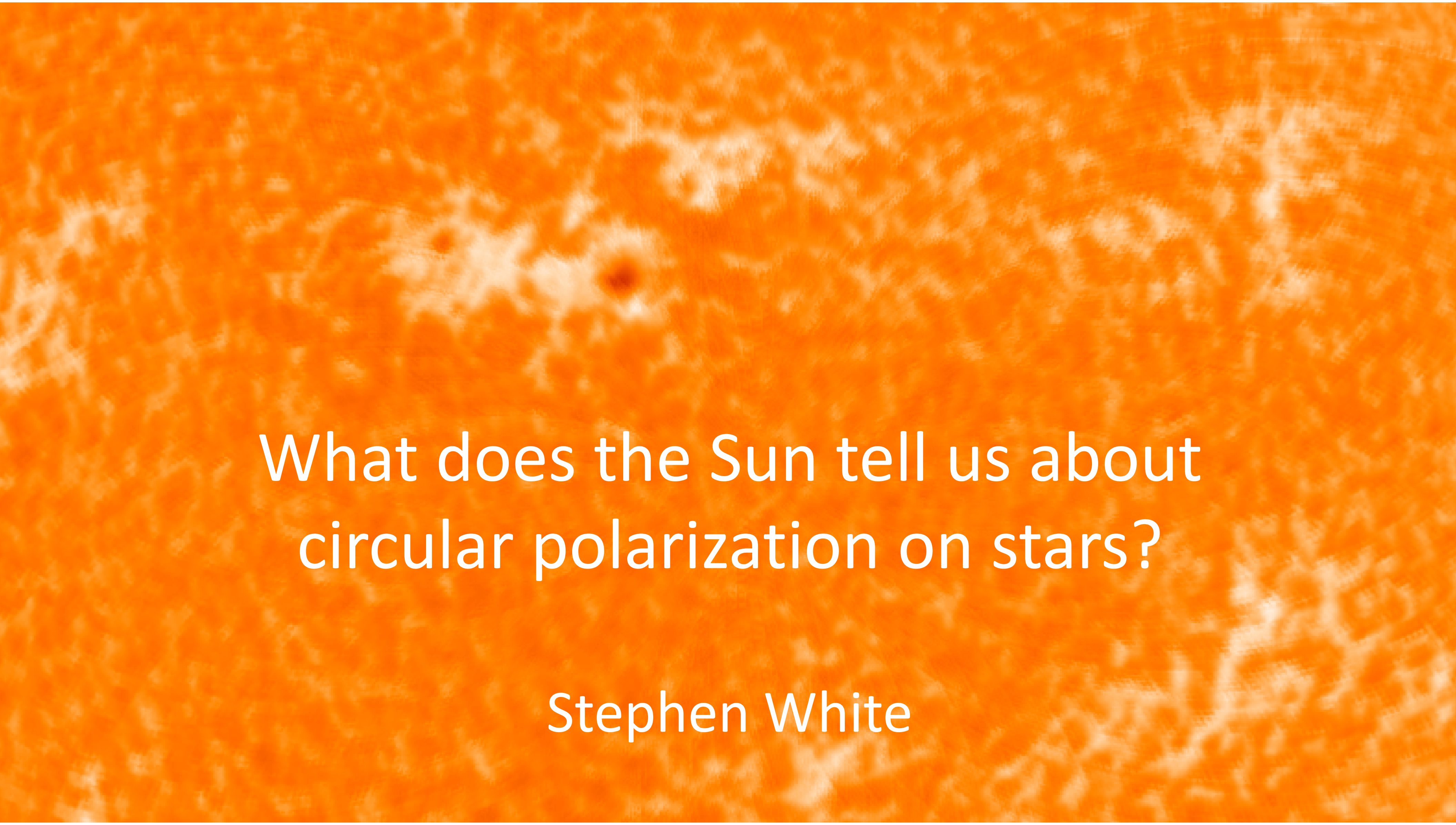
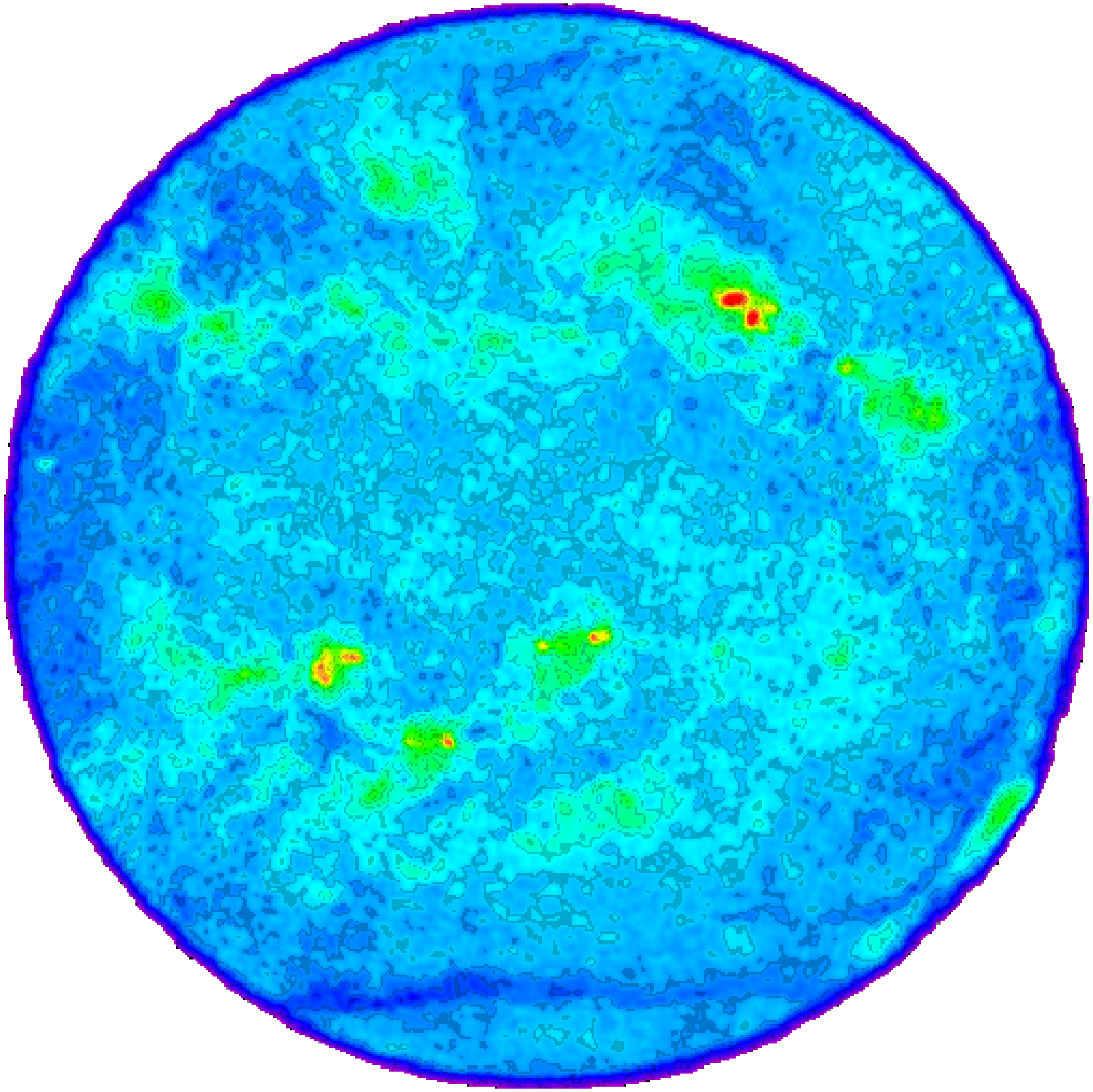


What does the Sun tell us about circular polarization on stars?

Stephen White

The Radio Sun at 4.6 GHz



Combination of:

- optically thick upper chromosphere,
- optically thick coronal gyro-resonance where B>500 G in active regions, and
- optically thin coronal bremsstrahlung

Radio Emission Mechanisms

Bremsstrahlung due to thermal plasma occurs throughout the solar atmosphere and is the dominant mechanism in most of the corona. It is optically thin above a few GHz and usually weakly polarized (plasma response).

Gyroresonance emission (emission from nonrelativistic thermal plasma at low harmonics of the electron gyrofrequency 2.8 B MHz) is strong wherever B > 300 G in the corona and produces optically thick emission in active regions which may be highly polarized.

Gyrosynchrotron emission (emission by mildly relativistic electrons at harmonics 10-100 of the gyrofrequency) is produced by nonthermal electrons in flares; broad frequency response.

Cyclotron maser emission (maser emission at harmonics 1-2 of the gyrofrequency) is produced by energetic electrons with free energy in their pitch angle distribution (loss cone or horseshoe): spiky, highly polarized.

Plasma emission is produced by energetic electrons at low harmonics of the plasma frequency $f_p=9000n^{1/2}$: produces bright highly polarized bursts at low frequencies. In the presence of magnetic fields, fundamental plasma emission is highly polarized.

Circular polarization comes from magnetic fields

The presence of a magnetic field in a plasma breaks the degeneracy of the two propagating transverse electromagnetic modes.

Except when looking perpendicular to B, the natural radiation modes are predominantly circular. Electrons gyrate in magnetic fields, so they interact most strongly with the mode that matches their sense of rotation.

This argument does not refer to a specific radiation mechanism.

Happily, Faraday rotation in the solar corona at radio wavelengths is large and wipes out linear polarization.

Gyroresonance emission

Opacity results from electrons gyrating in coronal magnetic fields at $f_B = 2.8\ 10^6$ B Hz: linear scaling of B with frequency.

In the non-flare (non-relativistic) corona this produces narrow resonances, i.e. physically very thin layers (tens of km). Usually optically thick!

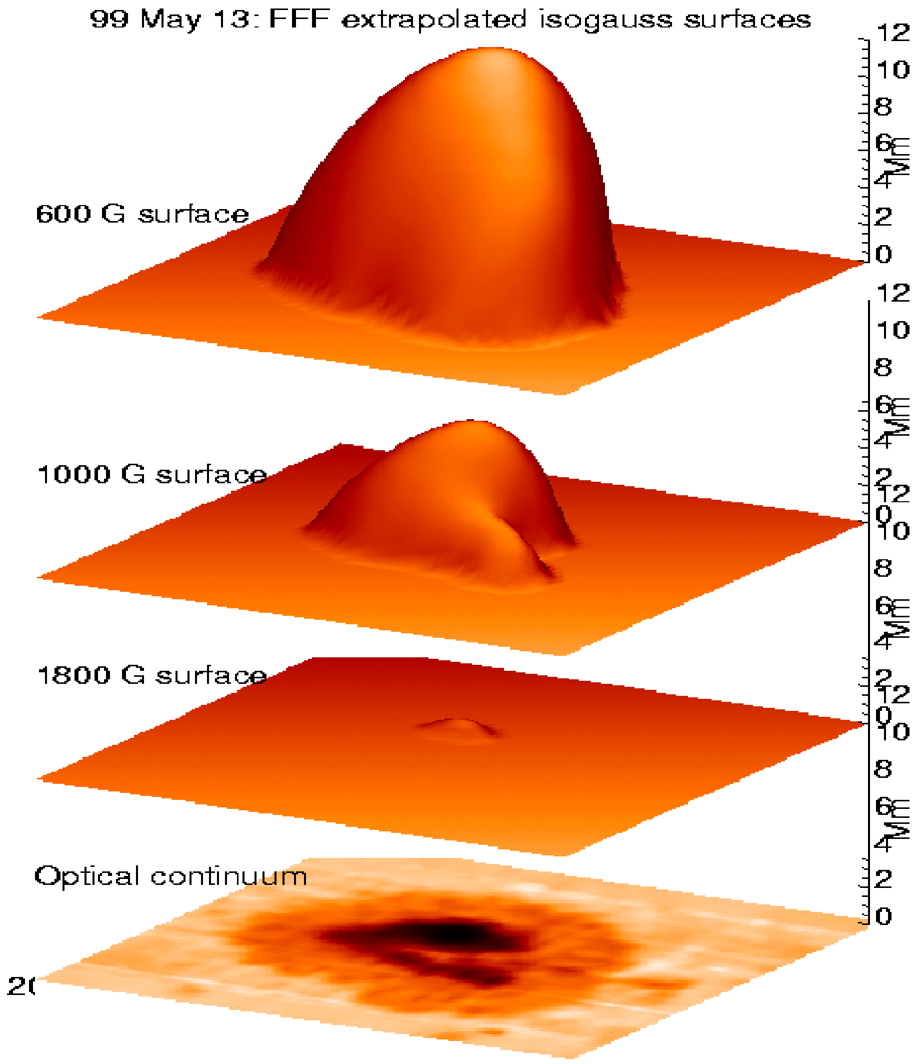
$$\text{Opacity} \propto \ n \quad B/(\partial B/\partial l) \quad (T/mc^2 \sin^2\theta)^{s-1}$$

where s = 1, 2, 3, … is the harmonic

Because T/mc^2 is 1/3000 on the Sun, opacity drops by 3 orders of magnitude from one layer to the next. On active stars, perhaps T/mc^2 is 1/300

Big difference in opacity of two polarizations of electromagnetic waves: extraordinary mode interacts more with electrons than ordinary mode

Gyroresonance layers



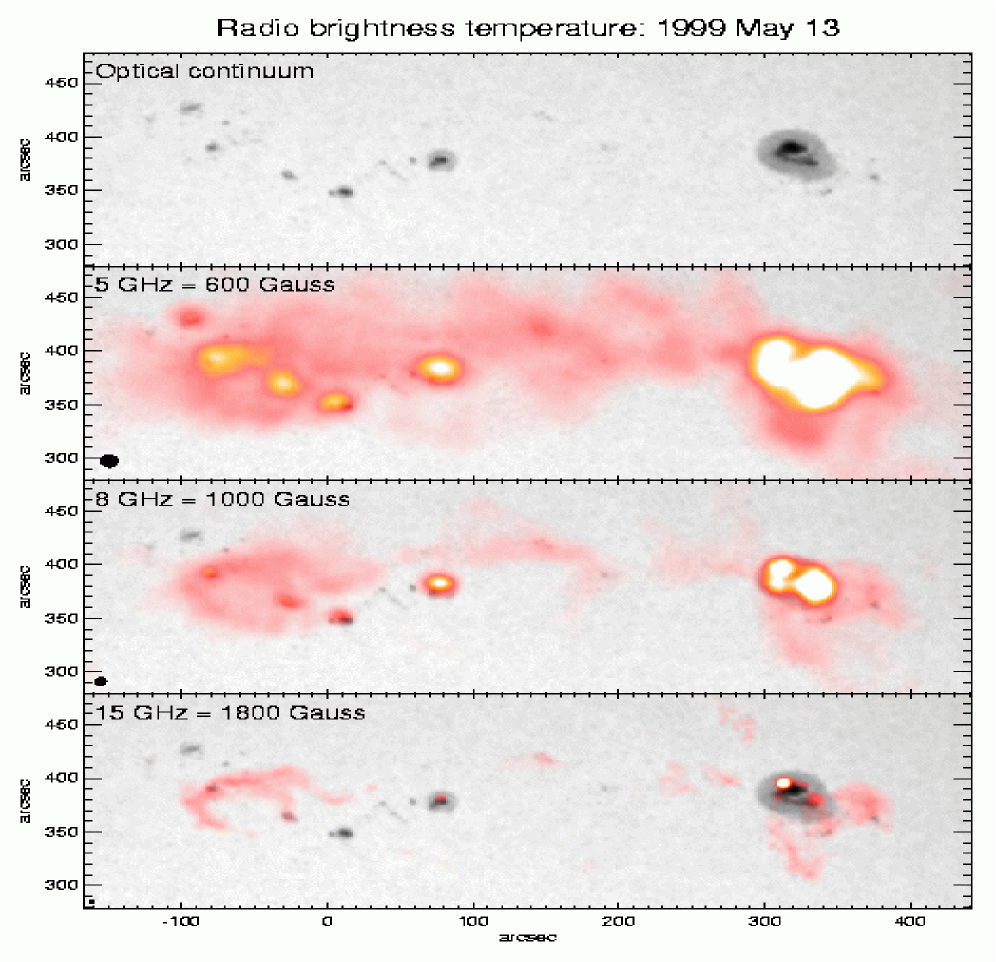
Gyroresonance opacity is the only mechanism capable of making the corona optically thick at frequencies above 4 GHz

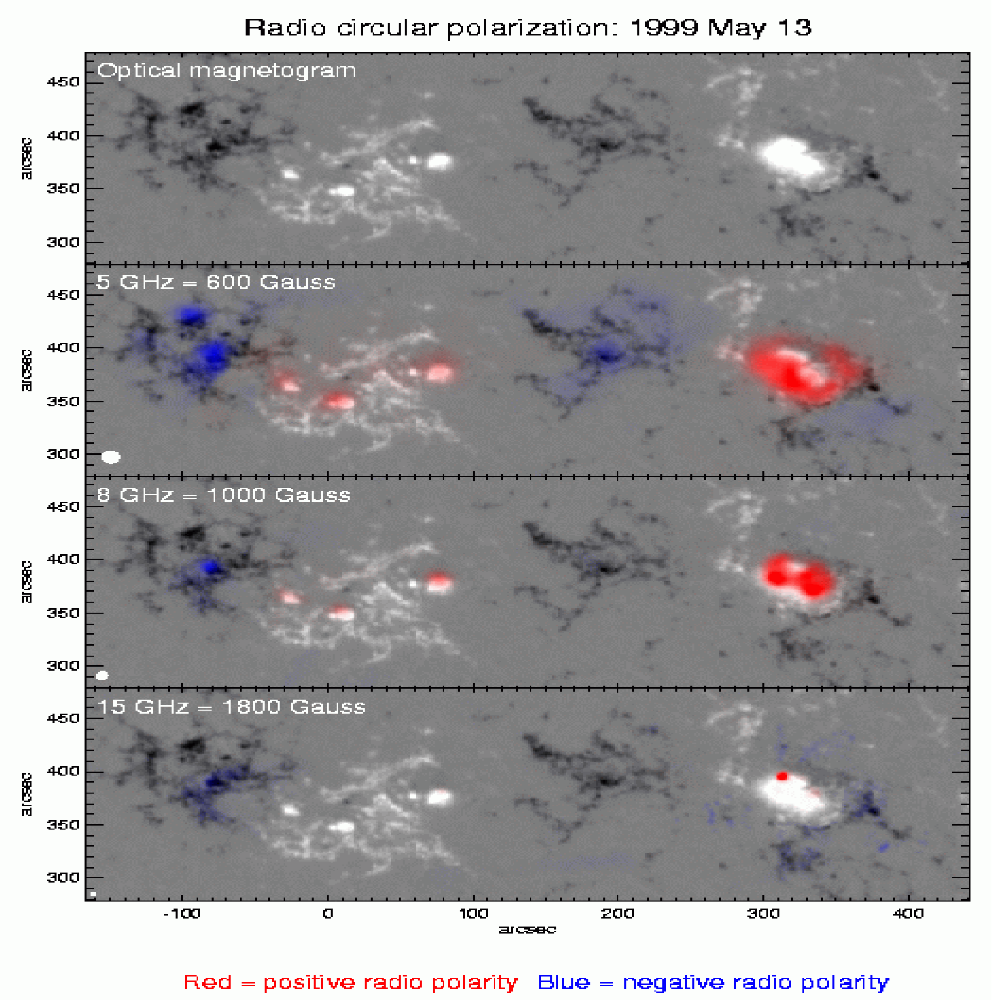
Emission comes from a surface of constant magnetic field in the corona

Coronal temperatures indicate the presence of magnetic field strengths at appropriate strengths: microwaves are sensitive to fields in the range 200–3000 G.

High levels of circular polarization also indicate presence of strong magnetic fields and can be used to measure temperature gradients

Radio emission from the solar corona above active regions



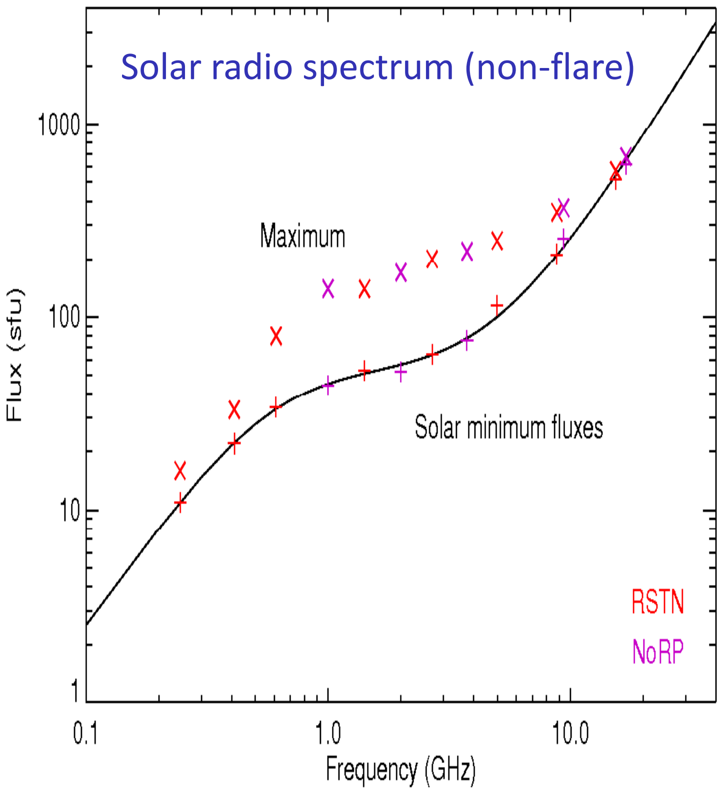


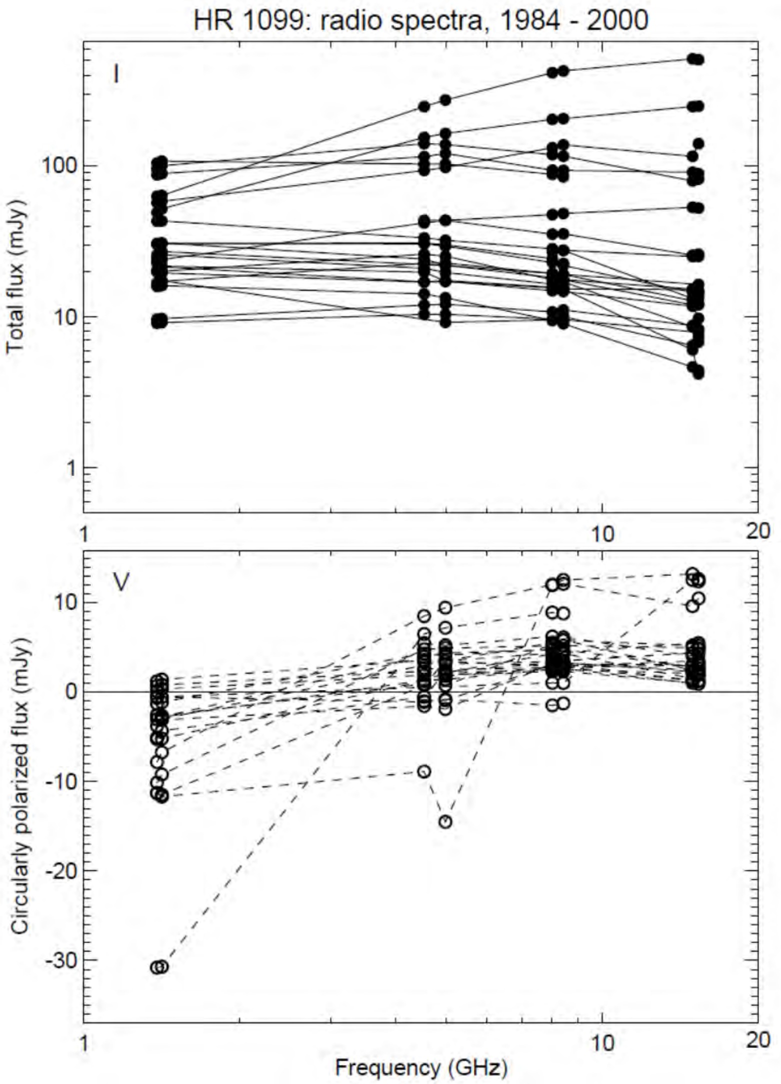
Stellar spectra: nonthermal gyrosynchrotron corona?

Active stars such as RS CVn’s and M dwarves have relatively flat radio spectra in the microwave range.

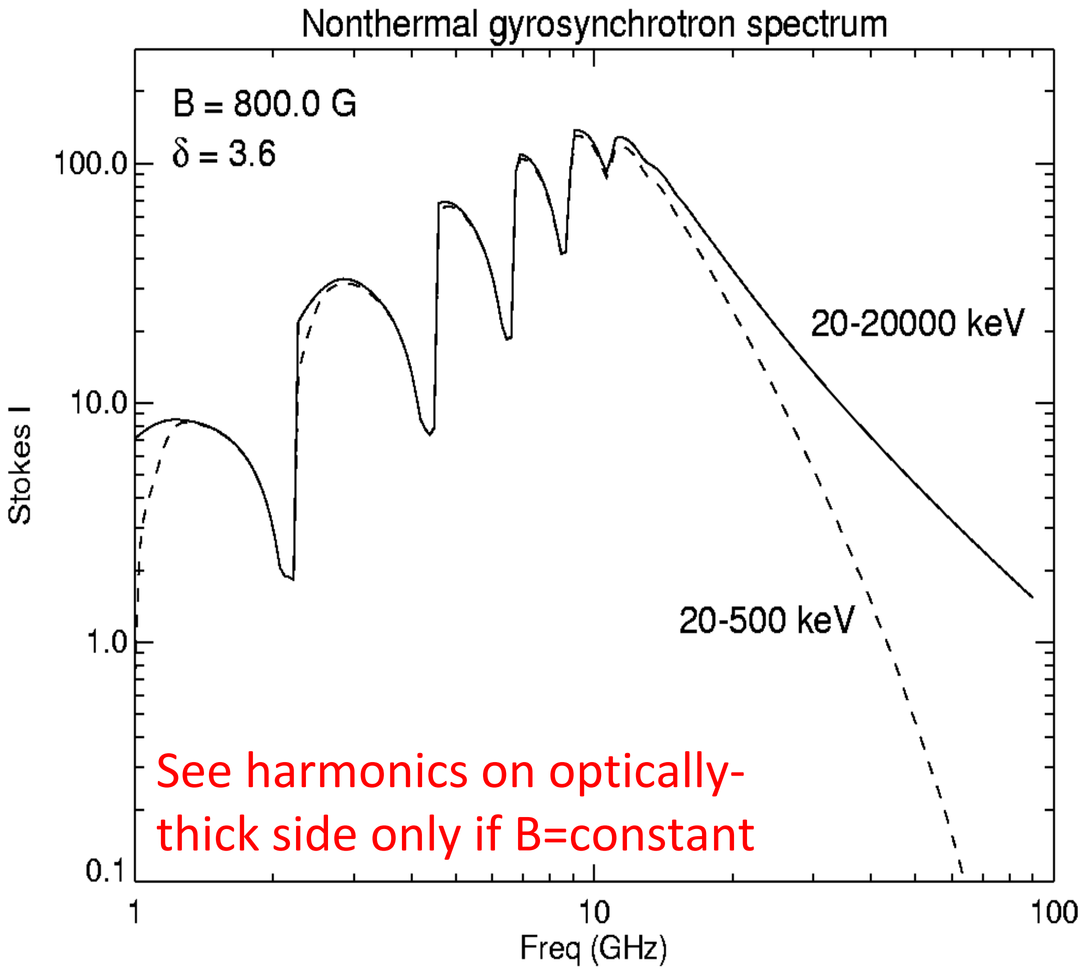
VLBI data suggest 10^9 K brightness temperatures

Contrasts with solar spectrum dominated by ~ f^2 spectrum above 10 GHz due to optically thick chromosphere

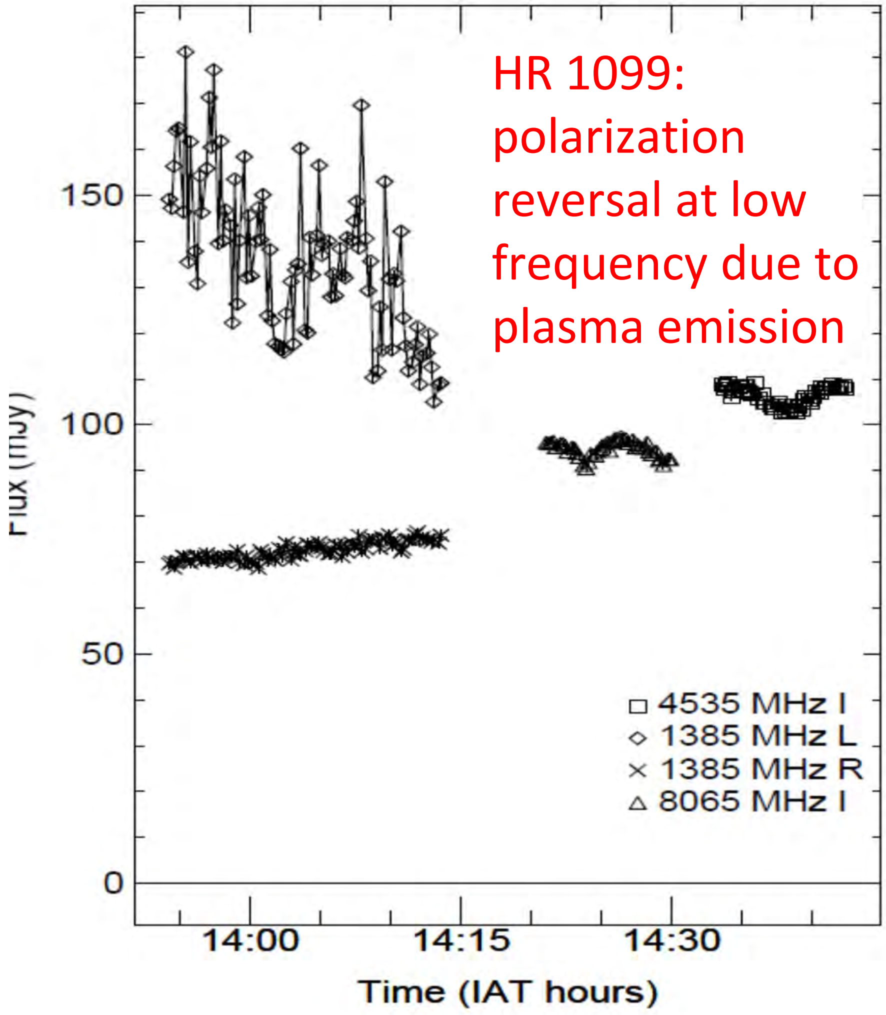




Gyrosynchrotron emission



See harmonics on optically-thick side only if B=constant



HR 1099: polarization reversal at low frequency due to plasma emission

SW + E. Franciosini

Magnetic fields from thermal bremsstrahlung

Two modes are optically thick in different layers due to the magnetic field effect: the polarization of free-free emission depends sensitively on the (unknown) temperature gradient.

Work by Grebinskij et al. (2000) gives a breakthrough. The basic idea is that the radio spectrum itself measures the temperature gradient!

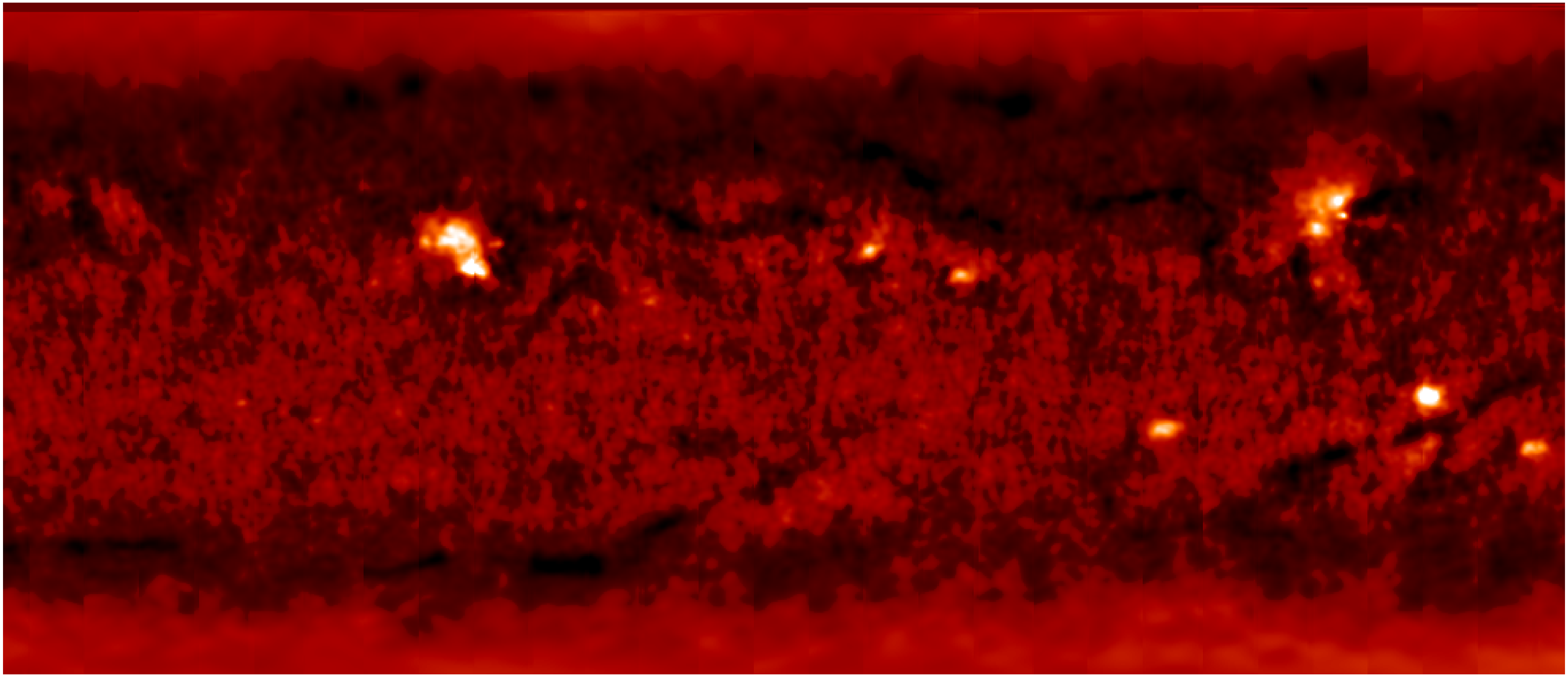
If we consider the local slope of the free-free emission brightness temperature spectrum, $n = d\log T/d\log f$, then the degree of polarization becomes

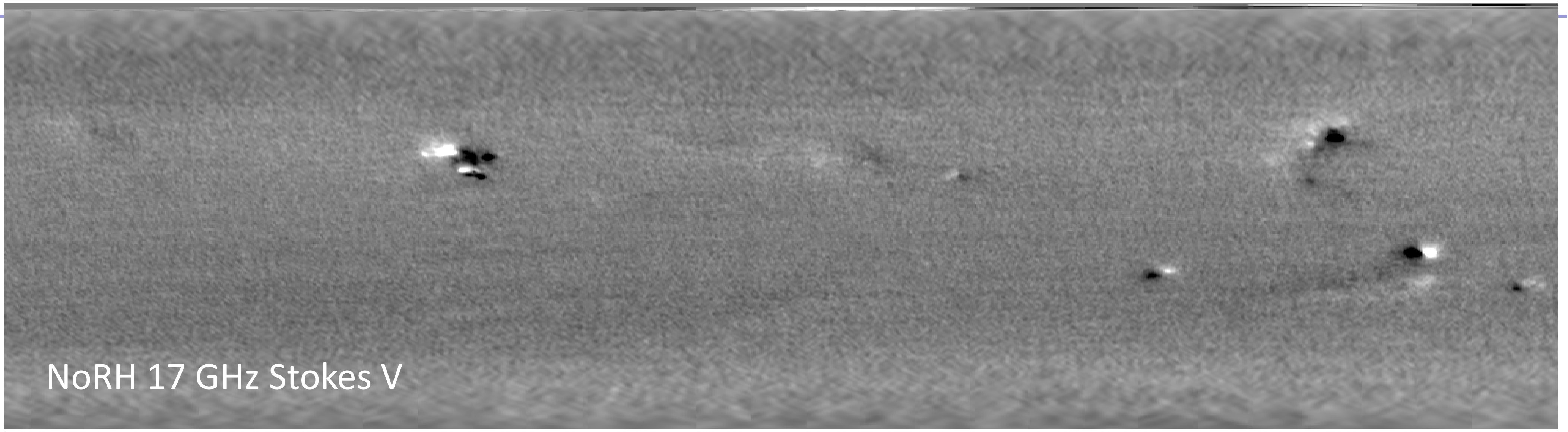
$$P = -n\,(f_B/f\,)\cos\theta = -\,(n\;2.8\mathrm{x}10^6\,/f\,)\,B_l$$ where θ is angle of B to LOS

Thus, $B_l = Pf\,/(2.8\mathrm{x}10^6\,n)$.

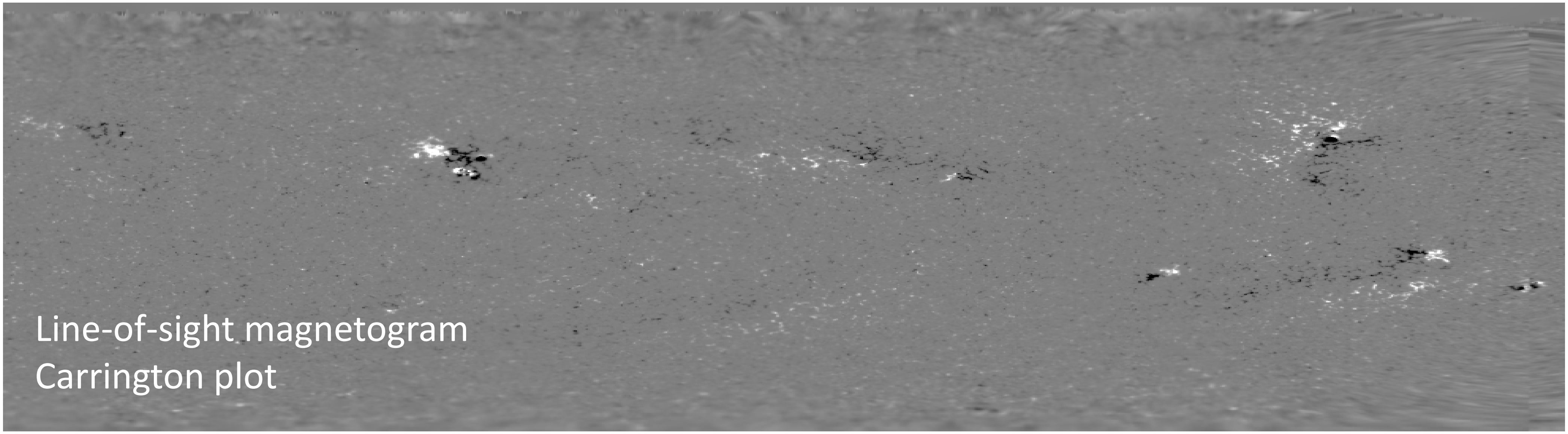
This sounds too simple, but it works!

17 GHz Carrington plot: 2011 January



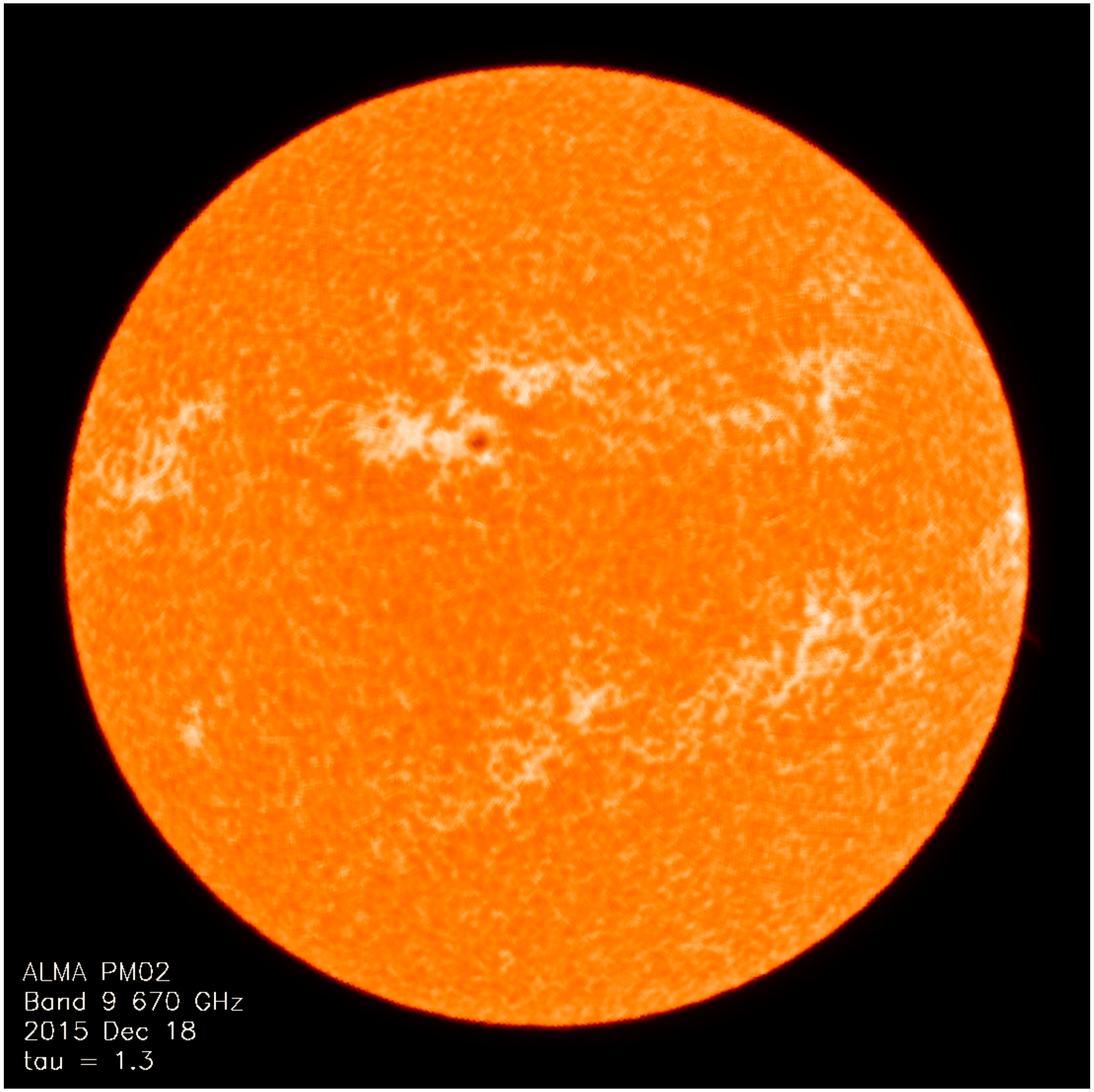


NoRH 17 GHz Stokes V



Line-of-sight magnetogram
Carrington plot

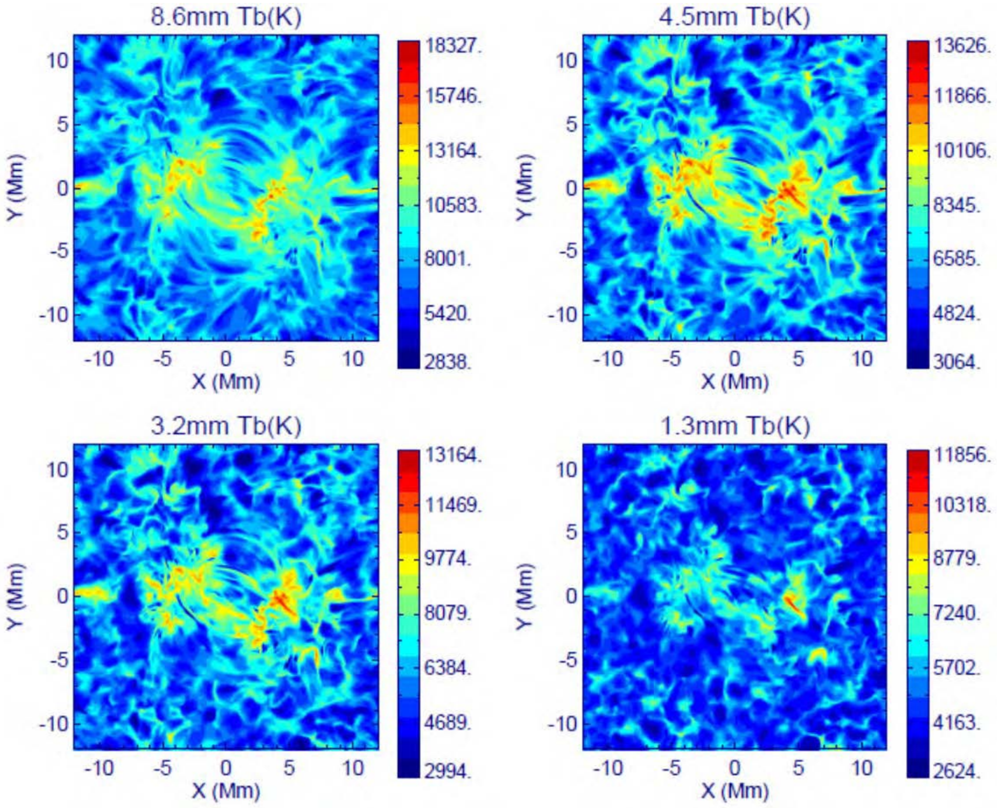
Polarization in the solar chromosphere (ALMA)



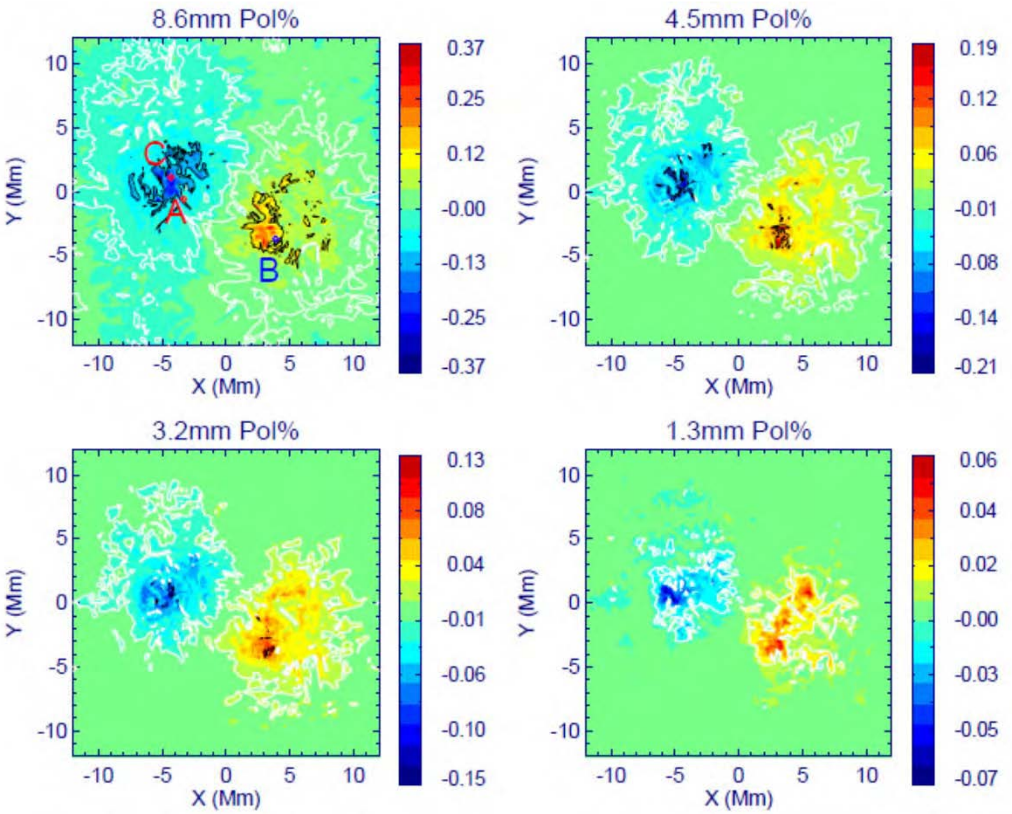
Solar atmosphere transitions from thermally-dominated in photosphere to magnetically dominated in chromosphere: so chromospheric B is a better boundary condition for coronal magnetic fields than photospheric. ALMA is the obvious way to measure B via polarization of thermal bremsstrahlung.

Value of radio data for chromospheric studies is that it is formed in LTE.

Simulations of ALMA quiet-Sun polarization (Loukitcheva et al 2017)



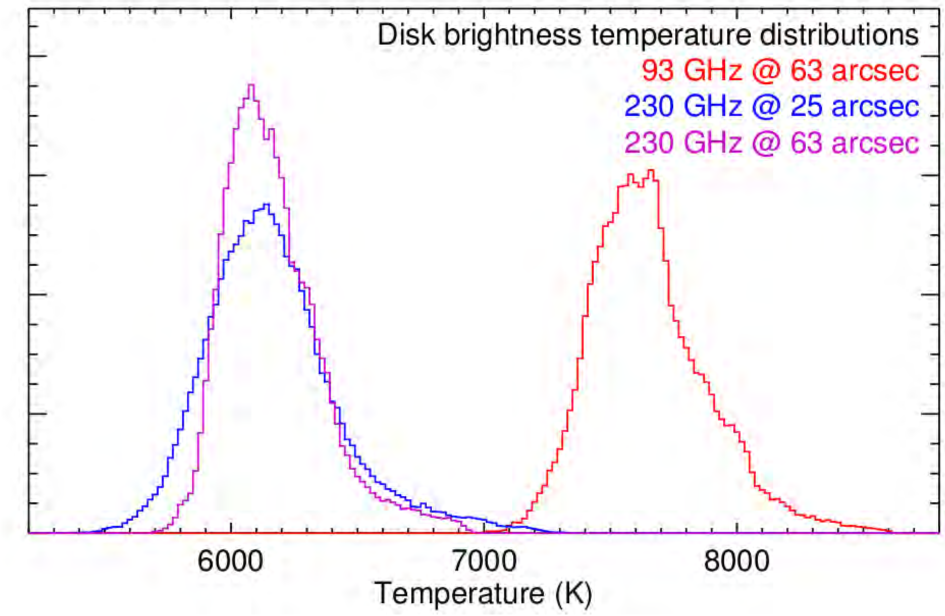
Models of brightness temperatures derived from complex *Bifrost* radiative MHD simulations of the lower atmosphere

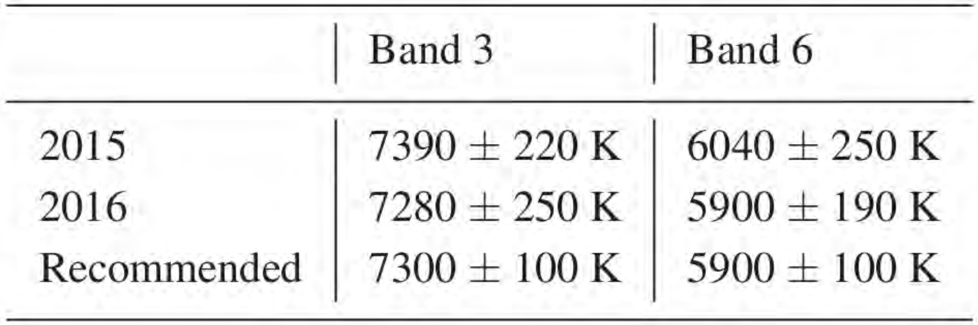


Models of degree of circular polarization derived from *Bifrost* simulations.

Scale on the right is in percent!

Chomospheric temperature





	Band 3	Band 6
2015	7390 ± 220 K	6040 ± 250 K
2016	7280 ± 250 K	5900 ± 190 K
Recommended	7300 ± 100 K	5900 ± 100 K

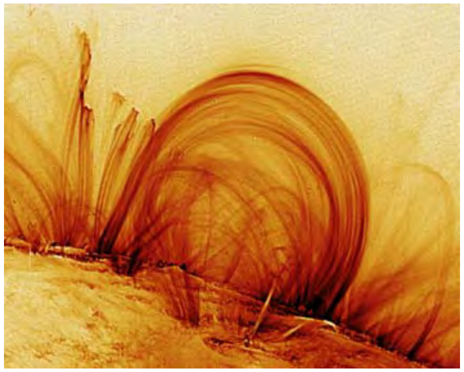
Millimeter measurements of brightness temperatures play an important role in atmospheric modelling and energy transport modelling because they are direct temperature measurements.

Initial ALMA results show higher temperatures than radiative MHD models predict.

But no Stokes V results yet! Still being commissioned.

Stars: large polar fields?

Cyclotron maser emission ($f_B > f_p$)



Electrons generated and/or trapped on closed magnetic fields develop pitch angle distributions that give you "negative" absorption coefficients, i.e., maser amplification.

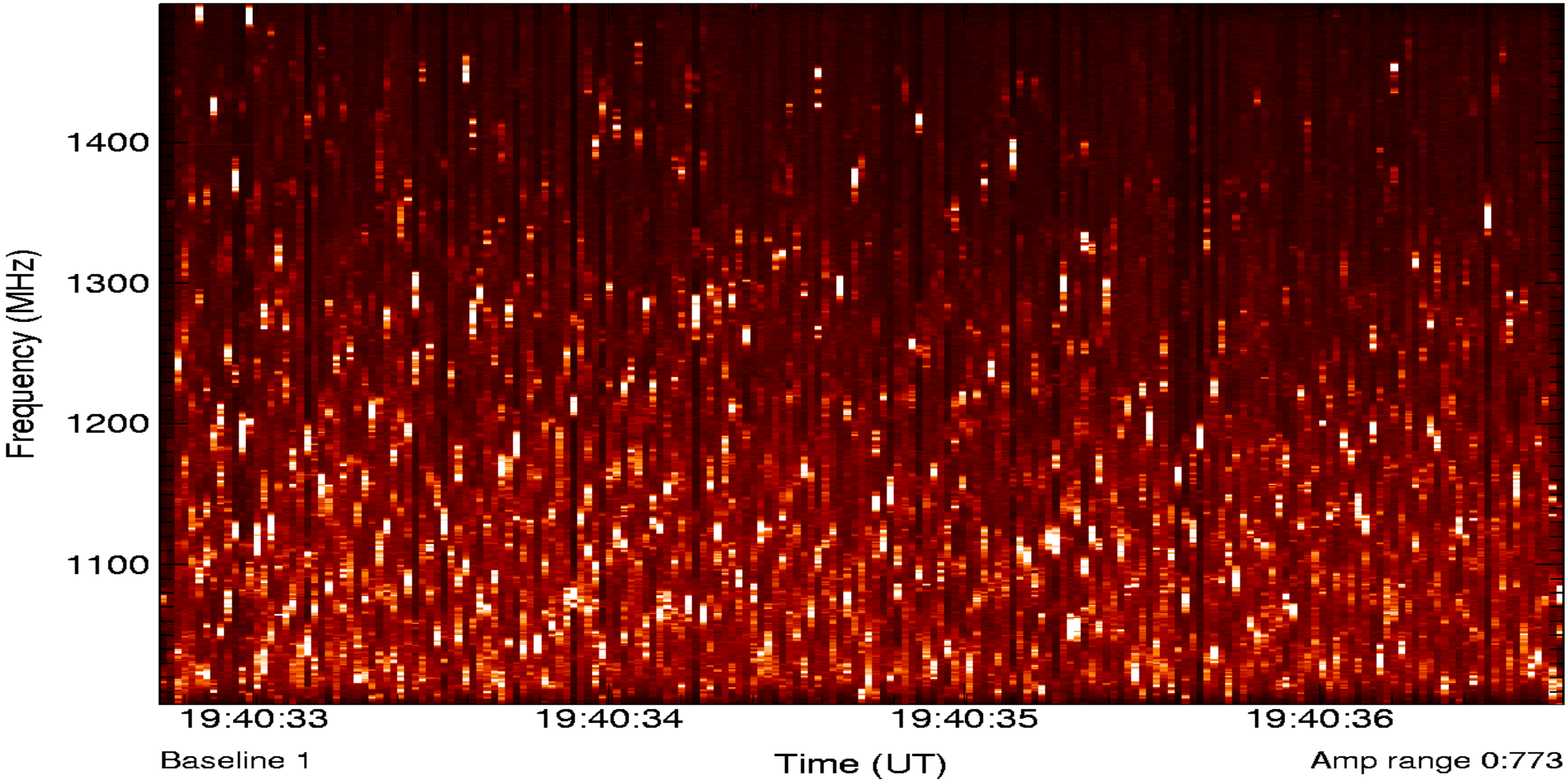
Emission is at the electron cyclotron frequency, $2.8B_{gauss}$ MHz, and its 2nd harmonic.

Typically highly circularly polarized.

Common to argue about whether a given type of solar radio burst is cyclotron maser or plasma emission.

Produces strong beamed emission from planets (Jupiter!), associated with radiation belts/aurorae, this model is applied to some Bp stars and cool dwarfs and also to radio detection of extrasolar planets.

Spike bursts in the 2006 Dec 6 flare: electron cyclotron maser?



Spike bursts at 1 microsecond resolution

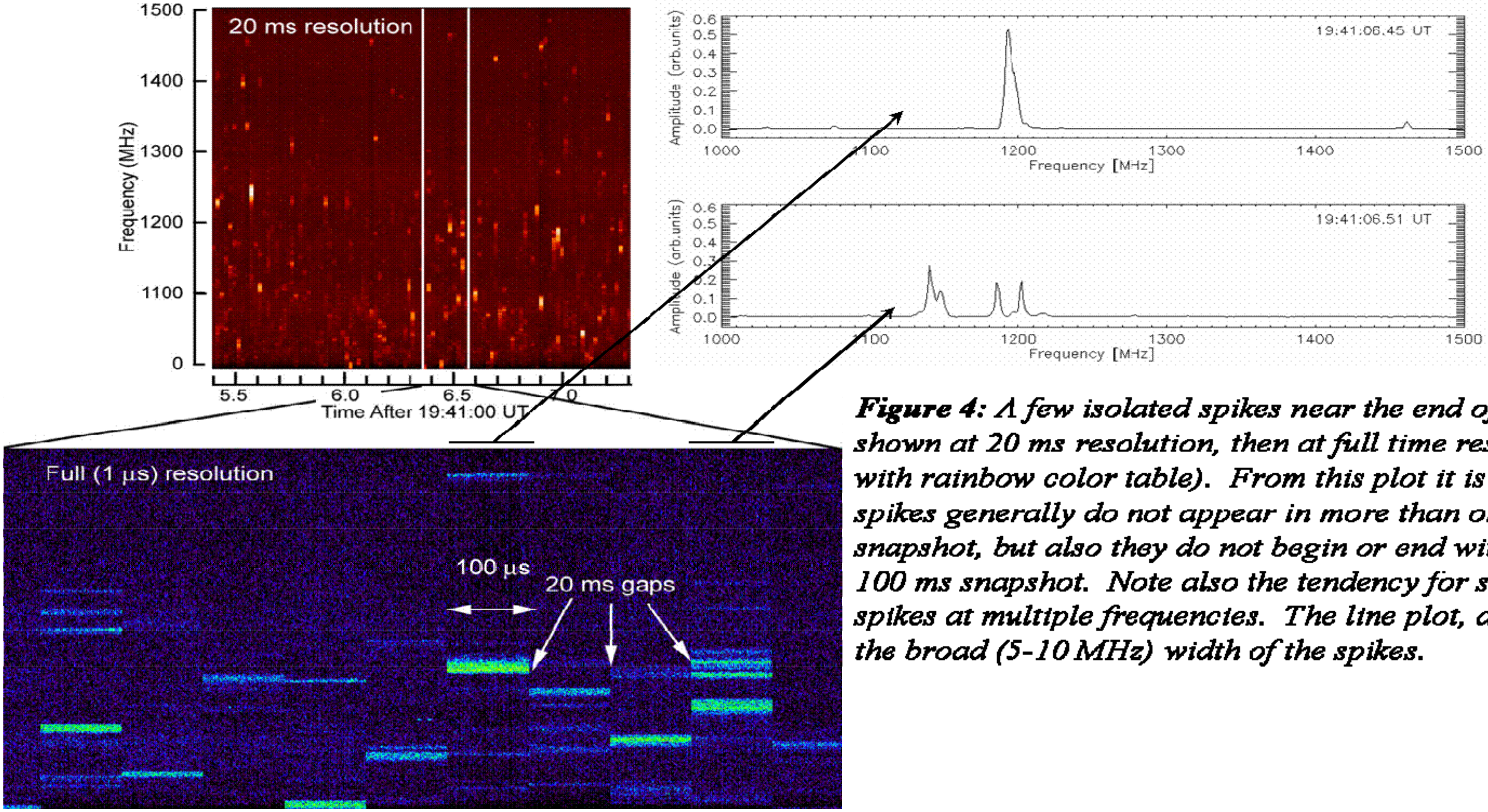
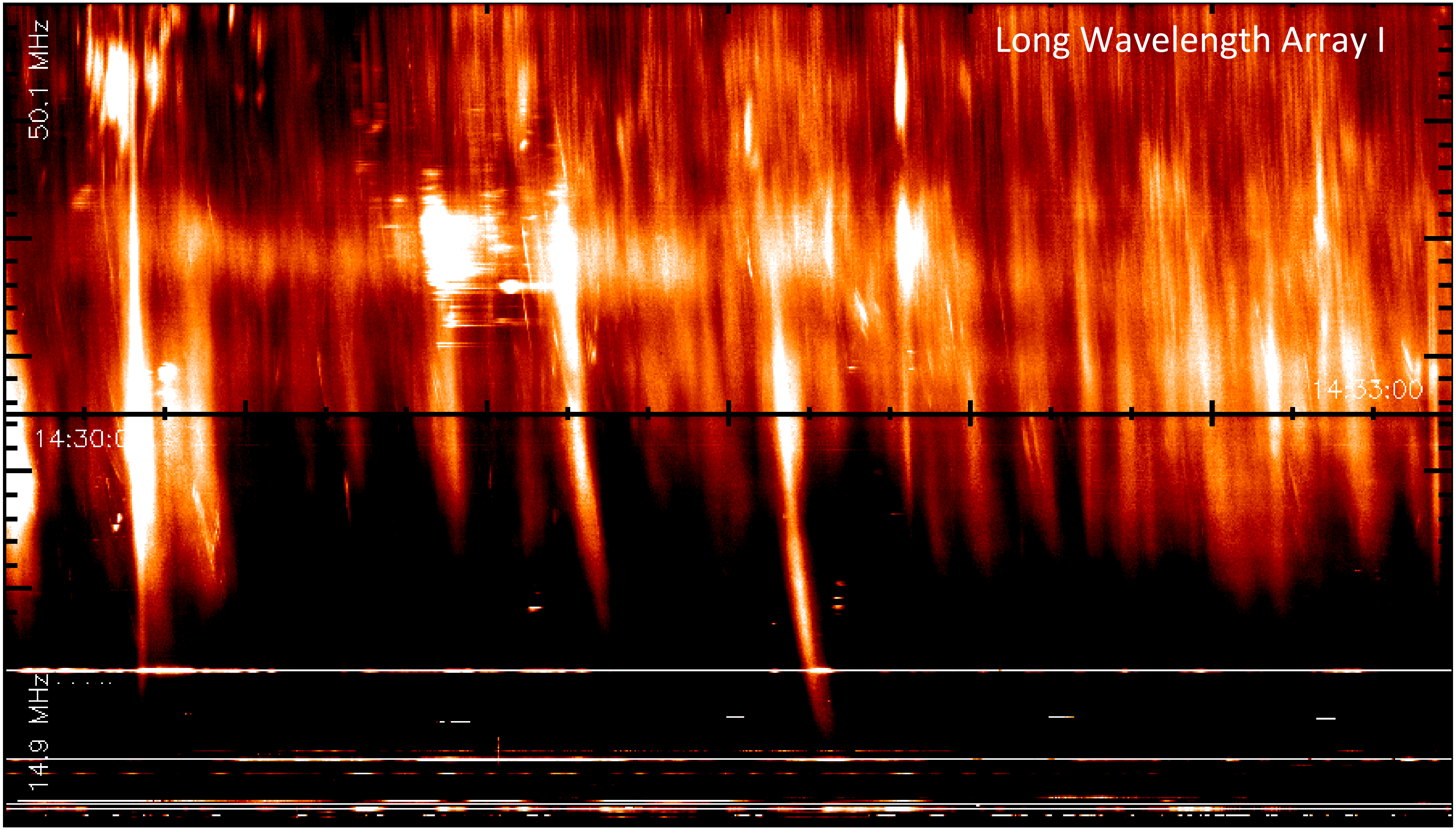


Figure 4: *A few isolated spikes near the end of the burst, shown at 20 ms resolution, then at full time resolution (plot with rainbow color table). From this plot it is clear that spikes generally do not appear in more than one 100 µs snapshot, but also they do not begin or end within a single 100 ms snapshot. Note also the tendency for simultaneous spikes at multiple frequencies. The line plot, above, shows the broad (5-10 MHz) width of the spikes.*

Long Wavelength Array I



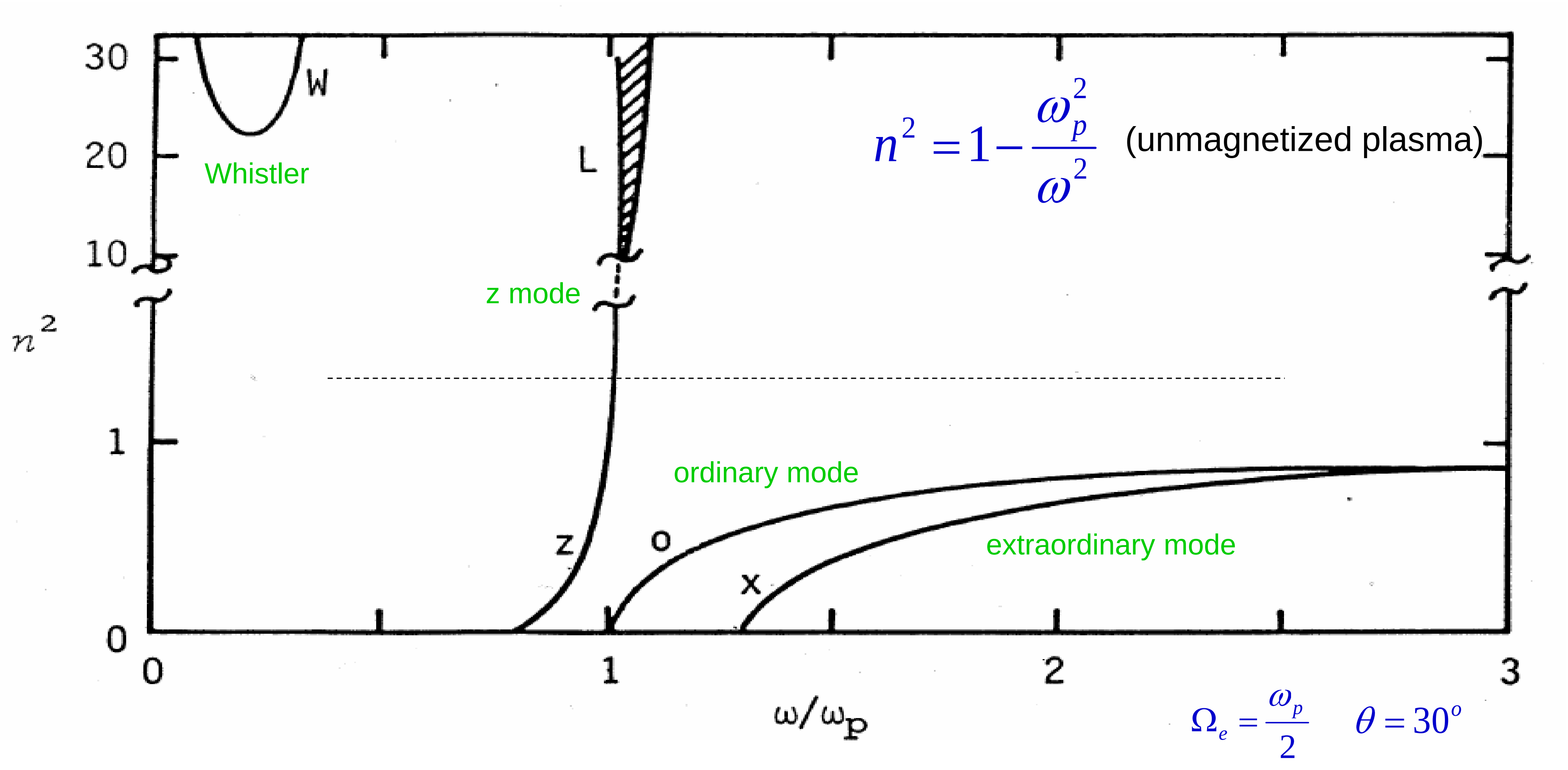
Plasma emission (coherent; $f_p > f_B$)

Two levels to the problem: (i) beam propagation and interaction of beam and Langmuir waves; (ii) generation of propagating electromagnetic emission.

- The brightest emission from flares below 1 GHz is plasma emission.
- Electron beams with energies of several keV are very efficent at generating electrostatic Langmuir waves at the plasma frequency $f_p = 9000 n_e^{0.5}$, n_e = e per cm^3.
- Get EM emission by decay of Langmuir waves (L) into low-frequency electrostatic waves (S) and other Langmuir waves (L -> L' + S) or transverse waves at frequency f_p ("fundamental" emission, L -> T + S) and at $2f_p$ ("harmonic" emission, L + L' -> T: fundamental emission should be 100% polarized, 2nd harmonic much less polarized.
- $f_p = 9000 n^{1/2}$ so frequency => density for plasma emission, and frequency drift rate reflects speed across coronal density gradient: electron beam speed for Type III bursts, shock speed for Type II bursts.
- Collisions absorb plasma emission at higher frequencies, but this can be compensated if temperature is higher, e.g., active stars:

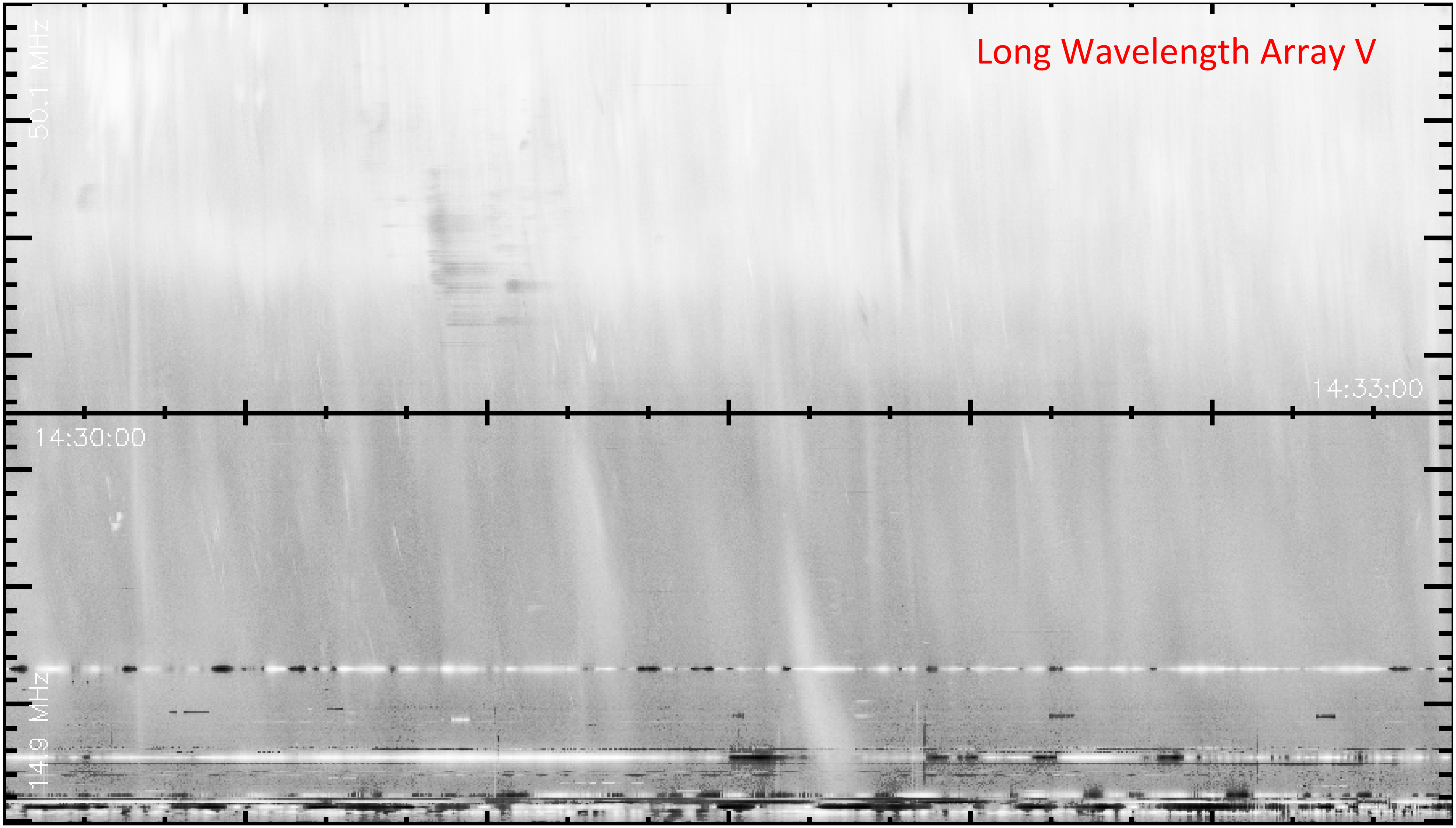
  collisional absorption of f_p plasma emission $\sim n^2 T^{-1.5} \sim f_p^4 T^{-1.5}$

Wave modes supported by a cold, magnetized plasma



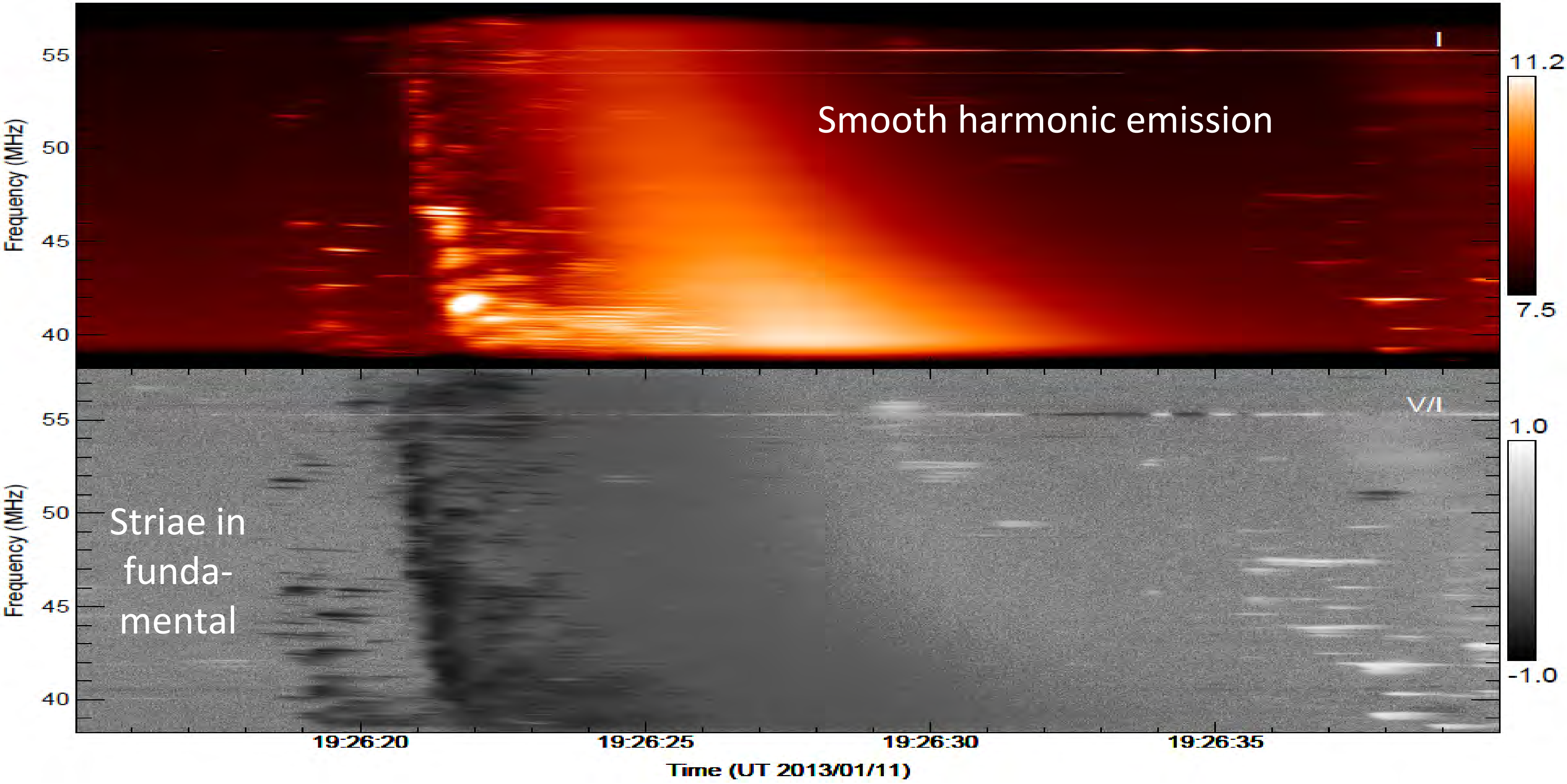
$$n^2 = 1 - \frac{\omega_p^2}{\omega^2}$$ (unmagnetized plasma)

$$\Omega_e = \frac{\omega_p}{2} \qquad \theta = 30^o$$



Long Wavelength Array V

Fundamental-harmonic structure in a solar Type III radio burst



Questions?