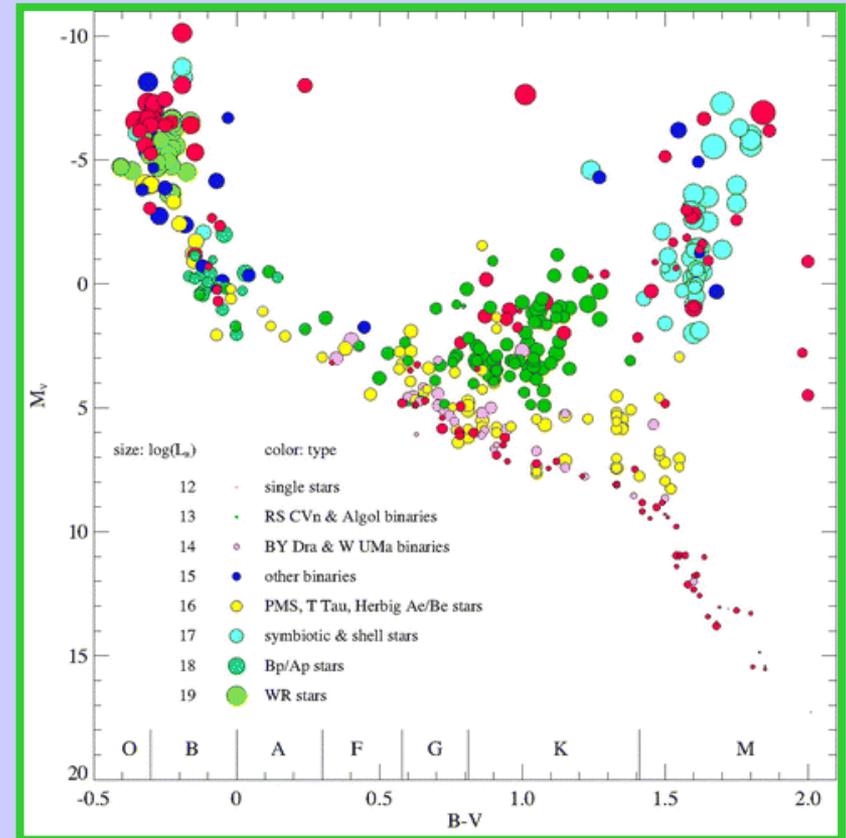


Radio emission from stars

(Guedel, Annual Rev.Astro. Astrophys, 2002, 40, 217)

- Almost all the usual features of an HDR are recovered, testifying the importance and the ubiquity of radio emissions. (The location of some stars on the HDR is compromised by the limited quality of distance and color measurements, or in multiple systems by the uncertain attribution of the radio emission to one of the components.)
- Common to most cool star radio emitters is their nonthermal nature, which especially in its quiescent form, constitutes one of the most significant discoveries in stellar radio astronomy, suggesting the presence of magnetic fields and high-energy electrons.
- Moving toward A-type stars a dearth of radio detections owing to the absence of magnetic dynamo action is found. This is the region of chemically peculiar Ap/Bp stars that possess strong magnetic fields and of pre-main sequence Herbig Ae-Be
- The hot-star region is heavily populated by luminous O,B and Wolf-Rayet stars showing evidence of either thermal or nonthermal radio emission.



Hertzsprung-Russell diagram (HRD) showing 440 radio-selected stars detected between at 1 and 10 GHz.

Theory of radio emission from stellar atmospheres (1)

- **Bremsstrahlung:** a thermal plasma emits free-free emission across the electromagnetic spectrum. Optically thick bremsstrahlung shows a ν^2 dependence, whereas optically thin flux is nearly independent of ν . A homogeneous optically thin magnetized source is polarized, whereas an optically thick source is unpolarized.
- **Gyromagnetic emission:** electrons in **B**. The gyrofrequency is:

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

and $\nu_{c,rel} = \nu_c / \gamma$

Three categories of gyromagnetic emission:

Cyclotron emission ($\gamma \sim 1$) nonrelativistic, typically thermal electrons

Gyrosynchrotron ($\gamma \leq 2-3$) mildly relativistic electrons

Synchrotron emission ($\gamma \gg 1$) relativistic electrons

Because the relativistic effects play an increasingly important role, the fundamental properties (directivity, bandwidth, polarization) change between the three categories.

Theory of radio emission from stellar atmospheres (2)

The brightness T of synchrotron emission is limited to $T_b \leq 10^{12} K$ by inverse Compton scattering. If higher T is observed, then a **coherent radiation mechanism** should be considered. Two mechanisms have received most attention:

- **Plasma radiation** is a useful means 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.
- **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%.

Radio Flares from cool stars

Incoherent Flares:

- Time scales of minutes to hours, broad-band spectra, and moderate degrees of polarization are thought to be the stellar equivalents of solar microwave bursts. They show evidence for the presence of mildly relativistic electrons radiating gyrosynchrotron emission in magnetic fields.
- Many flares of this type are observed in F/G/K stars, in M dwarfs above 5GHz, in contact binaries and in other active subgiants and giants.

Coherent Radio bursts:

- Probably represent stellar equivalent of metric and decimetric solar bursts.
- Observed in M stars, in RS CVn binaries.
- Carry important information: radio spike of 5-20ms implies source size of $r < c\Delta t \approx 1500 - 6000 km$ and brightness $T \sim 10^{16} K$, a clear proof of the presence of a coherent mechanism.
- If the elementary frequencies relevant for coherent processes, $\nu_c - \nu_p$ evolve in the source, or the radiating source itself travels across density or \mathbf{B} gradients, the emission leaves characteristic traces on the frequency-time plane, i.e., on dynamic spectra.

$$\nu_c = \frac{eB}{2\pi m_e c} \approx 2.8 \cdot 10^6 B [Hz]$$

Girofrequency

$$\nu_p = \left(\frac{n_e e^2}{\pi m_e} \right)^{1/2} \approx 9000 n_e^{1/2} [Hz]$$

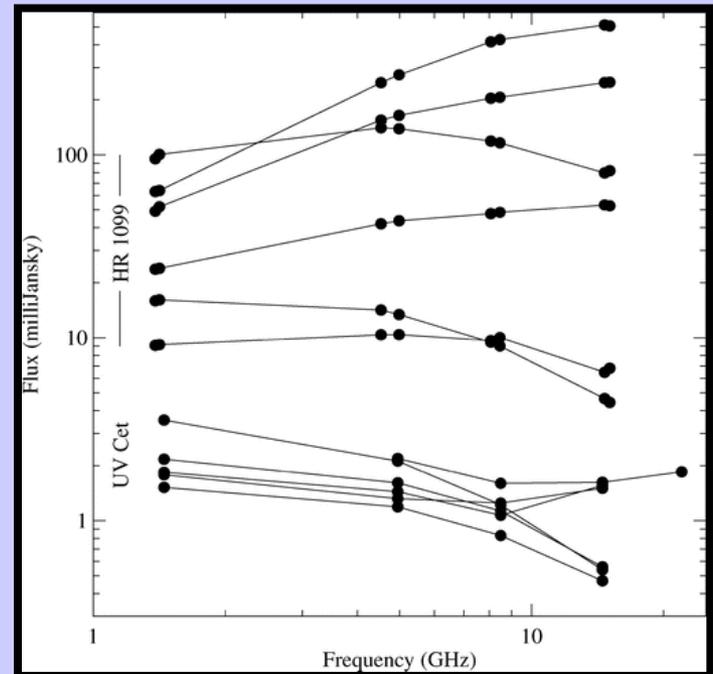
Plasma frequency

Cool Stars: quiescent emission from coronae

- **Phenomenology:** the discovery of quiescent radio emission from magnetically active stars was one of the fundamental and the least anticipated achievements in radio astronomy of cool stars because there simply no solar counterpart. The Sun emits steady, full-disk, optically thick thermal radio emission at chromospheric and transition region levels of a few 10^4 K. Such emission cannot be detected with present-day facilities, except for radiation from the very nearest star. Quiescent emission is defined by the absence of impulsive, rapidly variable flare-like events: slow variations on time scales of hours and days; low polarization degrees; brightness temperatures is in excess of coronal temperatures measured in X-ray.

Cool Stars: quiescent emission from coronae

• **Model:** non thermal energy distribution (such as a power law with indices of $\delta \sim 2-4$) of mildly relativistic electrons in $\sim 100G$. Good match with the observed broad spectra with turnover frequencies in the range 1-10GHz (see figure).



Radio spectra of the RS CVn binary HR 1099 (*upper set*) and the dMe dwarf UV Cet (*lower set*) at different flux levels. The gently bent spectra are indicative of gyrosynchrotron emission, and the high-frequency part of the U-shaped spectra for UV Cet has been interpreted as a gyroresonance component.

Radio flares and coronal heating

The question of the nature of stellar **quiescent radio emission** has defined one of the most fascinating aspects of stellar radio astronomy: it could be the sum of unresolved flares.

- VLBI observations of RS CVn suggest that flare cores progressively expand into a large-scale magnetosphere around the star, radiating for several days.
- The electron distributions evolve from initial power-law distributions as they are subject to collisional losses affecting the low-energy e and to synchrotron losses affecting the high-energy e .

The correlation between quiescent radio and X emission (1)

Radio detections are preferentially made among X-ray brightest stars. For binary systems (Algol, RS CVn) one finds a correlation :

$$L_R \propto L_X^{1.0-1.3}$$

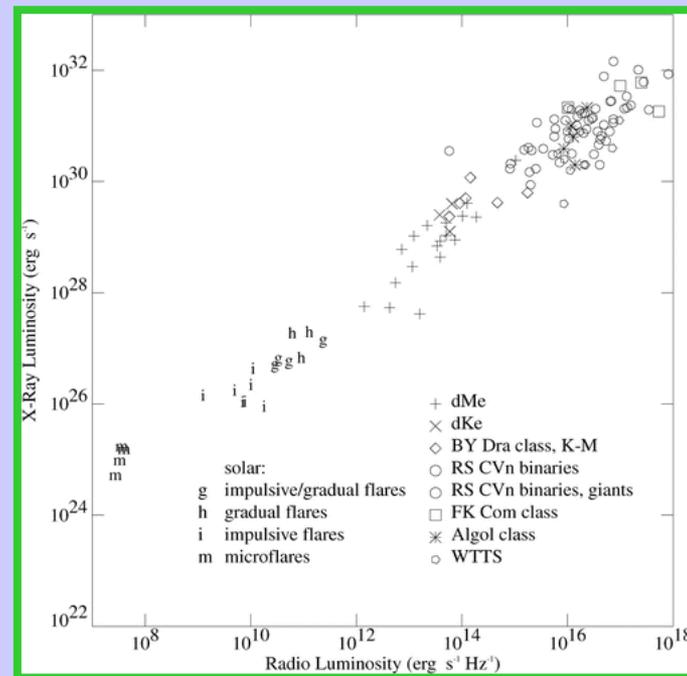
Similar relation for several classes of active stars and solar flares. Overall, for 5-8 GHz emission (see figure):

$$L_X / L_R \approx 10^{15 \pm 1} [Hz]$$

The relation suggest that both radio and X-ray emissions are actively indicators that reflect the level of magnetic activity. A simple model that assumes that the hot plasma emits both thermal X-ray and nonthermal gyrosynchrotron radiation predict steep optically thin spectra, not observed.

For example Chiuderi+1993 argued that the build-up of magnetic energy in magnetic loops is proportional to B^2 and to the gradient of the turbulent velocity (assumed similar in all stars). Because most of the energy in B is eventually radiated away in X-ray (V volume of the source):

$$L_X \propto B^2 V$$



Per $\Delta=3$ si ottiene un valore compatibile con quello osservato:

$$L_R \propto L_X^{1.24}$$

The correlation between quiescent radio and X emission (2)

A power-law electron population in the same loop emits optically thin radio radiation

as: $L_R \propto B^{-0.22+0.9\delta} V$ for a given frequency

Therefore: $L_R \propto L_X^{0.45\delta-0.11} V^{1.11-0.45\delta}$ V source volume

For $\delta = 3$ the dependence on V is small and close to the reported relations.

Stellar Magnetic Fields

(some results, see ref. in Guedel 2002)

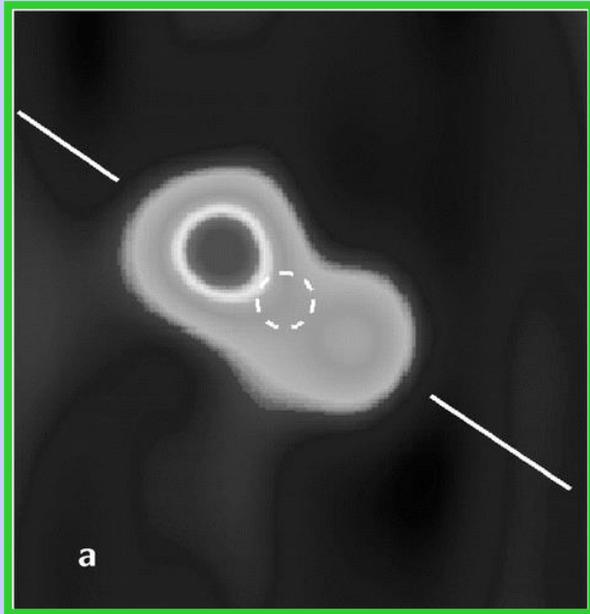
- $B \sim 250-500$ G estimated from the electron cyclotron maser emission
- $B \sim 600-2070$ G estimated in active regions from coronal gyroresonance emission
- $B \sim 10-200$ G estimated from VLBI measurements of large coronal sizes
- $B \sim 5$ and several tens of G for RS CVn halo sources, from a few tens to several hundreds G for the cores

The synchrotron turnover peak frequency determines B as: $B = 2.9 \cdot 10^{13} \nu_{peak}^5 \theta^4 S^{-2}$

where theta is the source diameter (in arcsec) and S the flux density (in mJy at peak frequency).

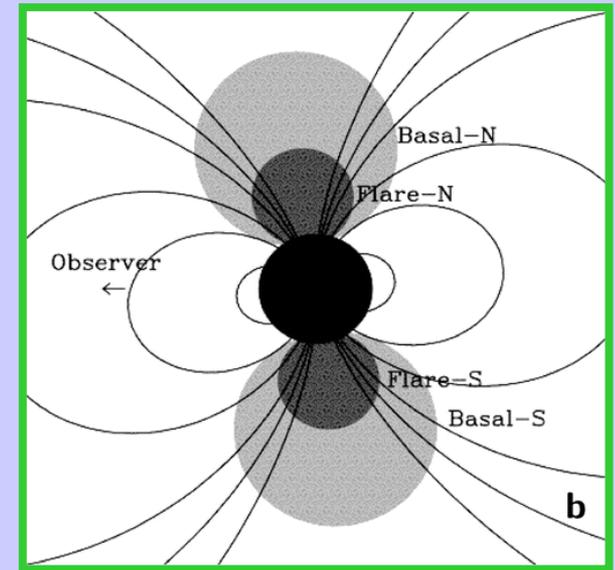
- For a typical RS CVn with size of ~ 1 mas (VLBI), a turnover at ~ 5 GHz and a flux density of ~ 10 mJy B are up to a few hundred G

Radio Coronal Structure: VLBI



VLBI provides coronal mapping at <1 mas angular resolution.

VLBA image of the **dMe star UV Cet**; the two giant radio lobes have sizes up to 2.4×10^{10} cm and a separation of 4-5 stellar radii along the putative rotation axis of the star, suggesting very extended magnetic structures above the magnetic poles. The straight line shows the orientation of the putative rotation axis, assumed to be parallel to the axis of the orbit of UV Cet around the nearby Gl 65 A. The small circle gives the photospheric diameter to size, although the precise position is unknown (after **Benz et al. 1998**).

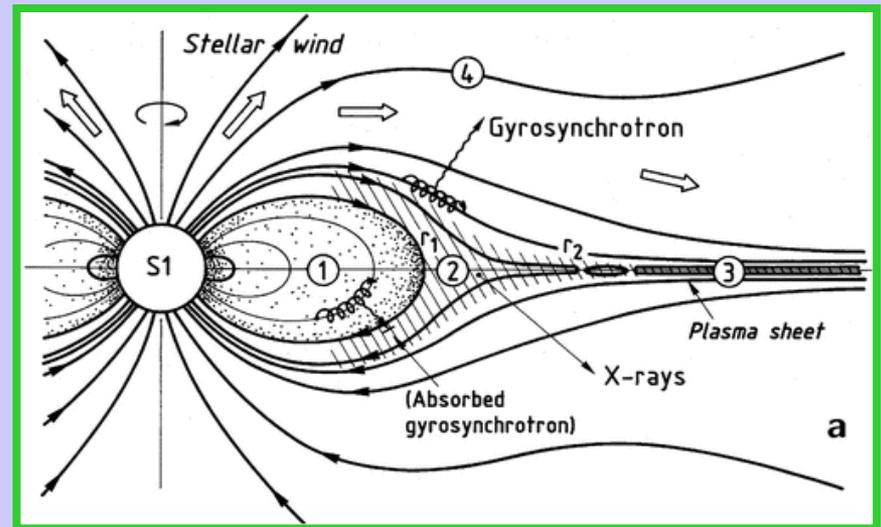


Sketch for radio emission from a global dipole consistent with the VLBI observation (**Mutel et al. 1998**)

The radio structure of RS CVn e Algol-like binaries is composed by a compact core plus extended halo radio structure of a total size similar to the binary system size.

Magnetospheric models

Geometric models of large magnetospheres around RS CVn and Algol binaries, T Tau stars and magnetic Bp/Ap stars have been designed based on VLBI results, radio spectra and polarization. Common to all is a global, dipole-like structure (Van Allen belts).



Equatorial model for the magnetosphere of the young B star S1 in ρ Oph

Activity Cycles

- Long-term measurements indicate the presence of activity cycles (similar to the solar 11-year cycle) with duration of several years in low-activity stars, but irregular long-term variations on active stars.
- One would expect reversals of the magnetic polarity. After decades of monitoring, many active stars show a constant sign of radio polarization (in quiescent and during flares). This suggests the presence of some stable magnetospheric structures or a predominance of strong magnetic fields in one polarity.

Lower Atmospheres of Cool Stars

Stellar transition regions and chromospheres are expected to be radio sources.

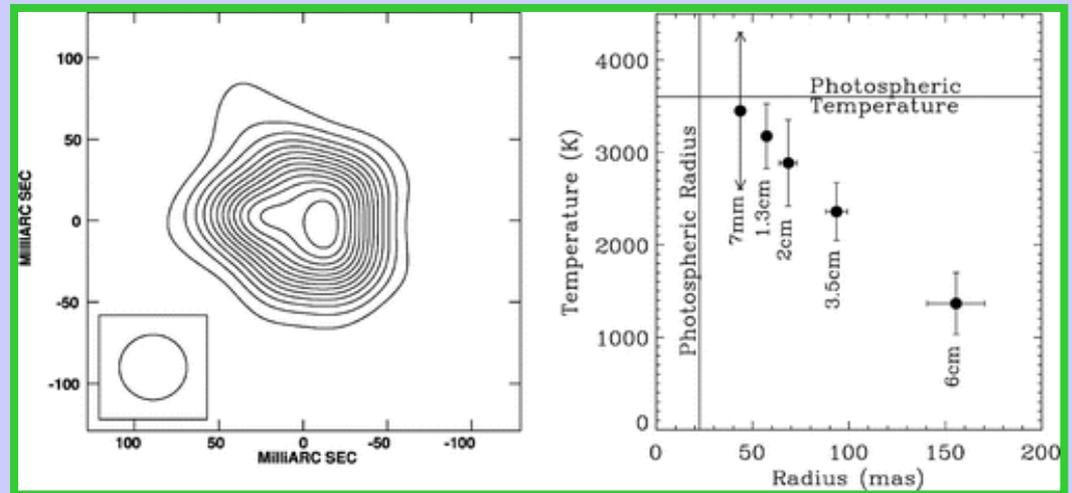
T derived from radio measurements drops systematically from the optical-photospheric levels outward.

Cool material completely dominates the outer atmosphere.

(a) Betelgeuse observed at 43 GHz. The radio photosphere of this star is resolved, with an angular resolution of 40 mas.

(b) The atmospheric temperature of Betelgeuse as a function of radius, observed at different frequencies.

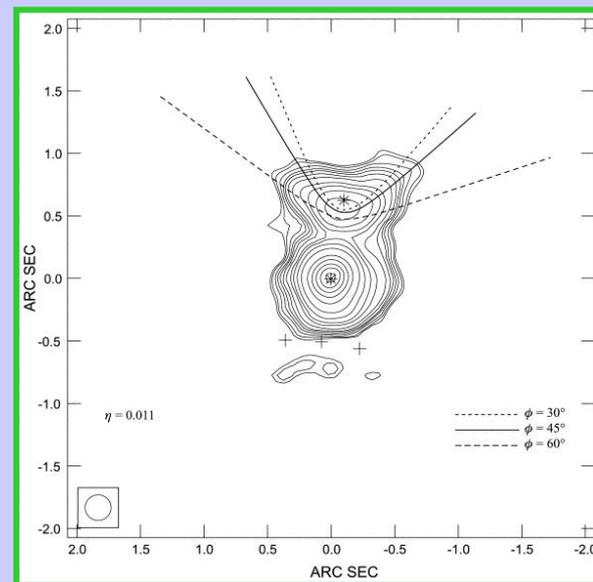
(From Lim et al. 1998)



Radio Emission from Hot Stars

Up to 50% of the WR stars appears to be nonthermal sources, also for OB stars. Hot stars are not thought to produce magnetic fields via a dynamo. Moreover, because the wind is optically thick to radio emission out to hundreds of stellar radii, the nonthermal component must originate at such large distances as well. The colliding-wind model found strong support when it became evident that most nonthermal sources are indeed binaries and the nonthermal sources are located between the two stars.

VLA map of the WR 147 system observed at 3.6 cm. Also shown are calculated model curves that follow the shock formed by the two-wind interaction (Contreras & Rodriguez 1999)

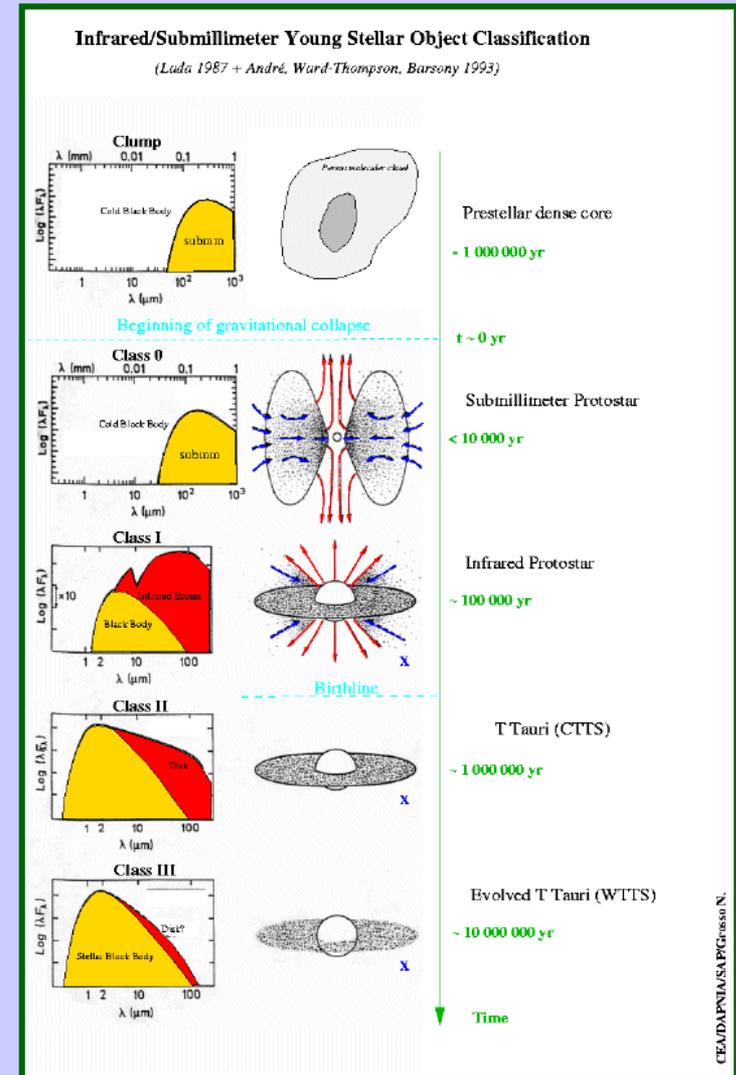


Radio Emission from Low-Mass Young Stellar Objects (1)

Large numbers of visible T Tau stars and embedded infrared sources in star-forming regions are strong radio sources.

- **Class 0:** cold condensation of infalling molecular matter, forming a hydrostatic low-luminosity protostellar object, with the bulk mass still accreting.
- **Class I:** formation of a deeply embedded protostar
- **Class II:** the classical T Tau phase with an optically visible star accompanied by a thick, a weak outflow, and a possibly a a weakly ionized wind
- **Class III:** disk and circumstellar material have largely been dissipated and the star approaches the main sequence.

The evolutionary sequence is somewhat controversial and may in fact describe the evolutionary phase of the circumstellar material rather than of the star itself.



Stages of pre-main sequence evolution.

Radio Emission from Low-Mass Young Stellar Objects (2)

- **Class I sources:** often detected as thermal sources. This emission is predominantly due to collimated thermal winds or jets. These jets are probably ionized by neutral winds that collide with the ambient medium at distances at $\sim 10\text{AU}$ and are aligned with molecular outflows. However the discovery of polarization and variability provided definite evidence for magnetic fields and particle acceleration.
- **Class 0 sources:** centimetric thermal radio detections probably again related to jet/collimated winds that drive massive outflows, whereas the bulk of the emitted power leaves the system at mm/submm wavelengths from cold ($<20\text{K}$) dust. Radio emission is a sensitive tracer for the presence of an embedded, nascent but already formed protostellar core.

Radio Emission from Low-Mass Young Stellar Objects (3)

- Radio emission provides a reliable method for the detection of low luminosity YSOs and in particular for detecting the earliest stages of protostellar evolution where the source may still be embedded in its natal dust envelope.
- The dominant mechanism giving rise to continuum radio emission from class 0 and I objects is **thermal bremsstrahlung** (free-free emission), i.e. electrons accelerated by encountering another charged particle. **The radio free-free emission is expected to manifest from any environment populated by an ionized plasma.**
- Although the physics behind the ionization around high-mass stars are reasonably well understood as arising from photoionization due to the strong UV flux from such objects, **in the low-mass case a number of mechanisms have been proposed to produce the ionization responsible for the observed free-free emission.**

Magnetic field in stellar evolution(1)

Maeder et al. 2009, proceedings IAU Symposium No. 259

B and rotation strongly influence the course of evolution and all model outputs.

•Collapse and ambipolar diffusion:

B may contribute to cloud support. For contraction to occur it is necessary that the energy density of **B** < than the density of gravitational energy

$$\frac{B^2}{8\pi} < \frac{3}{5} \frac{GM^2}{R \left(\frac{4}{3} \pi R^3 \right)}$$

This defines a critical mass M_B above which gravitation dominates

$$M_B \approx \left(\frac{5}{18\pi^2} \right)^{1/2} \frac{\Phi}{\sqrt{G}} = 0.17 \frac{\Phi}{\sqrt{G}}$$

$$\Phi = \pi B R^2 \quad \text{magnetic flux}$$

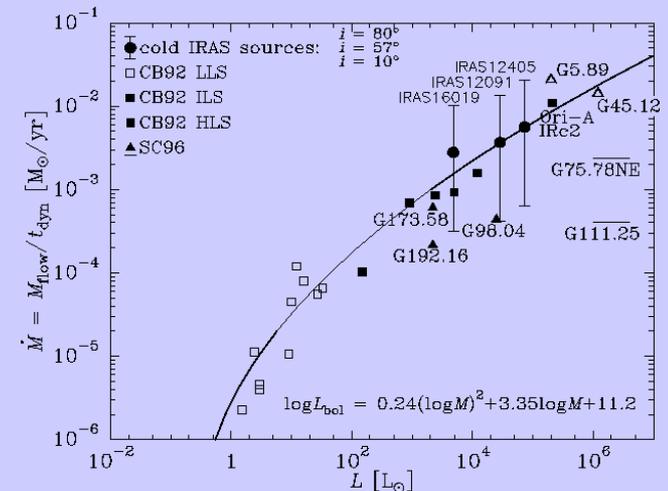
If $M > M_B$ large clusters or associations form; if $M < M_B$ no contraction occurs until the small ionized fraction ($\sim 10^{-7}$) to which the field is attached has diffused (in $\sim 10^7$ yr) out from the essentially neutral gas forming the cloud.

Magnetic field in stellar evolution(2)

•Bipolar Outflows:

Massive molecular outflows are often detected in region of star formation. A large fraction of the infalling material is not accreted by the central object but is ejected in the polar directions. In the massive stars, the ejection cones are relatively broad.

Mass outflow rates correlate with the luminosities of the central source over 6 decades in luminosity, from 1 to 10^6 solar luminosity.



Mass outflow rate vs. bolometric luminosity of the central source. The solid line represents the second-order polynomial fit to the data. LLS means low-luminous sources, ILS are intermediate-luminous sources, and HLS labels high-luminous sources (spectral type: mid-B to O). Adapted from Shepherd & Churchwell (1996b).

Magnetic field in stellar evolution(3)

- Disk locking:

From the dense molecular cloud to the present Sun, the specific angular momentum decreases by $\sim 10^6$. Among the processes reducing angular momentum in stars, disk locking is a major one. Fields of ~ 1 kG are sufficient for the coupling between the star and a large accretion disk. The contracting star is bound to its disk and it keeps the same angular velocity during contraction, losing a lot of angular momentum. The typical disk lifetime is a few 10^6 yr.

- Convective dynamos and magnetic braking:

Solar type stars have external convective zones which produce a dynamo. The resulting \mathbf{B} creates a strong coupling between the stars and the solar wind, which leads to losses of angular momentum.

Magnetic field in stellar evolution(4)

- **Dynamo in radiative zones:**

Is there a dynamo working in internal radiative zones?

This is the biggest question concerning magnetic field and stellar evolution.

- **Magnetic field in AGB stars, planetary nebulae and final stages:**

Red giants, AGB stars and supergiants have convective envelopes and thus dynamos. Evidence of **B** up to kG in some central stars of planetary nebulae are given, they contribute to shaping the nebulae. White dwarfs have magnetic fields from $\sim 10^4$ up to $\sim 10^9$ G.

Dynamos

- A magnetic field has great consequences on the evolution of rotation velocity by exerting an efficient torque able to impose a nearly uniform rotation. This influences all the model outputs (lifetimes, chemical abundances, supernovae types) as well as the rotation in final stages, white dwarfs, neutron stars or black holes.
- Biermann mechanism, proposed in 1950, is an efficient spontaneous process to generate large-scale **B** in stars and nebular clouds. The process leads to a distinctive magnetic-field geometry in a differentially-rotating star, namely a double toroidal field, the fields being oppositely circulating in the upper and lower hemispheres (Kemp 1982).

