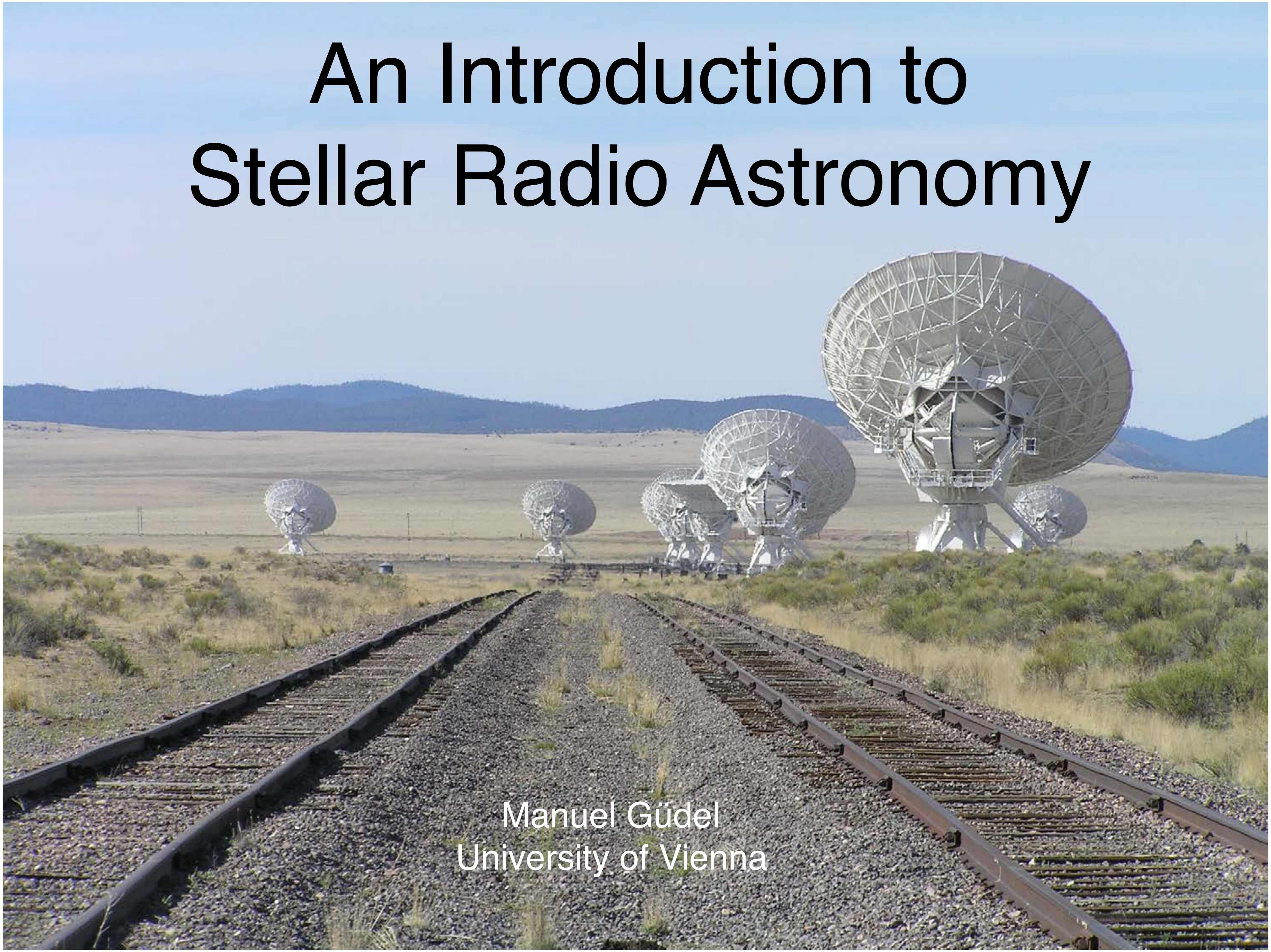
An Introduction to Stellar Radio Astronomy



Manuel Güdel
University of Vienna

Outline

1. Thermal bremsstrahlung
- stellar photospheres

2a. Gyromagnetic emission
2b. Coherent radiation in plasma

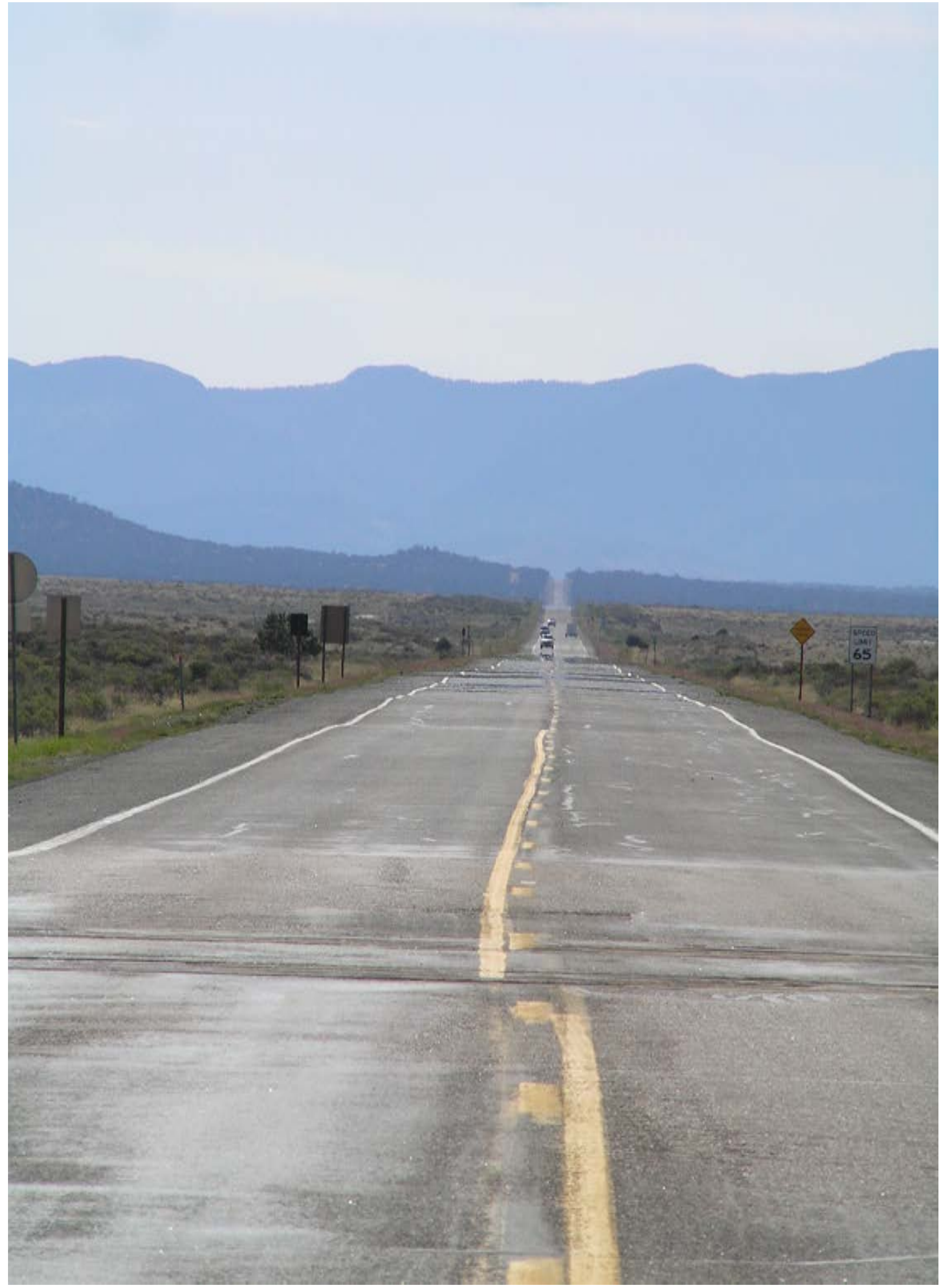
- stellar coronae
- flares
- brown dwarfs

3a. Thermal winds and
3b. radio lines (RR, masers)

- hot stellar winds
- colliding winds+
- cool winds+ & mass loss
- outflows & jets+
- circumstellar disks+
- masers+

4. Prospects

5. Conclusions

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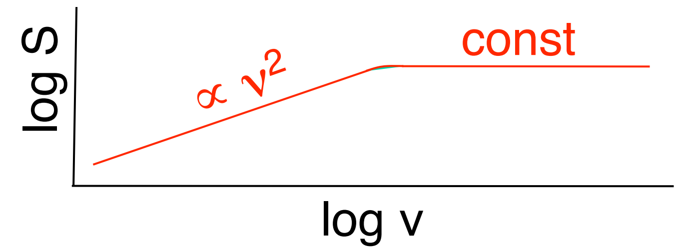
From Rayleigh-Jeans approximation:

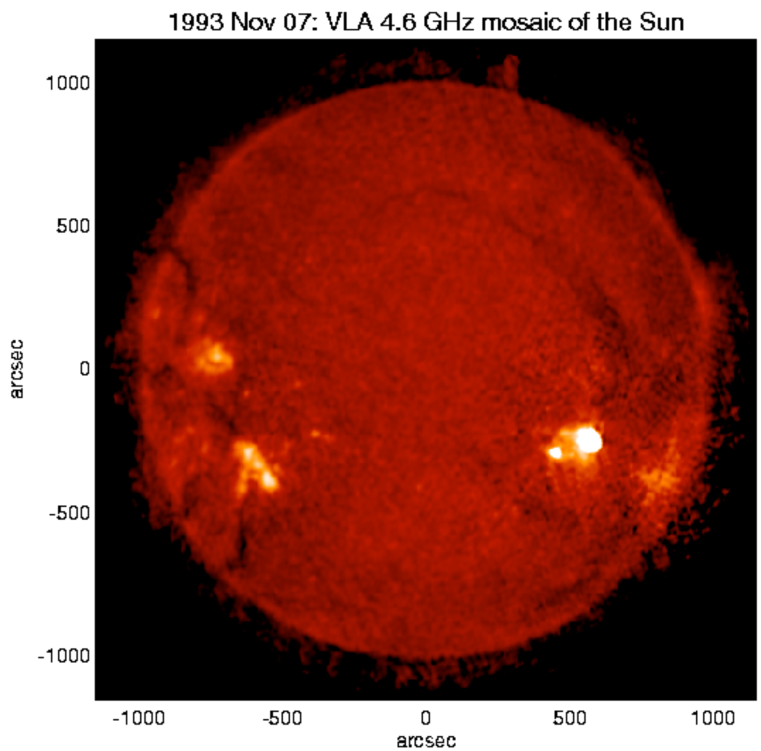
$$S_\nu = \frac{2kT_{\rm eff}\nu^2}{c^2}\frac{\pi R^2}{d^2}$$ opt. thick

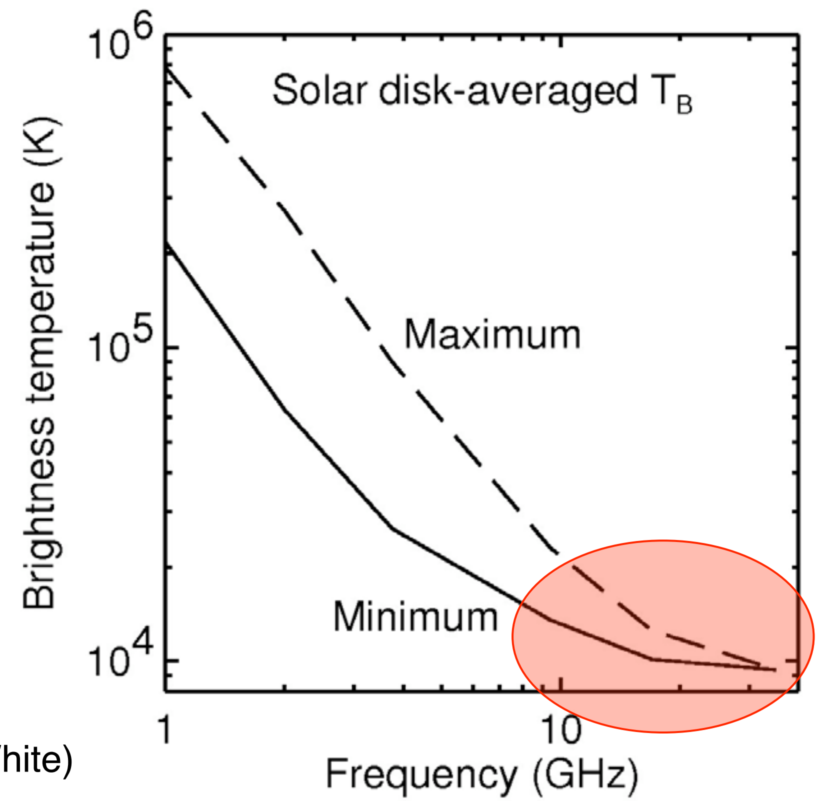
$$S_\nu = \frac{2kT_{\rm eff}\tau(\nu)\nu^2}{c^2}\frac{\pi R^2}{d^2}$$ opt. thin

Thermal (free-free) Bremsstrahlung

$$\tau = \int \kappa \mathrm{d}l \approx \frac{0.16}{\nu^2 T^{3/2}} \int n^2 \mathrm{d}l$$

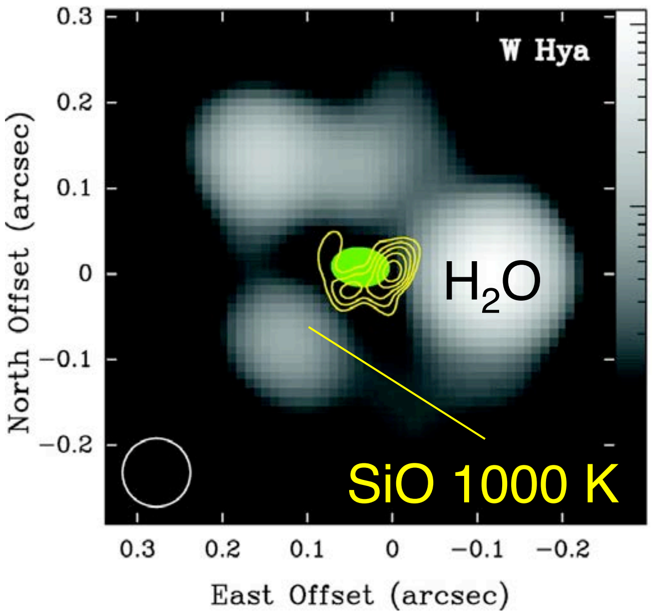


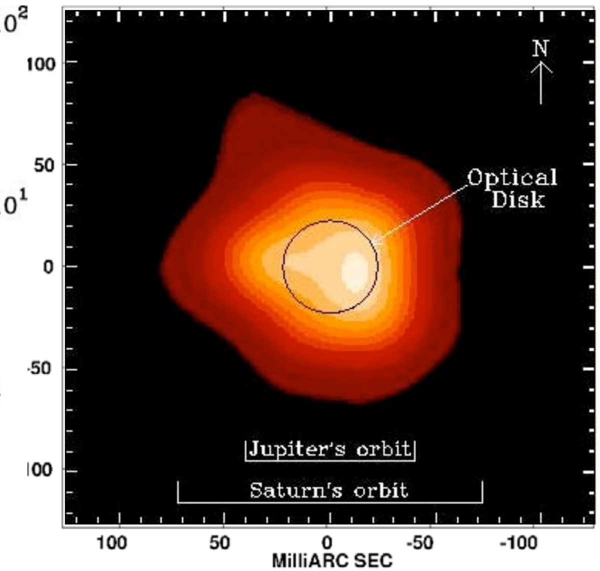


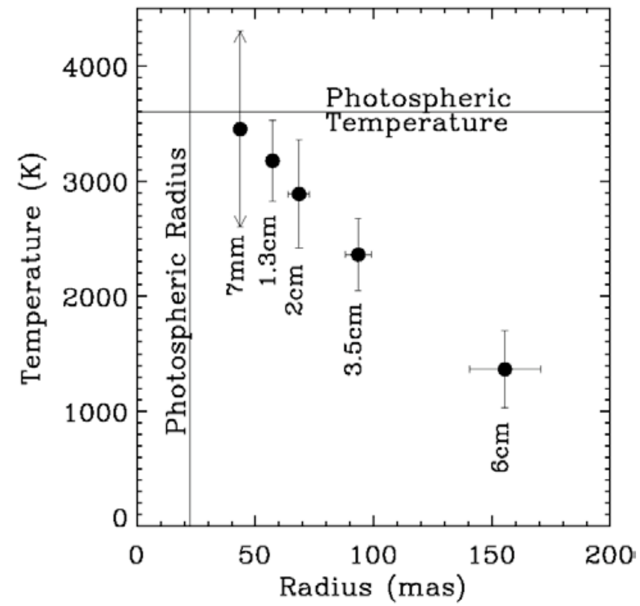


(S.M. White)

Stellar Photospheres/Chromospheres and their Surroundings







(Reid & Menten 1997, 2007)

(Lim et al. 1998)

W Hya: 43 GHz photosphere
+ 1.563 GHz SiO maser
+ 22 GHz H_2O maser:

photosphere 1600 K, 10^{12} cm^{-3}
SiO maser: 1000 K, $<10^{10}$ cm^{-3}

Betelgeuse: Spatially resolved radio photosphere ("opt. thick"): temperature decreases with radius (dominates chromospheric gas)

Dust formation driving an outflow?

Magnetic Fields, High Energy: Gyrosynchrotron and Synchrotron

1. <u>Ultrahot electrons</u> ($> 10^8$ K) →

   mildly relativistic effects,

   high harmonics s = 10-100

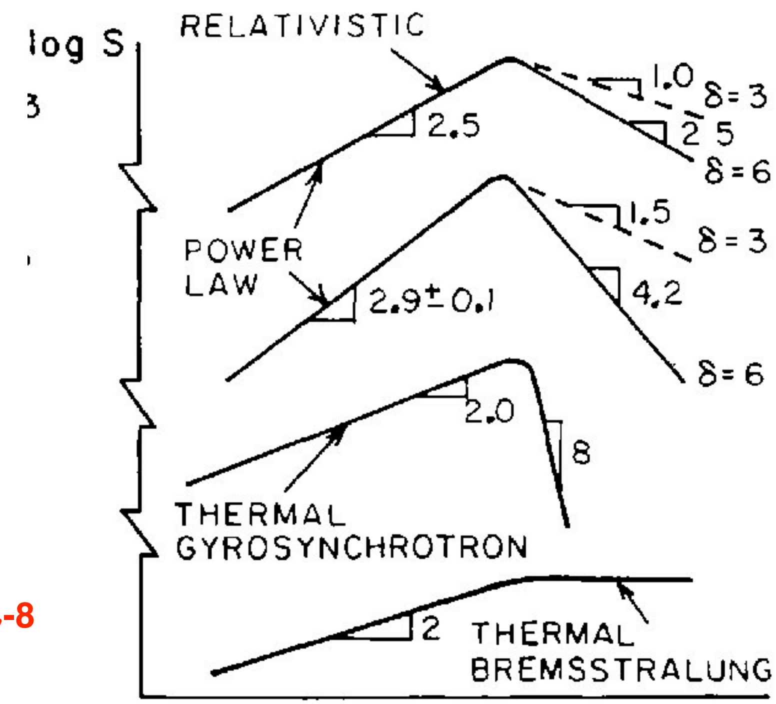
   Maxwellian → spectrum drops like ν^{-8}

or

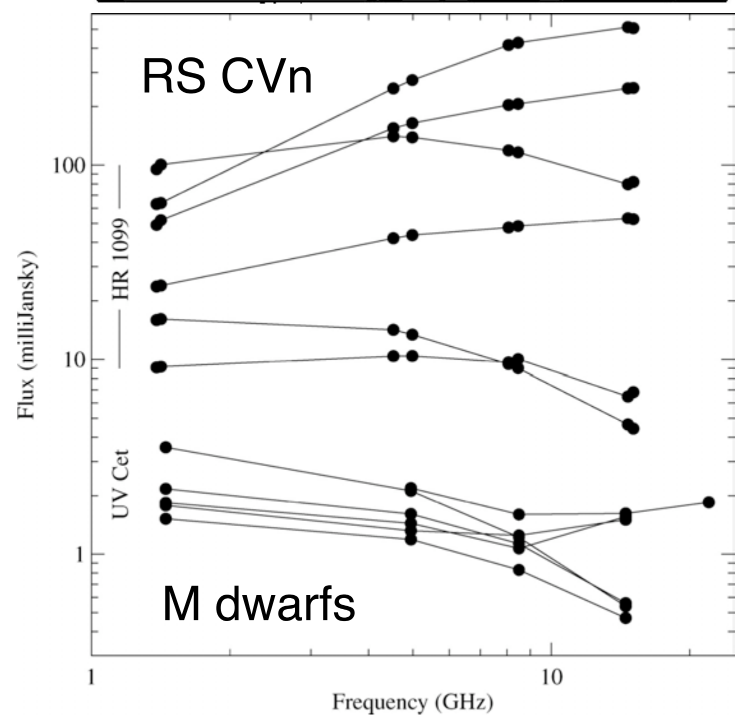
2. <u>Non-thermal, accelerated electrons</u>

$$n(\gamma) = K(\gamma - 1)^{-\delta}$$

stellar *coronal* gyrosynchrotron spectra are mostly non-thermal, like solar flares!

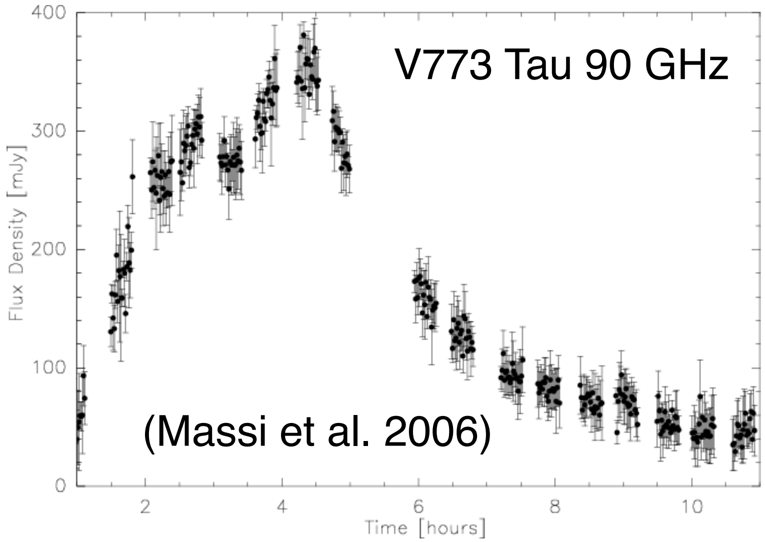


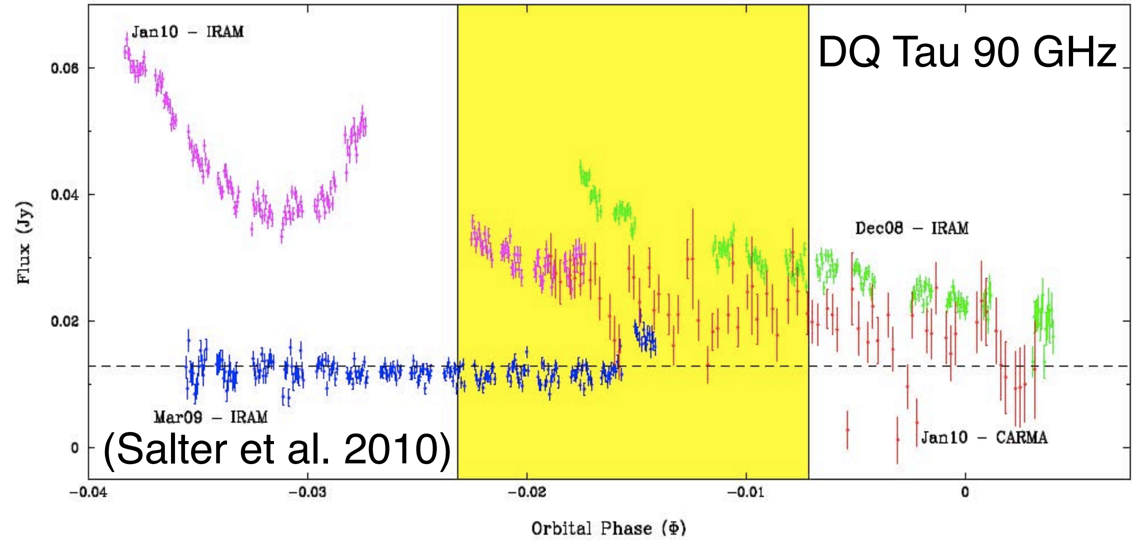
(Dulk & Marsh 1982)



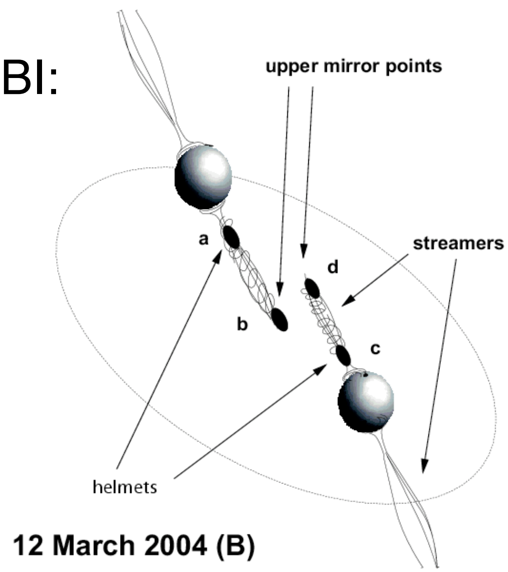
(Güdel 2002)

Millimeter Flares: Evidence for the Highest-Energy Electrons

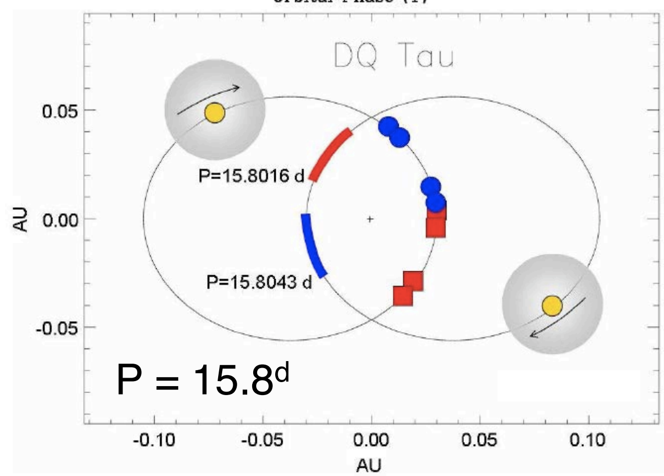




from VLBI:



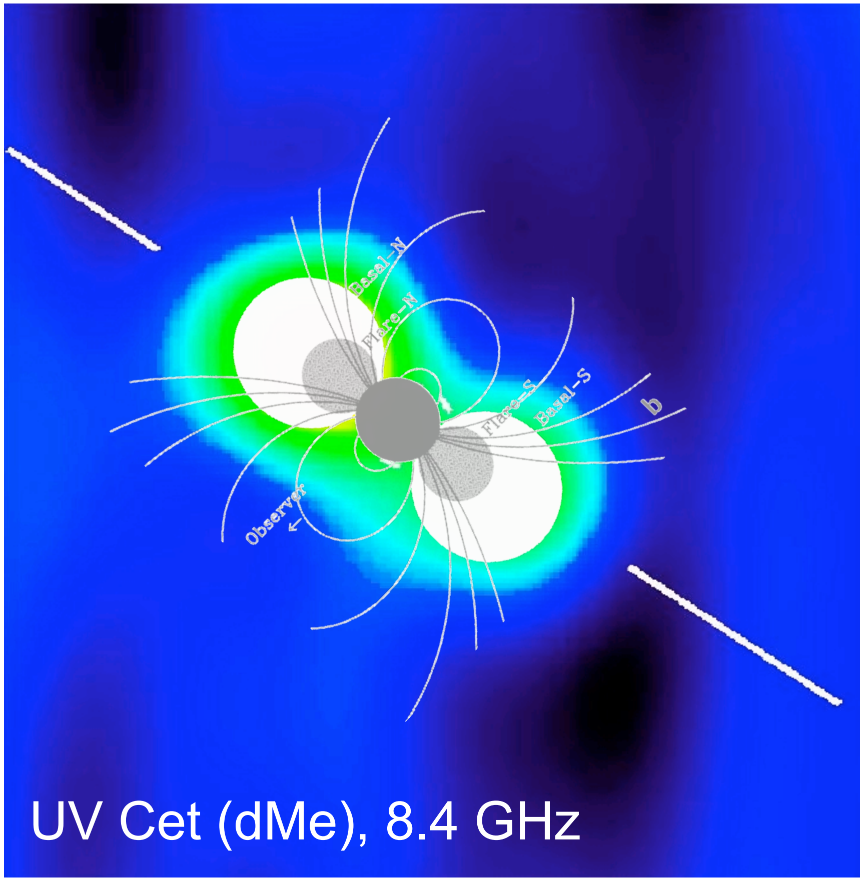
(Massi et al. 2008)

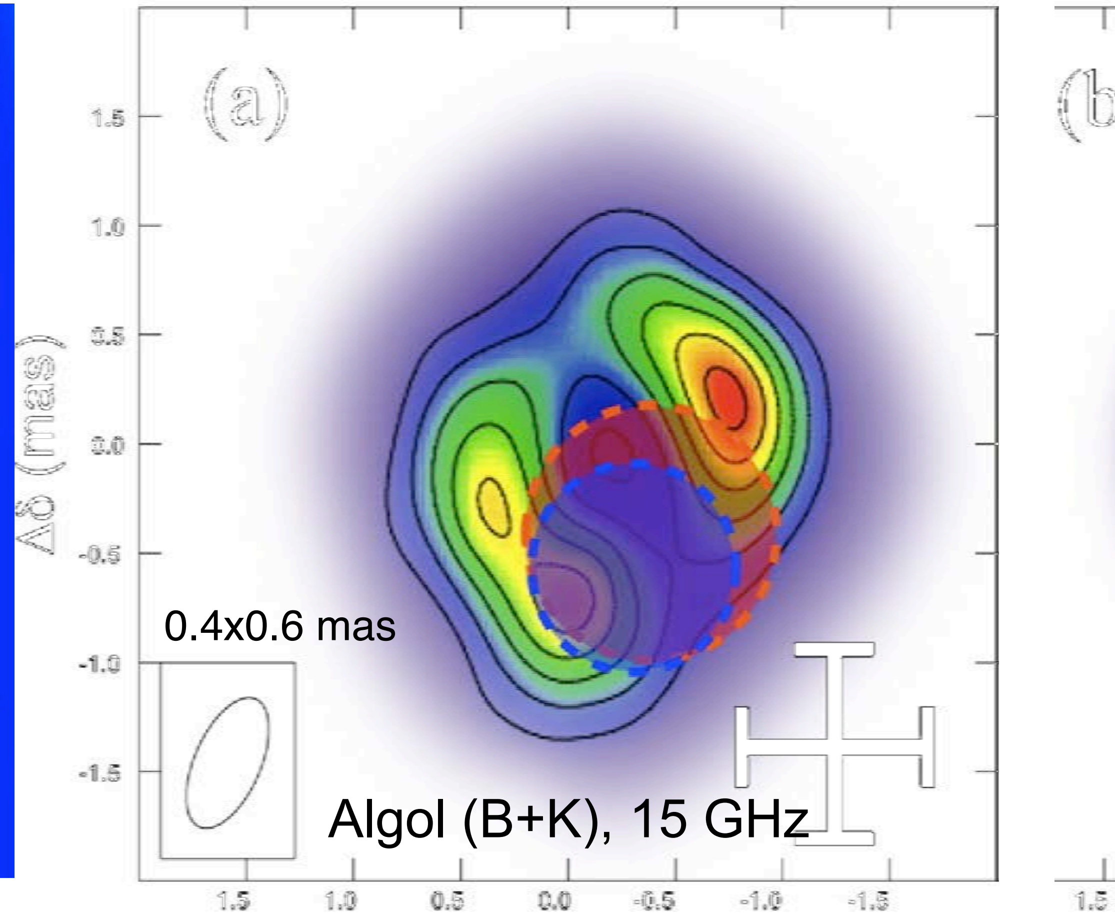


Evidence for large γ > 100 (synchrotron)

periodically interacting "coronal streamers" and magnetospheres with reconnection?

Imaging Stellar Magnetospheres with VLBI





$L_R \approx 2\text{x}10^{13}$ erg/s/Hz

$T_B \approx 10^8$-10^9 K

trapped electrons in 10-100 G field

(Benz et al. 1998)

$L_R \approx 4\text{x}10^{17}$ erg/s/Hz

trapped electrons in coronal loops

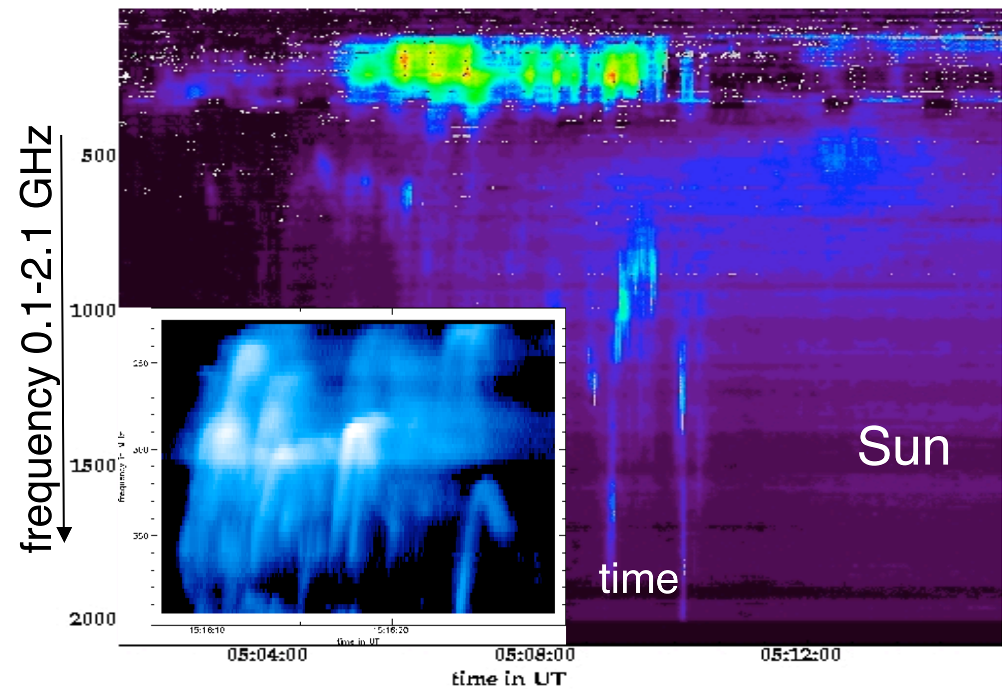
(Petterson et al. 2010)

Coherent Radio Emission in Dynamic Radio Spectra

Plasma radiation at
ν_p or $2\nu_p$: *measures n_e*

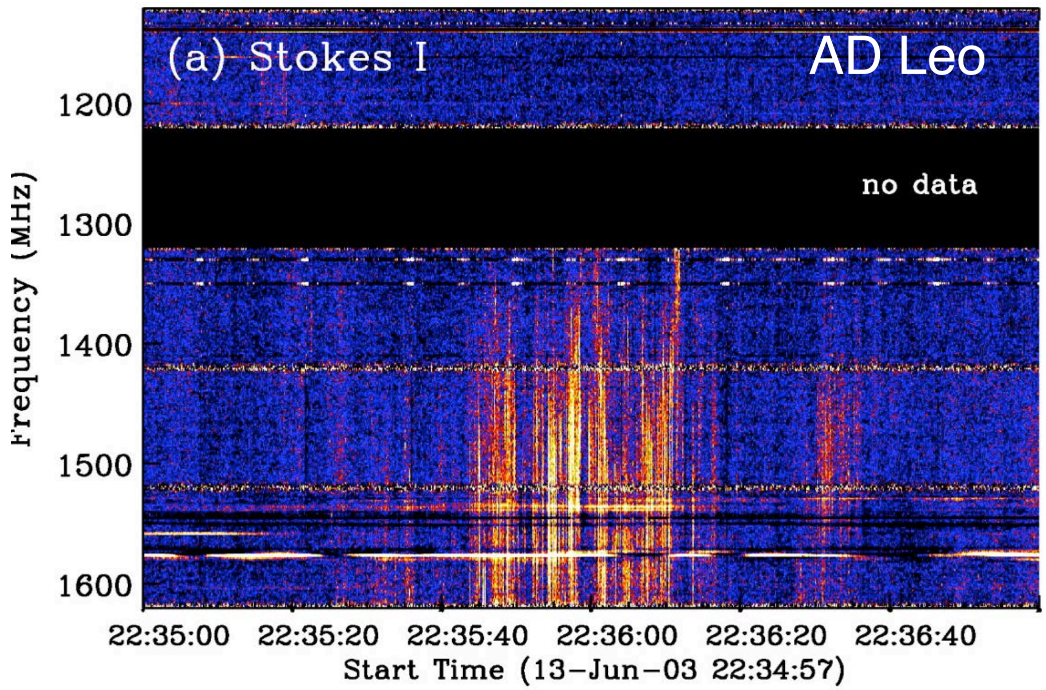
Electron cyclotron maser at
ν_c or $2\nu_c$: *measures **B***

$I(\nu,t) \rightarrow$ trace in n_e or B



AD Leo:
20 ms bursts (source <9000 km)
>90% polarization
narrow bandwidth (5%)
fast drifts

opacity in hot gas → plasma em.

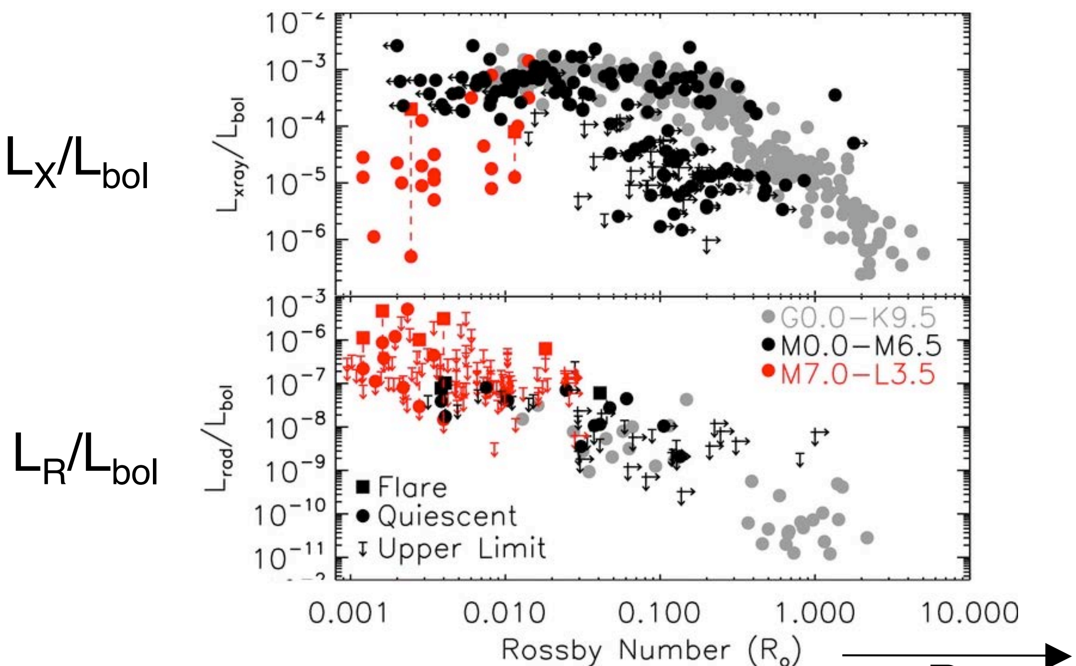


(Osten & Bastian 2006)

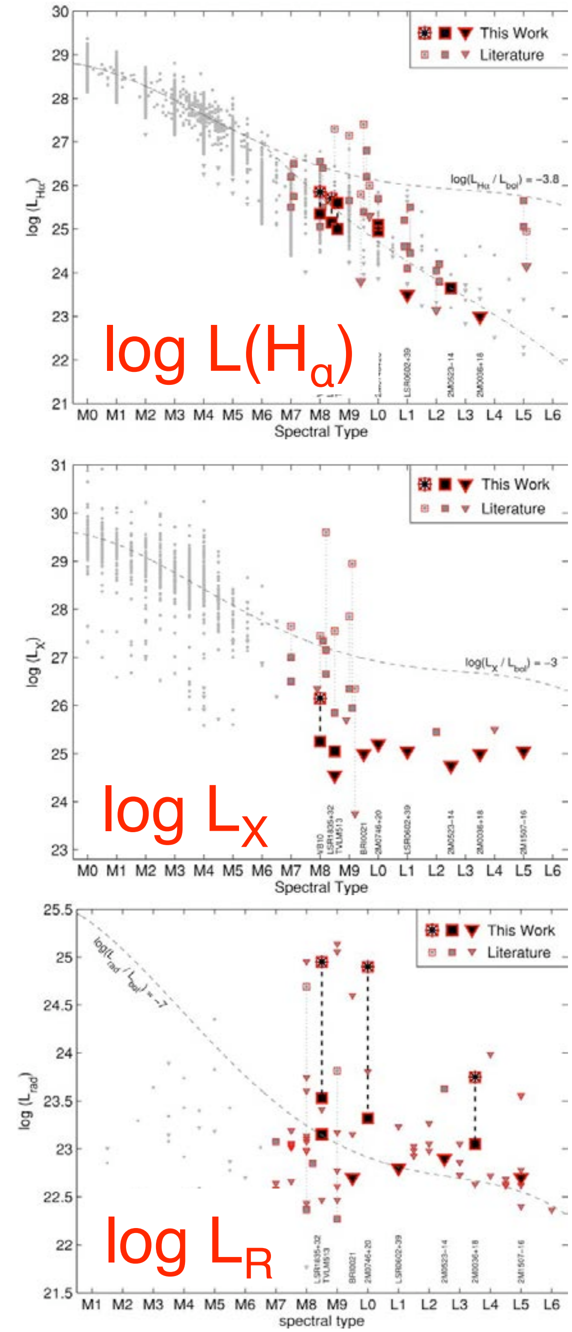
Particle Accceleration in Brown Dwarfs

Hα, X: Increasing photospheric neutrality in cool photospheres No build-up of non-potential fields?

Not true for radio emission!
Particle acceleration remains prominent...
and rotation matters (dynamo)!

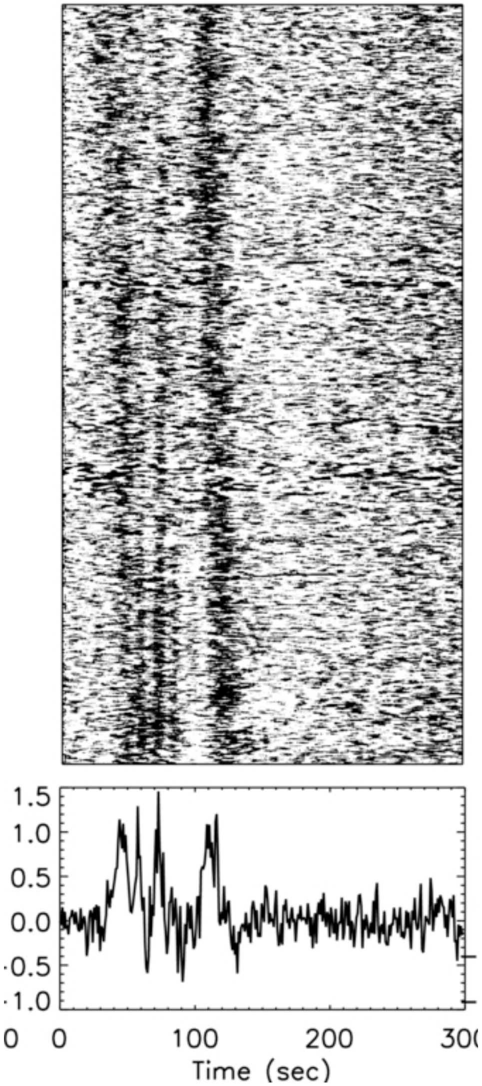


(McLean et al. 2012)

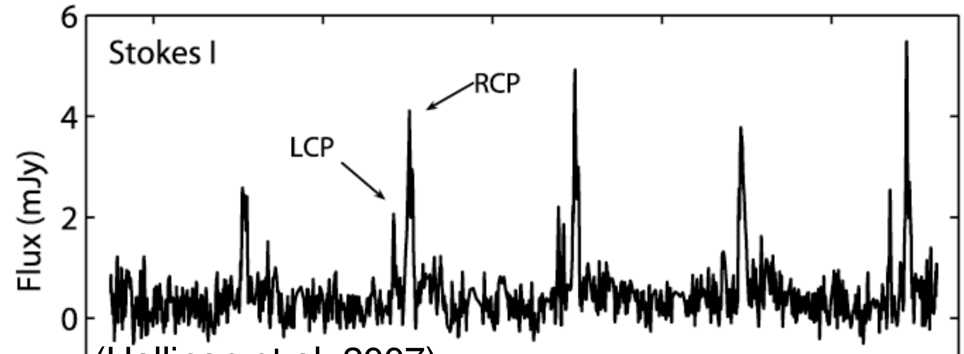


(Berger+ 2010)

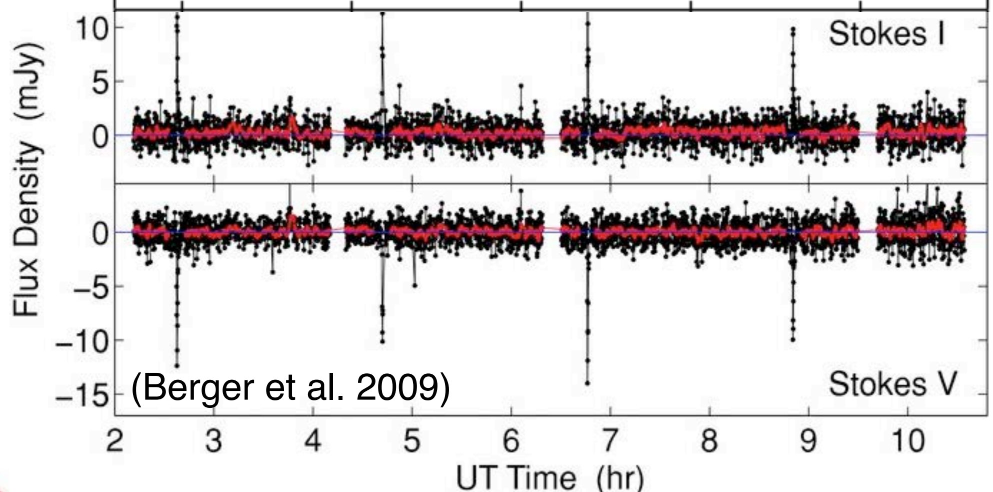
Pulses!



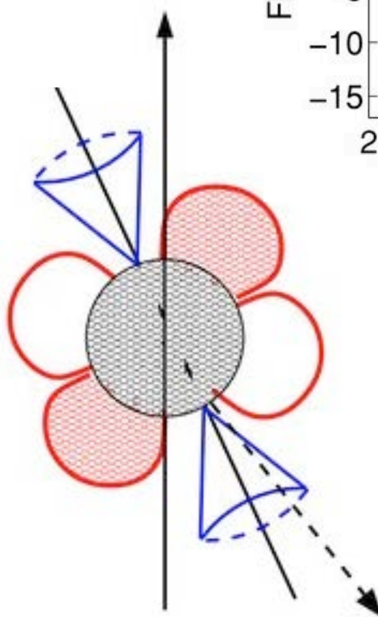
(Route &Wolsczczan 2012)



(Hallinan et al. 2007)



(Berger et al. 2009)



(Berger et al. 2009)

periodic *pulsing* *(per rotation)*

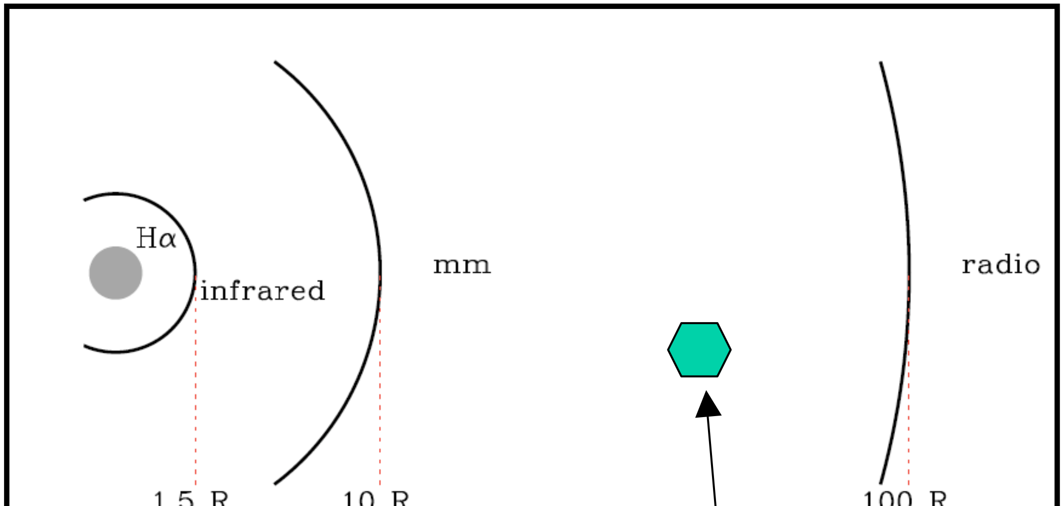
drifting, 70-90% circ. polarized, T_B >10^{11} K: coherent emission from propagating emitter

Free-Free Emitting Winds and Stellar Mass Loss: OB and WR Stars

Observe optically thick surface of wind: *frequency dependent radius*

$$S_\nu \propto \left(\frac{\dot{M}}{v_\infty \sqrt{f}}\right)^{4/3} \nu^{2/3}$$

(Wright&Barlow/Panagia&Felli/Olnon 1975)

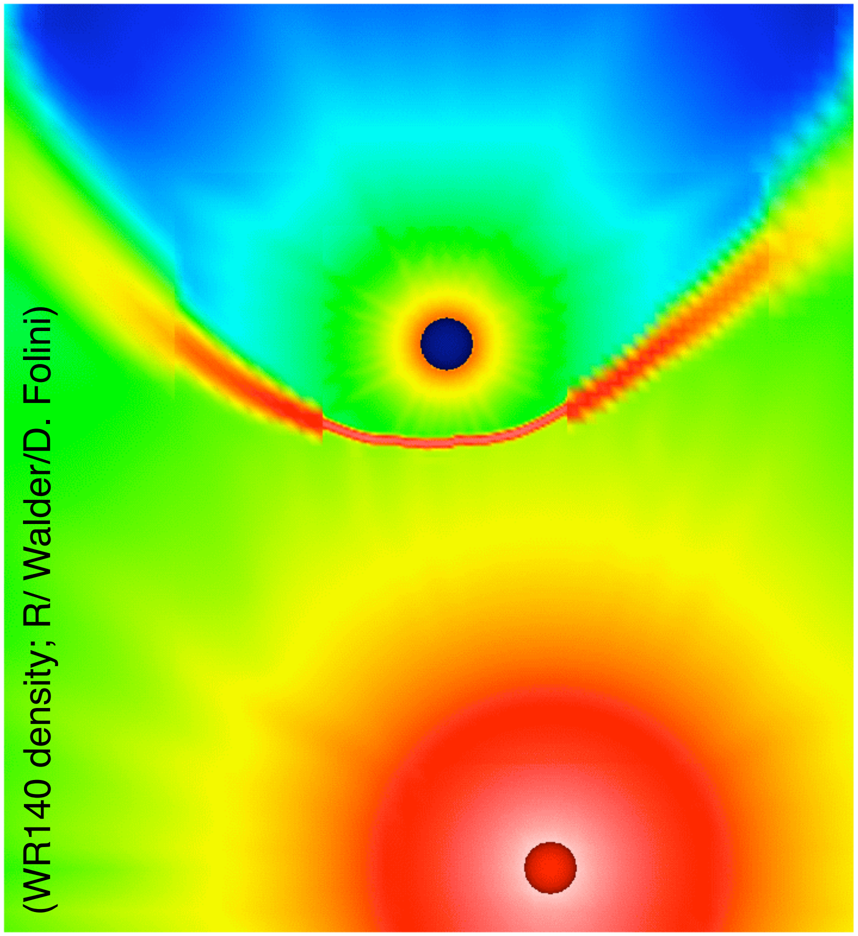


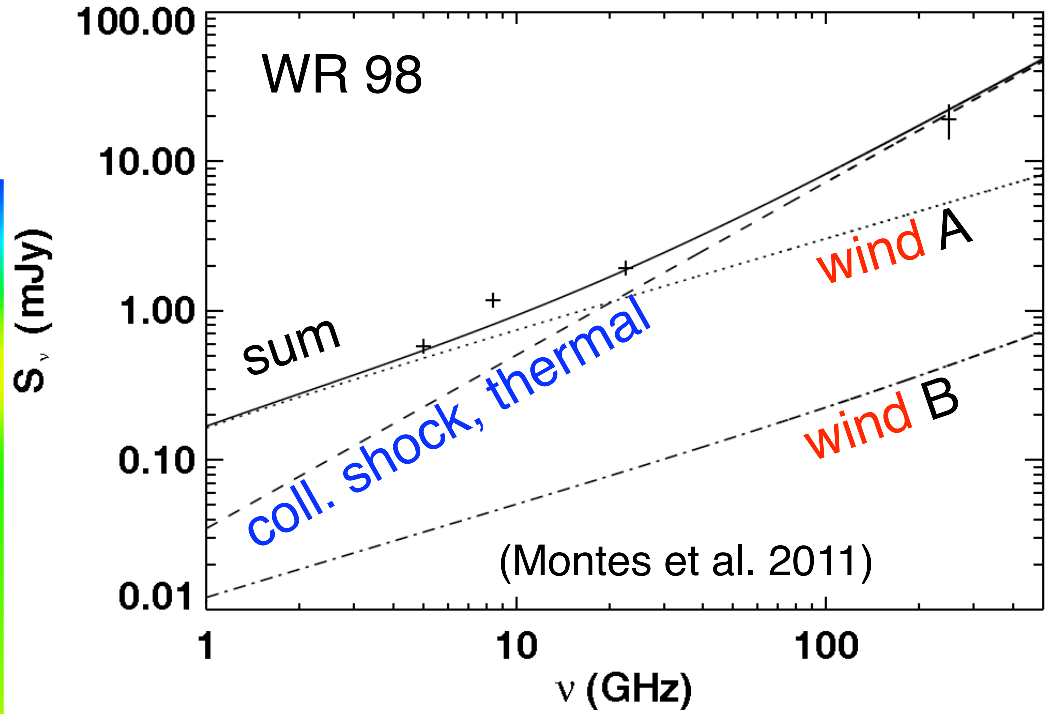
(Blomme 2011)

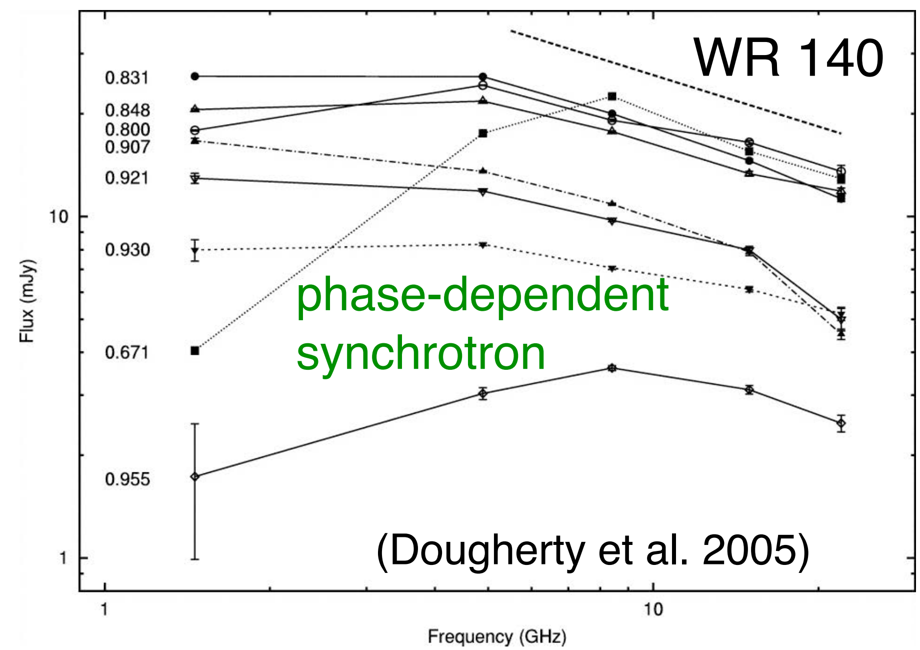
Wind mass loss conistently too high
compared to e.g. X-ray line (a)symmetry diagnostics:

Wind clumped: higher density regions, bremsstrahlung $\propto$ n^2
$\rightarrow$ *lower mass loss required*

Thermal & Non-Thermal Emission from Colliding Winds

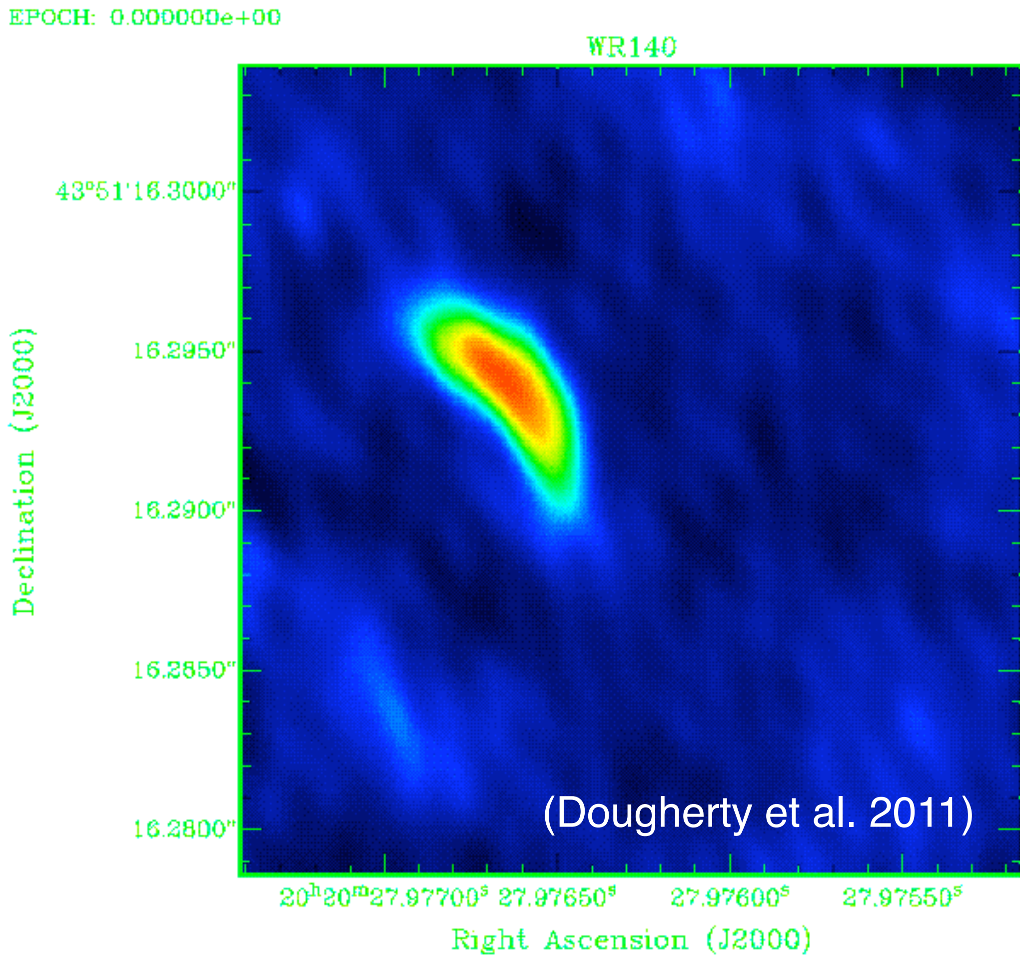


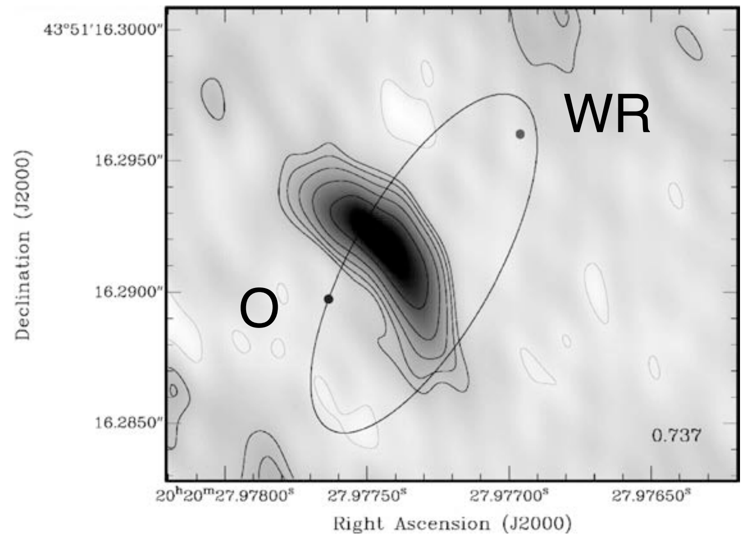




→ accelerated e^- and B fields, seen only in binaries
(OB: Dougherty & Williams 2000; WR: De Becker '07, Cappa+ 04, Chapman+ 99)

VLBA: The Structure of Colliding Wind Shocks

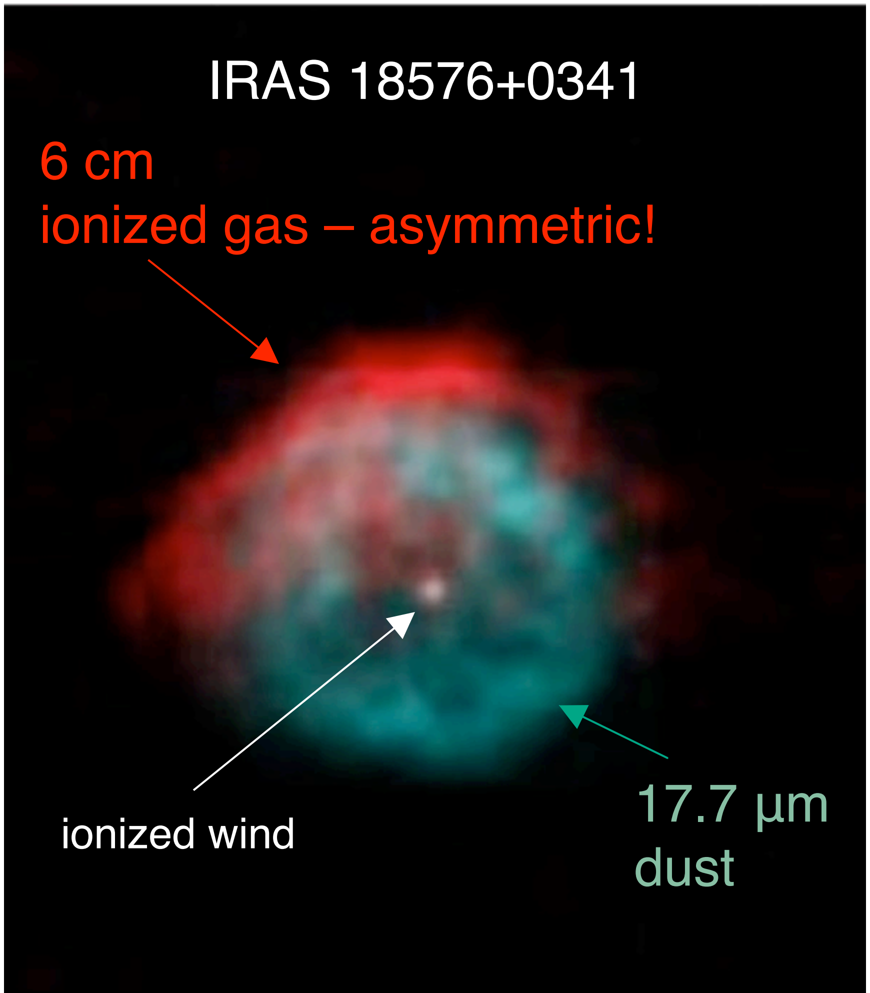




(Dougherty et al. 2005)

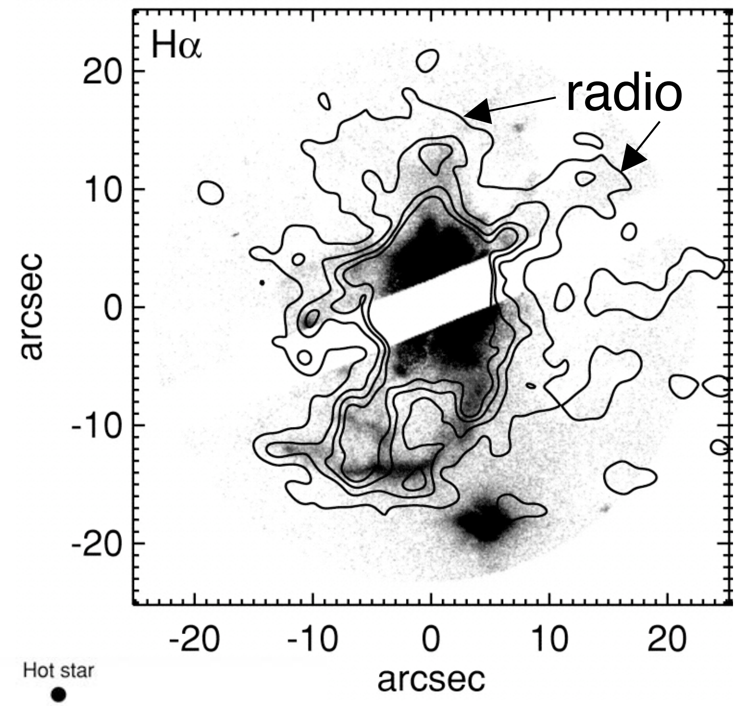
Phase-dependent variability:
intrinsic (distance!), free-free absorption,
synch self-absorption, IC,Razin,...

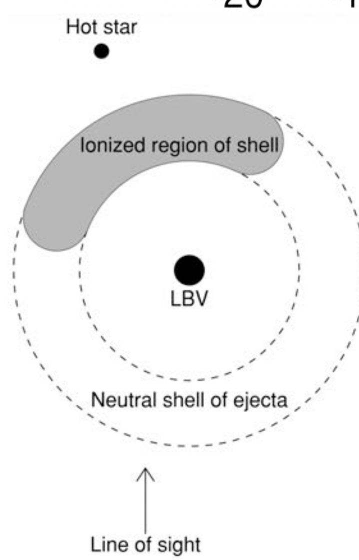
Mass Loss From O to WR: Luminous Blue Variables



LBV: 20-120 $M_\odot$, 10^4 $L_\odot$
Trace mass-loss history (w/ IR) and present mass loss rate: 1.5×10^{-6} $M_\odot yr^{-1}$. Asymmetries!

(Buemi et al. 2010)

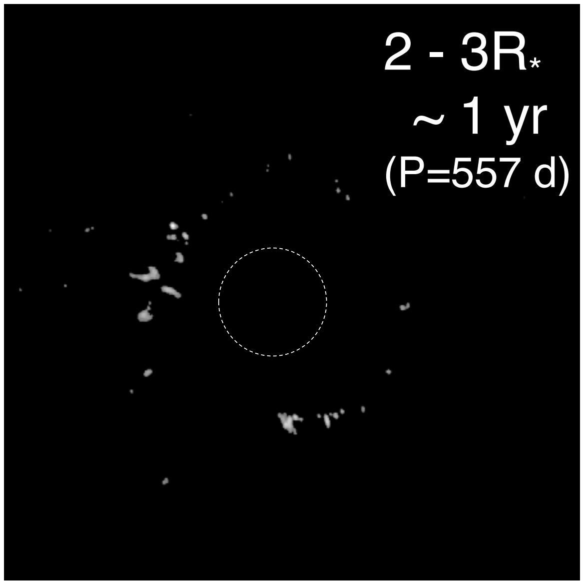


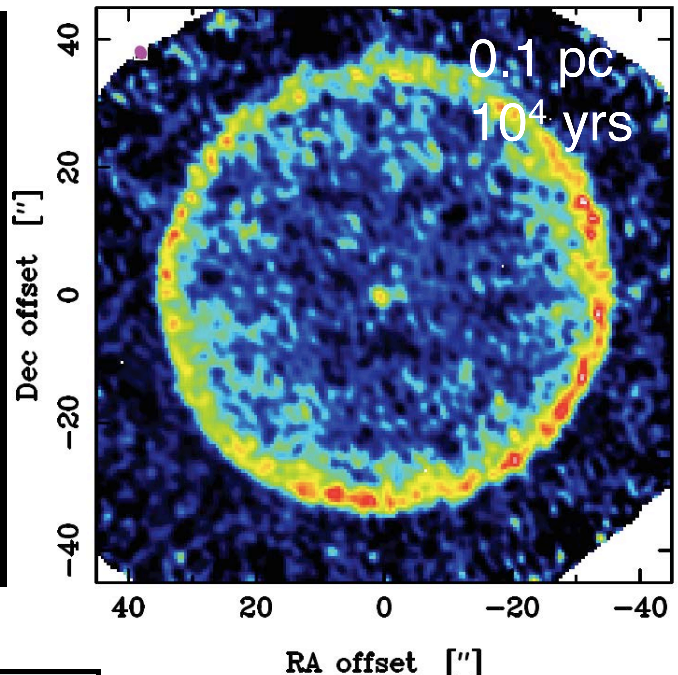


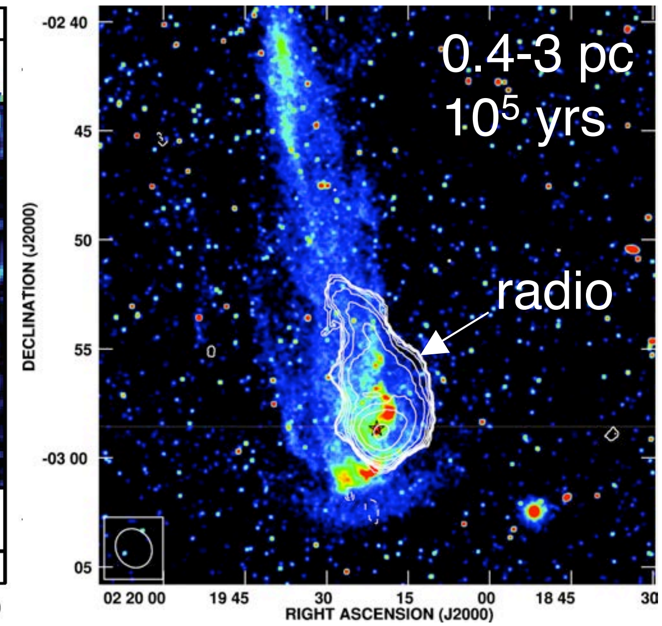
Asymmetry: external ionisation of wind by companion?

(White 2000)

Masers, CO(1-0), and HI: Probing (Episodic) AGB Mass Loss at all Scales







VLBA 43 GHz SiO Maser, TX Cam (Diamond & Kemball 2003; Kemball et al. 2009)

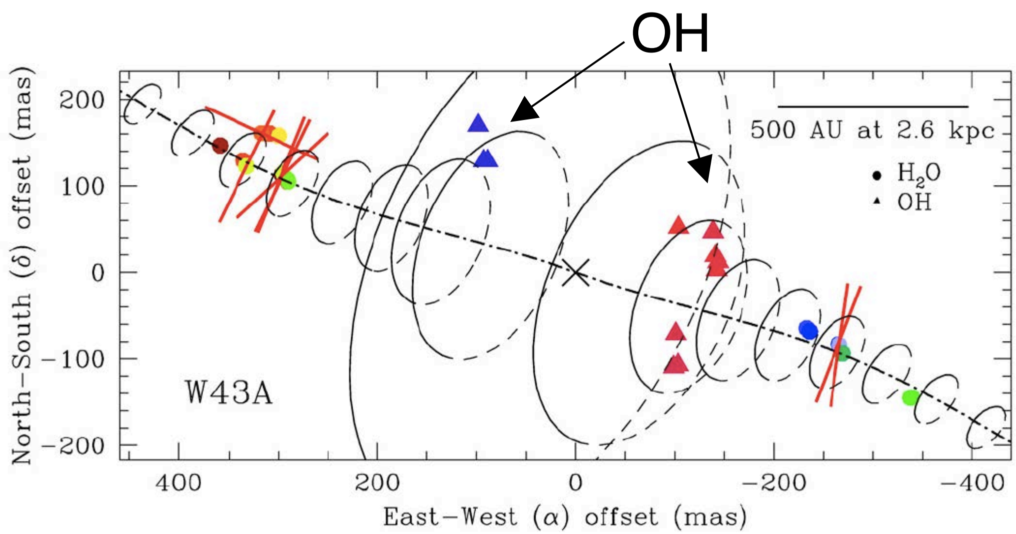
tangential amplification; pulsation→ flows; kinematics as f(phase); comparison with hydro; motion related to B?

CO(J=1-0) TT Cyg
115 GHz (Olofsson et al. 2000)

Very short mass loss episode, 7000 yrs
13 km/s, >250 cm^{-3}

HI (+FUV) Mira
21 cm (Matthews et al. 2008)

atomic cometary-like tail, 128 km/s vs ISM; age 1.2×10^5 yrs!



22 GHz H_2O + 1612 MHz OH maser,
W43A (AGB - proto-planetary nebula):

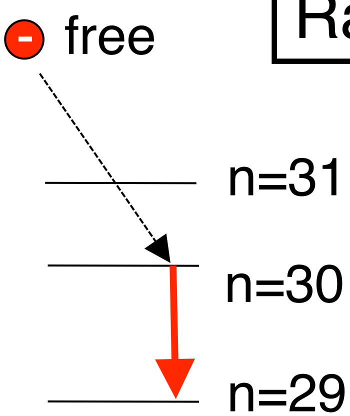
toroidal magnetic field in a
in a jet from an AGB star;

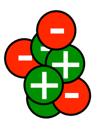
B = 200 mG

dynamo? Collimation?

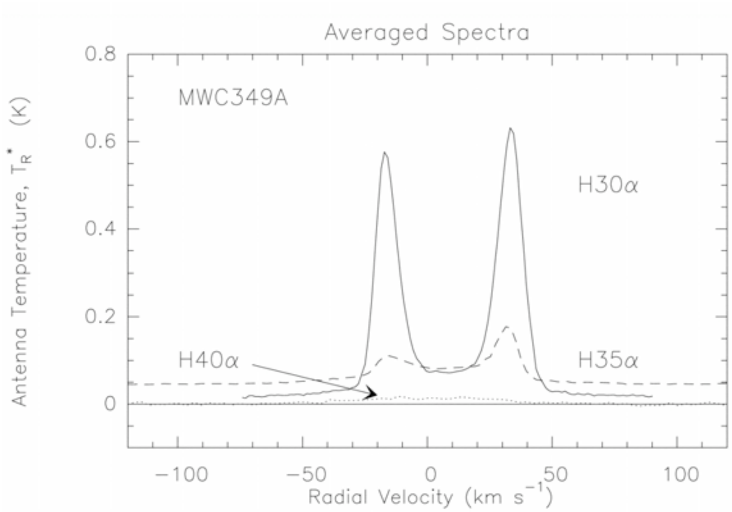
(Vlemmings et al. 2006, Amiri et al. 2010)

Radio Recombination Lines

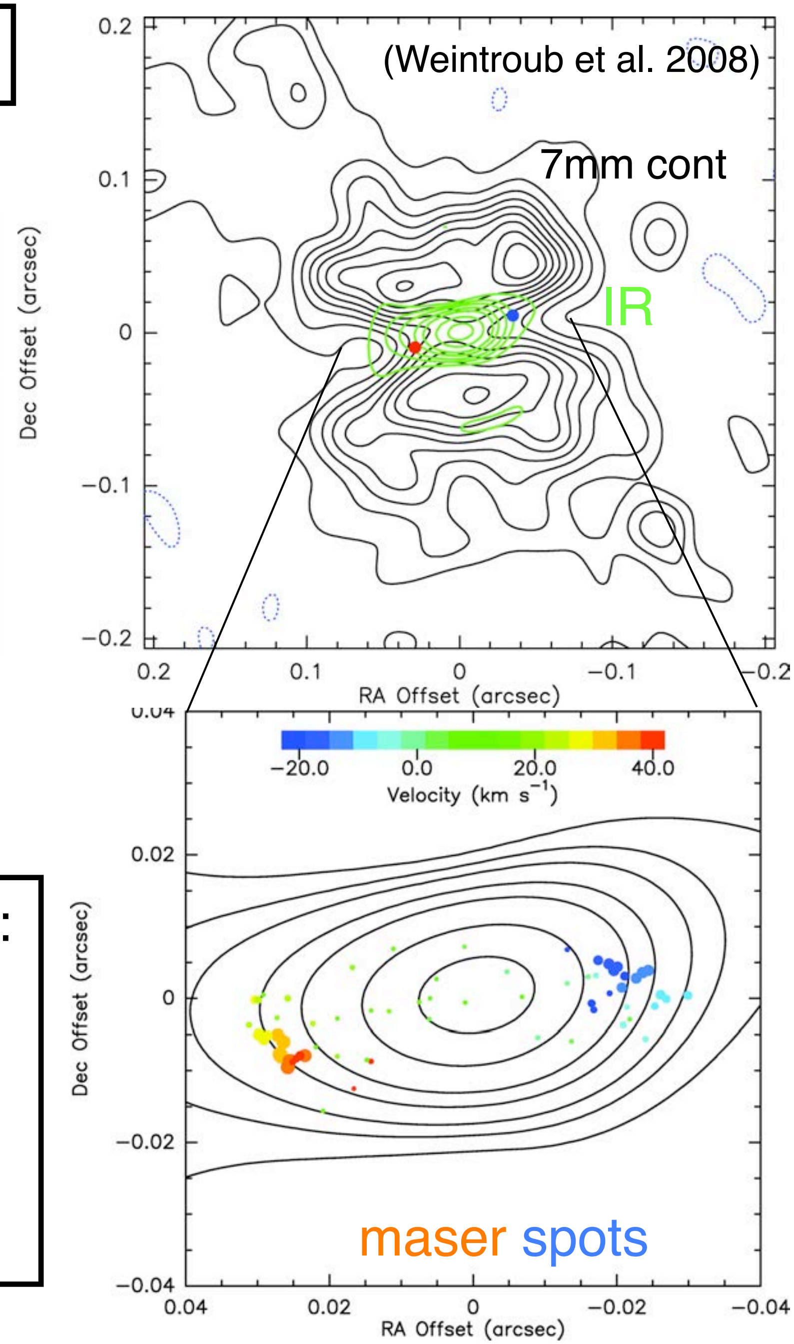




Z=1



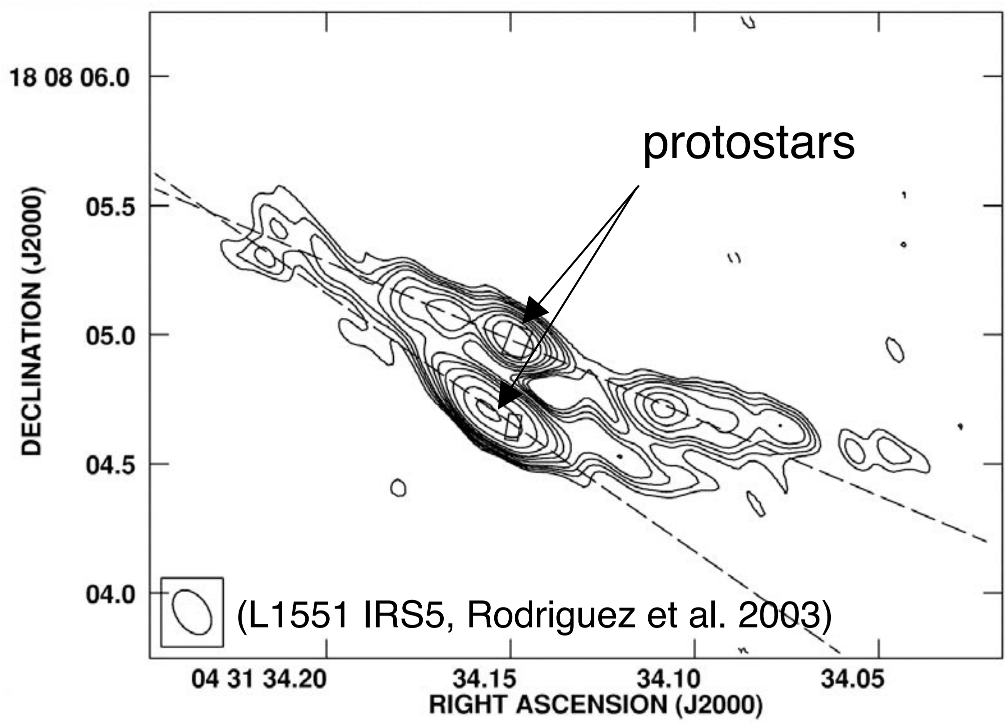
(Gordon et al. 2001)

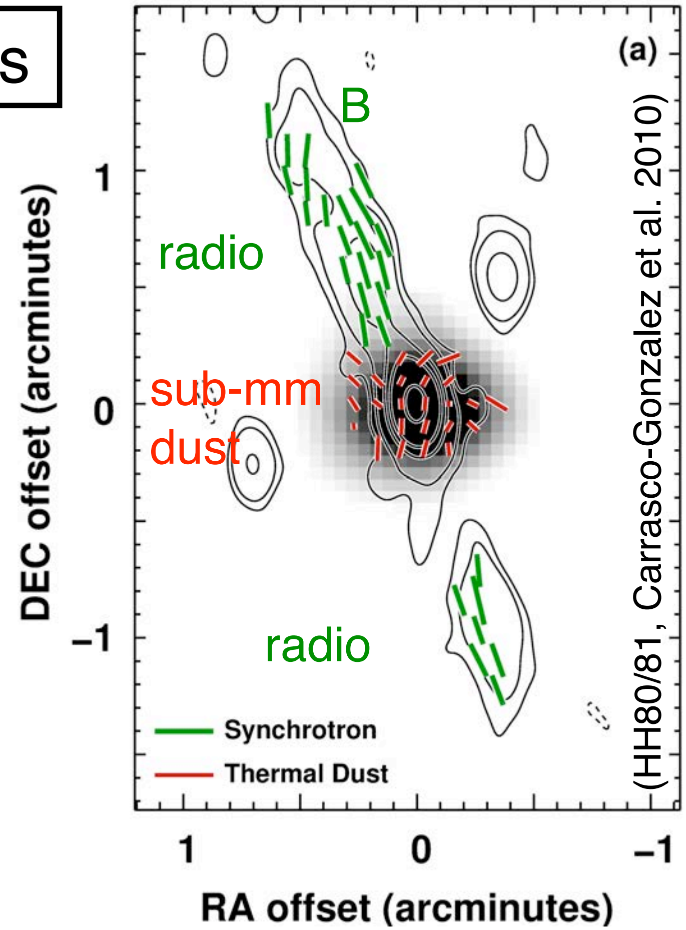


H30α (231 GHz) & H35α (147 GHz) w/ SMA:
MWC 349A (B[e] star)

Analysis of freq. dependent velocities and broadening → edge-on Keplerian disk with sources on spiral density waves

Radio Emission from Protostellar Jets





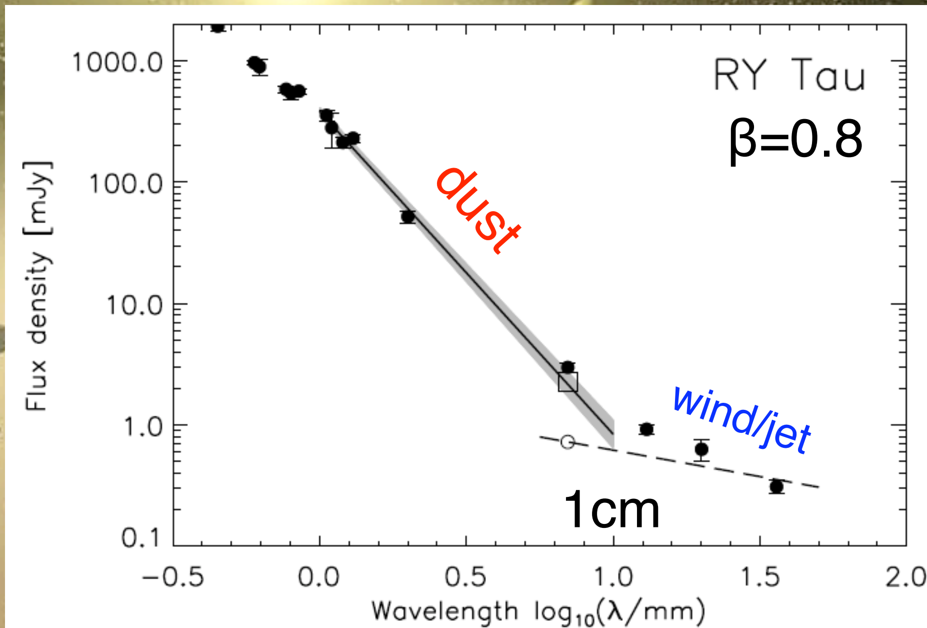
Protostellar jets often thermal....

- bremsstrahlung from 10^4 K gas
- masking underlying non-thermal emission from star?

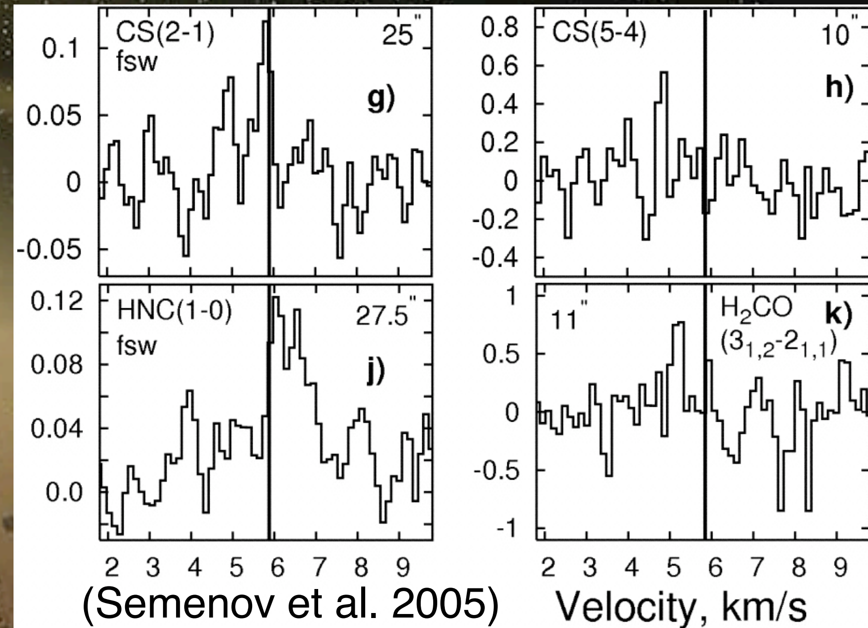
but non-thermal radiation exists:

- lin. polarized synchrotron
- negative spectral index
- shock acceleration, 0.2 mG

Probing Protoplanetary Disks: The Origin of Planets



continuum



lines

DUST (1%):	GAS (99%):
measuring <u>grain growth</u> and sizes:	probing <u>chemistry</u> w. molecular lines:
Opacity $\kappa_\nu \propto \nu^\beta$ → $\beta = \alpha - 2 \approx 1$	HCN, HNC, HCO^+, H_2O, CS, H_2CO,...
→ ≥ millimeter-sized "pebbles" (Rodmann et al. 2006)	e.g., evidence for radiative synthesis and/or destruction of organics/water

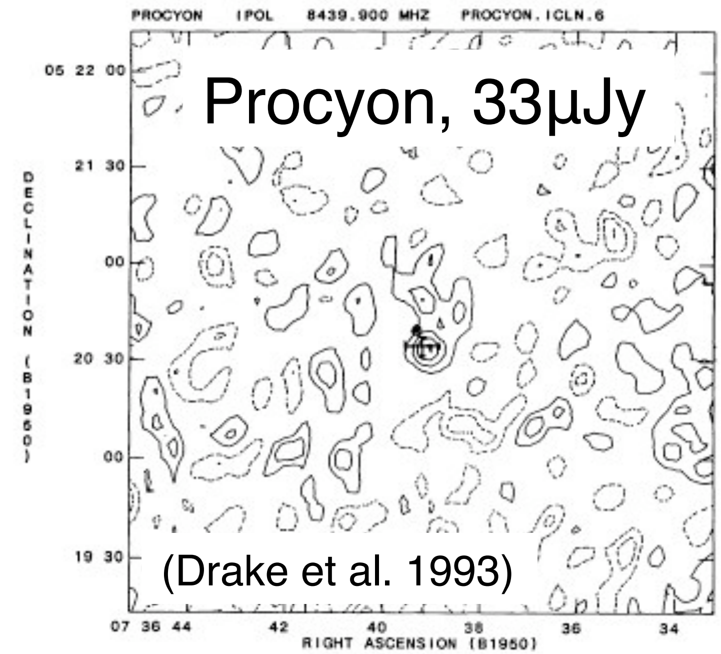
Where to go from here?

A biased view...

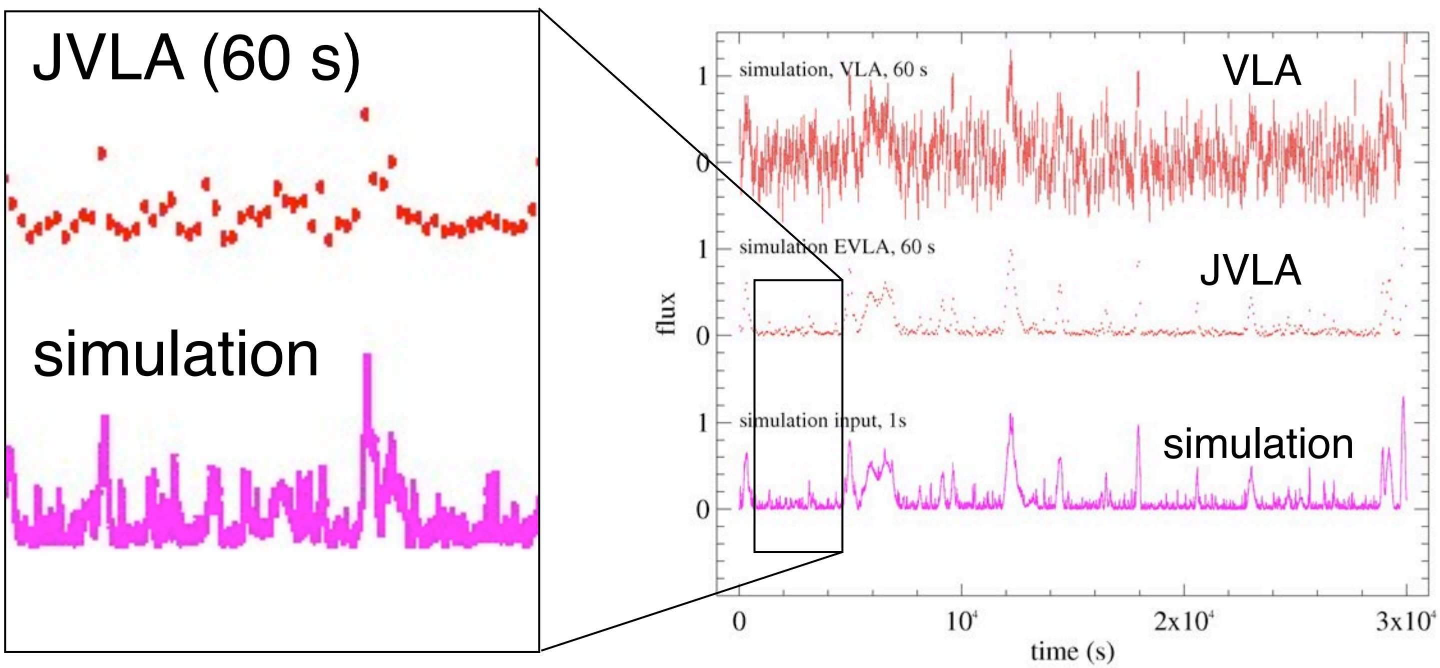
Sensitivity: toward μJy

Getting to stellar photospheres
and chromospheres

short, faint phenomena:
bursts, transients



JVLA,
ATCA,
e-MERLIN,
GBT,
Effelsberg,
Arecibo,
ALMA,
SKA

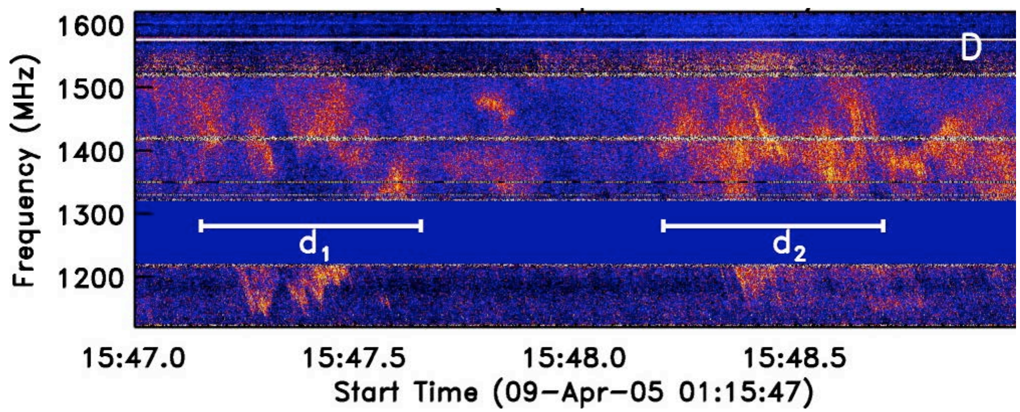


Bandwidth and Resolution

- Probing dynamic phenomena in dynamic spectra

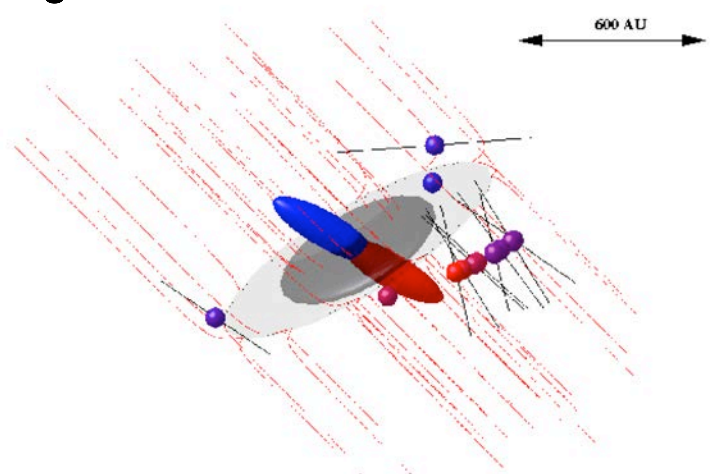
- Measuring magnetic fields!

JVLA, ATCA, Arecibo, ALMA



(Osten & Bastian 2008)

6.7 GHz methanol maser, Cep A HW2 protostar with magnetized disk



(Vlemmings et al. 2010)

Frequency Ranges

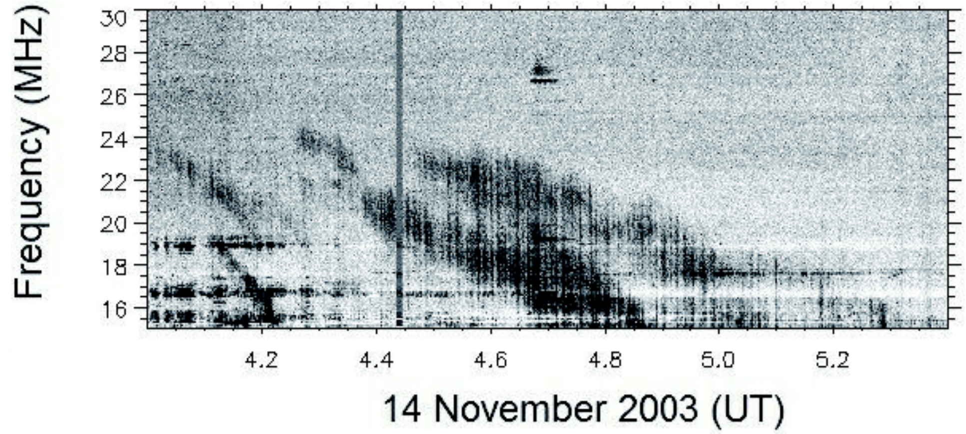
- Low frequencies: getting to exoplanetary radio emission?

LOFAR
GMRT

- Millimeter/sub-millimeter range: Probing astrochemistry, water and organics

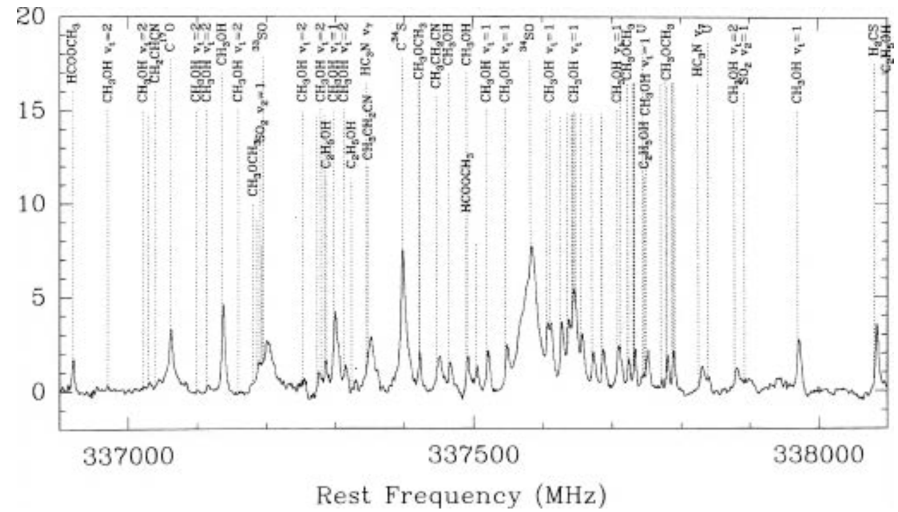
ALMA, CSO, IRAM...GBT

Jupiter Decametric Radiation



(Echer et al. 2010)

Orion KL, CSO @ 1 mm



(Schilke et al. 1997)

Conclusions

Radio astronomy has become indispensable for stellar astrophysics, providing unique information:

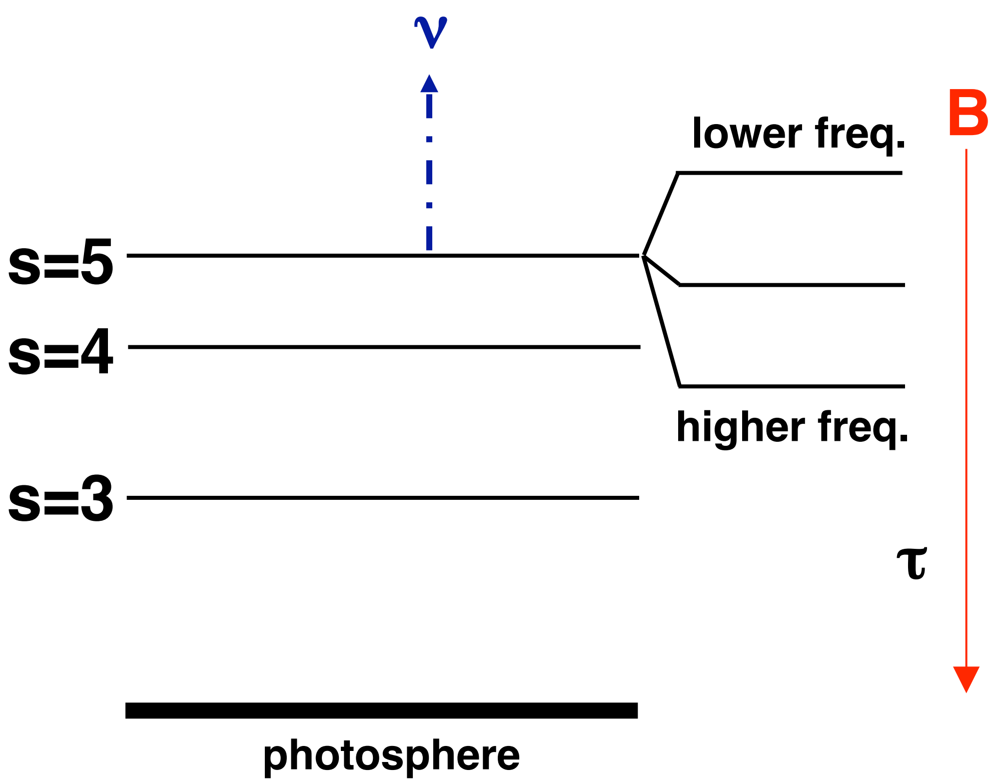
- magnetic fields
- stellar atmospheres
- wind and outflow mass loss
- accelerated particles
- shocks
- astrochemistry
- planet formation, ...

especially with the now much improved instrumentation.

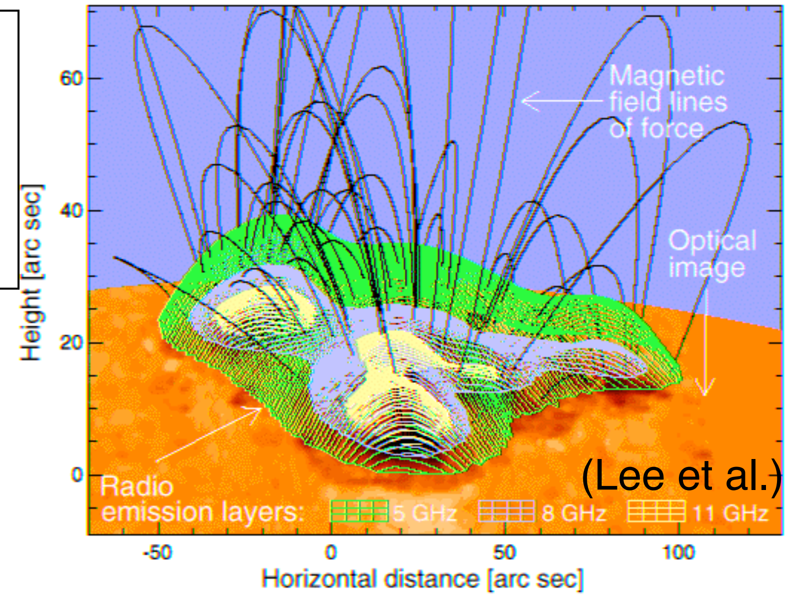
END

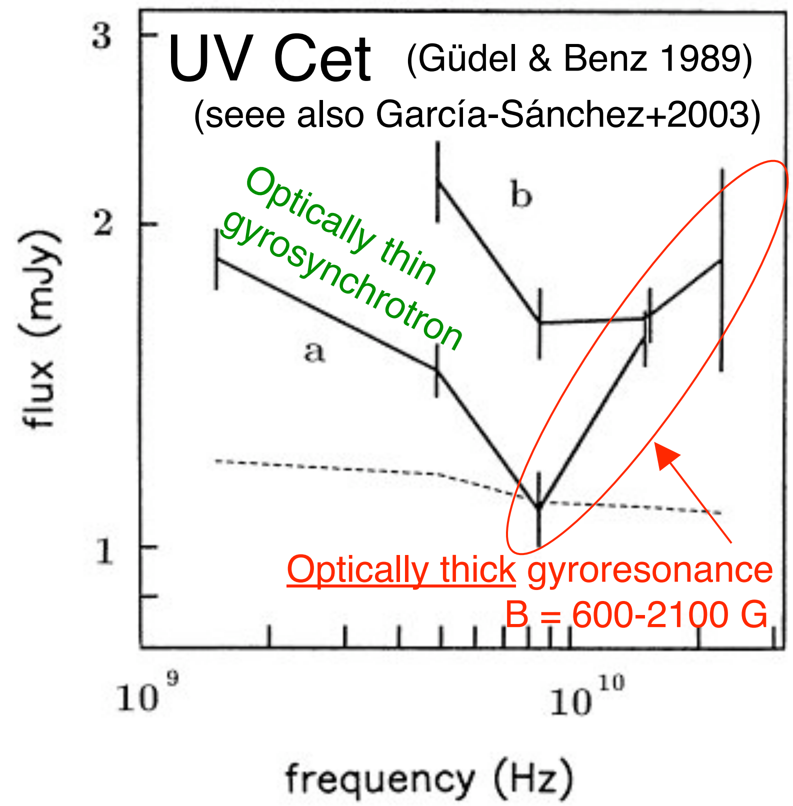
Gyroresonance emission

Increase opacity by magnetic field in corona:
optically thick gyroresonance emission

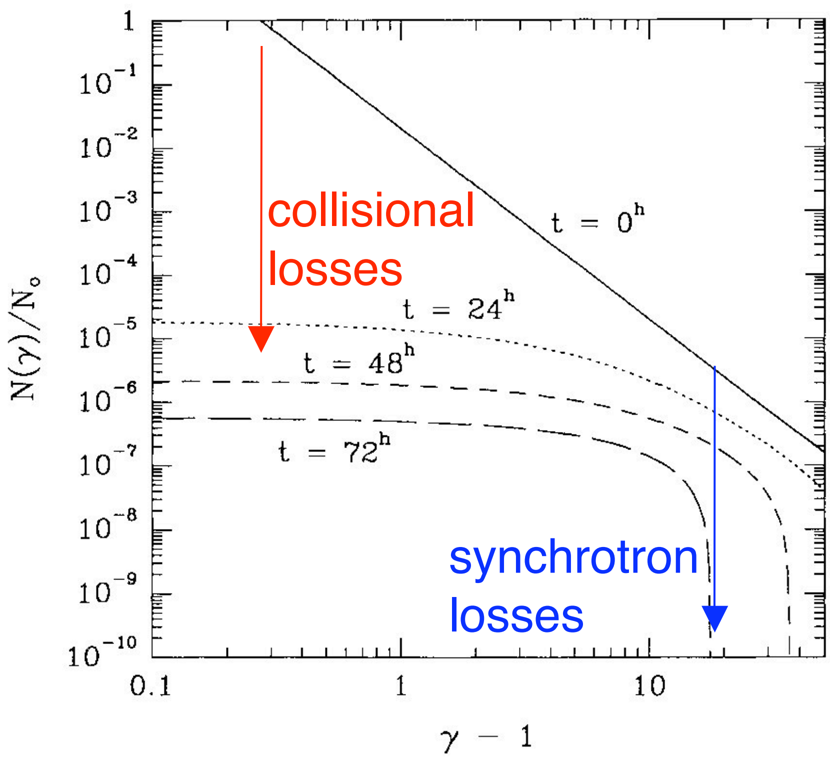


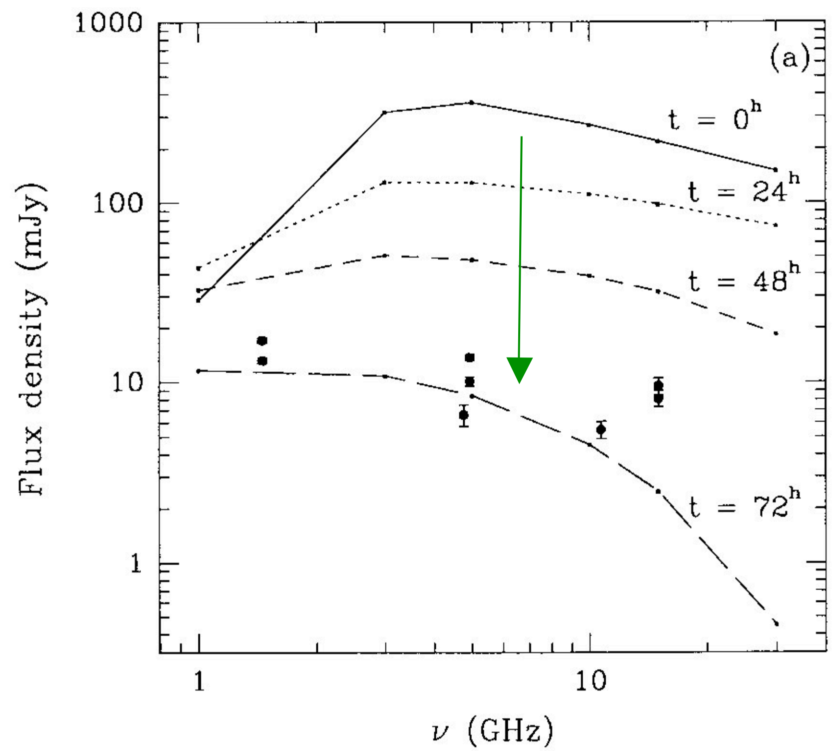
*The highest optically thick **s** is relevant, typically s = 3, 4, 5*





Evolution of Non-Thermal Particle Populations

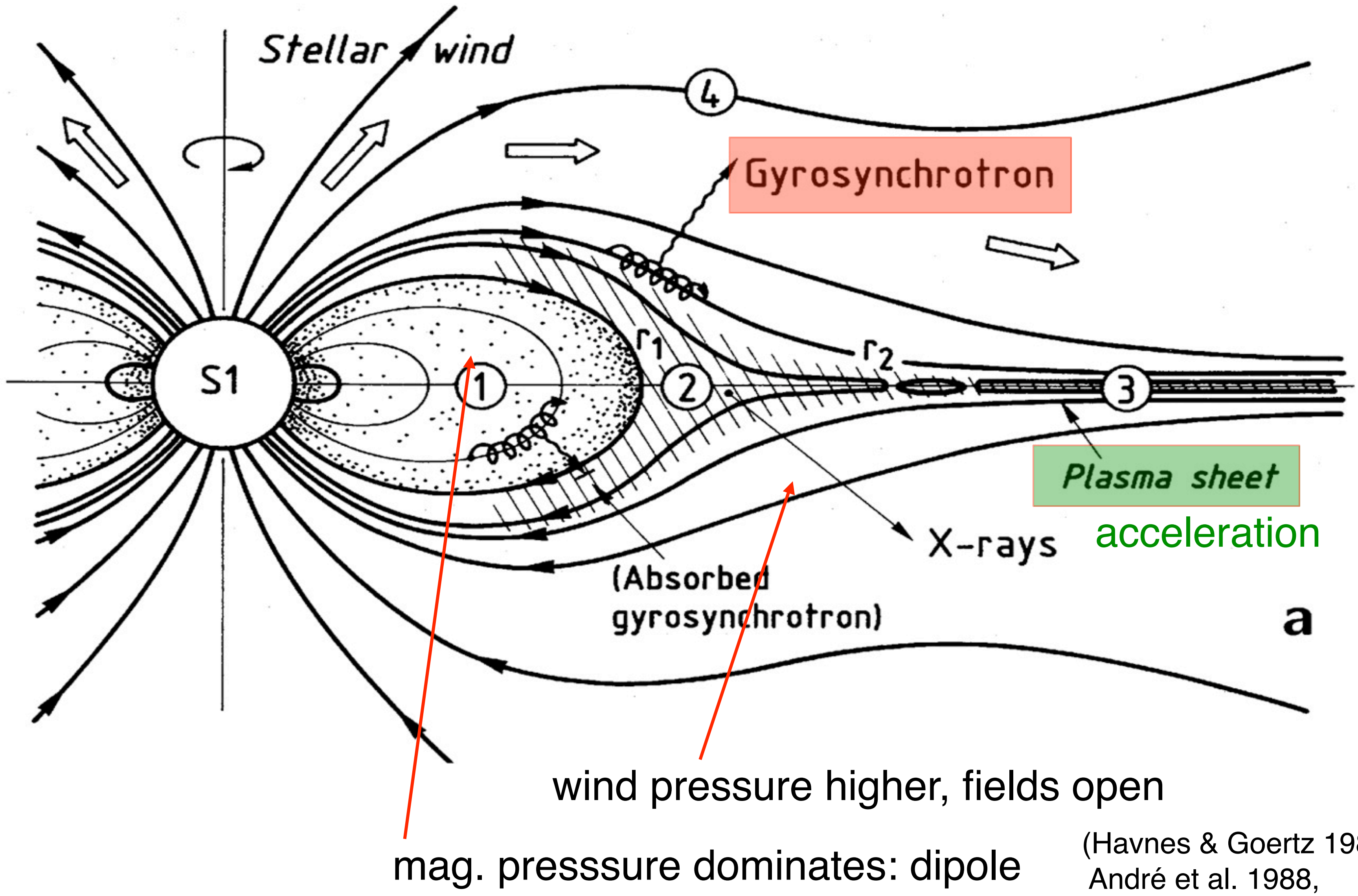




ageing of electron distribution → Spectral development

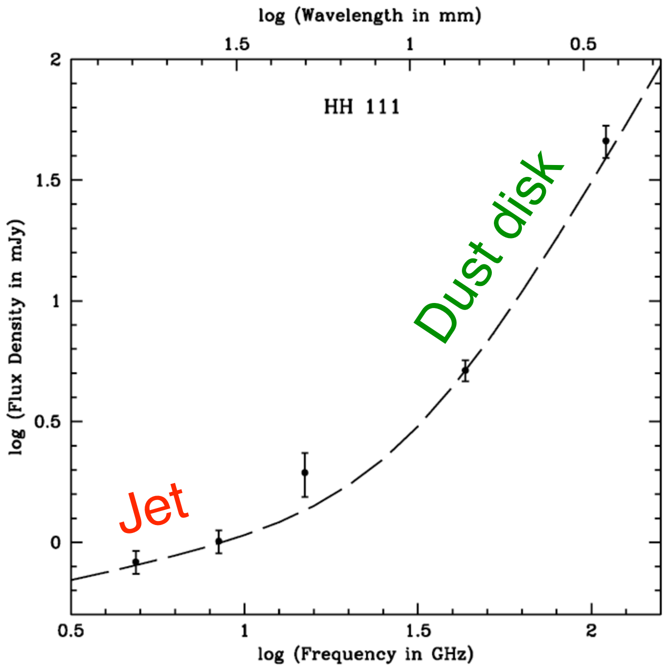
(Chiuderi Drago & Franciosini 1993)

Magnetic Ap stars, O stars, Herbig stars, Massive Protostars...

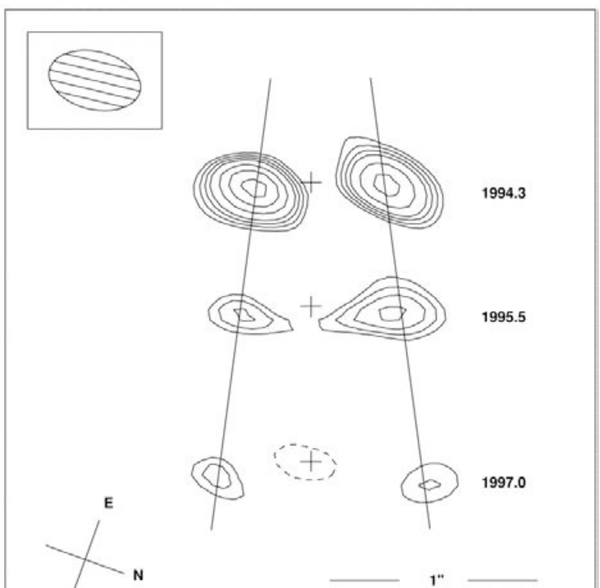


(Havnes & Goertz 1984,
André et al. 1988,
Linsky et al. 1992)

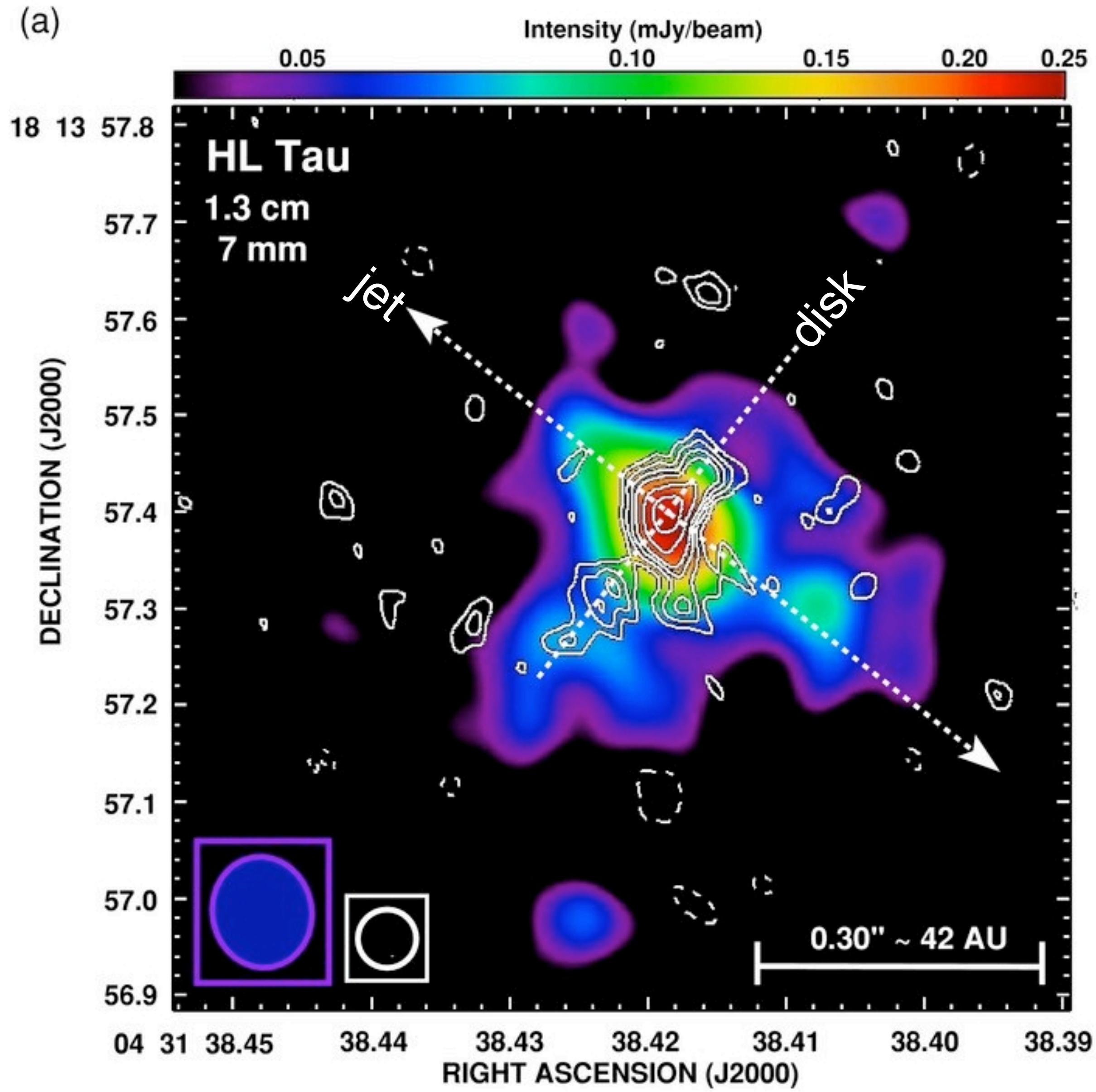
Jets and Outflows



(Rodriguez et al. 2009)



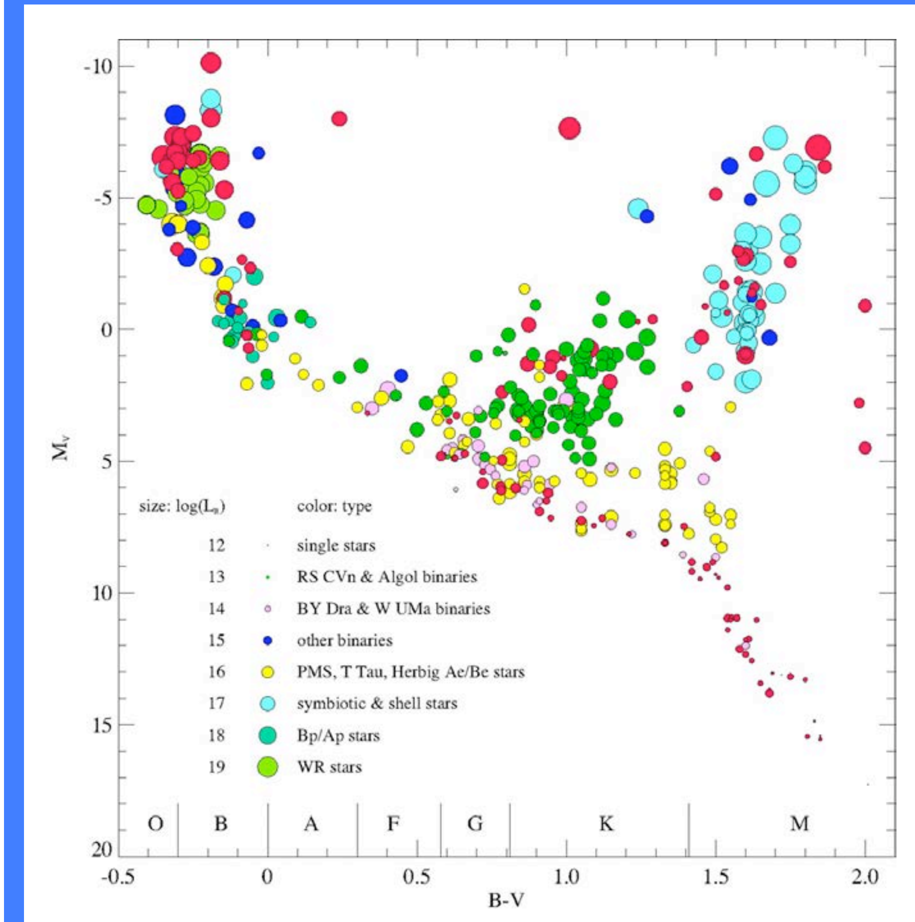
(Martí et al. 1998)



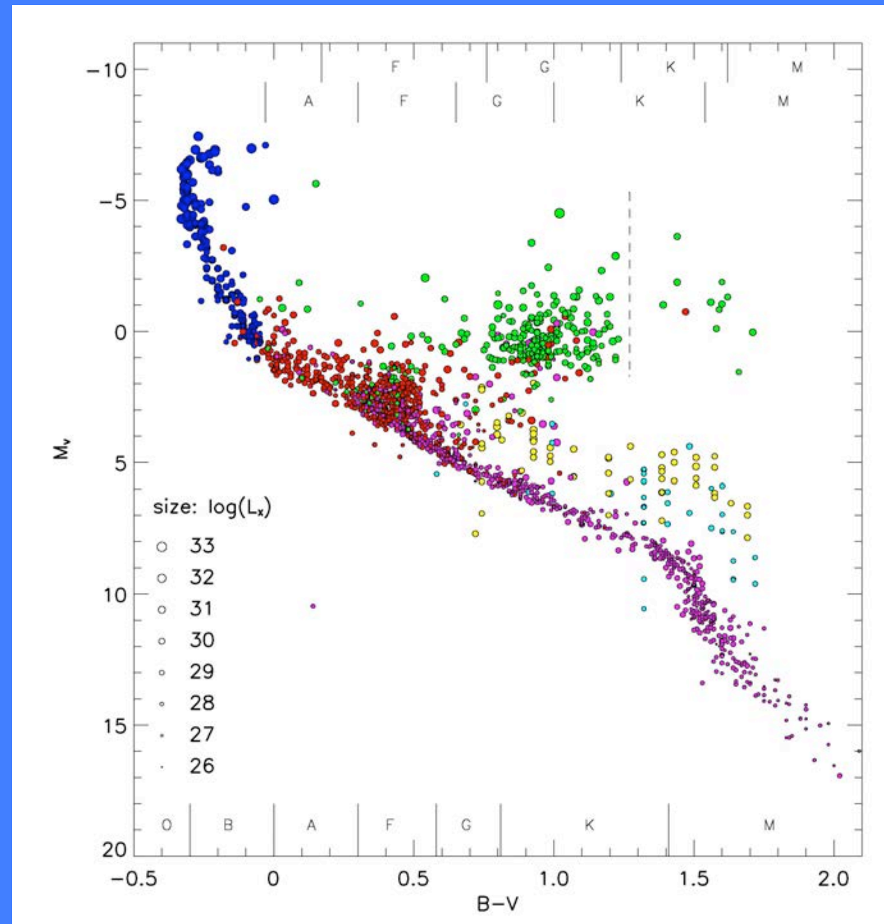
(Carrasco-Gonzalez et al. 2000)

Radio

X-rays

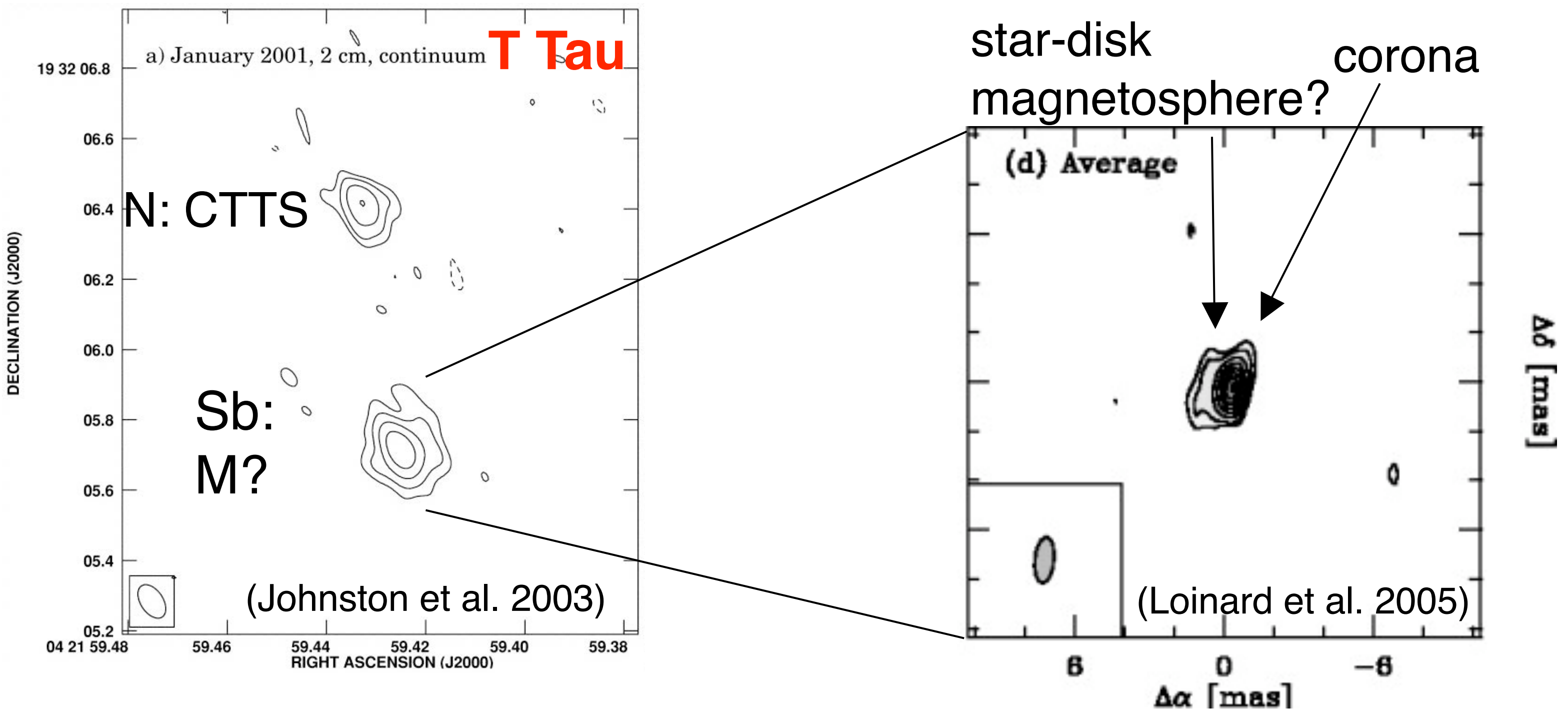


size: log(L_R)
color: type
12 single stars
13 RS CVn & Algol binaries
14 BY Dra & W UMa binaries
15 other binaries
16 PMS, T Tau, Herbig Ae/Be stars
17 symbiotic & shell stars
18 Bp/Ap stars
19 WR stars
O B A F G K M
M_V
B-V



size: log(L_X)
33
32
31
30
29
28
27
26
F G K M
A F G K M
O B A F G K M
M_V
B−V

Winds and B Fields in T Tauri Stars and Protostars



<u>Classical T Tauri stars</u>....

- thermal wind/jet sources
- few are non-thermal:

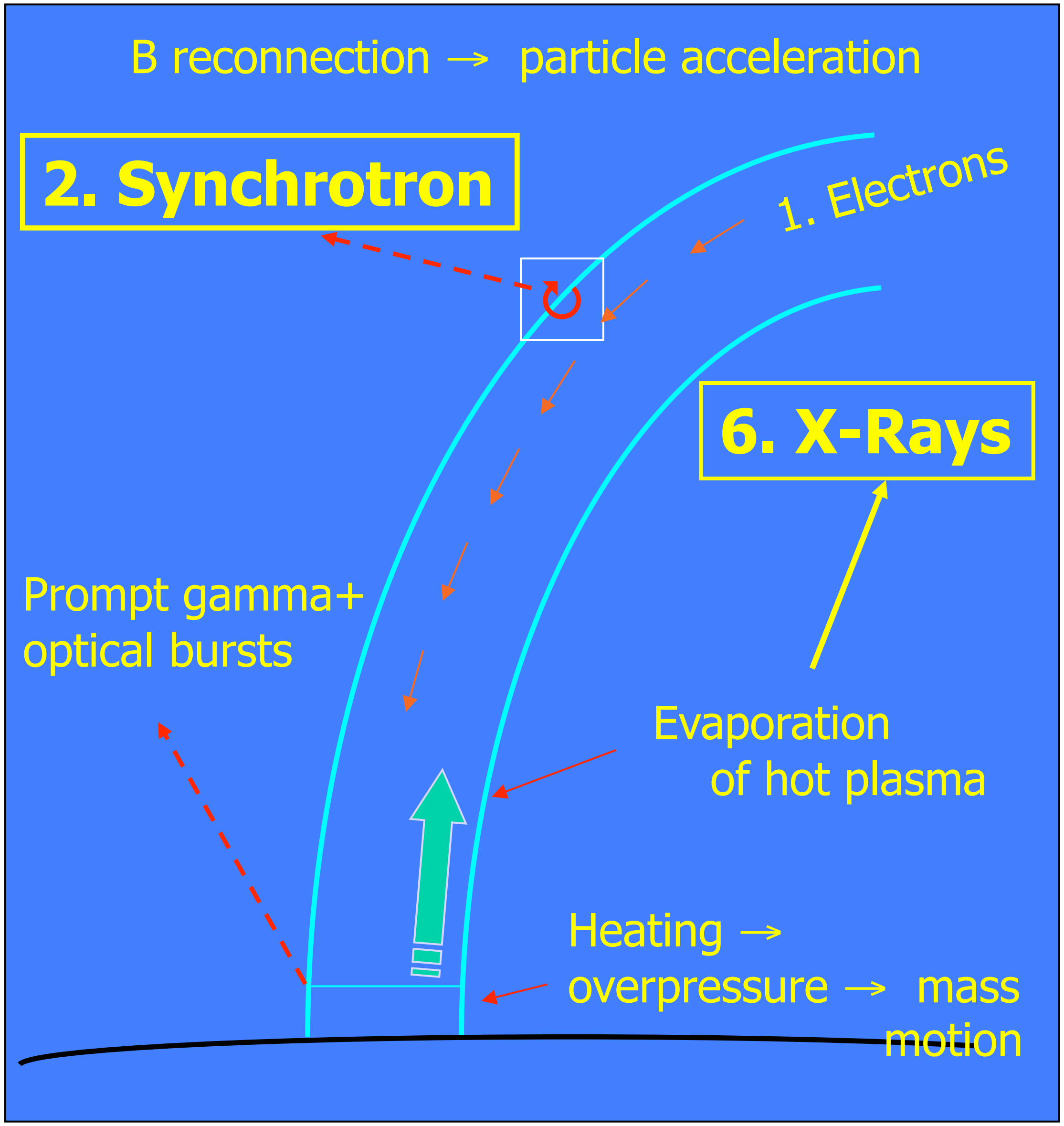
- absorption by wind

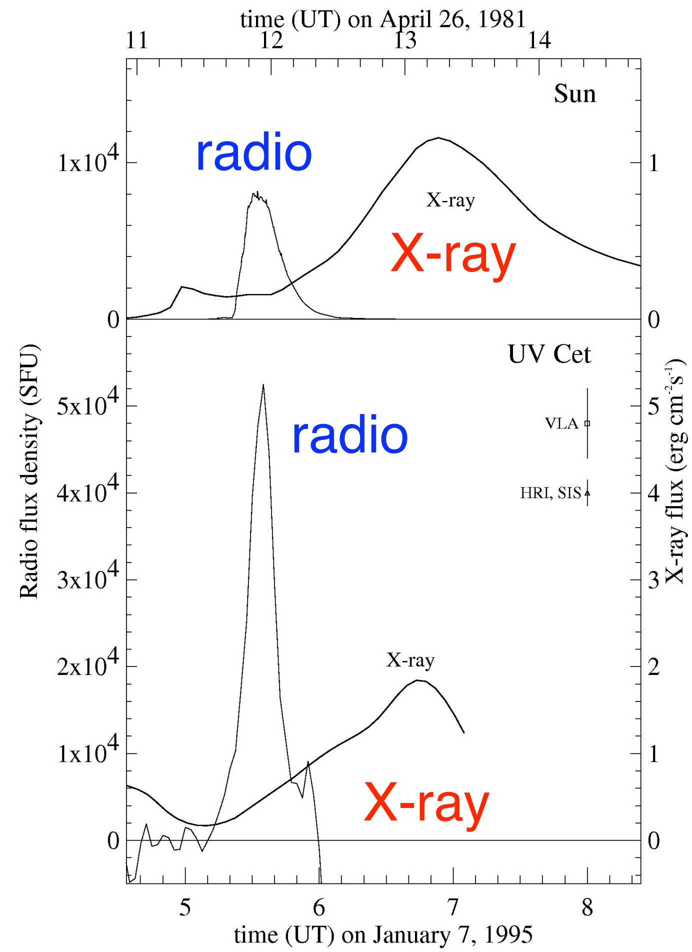
<u>Embedded protostars</u>....

- may show jets (next slide), but
- can be non-thermal gyrosynchrotron sources

- corona + star-disk magnetospheres (few R_*)

Standard flare scenario: particle acceleration

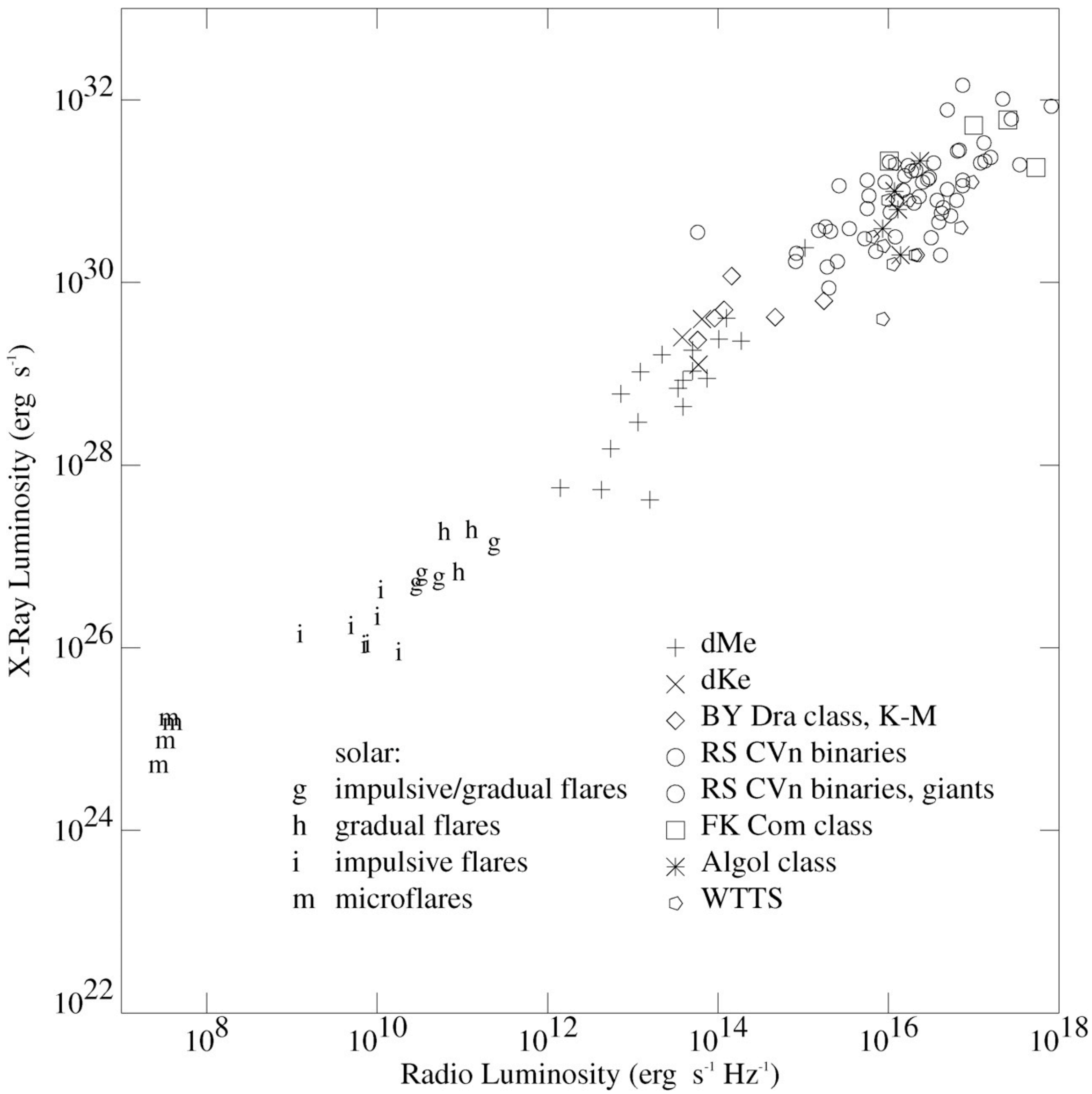




(Güdel et al. 1996)

"Neupert Effect“
(energy relation)

Energetics of High-Energy Particles in Stellar Coronae



(Güdel & Benz 1993; Benz & Güdel 1994)

1. Nonthermal electrons frequently injected by *flares*

2. "Neupert relation" acceleration-heating

1. Statistical average:

$$L_R \propto L_X$$


We don't dial 911