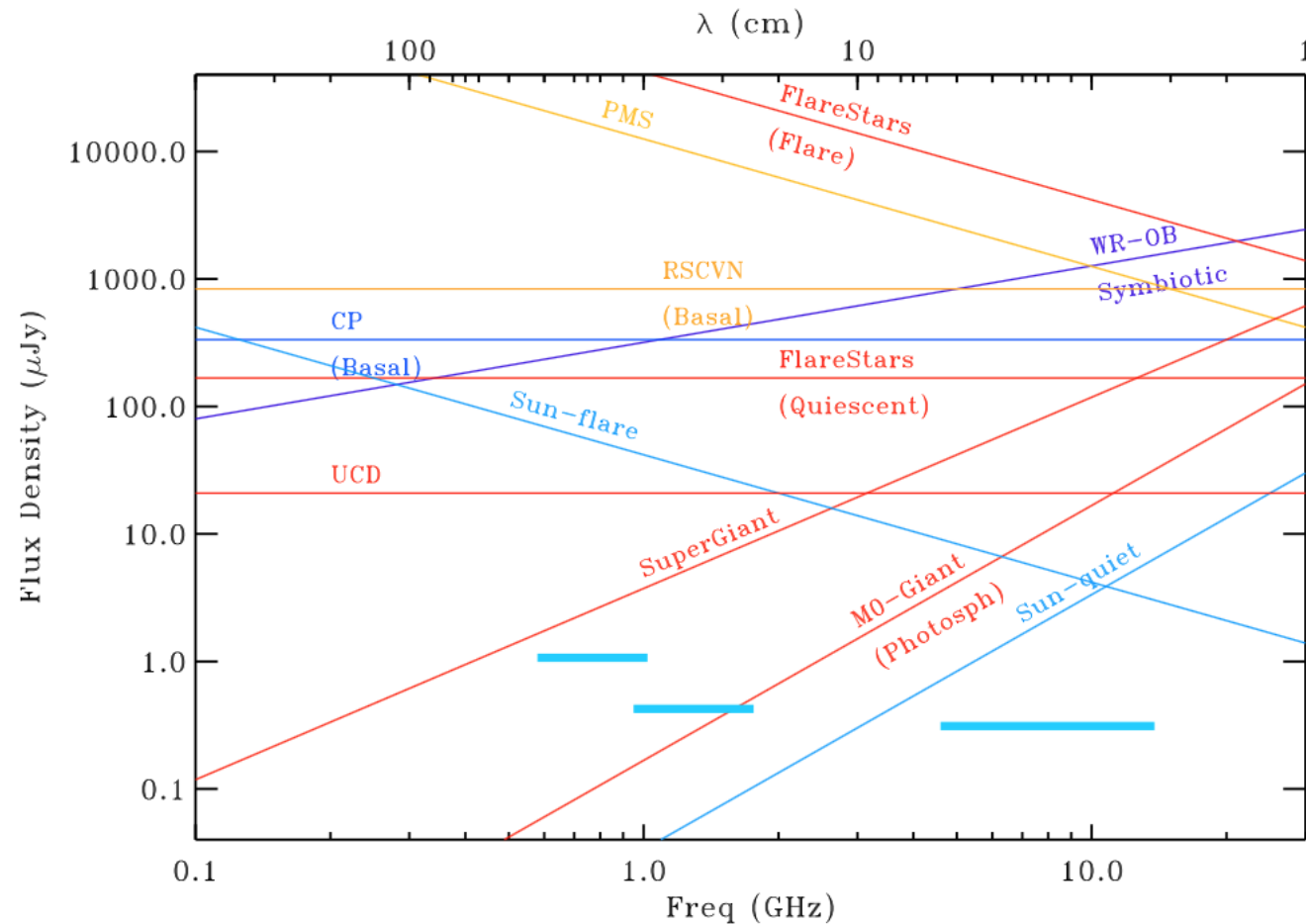


Figure 2.6: Average spectrum of common radiostars classes. The WR-OB and giant stars are assumed to be at 1 kpc, the MCP at 0.5 kpc, the RS CVn, flare stars and sun-like stars at 10 pc and the Ultra Cool Dwarf (UCD) at 20 pc. The pale blue horizontal lines represent the SKA-1 1σ for an hour of observation at the three different bands.

Radio star detectability with forthcoming facilities (2)

Useful plot to determine the relative luminosities between classes of stars

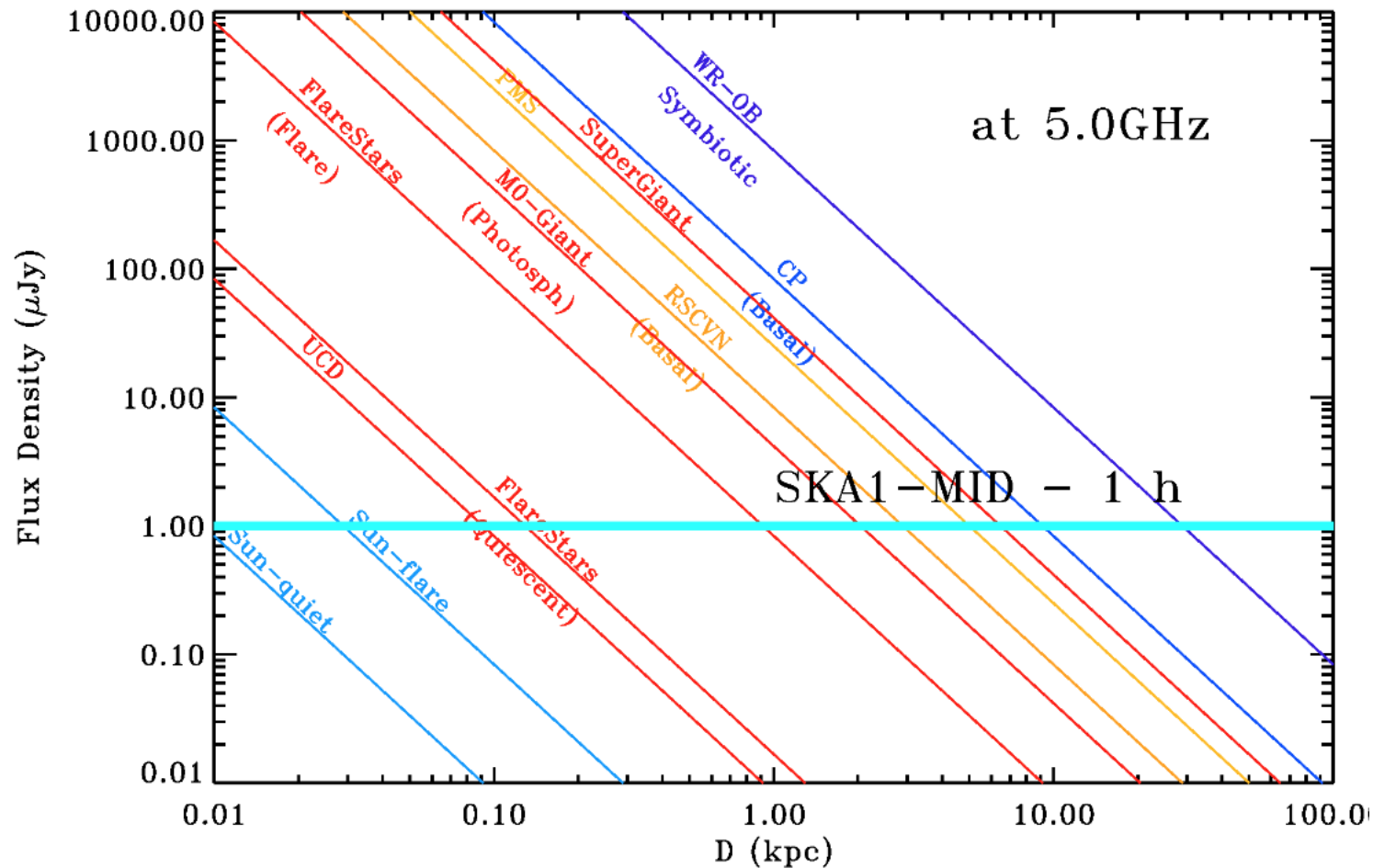


Figure 2.7: Expected flux of common radio stars classes versus their distance from the Earth at 5 GHz. The pale blue horizontal line represents the SKA1 1σ 1-hour observation.

Radio stars, a summary

- Low luminosity emitters
- Some classes of stars are often detected at radio wavelengths, showing either thermal or non – thermal (or both) emission.
- The presence of B fields is widespread, often very important!
- Objects with large magnetic fields / magnetospheres are better detected in the radio window
- Flares (bursts) are a common phenomenon in the photosphere & chromosphere of a radio star, leading to variability over a quiescent emission
- Radio emission in stars is important since is little or at all absorbed at cm wavelengths, allowing a full census of the various classes in the MW, ⇒ a strong verification of the IMF.

- (a) the discovery of steady and flaring non-thermal and polarized emission in cool stars, testifying to the importance of highly energetic processes;
- (b) the recognition that these phenomena are ubiquitous in many classes of convective-envelope stars;
- (c) observations of very large, apparently stable magnetospheric structures, unlike anything known from the Sun, around various types of magnetically active stars such as T Tau stars, Bp stars, dMe stars, or RS CVn binaries;
- (d) the discovery of non-thermal emission produced in (wind-collision) shocks of hot-star atmospheres;
- (e) gyromagnetic and flaring emission from deeply embedded protostellar objects, testifying to the importance of magnetic fields back to the earliest moments of a stellar life; and
- (f) flaring radio emission from substellar objects not previously thought to support stellar-like convective outer envelopes. Radio methodology has become a standard to estimate magnetic fields in cool stars, to determine mass loss in stars with ionized winds, to spatially resolve and map structures at the milliarcsecond level, and to simply prove the presence of magnetic fields through polarization measurements.

Far from being an auxiliary science to research at other wavelengths, stellar radio astronomy should prepare to address outstanding problems to which it has unique access, although more sensitive instruments are needed.

Questions of particular interest include:

- Are there relevant high-energy processes and magnetic fields in class 0 protostars?
- Are accretion processes important for the high-energy mechanisms and the generation of large-scale magnetic fields?
- Are there magnetic fields in hot stars, and what role do they play in the winds?
- Are brown dwarfs usually quiescent radio emitters? Do they maintain stable magnetic fields? What is the structure of their coronae?
- Are there intra-binary magnetic fields in close binary stars?
- How do large magnetospheres couple to the more compact X-ray coronae?
- Are quiescent coronae fed by numerous (micro) flares?

Relevant to to problem "Origin of cosmological magnetic fields"

Plasma gyromagnetic emission: function of T, B, lots of details in Gudel (2002)

Gyro-magnetic frequency:

$$\nu_G = \frac{eB}{2\pi m_e c} \approx 2.8 \times 10^6 \frac{B}{\text{Gauss}} \quad [\text{Hz}]$$

$$\nu_{\text{em}} \approx \nu_G \cdot \gamma$$

$\gamma = 1$ Cyclotron

$\gamma \approx 2 - 3$ Gyrosynchrotron

$\gamma \gg 1$ Synchrotron

Propagation may be stopped if the frequency of emitted radiation is below $\nu_p \approx 9.0 \cdot \sqrt{n_e} \quad [\text{Hz}]$

Coherent emission:

(a) \Rightarrow at fundamental & second harmonic of ν_p , can account up to $T_B \sim 10^{18}$ K (low frequency stellar flares)

\Rightarrow (plasma radiation) [NEXT PAGE]

(b) \Rightarrow at fundamental and second harmonic of ν_g (cyclotron maser) up to $T_B \sim 10^{20}$ K

Narrow band emission, moving in frequency, short timescale.

Fundamental in the determination either of n_e (if a), or B (if b!)

Also cyclotron, gyro-synchrotron & synchrotron emission are fundamental in determining B

For synchrotron emission $T_B < 10^{12}$ K (otherwise Compton catastrophe!)

If higher T is observed (in a stellar atmosphere), then a **coherent radiation mechanism** should be considered. Two mechanisms have received most attention:

- **Plasma radiation** is a useful tool to approximately determine the electron density in the source. It can account for high brightness T (up to 10^{18} K), frequently observed in the Sun.
<http://adsabs.harvard.edu/full/1964NASSP..50..3770> (Oster & Altschuler 1964)
- Spectral profile similar to that of a broad spectral line, produced by coronal electrons excited by particle stream (which may induce variable B fields!)
- A second harmonic commonly exists
- Radiating electrons are not in thermal equilibrium with the undisturbed corona
- **Emitted radiation is that of bremsstrahlung by an ensemble of "coherent" particles.**
- **Electron cyclotron maser emission** can be used to determine **B** in the source. It accounts for the observed high T and polarization degrees up to 100%.