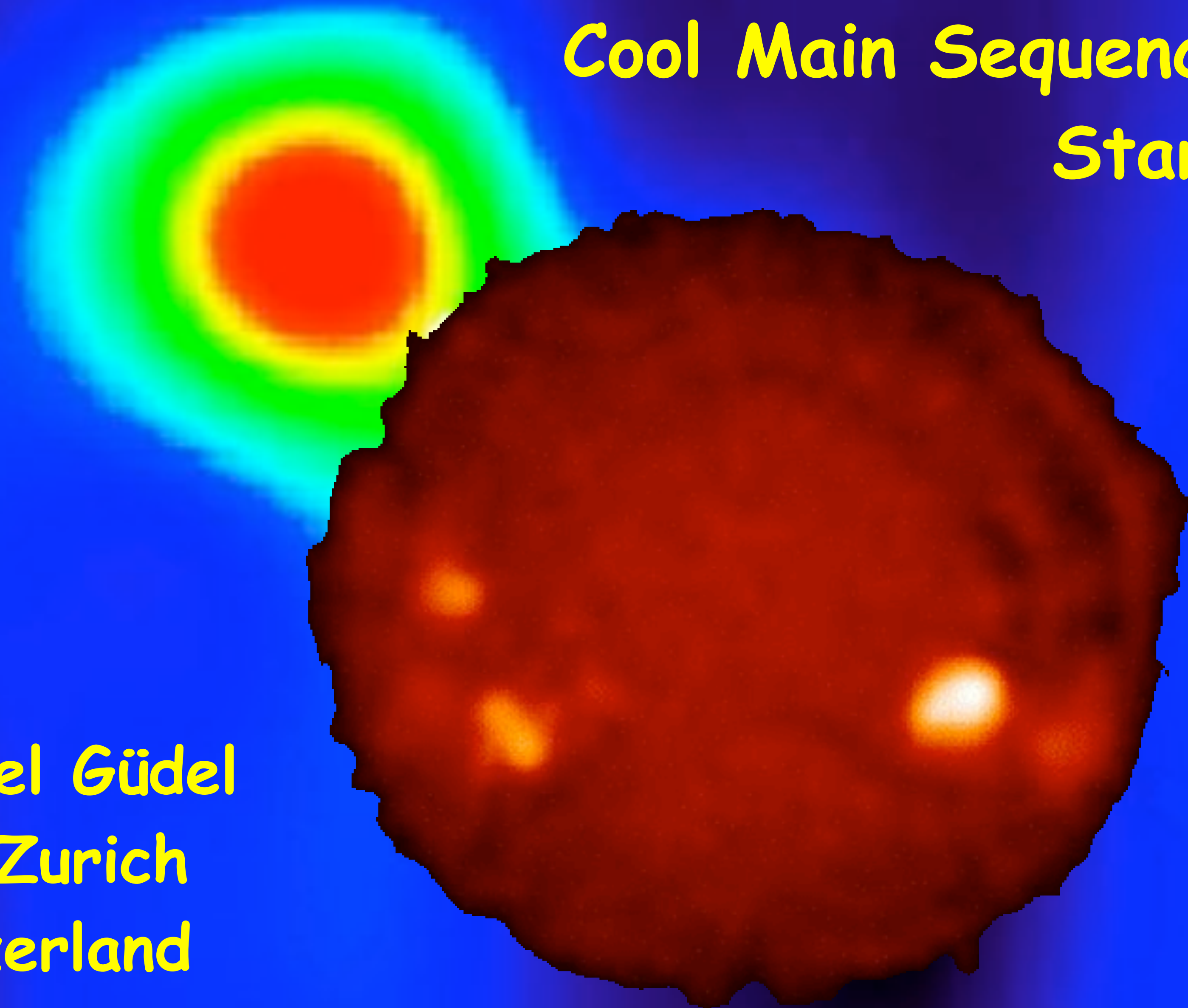
Radio Emission from Cool Main Sequence Stars



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Contents

The step from the VLA to the EVLA for cool stars:

What is known: gyrosynchrotron radiation

What is new: gyroresonance emission and bremsstrahlung

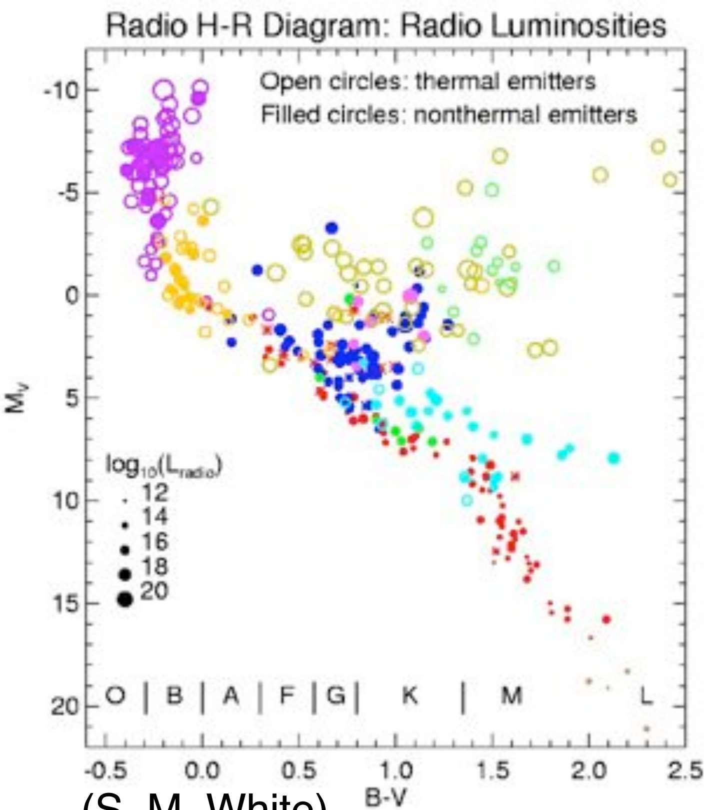
What needs to be done better: dynamic spectroscopy for coherent bursts

What deserves more consideration: sensitive monitoring of variability

The detection of *persistent* radio emission from cool main sequence stars (also RS CVn-type binaries) in the early days of the VLA was one of the most outstanding and least expected discoveries made by the Very Large Array.

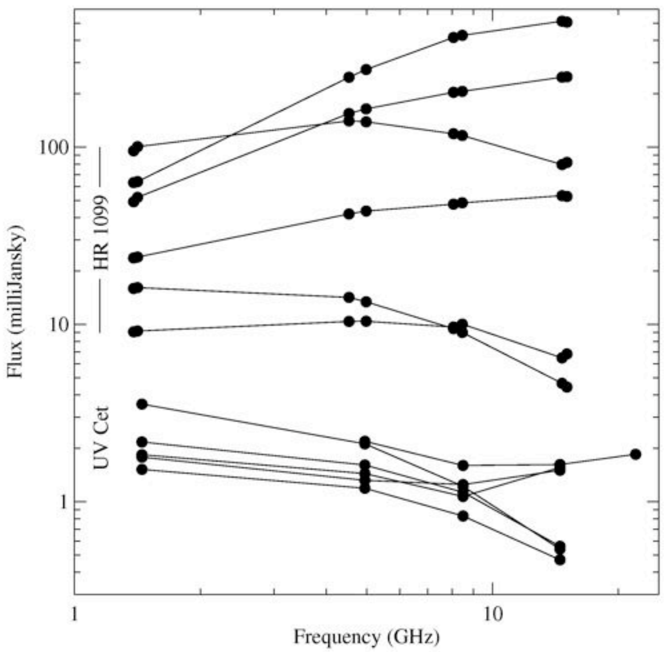
Why?

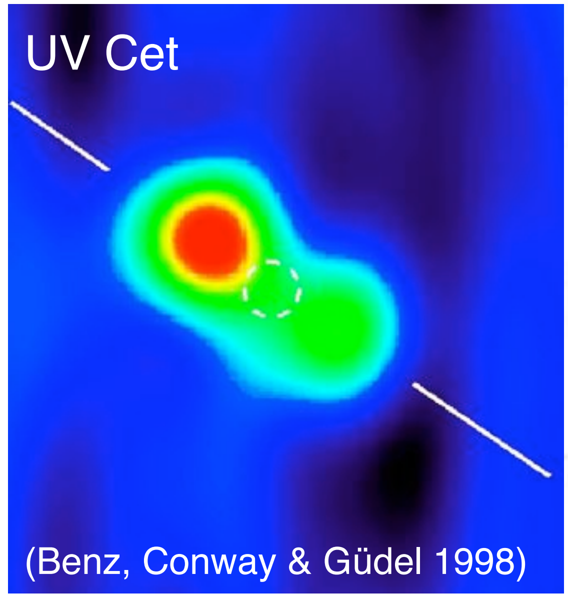
- ☞ Sun's radio emission at 1.3 pc: 15 μJy @ 20 cm (White 2000)
- ☞ Brightness temperatures assuming stellar size of source > $10^{8\text{-}9}$ K >> T_X
- ☞ Emission is *non-thermal*
- ☞ There is *no* solar analogy!



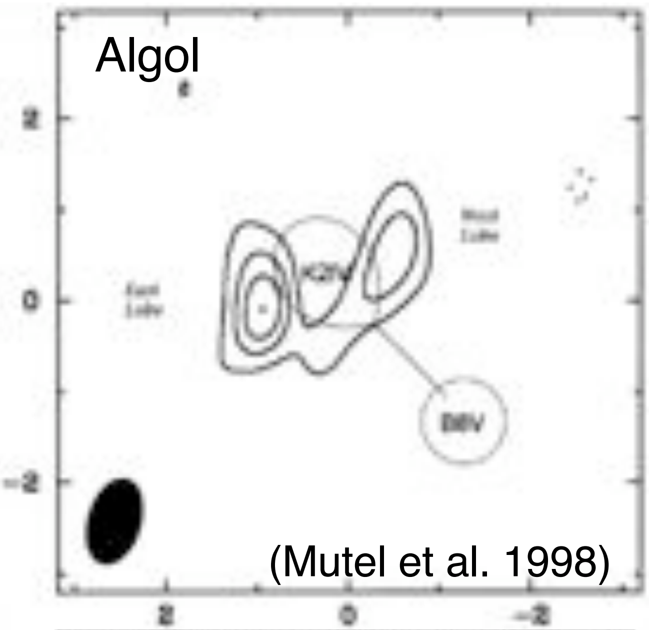
(S. M. White)

Known for a while: the (unexpected) gyrosynchrotron radiation

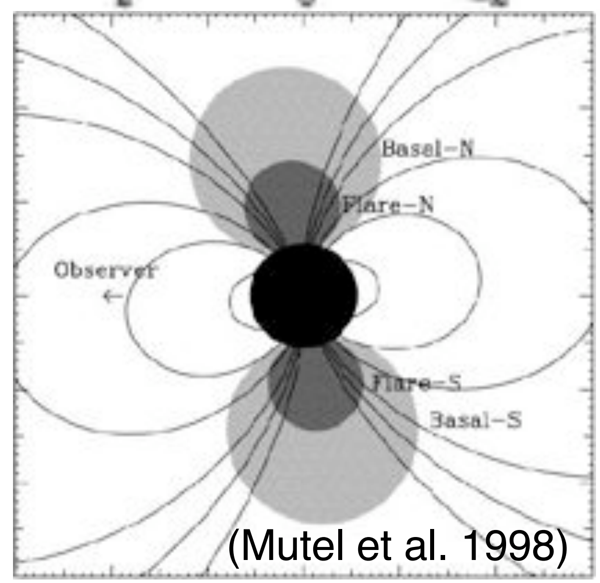




(Benz, Conway & Güdel 1998)

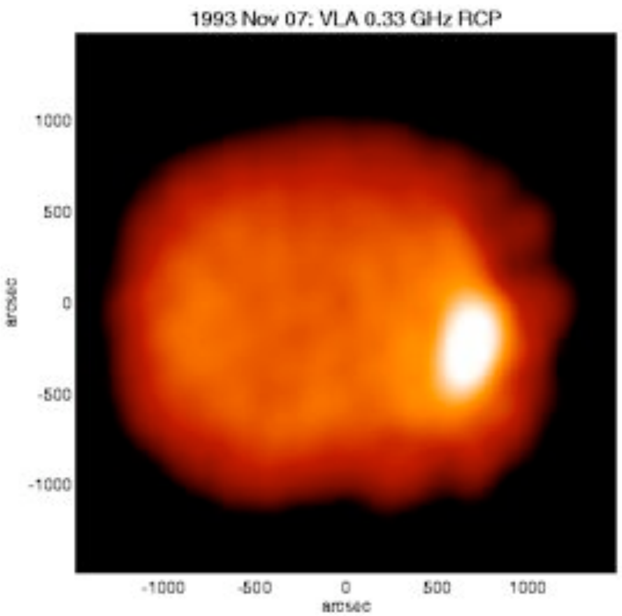


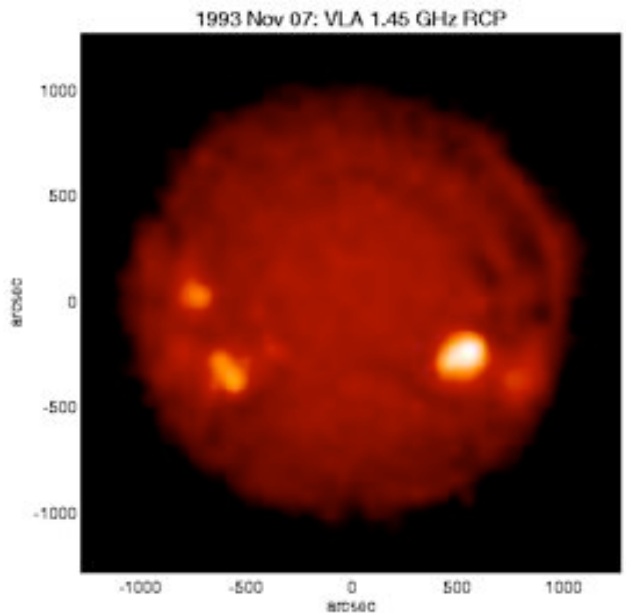
(Mutel et al. 1998)

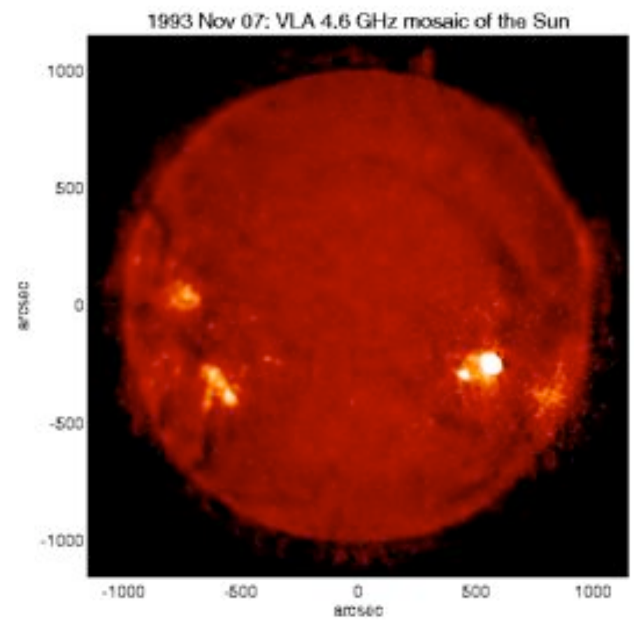


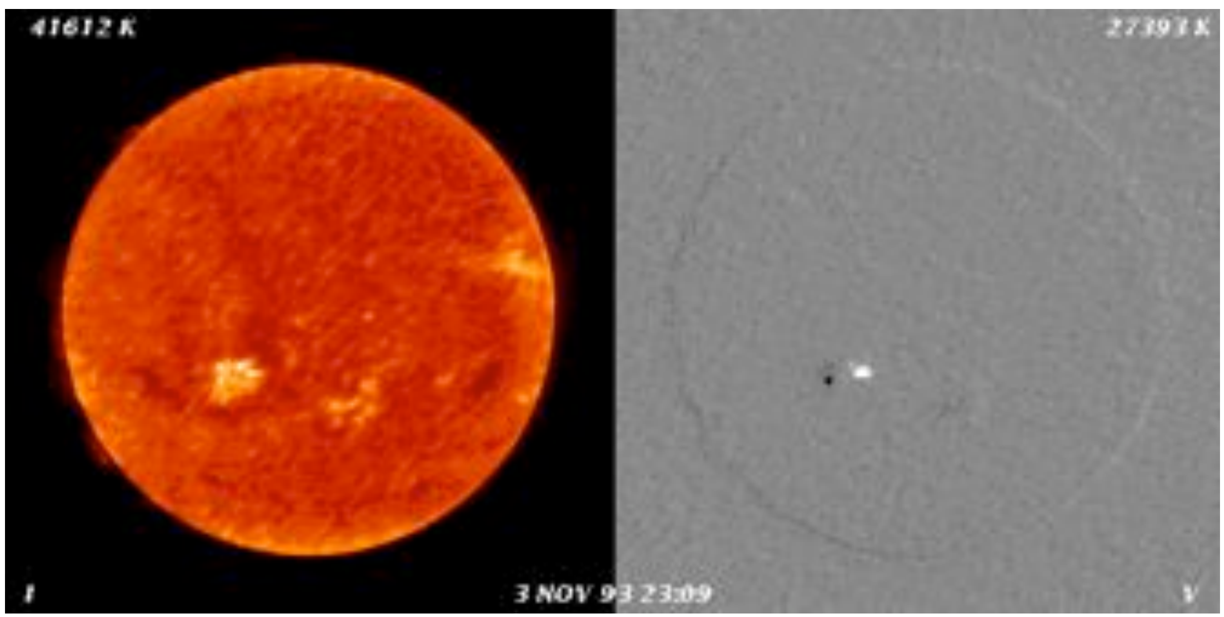
(Mutel et al. 1998)

- Broad spectra with turnover
- More optically thick at high flux
- Lower polarization at higer flux
- Polarization increasing with ν
- Polarization reversal @1-5 GHz
- Extended magnetospheres
- Slowly variable - “flare remnants”?
- B = a few 10 to a few 100 G





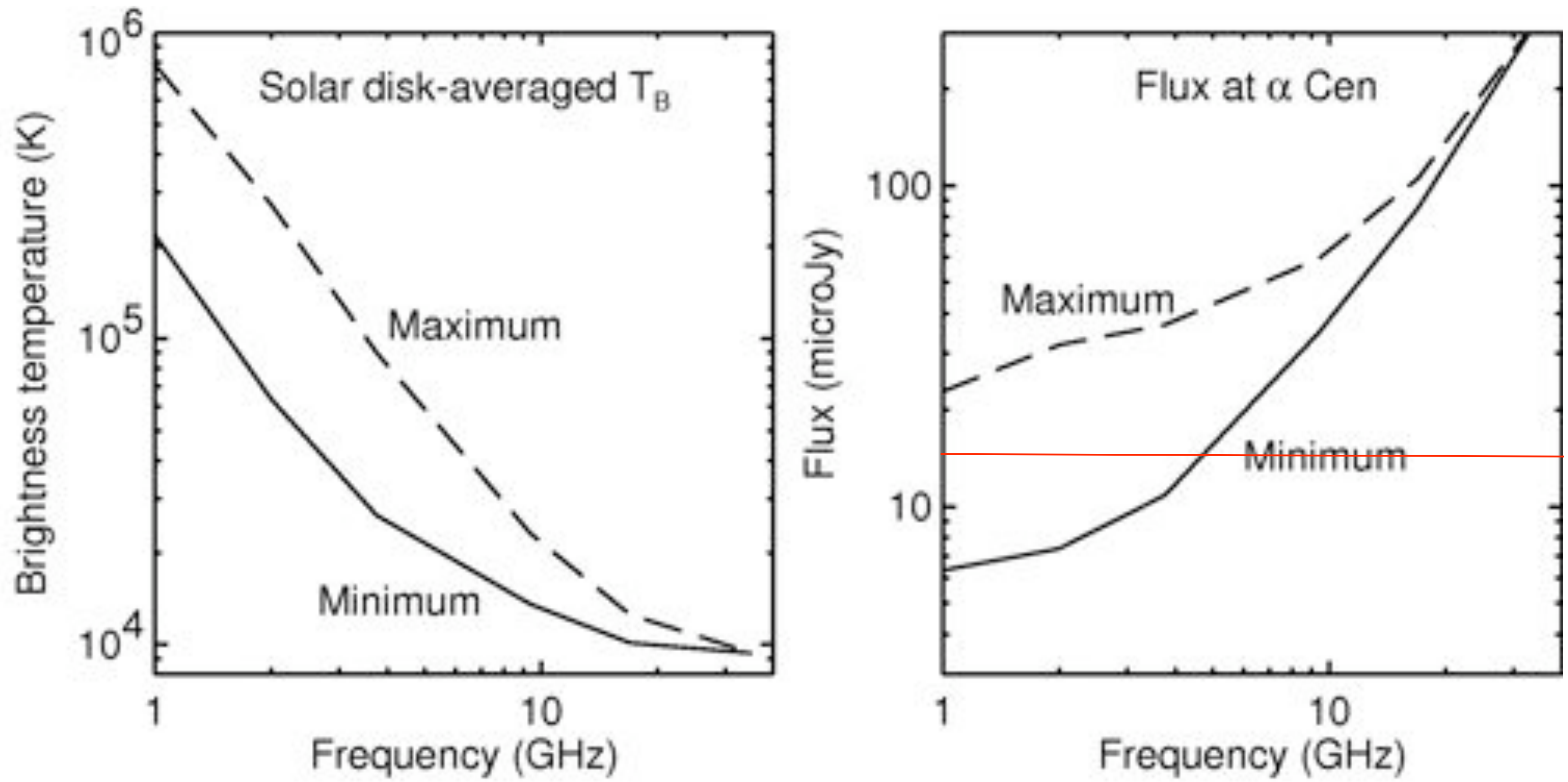




(S.M. White)

Full-disk bremsstrahlung ($2x10^4$ K): 40 μJy @ 10 GHz,1.3 pc (+ gyroresonance)

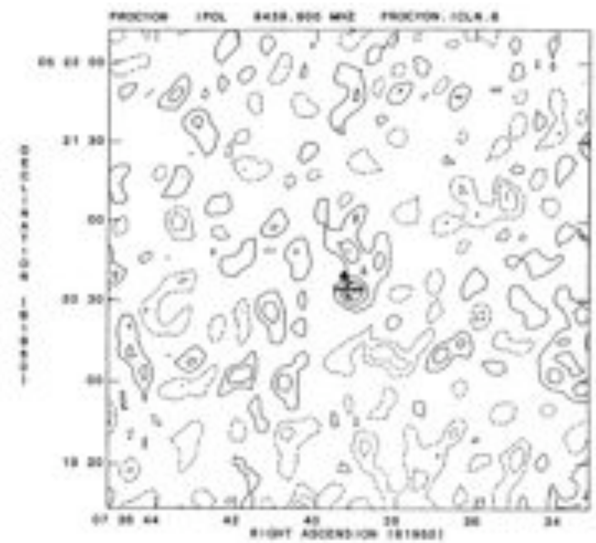
Quiet Sun at 1.3 pc



(White 2004)

Detected once by the VLA among main-sequence stars

Procyon, F5 IV-V subgiant, d = 3.5 pc



33 ± 8 μJy

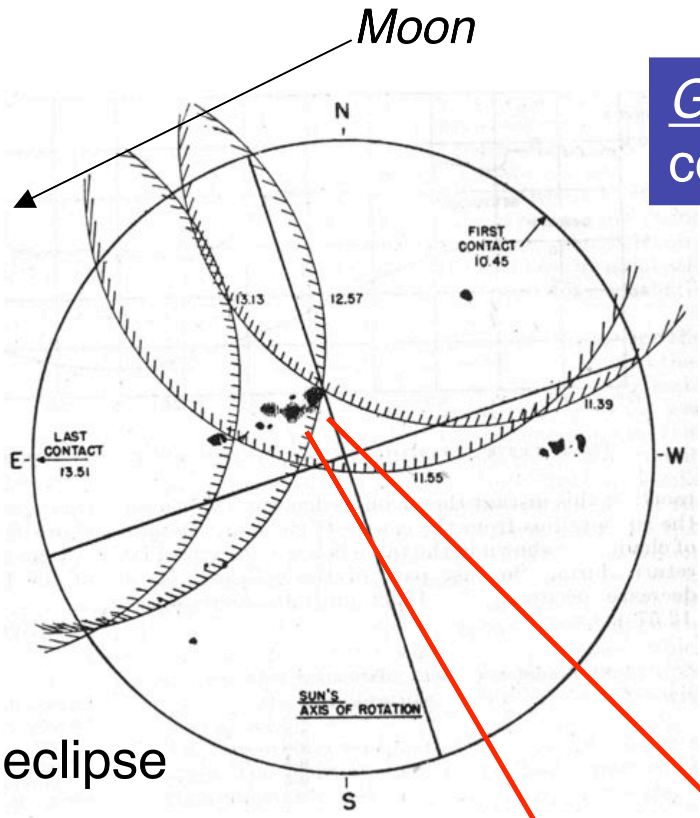
- consistent with optically thick "chromosphere" at 2×10^4 K (24 μJy)

- plus contributions from the optically thin thermal bremsstrahlung from the corona (12 μJy)

- Limit to ionized mass-loss rate: $2\times10^{-11}\ M_\odot \mathrm{yr}^{-1}$

(Drake et al. 1993)

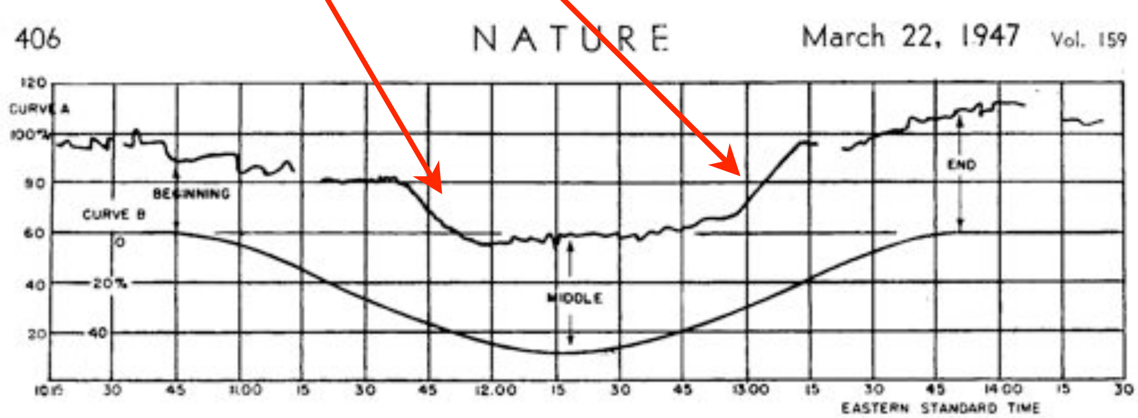
Going back to 1947:
coronal structure from 10.6 cm and eclipses



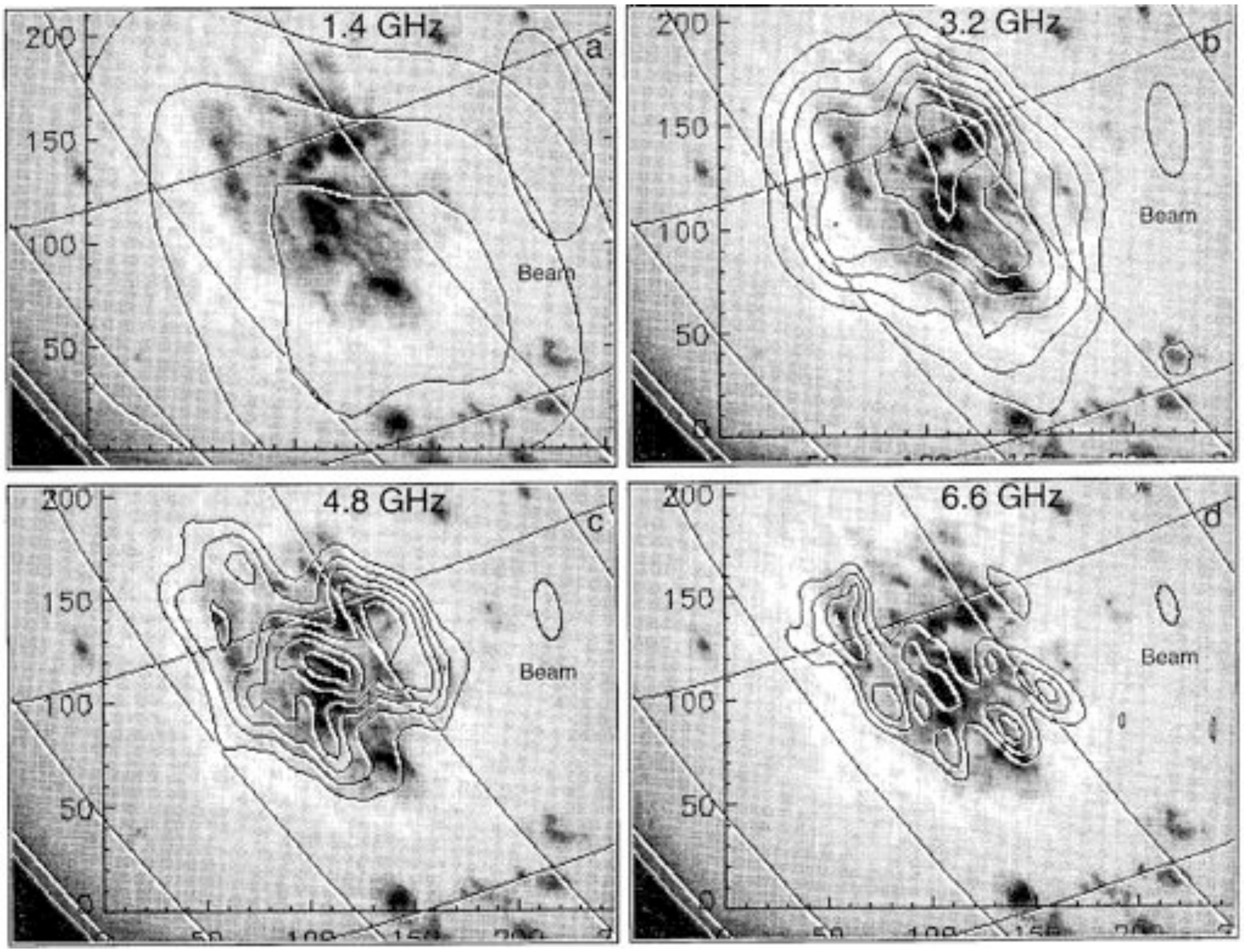
solar eclipse

"The ...region, totalling 2.2% of the sun's projected surface and containing the sunspot group....
With the present data, this area has an equivalent temperature of 1.5x10^6 K"

(Covington et al. 1947)



Solar active regions at radio wavelength



(Gary & Hurford 1994)

more compact and more structured at higher frequencies

Emission mechanisms for the non-flaring solar corona

1. Bremsstrahlung

$$\tau \approx 0.21\nu^{-2}T_e^{-3/2}\int n_e^2\,dl$$

- $f \propto \nu^{-2}$
- T_b in optically thick range
- EM or density at turnover $\tau = 1$

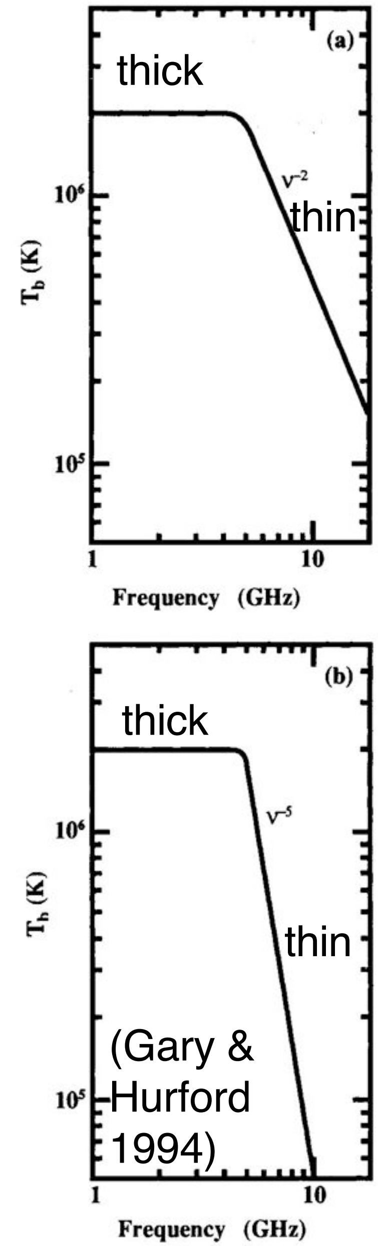
2. Gyroresonance emission

- Resonance at harmonics of gyrofrequency = $eB/2\pi m_e c$
- Inhomogeneous B fields → smeared to "continuum"
- Emission from highest harmonic that is optically thick*

- $f \propto \nu^{-5}$
- T_b in optically thick range
- maximum B field from turnover $\tau = 1$

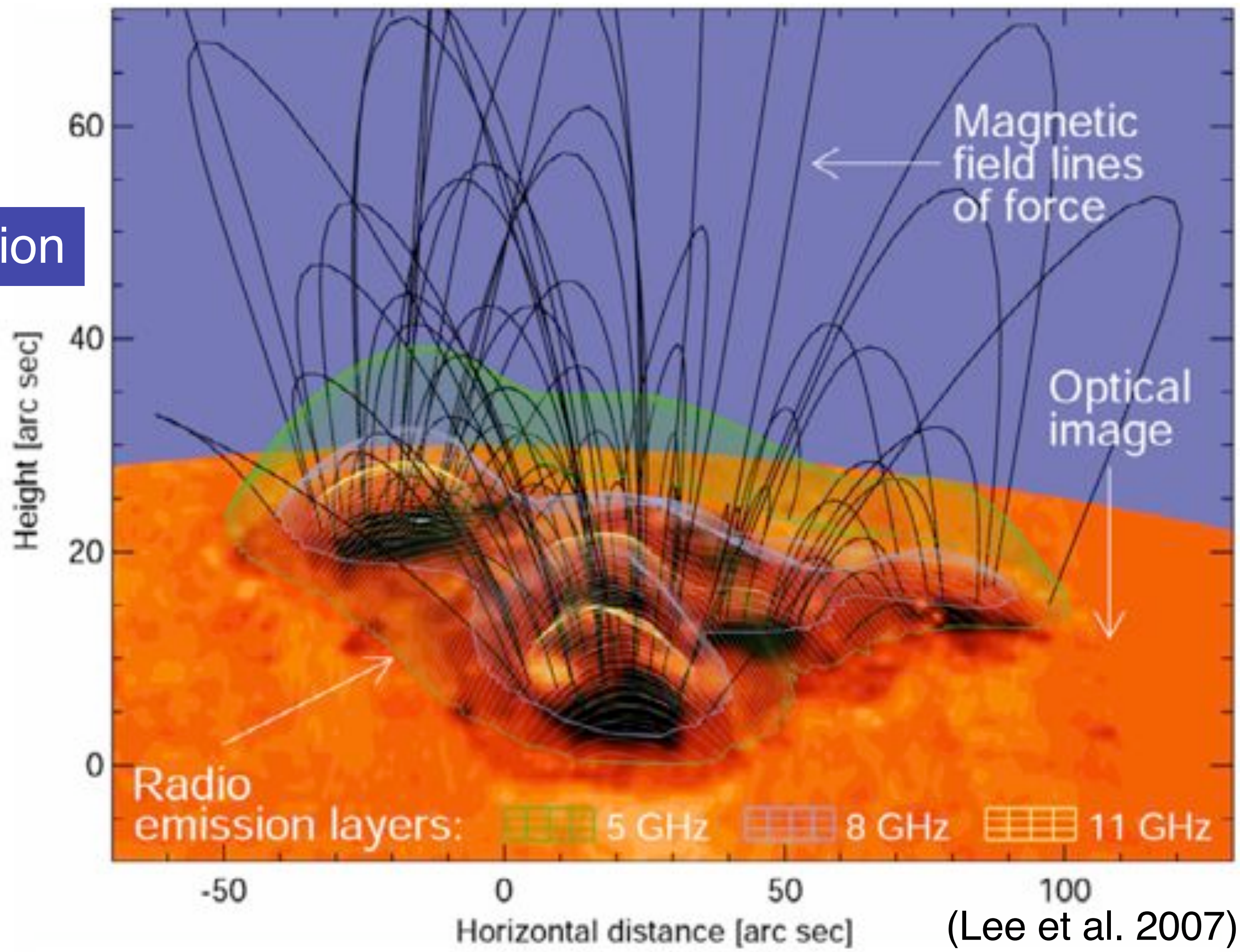
$$B_{\max} = \frac{\nu_{\tau=1}}{2.8 \times 10^6 s}$$

* *typically: s=2 or 3*



Brightness temperature spectra

Gyroresonance emission



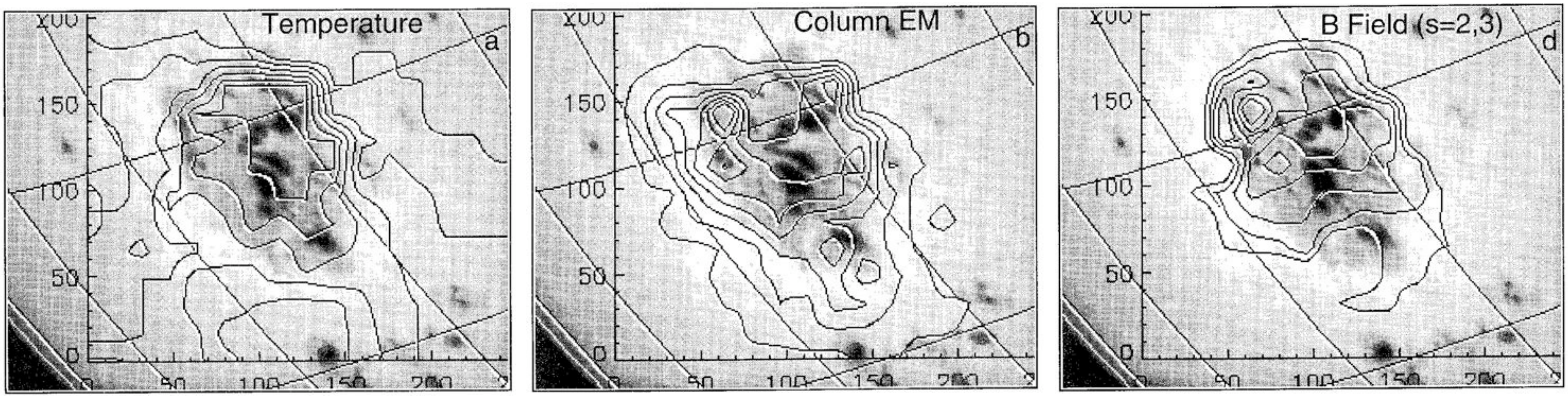
(Lee et al. 2007)

expanding B fields:

for given ν : emission at highest optically thick layer (typ. s = 2 or 3)

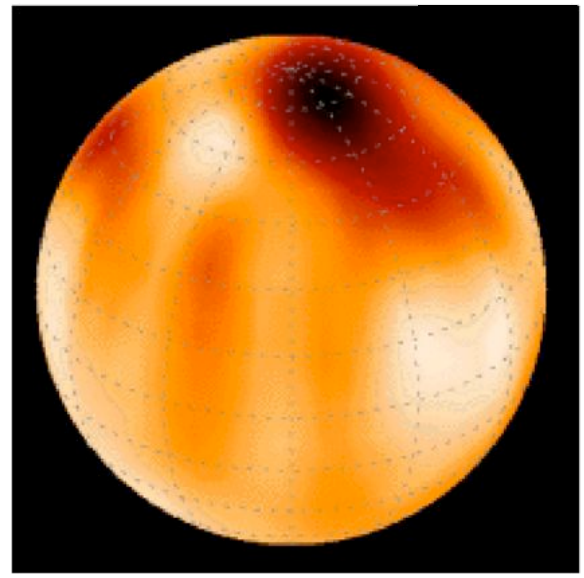
for spectrum: increasing ν $\rightarrow$ increasing B $\rightarrow$ decreasing height

frequency-dependent morphology of source



(Gary & Hurford 1994)

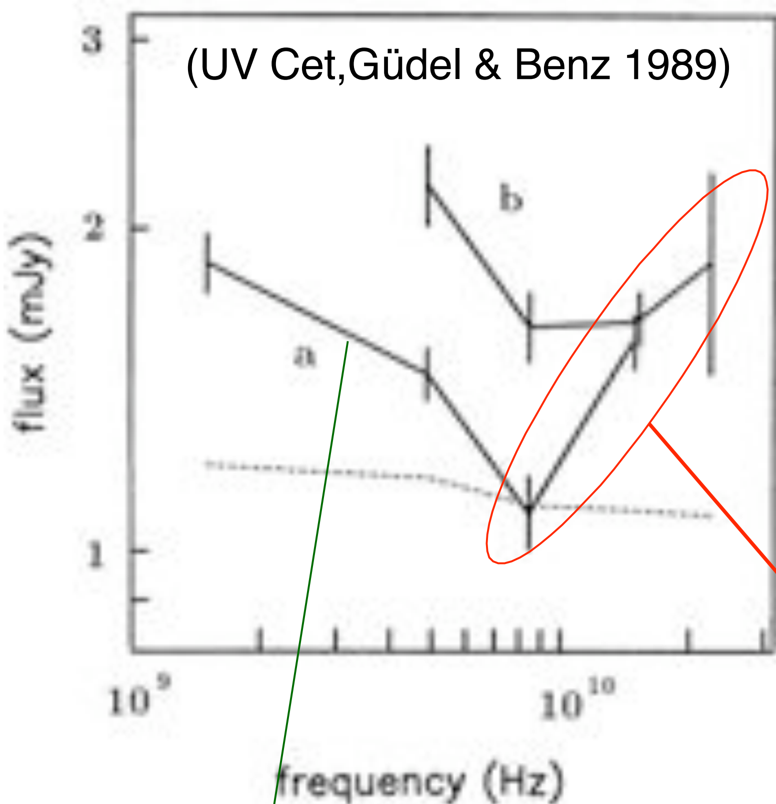
- $\mathbf{T_e}$ from X-ray observations
  → get filling factor (projected)
- get filling factor from Doppler images
  → estimate $\mathbf{T_e}$

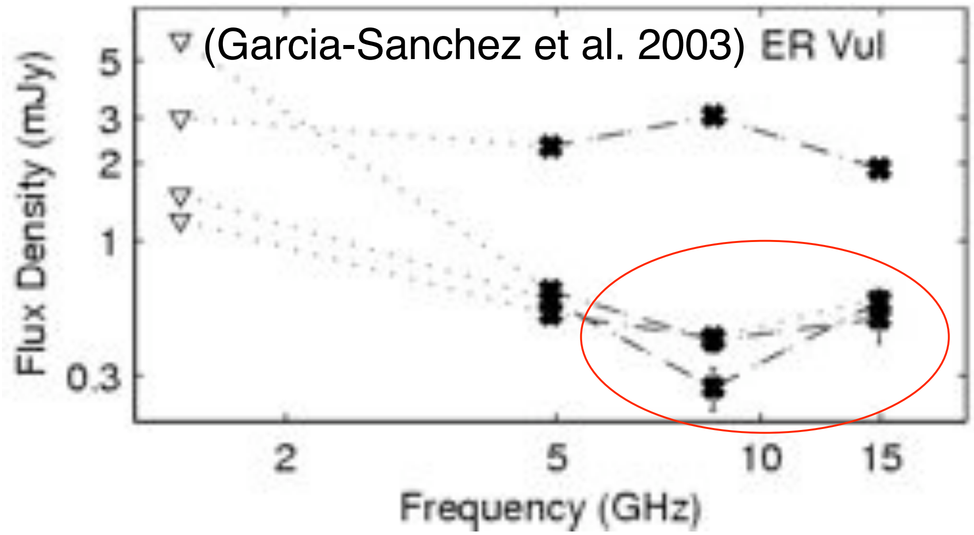


EK Dra, young solar analog
(Strassmeier & Rice 1998)

Caveat: Single observation may contain contributions from different gyroresonance layers; spatial resolution not available to stellar astronomer.

Gyroresonance emission from stars?





Optically thin gyrosynchrotron

Optically thick gyroresonance radiation in resonant coronal layer(s) with B = 600-2100 G, also observed in X-rays at 10 MK (constant, ~full disk)

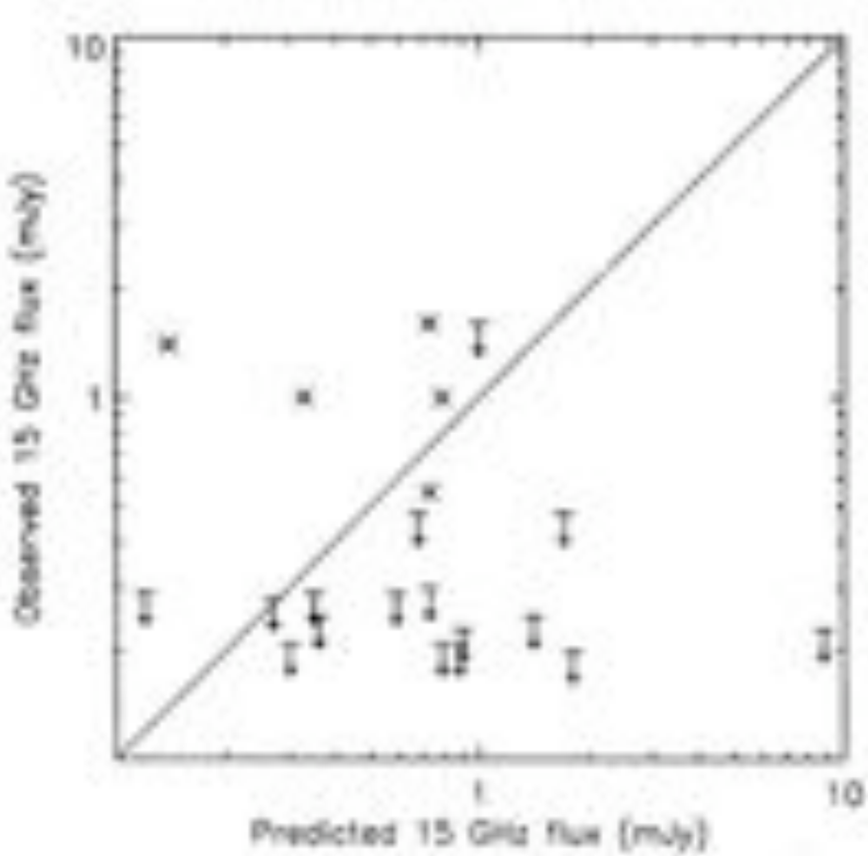
Gyroresonance detections in *active* M dwarfs (so far) exceptional:

Active M dwarfs with large
B surface filling factor (≈ 1).

Coronal T ≈ 10^7 K, B ≈ 1 kG:

Entire lower corona should be optically thick at 15 GHz due to gyroresonance opacity

→ should see rising, thermal spectrum with high 15 GHz flux, but...mostly not seen!



(White et al. 1994)

Hot plasma *not* in strong magnetic fields (in-between or above)?

Expectations for the EVLA: solar analogs, M dwarfs

projected area

$$S = \frac{2kT_b\nu^2}{c^2}\frac{A}{d^2}$$

<u>solar analog</u>
R = 7×10^{10} cm, filling factor f=10%: $A = f\pi R^2$
T_b = 10 MK
d = 10 pc

ν = 4.9 GHz

S = 12 μJy

<u>M dwarf</u>
$R = 2 \times 10^{10}$ cm (f=10%)
T_b = 7 MK
d = 5 pc

ν = 14 GHz

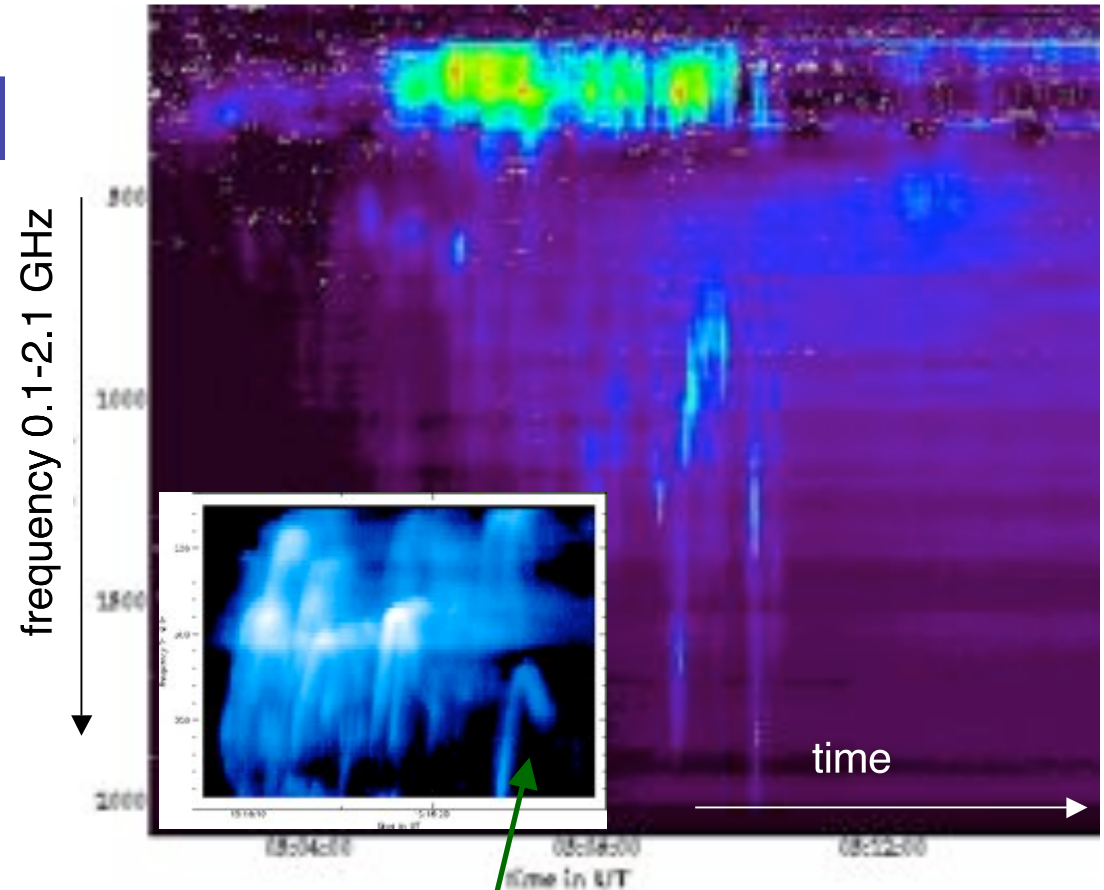
S = 22 μJy

Useful to derive
- *filling factor of active regions, and distribution on star (mapping)*
- *temperatures in low corona*
- *activity cycles*

Solar flare coherent emission

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

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



Characterized by traces in dynamic spectra:
$I(\nu,t) \rightarrow$ trace in n_e or B

<u>Examples</u>:
- Traces of *electron beams* (0.1-0.3c) in magnetic loops (local plasma freq.)
- *Pulsations*: MHD modes or pulsed particle acceleration
- Coronal *shock fronts* exciting plasma waves while traveling upward
- Shortest bursts (1-10 ms): “elementary” particle acceleration?

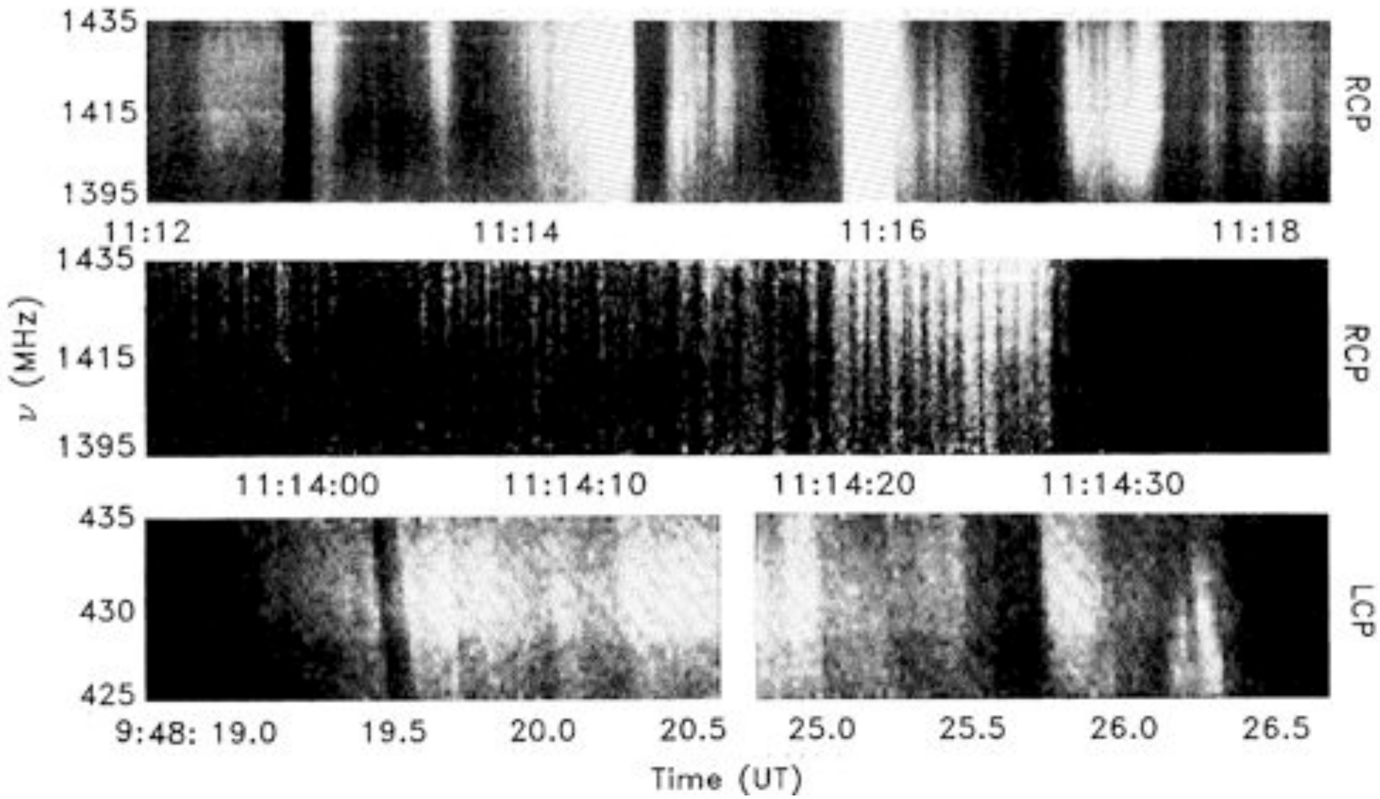
<u>Studies of particle acceleration timing, propagation speeds,B field strength...</u>

dMe stars: Δt = 20 ms; 32 channels, Arecibo

40 MHz

40 MHz

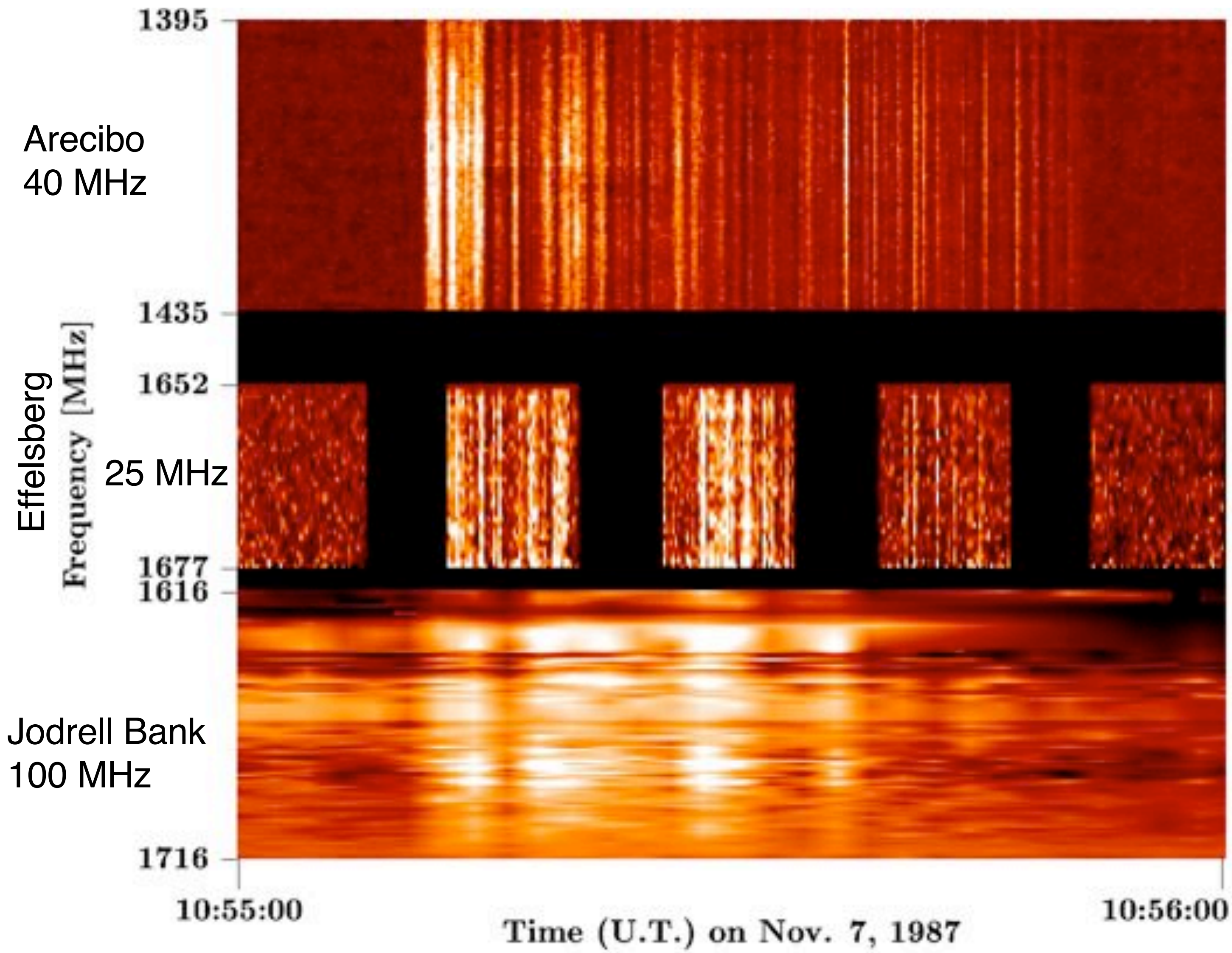
10 MHz



"sudden reductions"
<20 ms spikes → source < 6000 km → $T_b > 6.2 \times 10^{15}$ K
"pulsations"
drifting structures
100% polarization

(Bastian & Bookbinder 1990)

AD Leo with 3 observatories



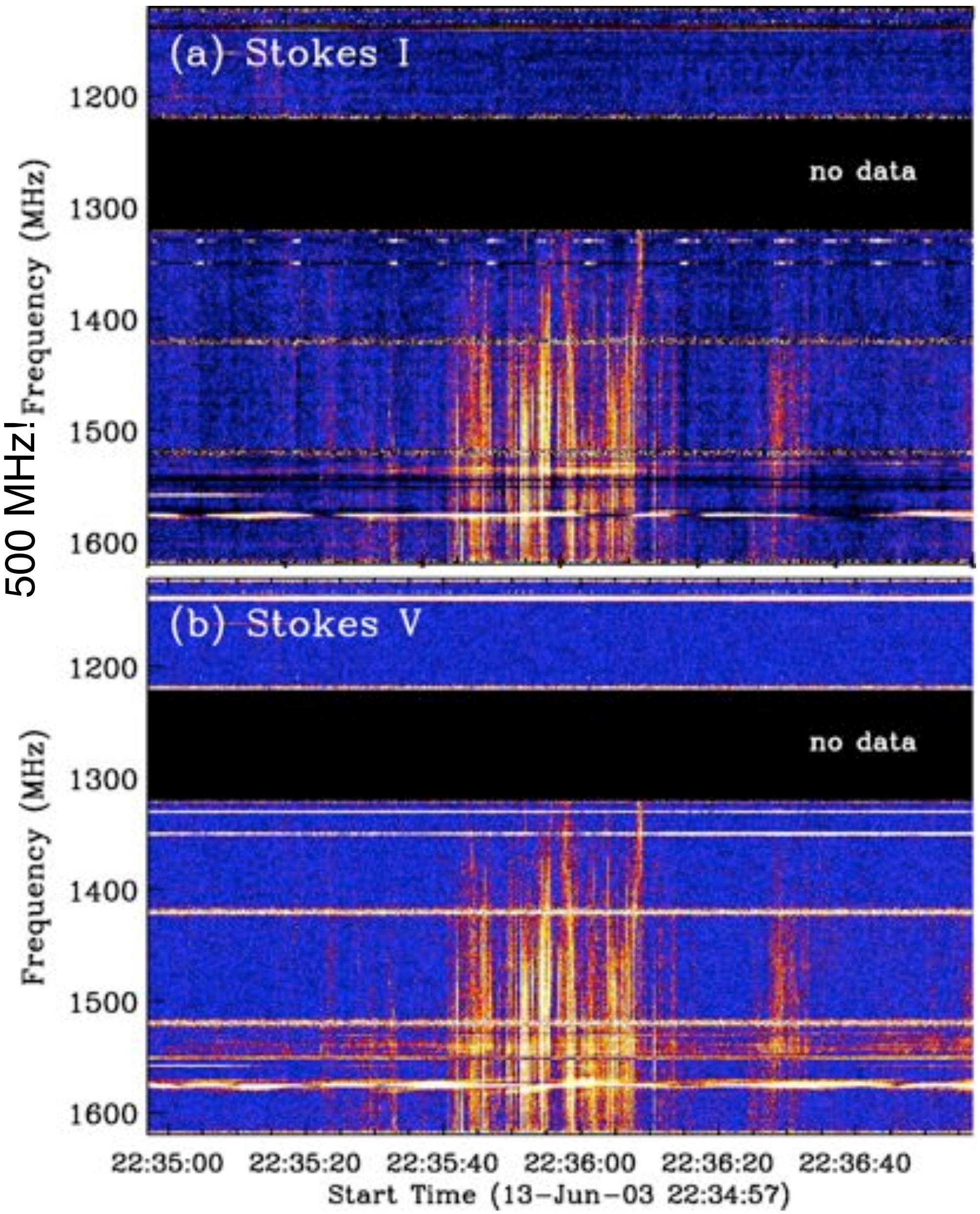
narrow-band
pulsation
100% pol.

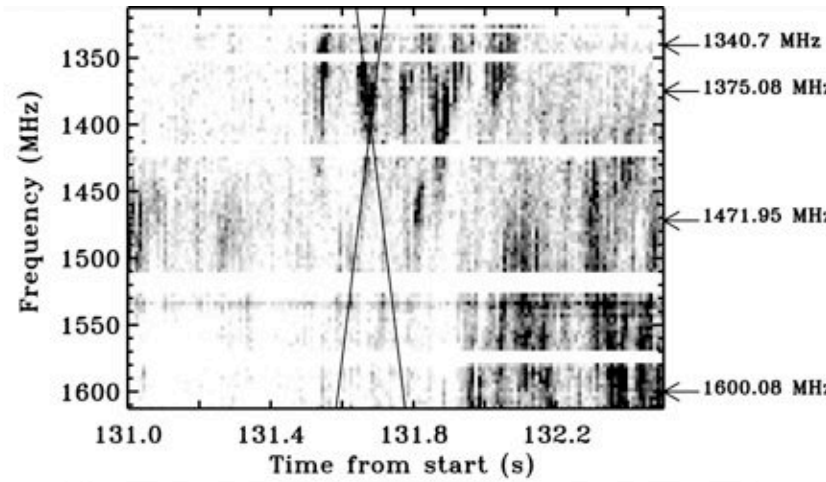
ECM?

(Güdel et al. 1989)

AD Leo, Arecibo, 10 ms

500 MHz!





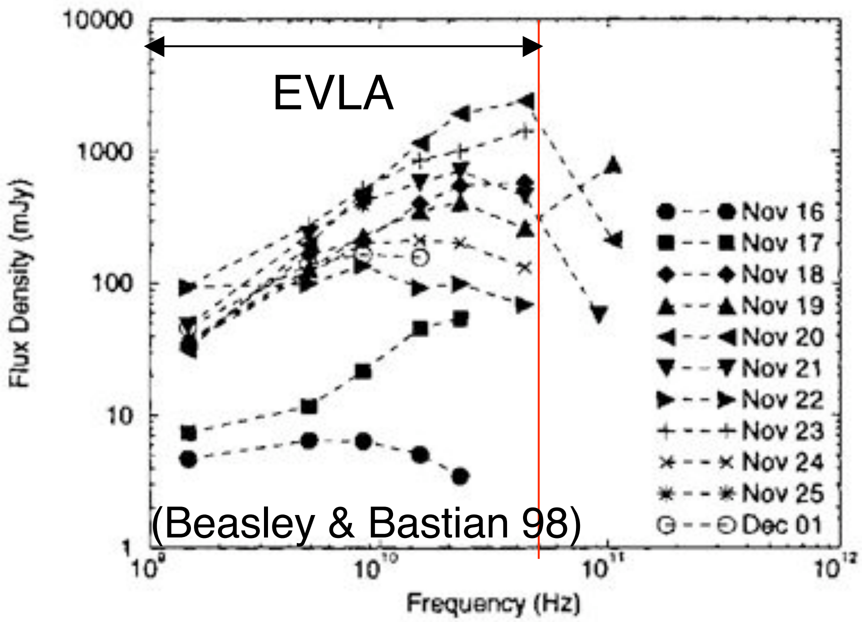
20 ms bursts (source < 9000 km)
>90% polarization
narrow bandwidth (5%)
fast drifts (Osten & Bastian 2006)

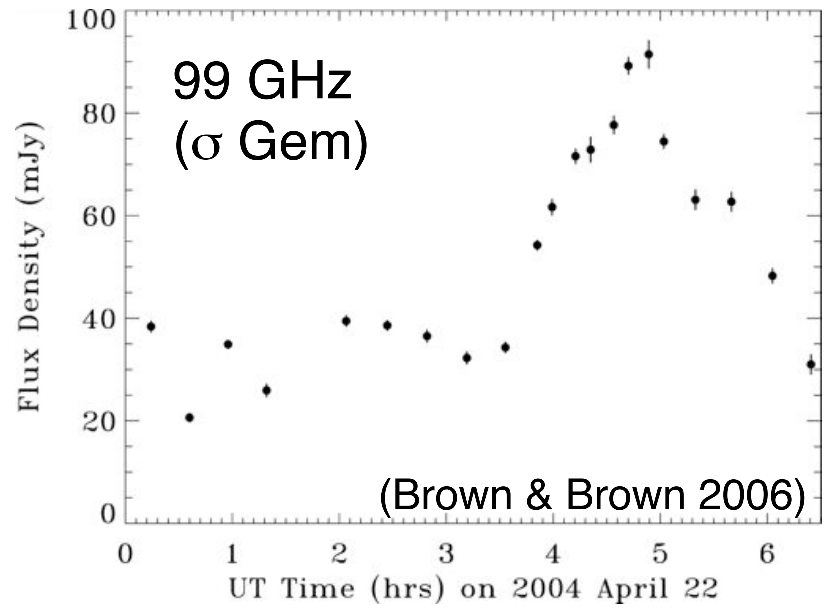
AD Leo's corona is hot (6-20 MK)

Gyrores: $\kappa \propto T^{s-1}$
Plasmaem.: $\kappa \propto T^{-3/2}$ (free-free)

escape more favorable for <u>plasma emission</u> in *hot* coronae

Incoherent gyrosynchrotron flares





Diagnostics from turnover: → B $\quad B \propto \nu^5_{peak} S^{-2} r^4$ (see Lang 1999)

(S = peak flux, r = source diameter)

dipolar models $\quad B_0 = 150\ \nu^{1.3}_{peak}$ (White et al. 1989)

(ν_{peak} in GHz)

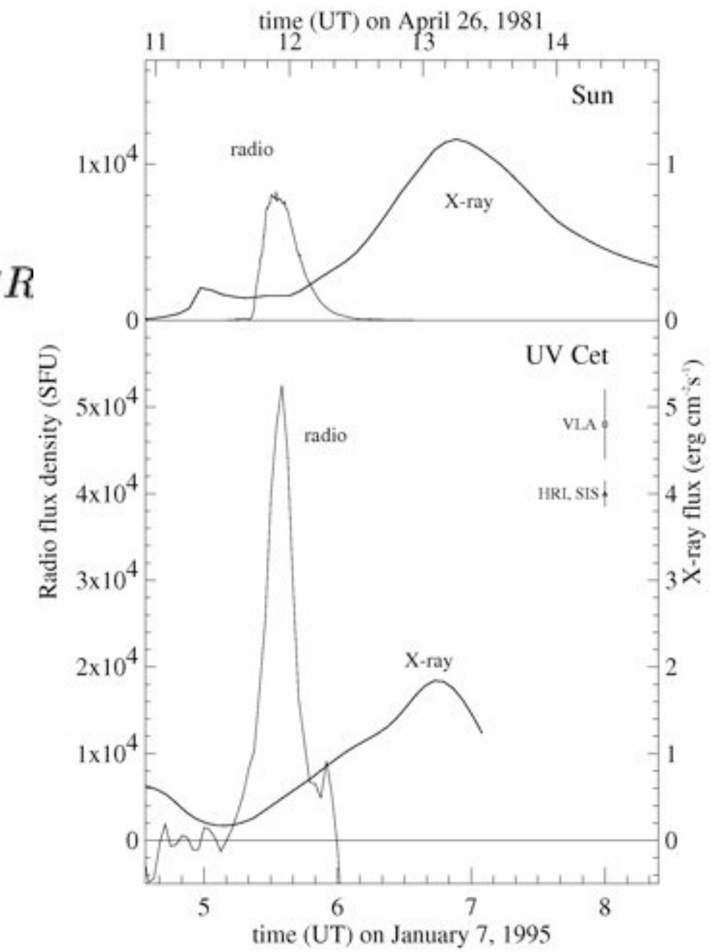
The “Neupert Effect”

approximation for
radiative loss time >> energy release time

$$\frac{d}{dt}(3n_e kTV) \quad \propto \quad \text{electron flux} \quad \propto \quad L_R$$

$$\frac{d}{dt}L_X \quad \propto \quad L_R$$

"Neupert Effect"
(the proportionality between thermal energy content and radiative loss is a crude approximation)

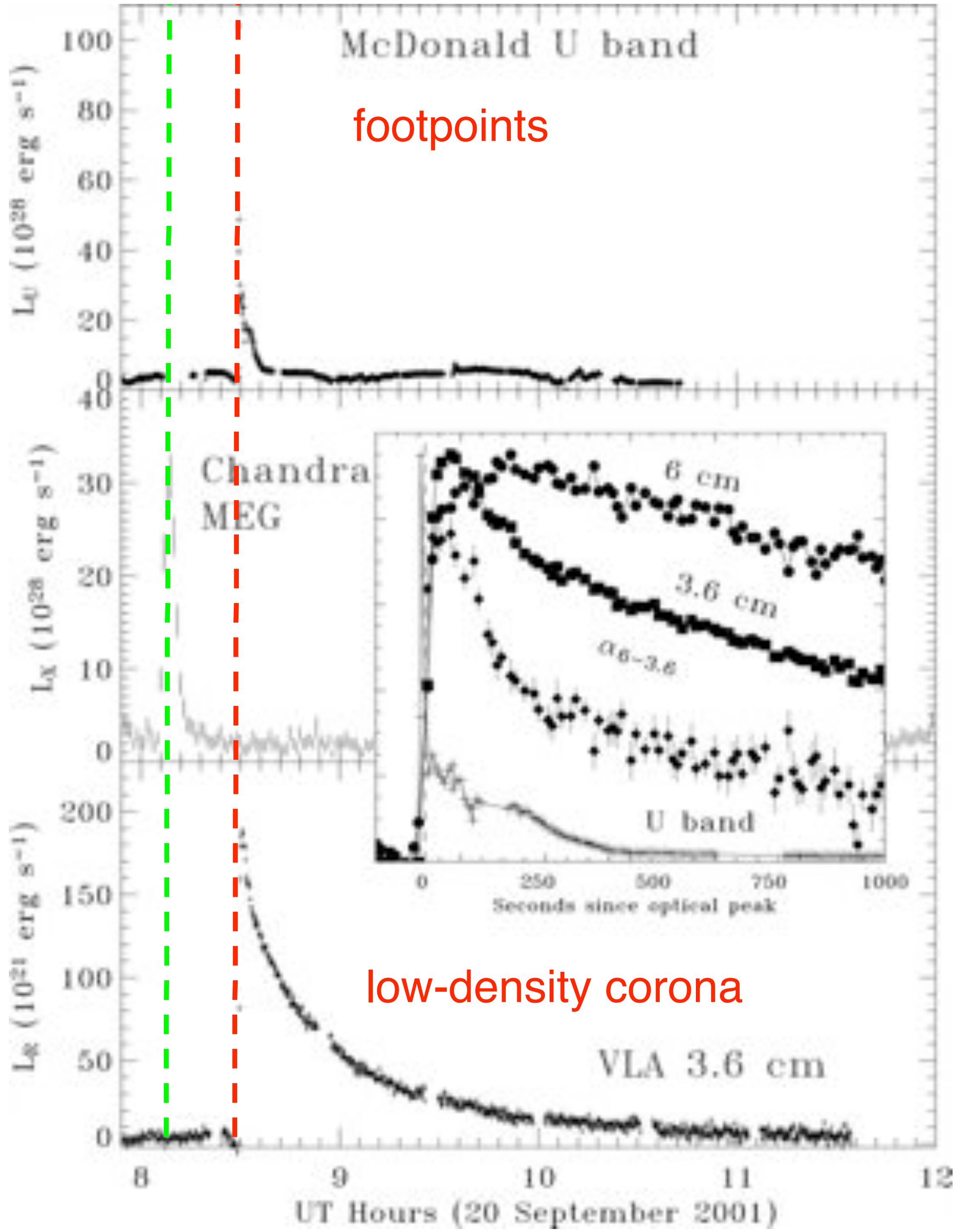


(Güdel et al. 1996)

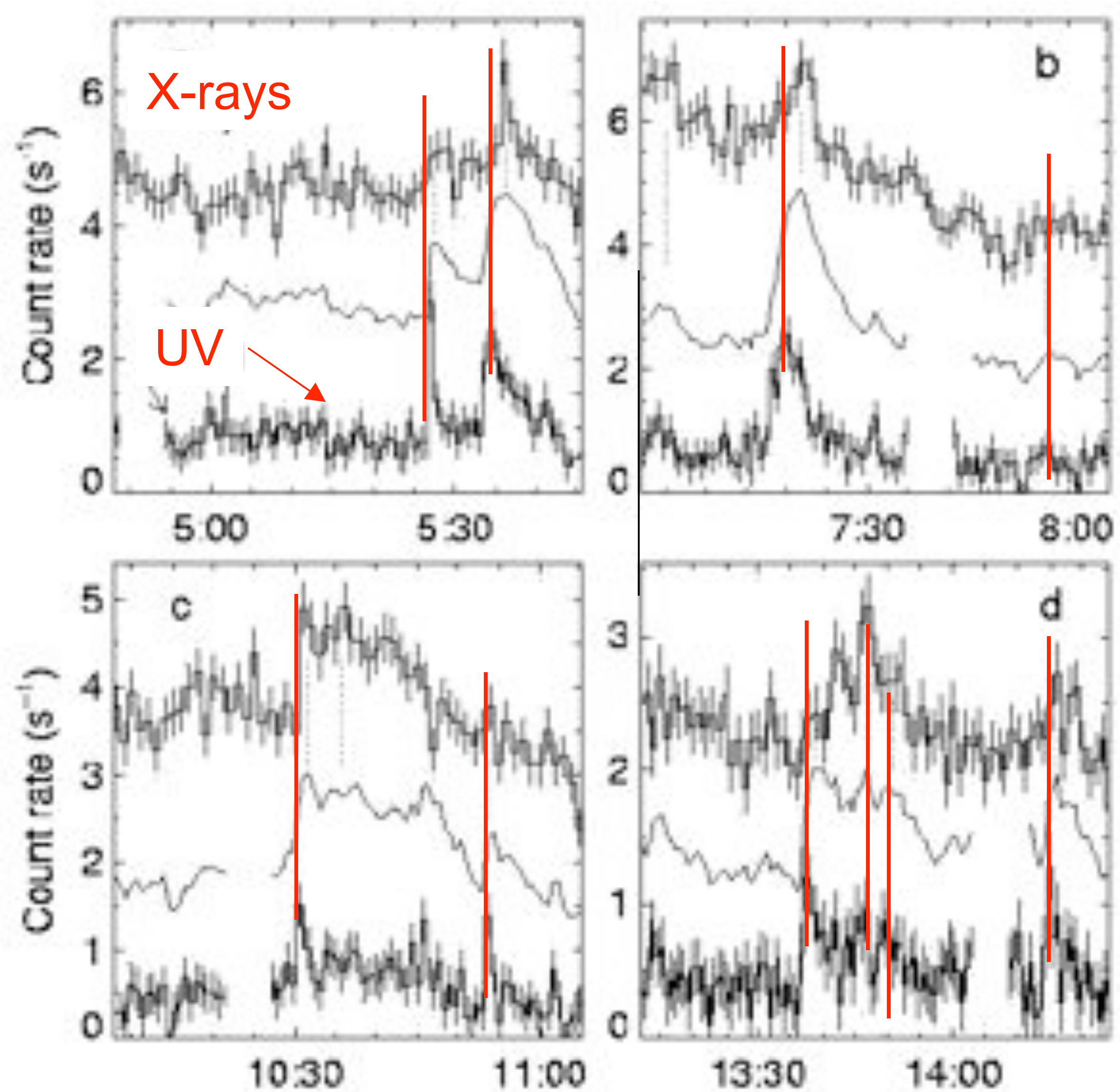
Counter-example:

EV Lac (Osten et al. 2005)

- no heating of / evaporation to corona?
- perfect trapping of electrons in corona (BUT: U band?)
- coronal flare of very low density?
- shadowing of some source?
- very-high energy particles penetrate deep into photosphere: no evaporation?



Smallest stellar flares seen in X-rays: Proxima Centauri



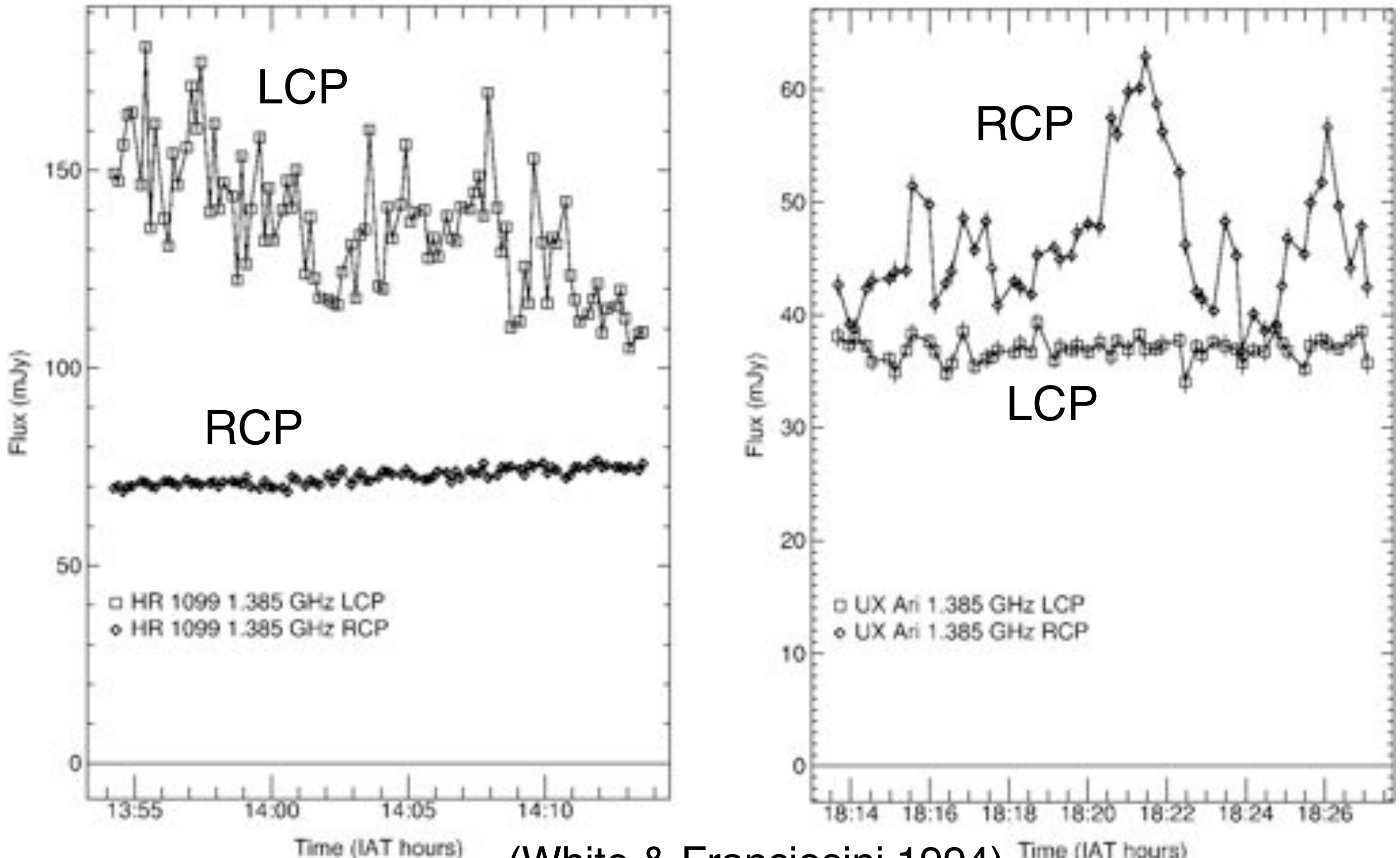
(Güdel et al. 2002)

UV another prompt tracer of accelerated electrons

<u>EVLA</u>: Signatures of particle acceleration,

i.e. primary energy release,

from radio?



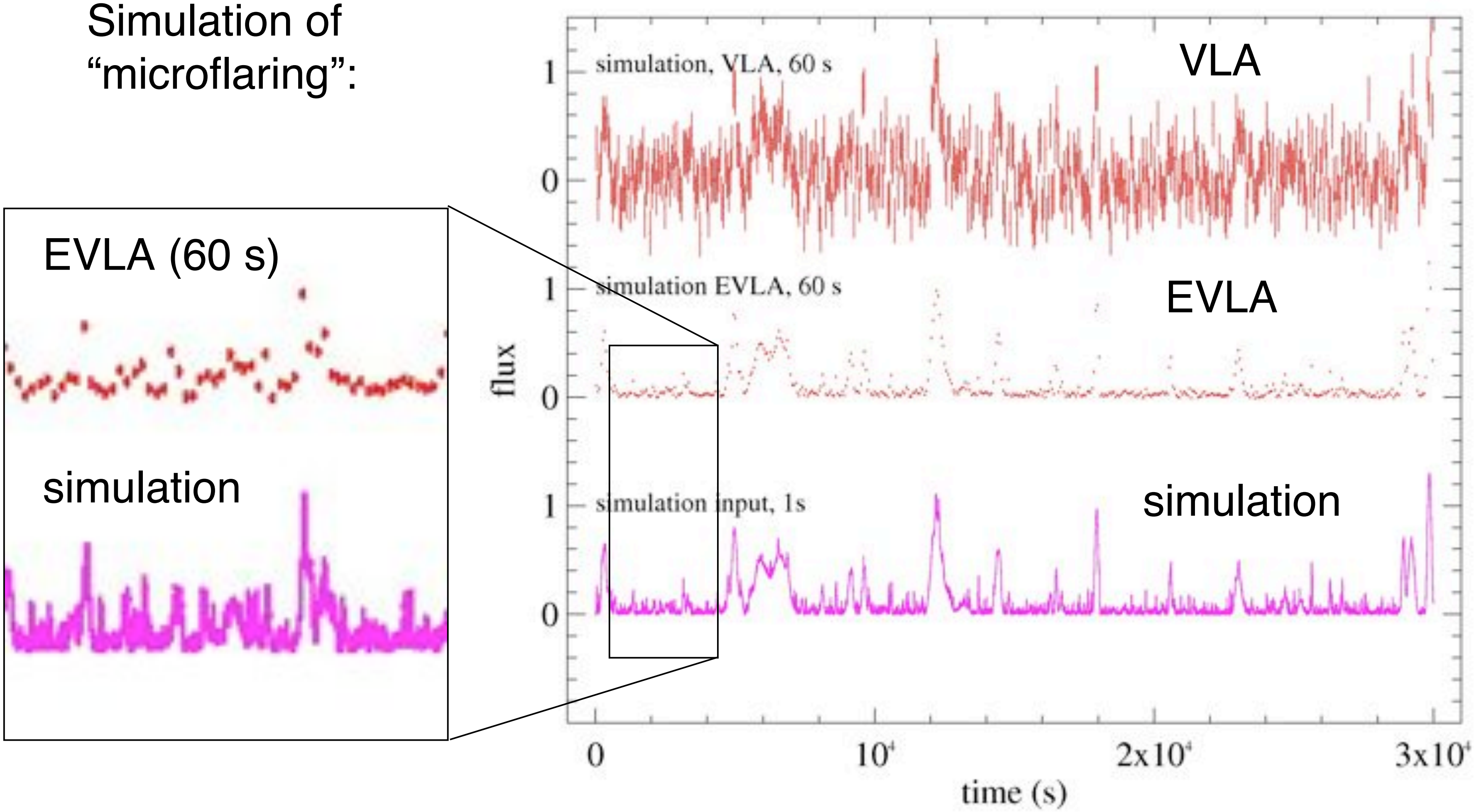
(White & Franciosini 1994)

Fluctuating coherent emission at L band ontop of gyrosynchrotron emission.
Opposite polarization to high-freq. gyrosynchrotron → <u>plasma emission</u>

Signature of very frequent, impulsive particle acceleration?
Need high sensitivity and spectral characteristics

What can the EVLA contribute?

Simulation of "microflaring":

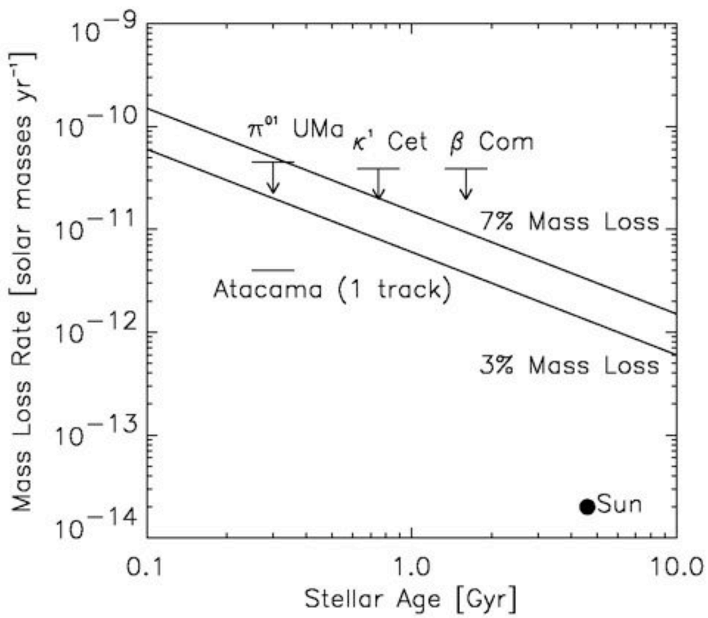


Stellar mass loss

Ionized-mass loss (optically thick) (Wright & Barlow 75): $S \propto \dot{M}^{4/3} \nu^{0.6}$

Faint Young Sun Paradox:
- The early (zero-age main sequence) Sun was only 70% as bright as today
- But early climates of Earth and Mars were milder & warmer
- Liquid water on Earth and Mars only with exceptionally strong greenhouses

Or: a more massive young Sun that has lost mass (a few %) in a strong wind?
(Sackmann & Boothroyd 2003)   Search for winds: S. Drake et al., Lim et al. (upper limits)



Need better sensitivity at higher frequencies for stars not "contaminated" by non-thermal radio emission

(Gaidos, Güdel & Blake 2000)

Summary

The EVLA's capabilities will provide novel access to stellar magnetic fields and energy release.

Characterization of active regions and flaring regions through

- *optically thick gyroresonance emission and bremsstrahlung*

- *coherent emission recorded in dynamic spectra*

- *variability in highly sensitive time series*

Link to solar physics!