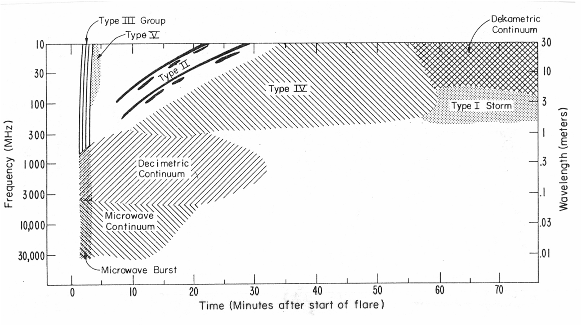
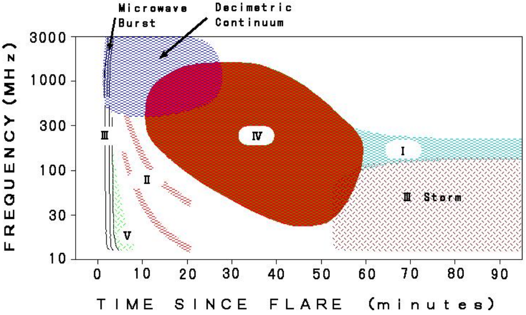
Radio astronomy and interferometry

Silja Pohjolainen

Third solar lecture 2015



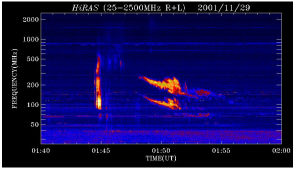
Plasma emission is typically observed at frequencies lower than ∼1–2 GHz



High frequencies = near the solar surface
Low frequencies = outward in the interplanetary space

Plasma emission

Radio emission can be produced by a two-stepped process, where electrostatic oscillations are first excited at or near the plasma frequency (e.g. by an energetic electron beam) and after that the Langmuir wave energy is converted to electromagnetic radiation via non-linear wave-wave interactions.



Plasma radiation occurs at or just above the plasma frequency ν_p and its second harmonic $2\nu_p$, but rarely at higher harmonics

Plasma emission

An electron in an ionized gas is subjected to a linear displacement and it behaves as an oscillator with the characteristic plasma frequency ν_p,

$$\nu_p = \frac{q}{2\pi}\sqrt{\frac{N}{\epsilon_0\, m}} \qquad \text{(Hz)},$$

where N is the particle density (m^{-3}), q is the charge of particle (C), m is the mass of particle (kg), and ϵ_0 is the permittivity of vacuum.

In the case of plasma with electron density N_e (m^{-3}) the plasma frequency becomes $\nu_p \approx 9\sqrt{N_e} \qquad \text{(Hz)}$

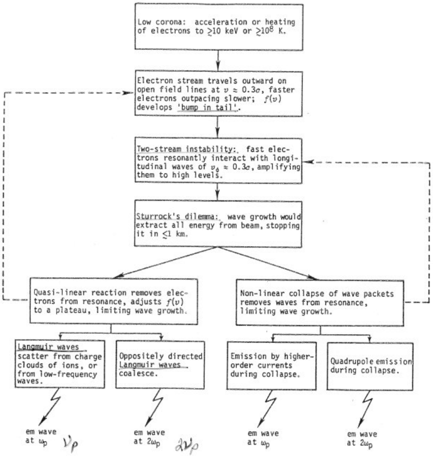


Fig. 8.1 - Steps in the theoretical description of emission of electromagnetic radiation by an electron stream in a plasma. The bottom half of the figure splits into two alternative theoretical lines of argument.

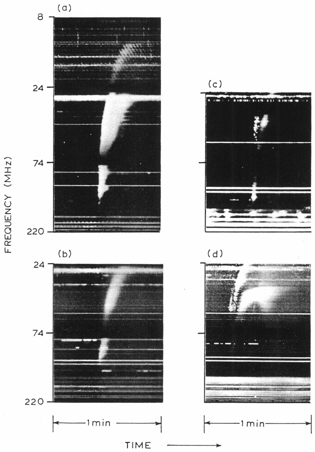


Fig. 12.1 – Dynamic spectra of several varieties of Type III bursts (examples from the Culgoora spectrograph records).
(a) Fundamental-harmonic pair, with 'ordinary' Type III bursts for both components (III-III pair).
(b) Structureless Type III burst.
(c) Type IIIb fundamental with smooth Type III harmonic (IIIb-III pair).
(d) Inverted-U burst.

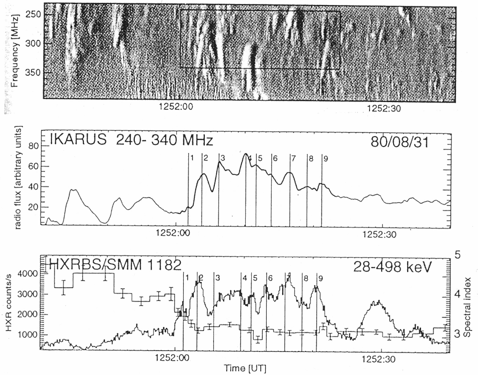
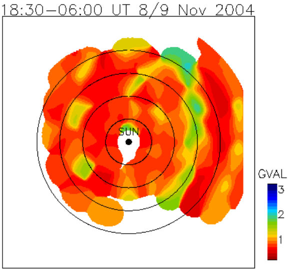
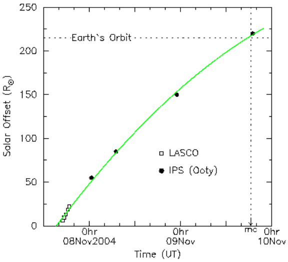


Figure 18 Correlated hard X-ray and decimeter structures (Aschwanden et al 1993). The upper panel shows an enhanced gray-scale representation of the decimeter dynamic spectrum during one minute of a flare observed jointly by the ground-based Ikarus spectrometer and by the hard X-ray instrument on the *Solar Maximum Mission*. The rapid fluctuations agree well with one another, as illustrated by the time series in the middle and lower panels.

(Hudson & Ryan, 1995)

Also used: Radio scintillation method





Intensity scintillations of compact radio sources (galaxies or quasars) are produced by the density fluctuations in the solar wind plasma. The presence of solar wind transients (e.g., CMEs) can be identified by the enhanced g-values (normalized scintillation index) which are due to the increase in the density-fluctuation, see Manoharan et al. 2001

Plasma diagnostics, in gaussian units

Plasma frequency (fully ionized plasma):

$$\nu_p \approx 9000 \sqrt{n_e} \qquad \text{(Hz)} \tag{1}$$

Sound speed (hydrogen plasma, primordial abundances – longitudinal wave propagates parallel to the field, compresses):

$$v_s \approx 1.5 \times 10^4 \sqrt{T} \qquad \text{(cm/s)} \tag{2}$$

Plasma diagnostics, in gaussian units

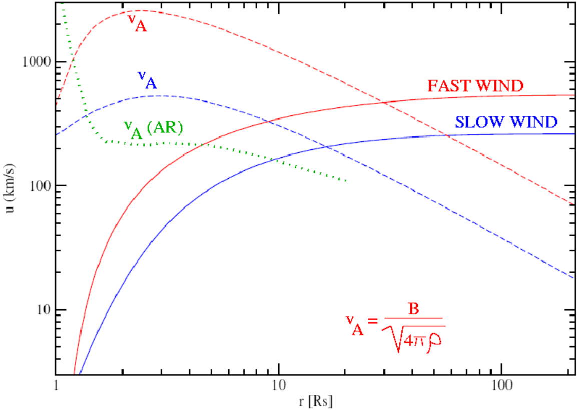
Alfvén speed (transverse wave that propagates parallel to the field, does not compress):

$$v_A \approx \frac{2 \times 10^{11} B}{\sqrt{n_e}} \qquad \text{(cm/s)} \tag{3}$$

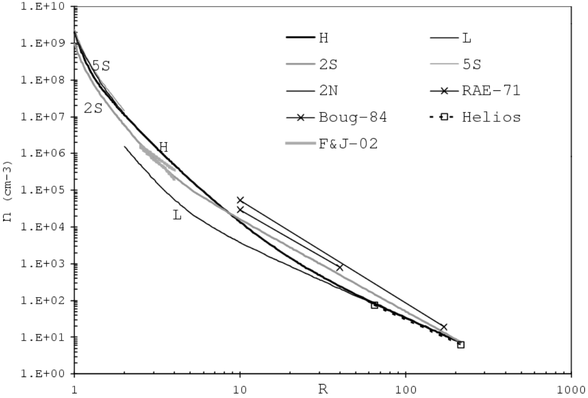
Magnetosonic speed (longitudinal wave propagates perpendicular to the field, also known as compressional Alfvén wave):

$$v_{ms} = \sqrt{v_s^2 + v_A^2} \tag{4}$$

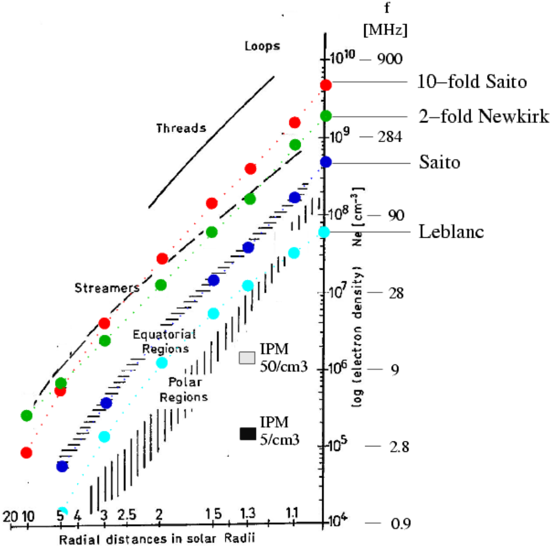
Alfvén speed at different heights and regions



Atmospheric densities



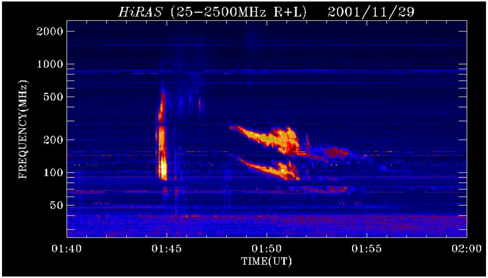
Densities near Earth 5 – 50 cm^{-3}, depending on solar activity cycle
H = hybrid model by Vrsnak et al. A&A, 2002

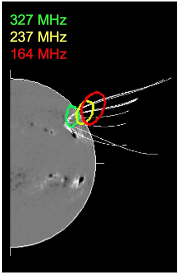


f
[MHz]
Loops
Threads
Streamers
Equatorial
Regions
Polar
Regions
IPM
50/cm3
IPM
5/cm3
10^{10} — 900
10^{9} — 284
10^{8} — 90
10^{7} — 28
10^{6} — 9
10^{5} — 2.8
10^{4} — 0.9
10–fold Saito
2–fold Newkirk
Saito
Leblanc
log (electron density) Ne [cm^{-3}]
20 10 5 4 3 2.5 2 1.5 1.3 1.1
Radial distances in solar Radii

Example 1:

A radio dynamic spectrum shows a frequency-drifting type II burst. The emission is observed to drift from 100 MHz at 01:50 UT to 70 MHz at 01:54 UT. Give an estimate of the burst source speed.





Always use the fundamental emission lane for calculations!

Table 2.1: Calculated electron densities and plasma frequencies (wavelengths in parenthesis) at different distances h ($R_\odot$) from the center of the sun ($R_\odot$=1 at the limb).

f_p (MHz)	λ (m)	n_e (cm^{-3})	h Saito	h Hybrid	h 2×Newkirk	h 10×Saito	h Leblanc[a]	h IP[a]
500	0.6	3.1×10^9	-	-	-	1.035	-	-
400	0.75	2.0×10^9	-	-	-	1.076	-	-
300	1	1.1×10^9	-	1.044	1.050	1.142	-	-
200	1.5	4.9×10^8	-	1.117	1.147	1.258	-	-
100	3	1.2×10^8	1.131	1.305	1.368	1.560	-	-
70	4.3	6.0×10^7	1.226	1.453	1.514	1.758	-	-
50	6	3.1×10^7	1.342	1.637	1.682	1.989	1.10	-
30	10	1.1×10^7	1.584	2.010	2.040	2.403	1.31	-
14	21.4	2.4×10^6	2.07	2.78	2.96	3.33	1.71	-
12	25	1.8×10^6	2.19	2.96	3.24	3.57	1.80	-
10	30	1.2×10^6	2.36	3.24	3.74	3.97	1.93	-
9	33.3	1.0×10^6	2.44	3.38	4.00	4.17	2.00	-
8	37.5	7.9×10^5	2.56	3.57	4.44	4.47	2.09	-
7	42.9	6.0×10^5	2.72	3.81	5.05	4.86	2.20	-
6	50	4.4×10^5	2.90	4.10	6.00	5.38	2.33	-
5	60	3.1×10^5	3.13	4.46	7.61	6.06	2.49	-
4	75	2.0×10^5	3.49	4.96	11.46	7.09	2.72	1.02
3	100	1.1×10^5	4.07	5.75	>30	8.88	3.07	1.37
2	150	4.9×10^4	5.18	7.07	>>	12.17	3.69	2.06
1	300	1.2×10^4	8.58	10.36	>>	21.30	5.42	4.16

a) n_0=4.5 cm^{-3} at 1 AU

Solution to Example 1:

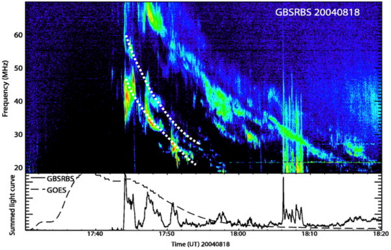
100 MHz corresponds to a height of 1.30 solar radius

70 MHz corresponds to a height of 1.45 solar radius

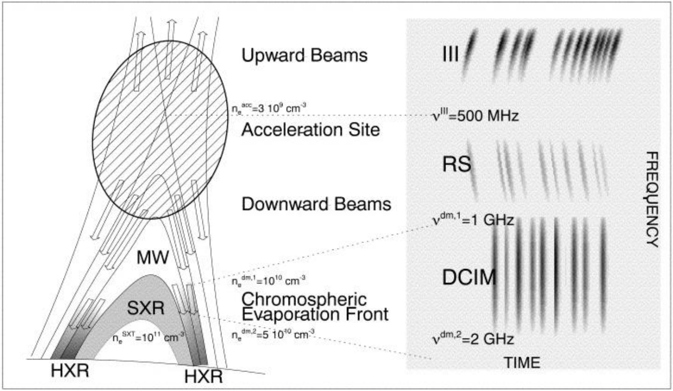
travelled distance (1.45-1.3)*696000 km, in 4 min = 435 km/s

No CME leading edge at these heights, maybe flare wave?

Band-splitting

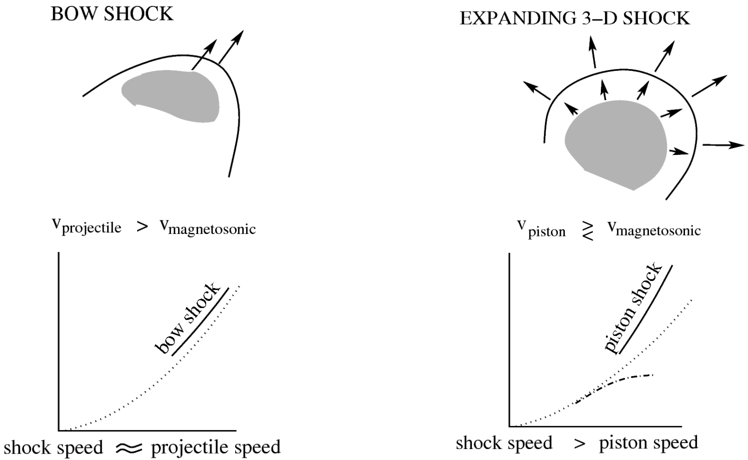


Emission at the upper and lower frequency branches in the fundamental band of the type II burst (dotted lines)
- band-split reveals the shock Mach number if it is a consequence of the plasma emission from the upstream and downstream shock region
- shock speed can be inferred from the frequency drift
→ Alfvén velocity and magnetic field can be estimated
(Cho et al. 2007; Vrsnak et al. 2002)

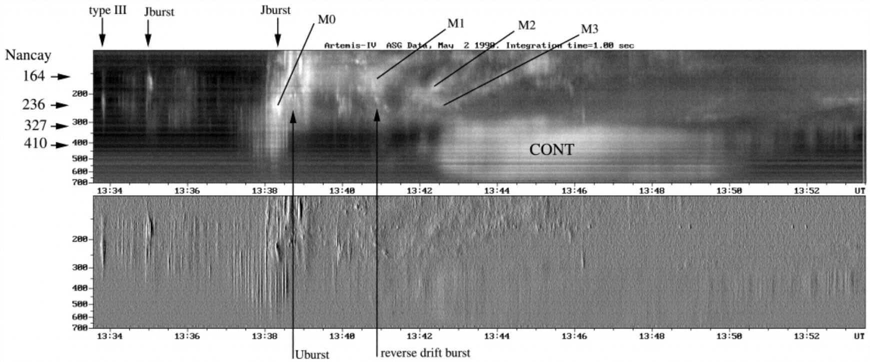


(Aschwanden & Benz)

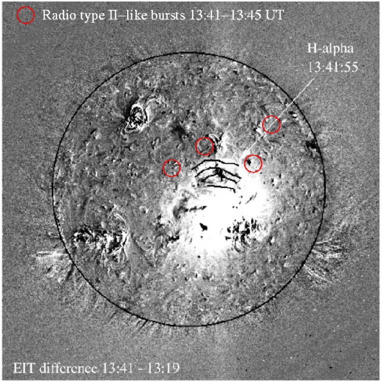
Driven shocks



Example of combining spectral information with source location

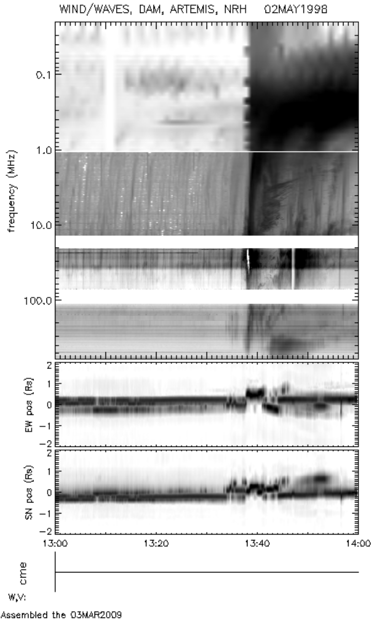


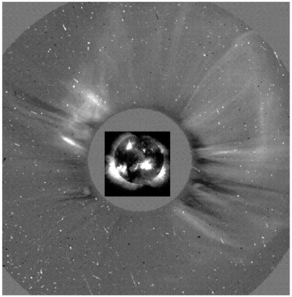
Group of fast-drift type II-like bursts on May 2, 1998 (M0...M3) in dynamic spectrum

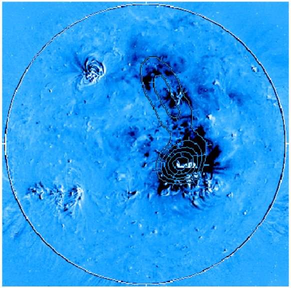


M1-M3 burst positions (source centers, imaged by Nancay Radioheliograph)

Type II-like burst driver = Moreton/EIT wave

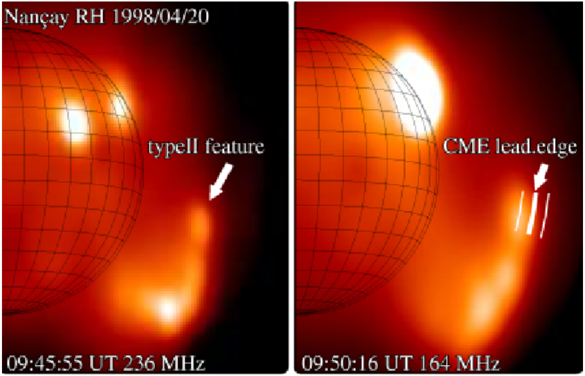






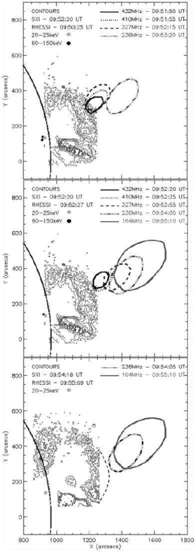
Type IV burst position corresponds to EIT dimming = depleted matter, CME lift-off

Observations: type II burst driver = CME bow shock



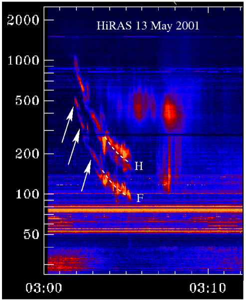
Maia et al. ApJ, 2000

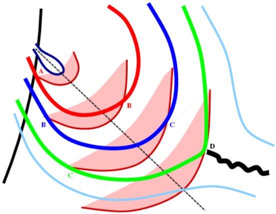
Type II burst driver = rising SXR loop

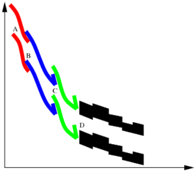


Dauphin et al. 2006

Type II burst source = passage through loops

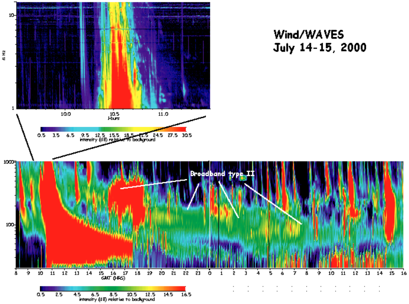






Very high frequency start, needed explanation
(Pohjolainen, Pomoell & Vainio, 2008)

Propagating interplanetary (IP) shock

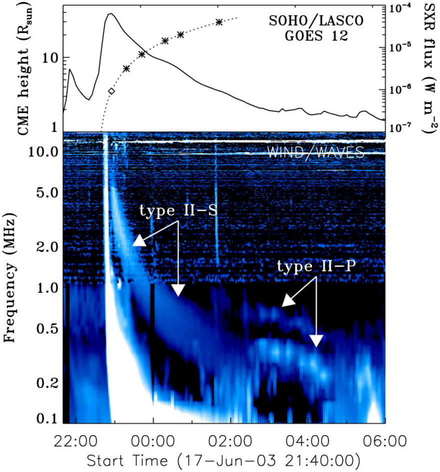


Wind WAVES dynamic radio spectrum at two frequency bands, 14–1 MHz (top) and 1 MHz– 20 kHz (bottom)

Plasma frequency near L1 is 30 – 50 kHz.

If electron density is dropping as $\sim 1/r^2$, the speed of the shock driver is about 2400 km/s (17 hours to reach Earth)

But: emission is not always plasma emission

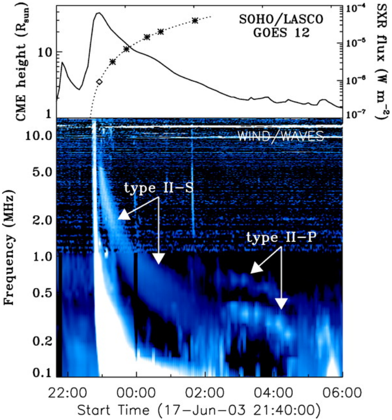


Bastian: plasma vs. synchrotron emission in IP space

Wide-band type II bursts

- Untypically smooth, diffuse, wide-band type II burst (II-S)
- No harmonic emission (seen in the later II-P burst)
- Height-time track does not match with n_e from plasma emission

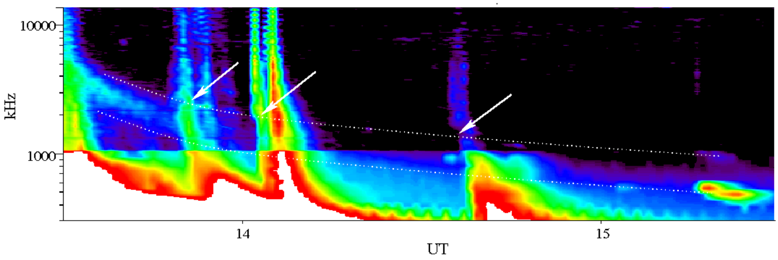
From Bastian T., ApJ 665, 2007



Alternative emission mechanism for wide-band bursts

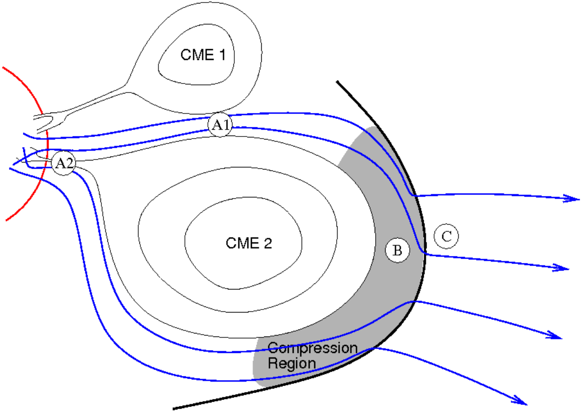
- Electron-cyclotron frequency $f_s \approx 2.8 \times 10^6$ B (Hz)
- Synchrotron emission from power-law electrons with a broad range of pitch angles, broad-band emission centered at: $f \approx f_s \gamma^2 \sin\theta/2$
- Magnetic field varies as $B \approx B_0 \, (r/R\odot)^{-\beta}$ within the CME (0.5 – 0.01 G within 3 – 30 $R\odot$)

Shocks on the way: tilted type III burst lanes?



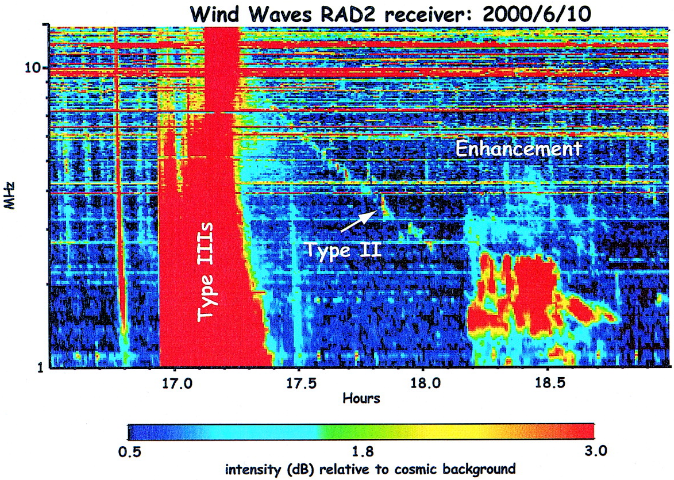
Lehtinen et al., 2008: Electron streams meet a propagating shock

Tilts due to passage through shock fronts



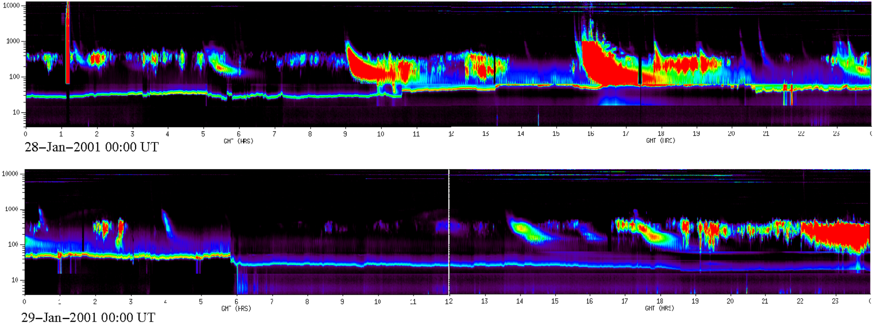
B: compressed high-density region, C: low density and low B

Features from interacting CMEs?

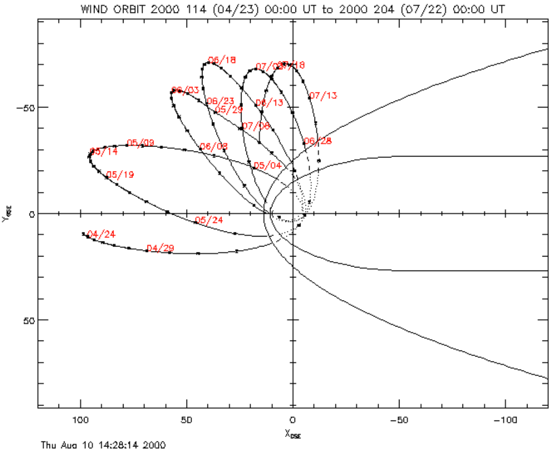


Gopalswamy et al. ApJ, 2001

Other radio emission features

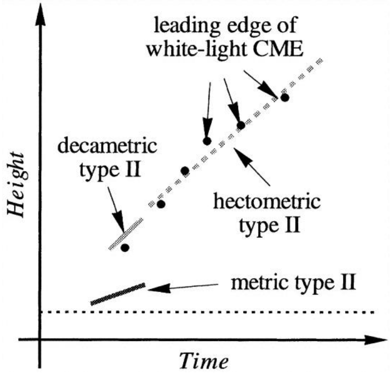


AKR - auroral kilometric radiation appears at 80 – 400 kHz, often in 12 hour episodes, mixed with features that have solar origin

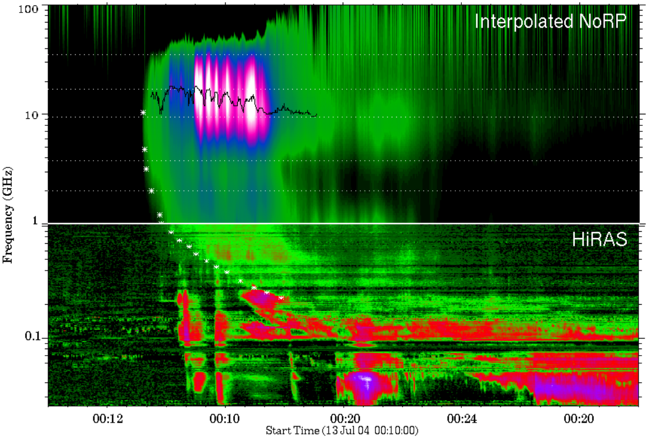


Wind WAVES orbit takes the satellite near Earth where AKR gets stronger

Things to evaluate on type IIs



- Atmospheric density models -> speed from density change
- Scale height + frequency drift -> may give different speed
- Corona: second harmonic stronger
- IP space: fundamental stronger
- Emission lanes can be band-split
- May not be plasma emission at all



Gyrosynchrotron + plasma emission (from separate sources)