Studies of Solar Eruptions using Type II Bursts from Ground and CMEs from Space

N. Gopalswamy, S. Yashiro, P. Mäkelä
NASA Goddard Space Flight Center

C. Monstein

ETH Zurich, Switzerland

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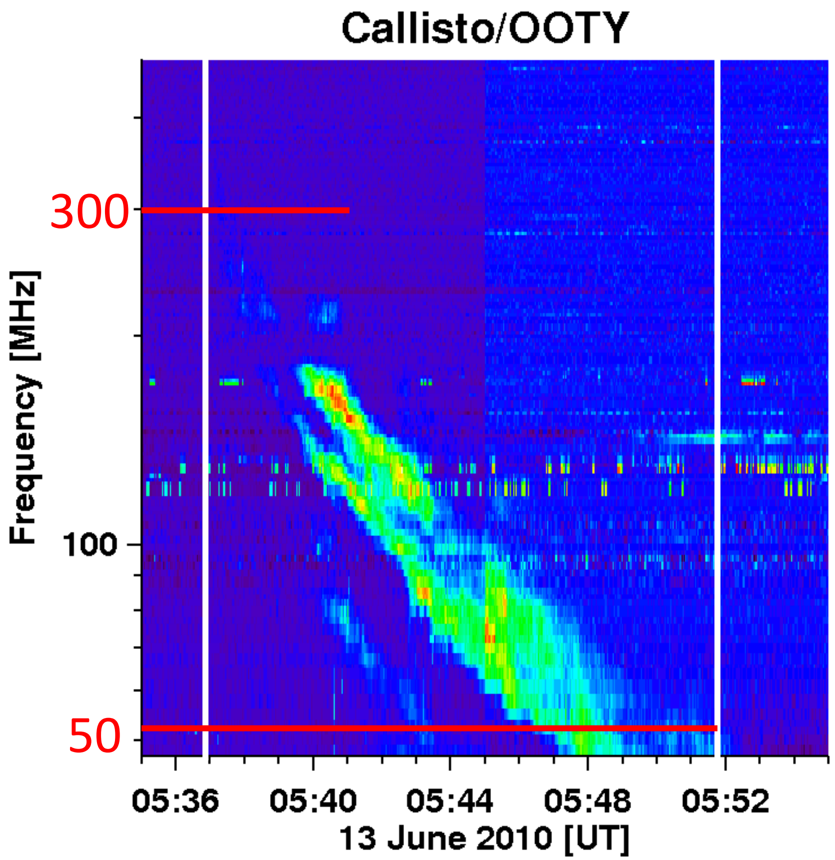
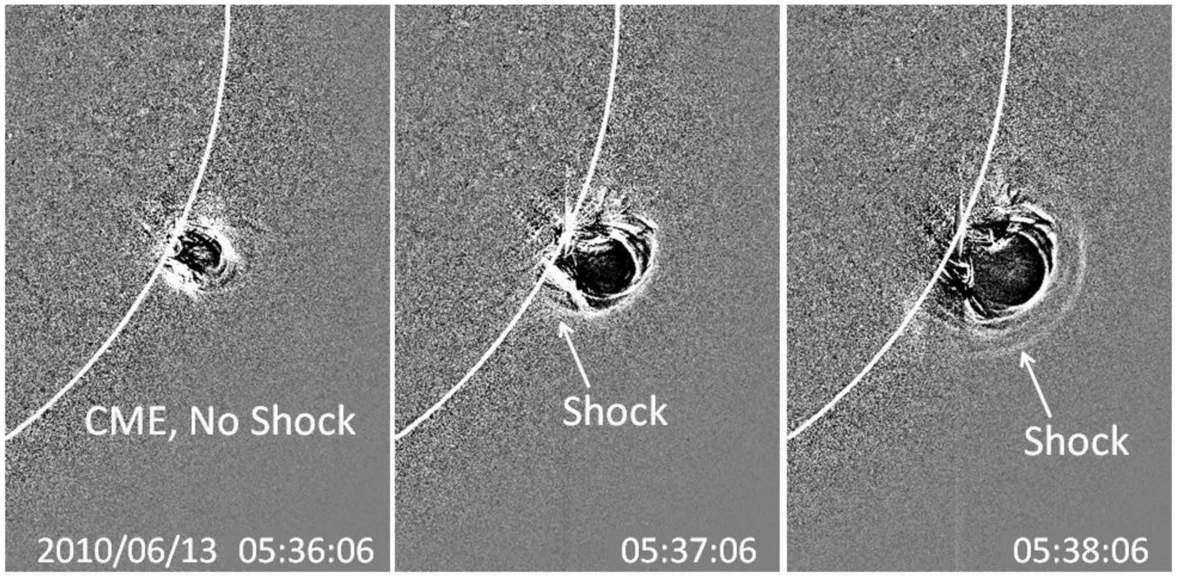
Motivation

- CME-driven shocks play an important role in space weather: source of particle radiation (SEPs, ESPs) and sudden commencements that are often followed by geomagnetic storms
- Type II bursts are a consequence of particle acceleration: energetic electrons produce Langmuir waves that get converted into electromagnetic radiation observed s radio bursts. Thus type II bursts are the earliest indicators of CME-driven shocks
- The CME height at the onset time of a type II burst indicates where and when the corresponding shock forms in the corona
- This height is important in determining the acceleration time of SEPs, the energies they attain, and their charge state properties (e.g. particles accelerated low in the corona may be subject to additional stripping)
- Type II bursts and CMEs help understand the shock evolution near the Sun (relative change in CME speed and coronal Alfven speed with height)
- Continuous monitoring of CMEs by spacecraft and type II bursts from ground and space is important for space weather prediction

Type II and Shock appear simultaneously



Radio dynamic spectrum showing a type II radio burst



Solar Dynamics Observatory (EUV 193 Å)

Type II burst starts exactly at the time the shock appears in the corona at 1.2 Rs

We can probe the coronal medium as well as the shock structure by combining type II and EUV/coronagraph observations

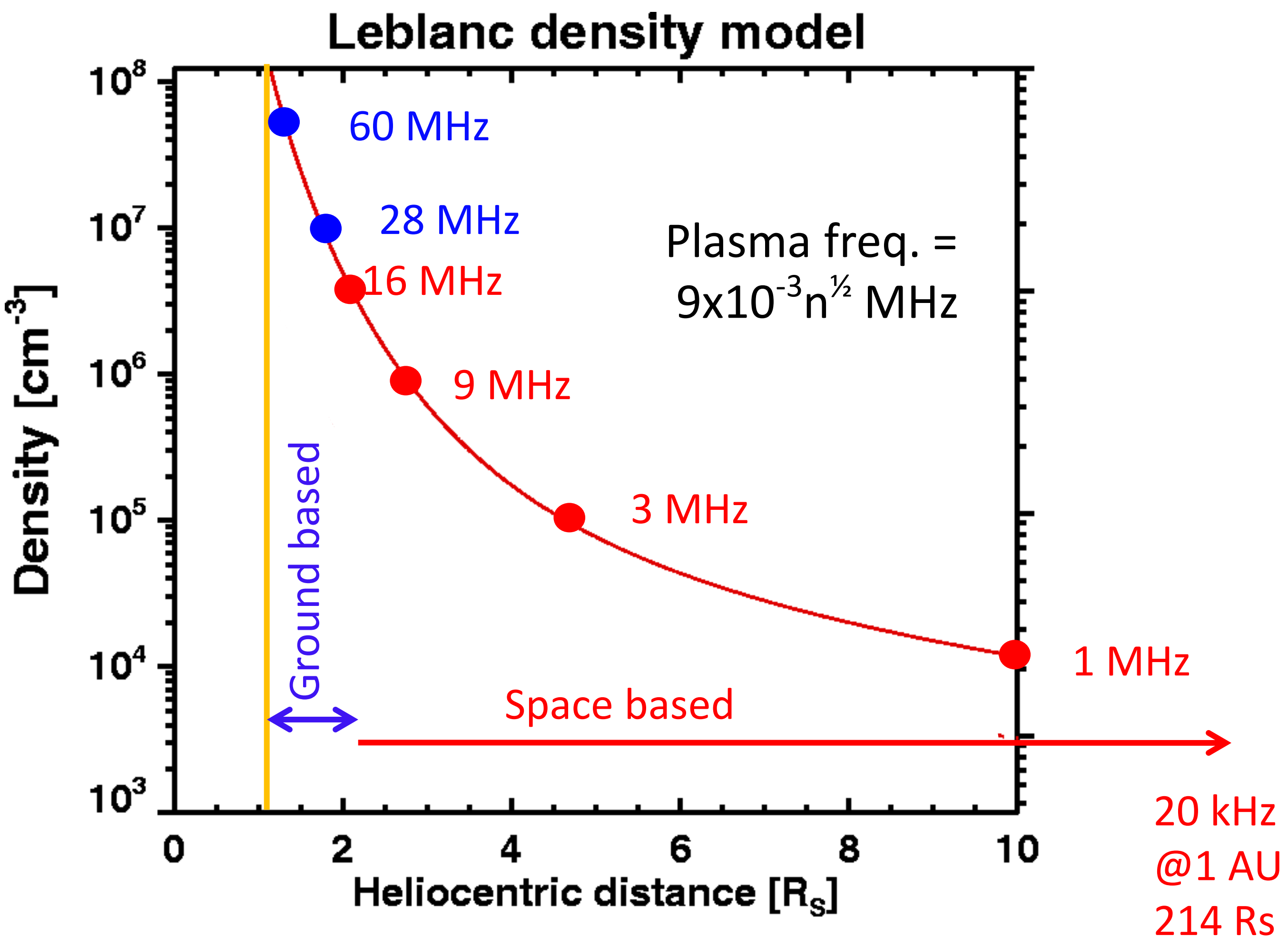
$V = 2L(1/f)(df/dt)$; $L = r/\alpha$ if $n = n_0 r^{-\alpha}$

$df/dt = 0.28$ MHz/s; $(1/f)df/dt = (0.28/175)\ s^{-1}$

V= 600 km/s; L = 189,000 km → α and hence the density distribution

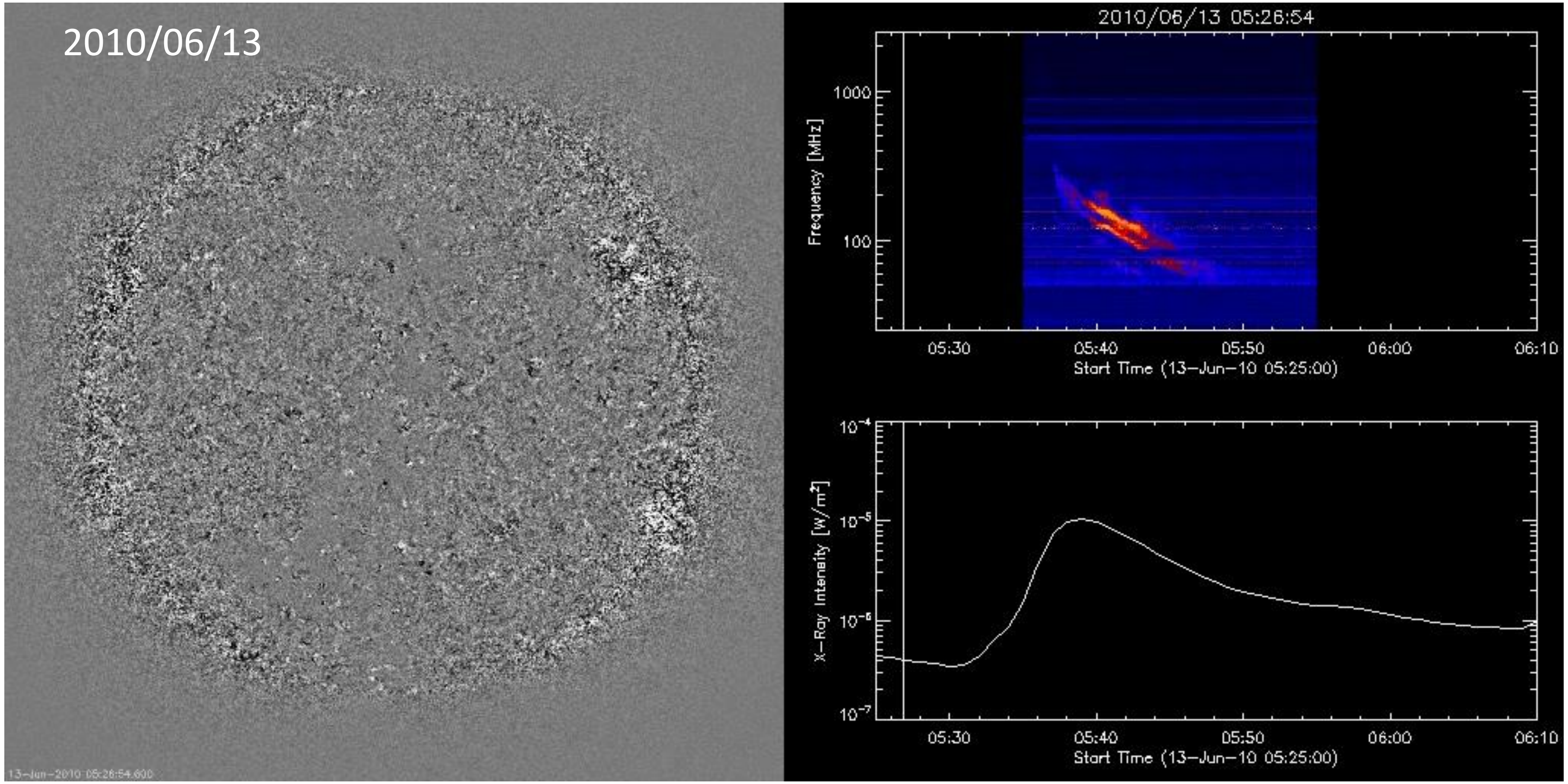
Density decrease in the corona → drift of radio emission in dynamic spectra (lower frequency emission at later times)

- As the shock moves away from the Sun, it crosses lower-density regions where the plasma frequency, and hence the emission frequency is lower causing the drift
- Ground based radio telescopes observe radio emission originating below ~2 Rs
- Space observations needed for 2 -214 Rs & beyond due to ionospheric cutoff



Ionospheric cutoff at ~15 MHz - Need for space observations

Where does the shock form? Or What is the shock/CME height when the type II bursts starts?

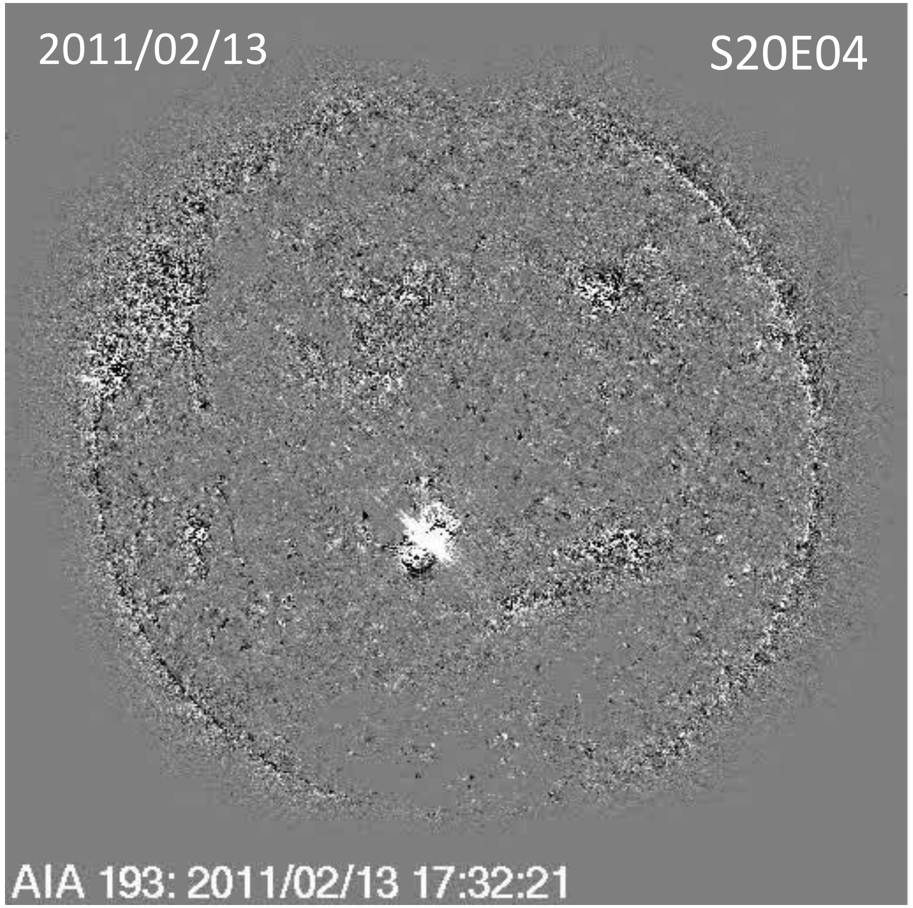


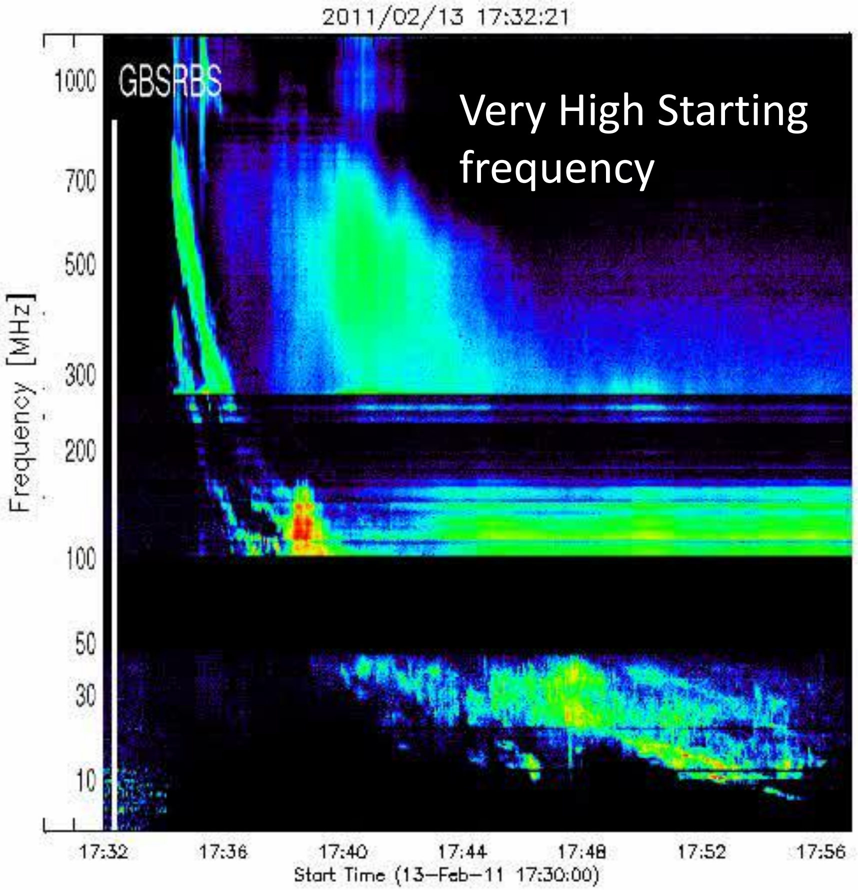
CME starts at 5:34 at 1.13 Rs; Type II starts at 5:36 when the CME at 1.17 Rs; shock 1.19 Rs

f_p = 150 MHz → n_p = 2.8×10^8 cm^{-3}

Gopalswamy et al., 2012 ApJ

A type II burst with very high starting frequency

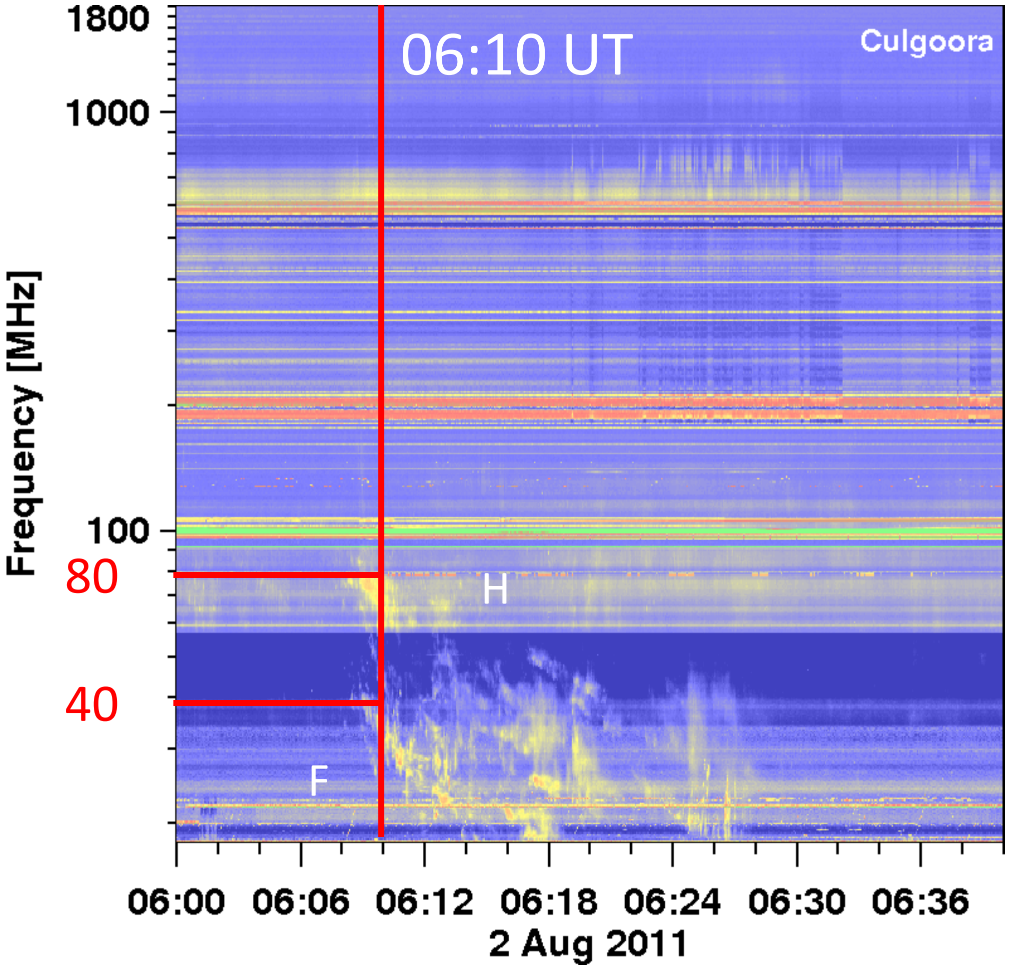


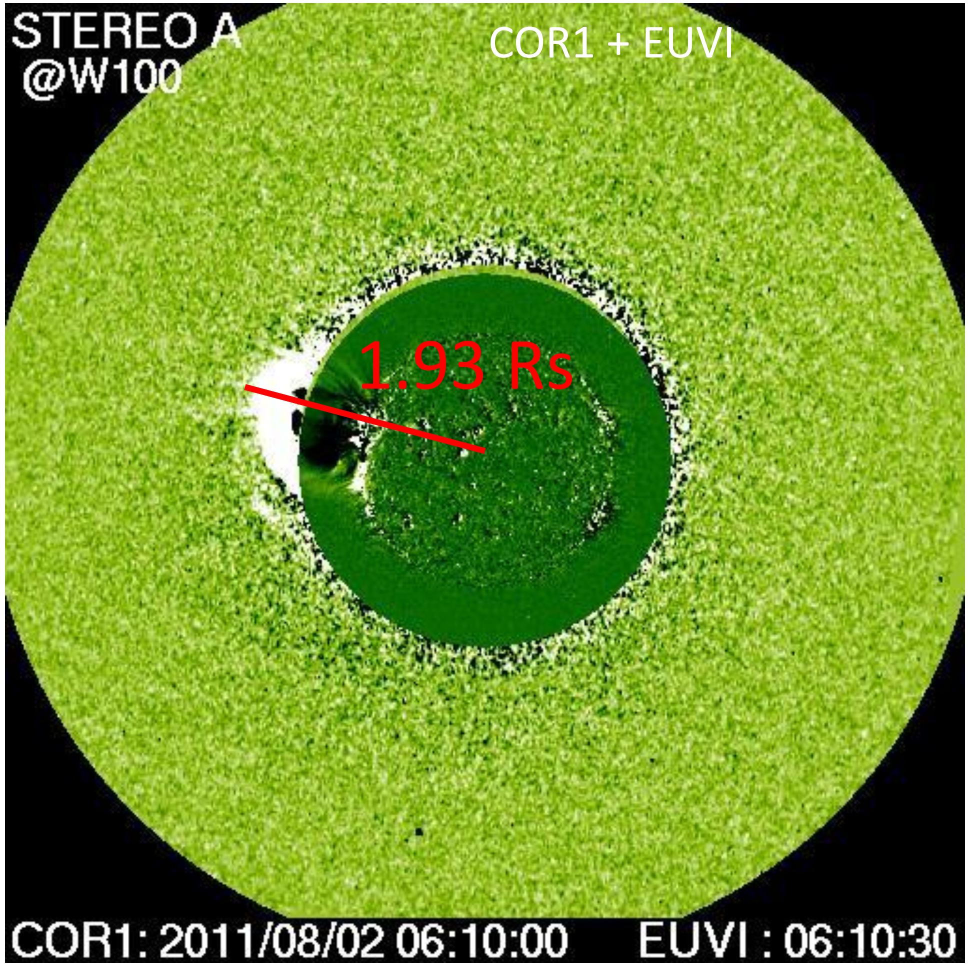


AIA wave radius @ type II onset = 0.14 Rs → Shock height in EUVI = 1.14 Rs

400 MHz → $n_p = 1.98 \times 10^9\ cm^{-3}$

CME already in the coronagraph FOV when the type II occurs

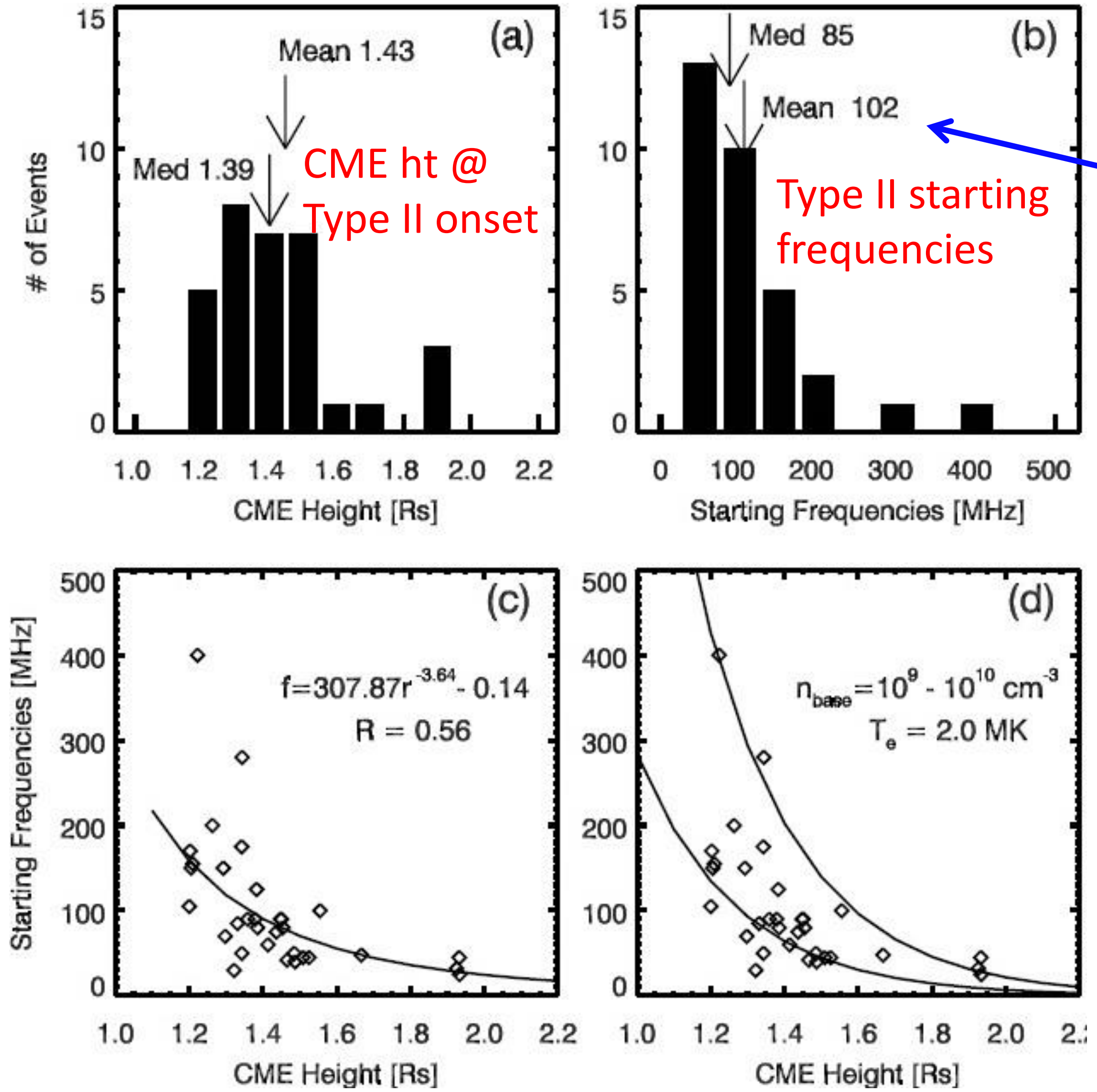




fp = 40 MHz → 1.98x10^{7} cm^{-3} Shock formation height is large: 1.93 Rs

Where in the Corona do shocks form? Statistics

32 Type II bursts
STEREO CMEs



$n = 1.2 \times 10^8$ cm^{-3}

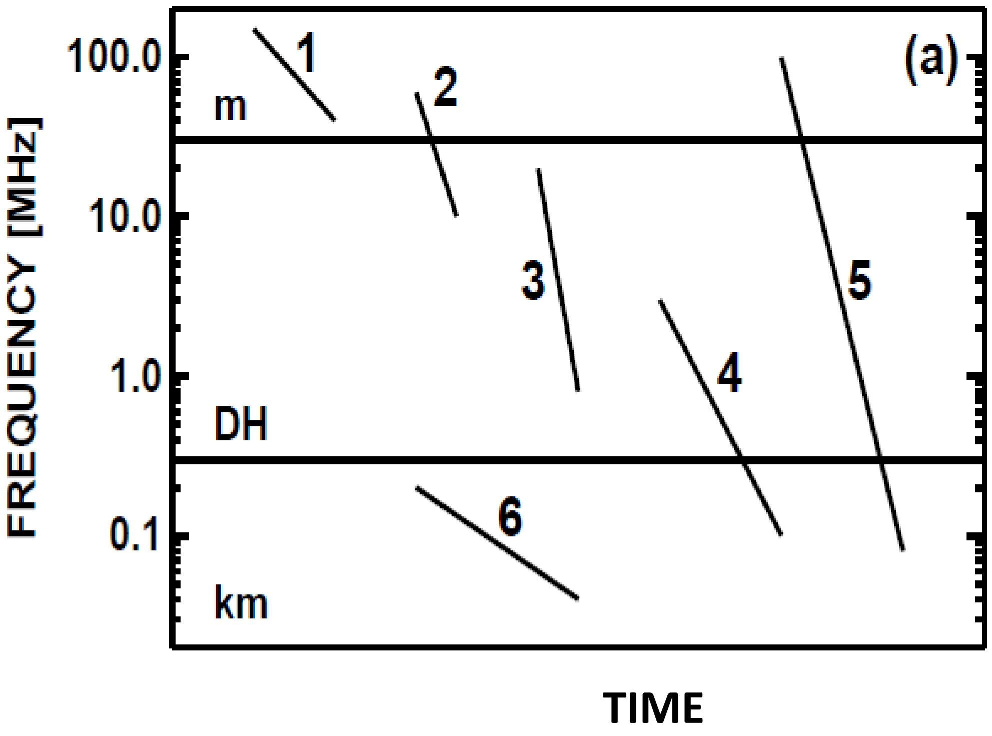
Type II heights indicate overall density decline with height

model: exponential fall off of n with a hydrostatic scale height

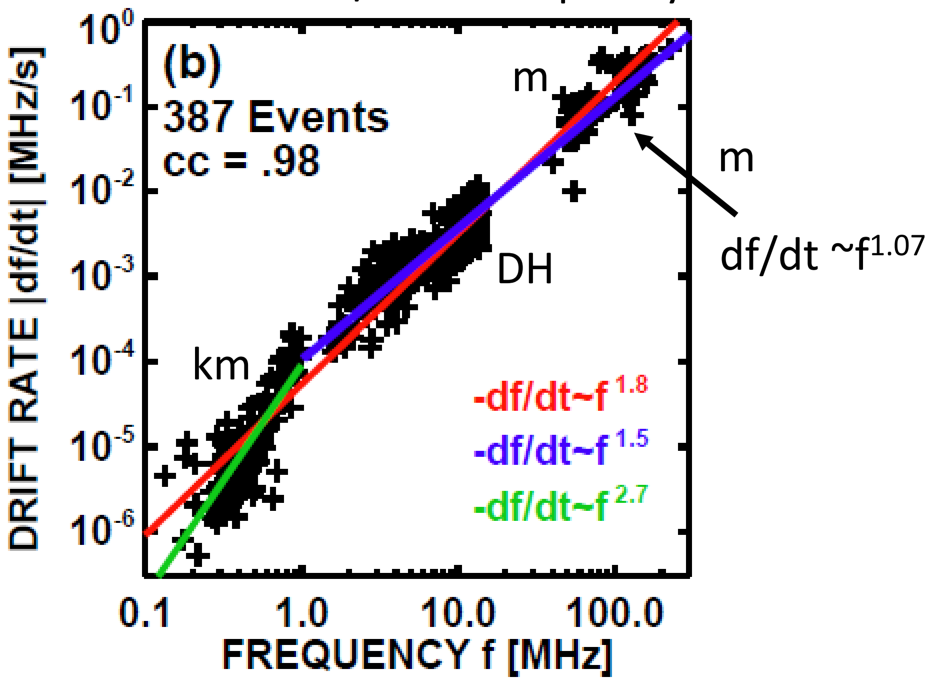
Gopalswamy et al. 2013 AdSR

Type II Burst Related to CME-driven Shock

Schematic dynamic spectra showing type II freq. range



drift rate df/dt vs. frequency f



Observed wavelength ranges of type II bursts

1,6: 600 km/s; 2,3,4: 1000 km/s; 4, 5: 1500 km/s (CME speed)

$df/dt \sim f^{\varepsilon}$

$n \sim r^{-\alpha}$ $f \sim r^{-\alpha/2}$

$V \sim r^{-\beta}$ CME speed

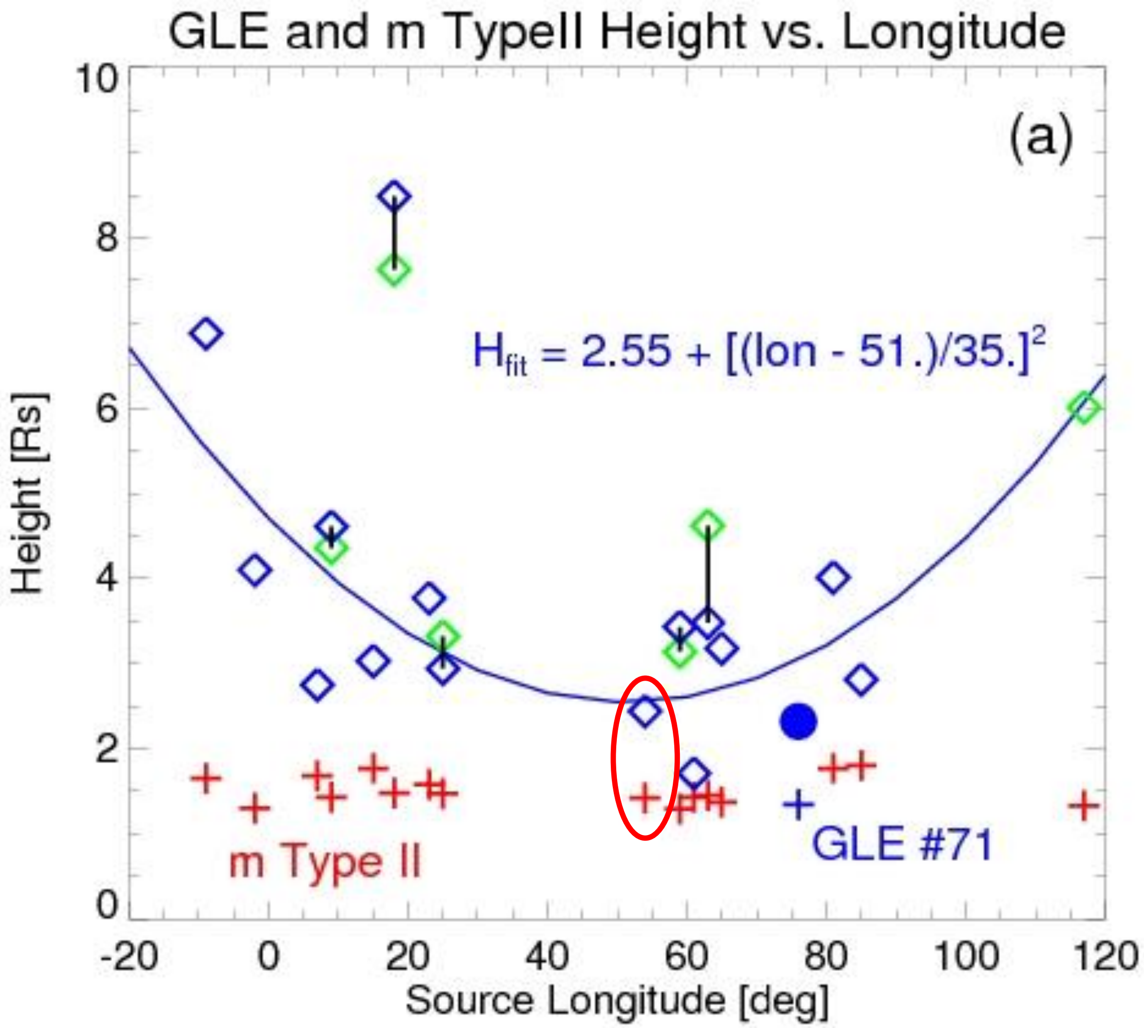
$\varepsilon = (\alpha + 2\beta + 2)/\alpha$

Inner corona: $\alpha \sim 6$; for $\varepsilon = 1.07$, $\beta = -0.79$ (CME still accelerating)

Outer corona: $\alpha \sim 4$; for $\varepsilon = 1.5$, $\beta = 0$ (CME attained constant speed)

IP medium: $\alpha \sim 2$; for $\varepsilon = 2.7$, $\beta = +0.7$ (CME decelerates due to drag)

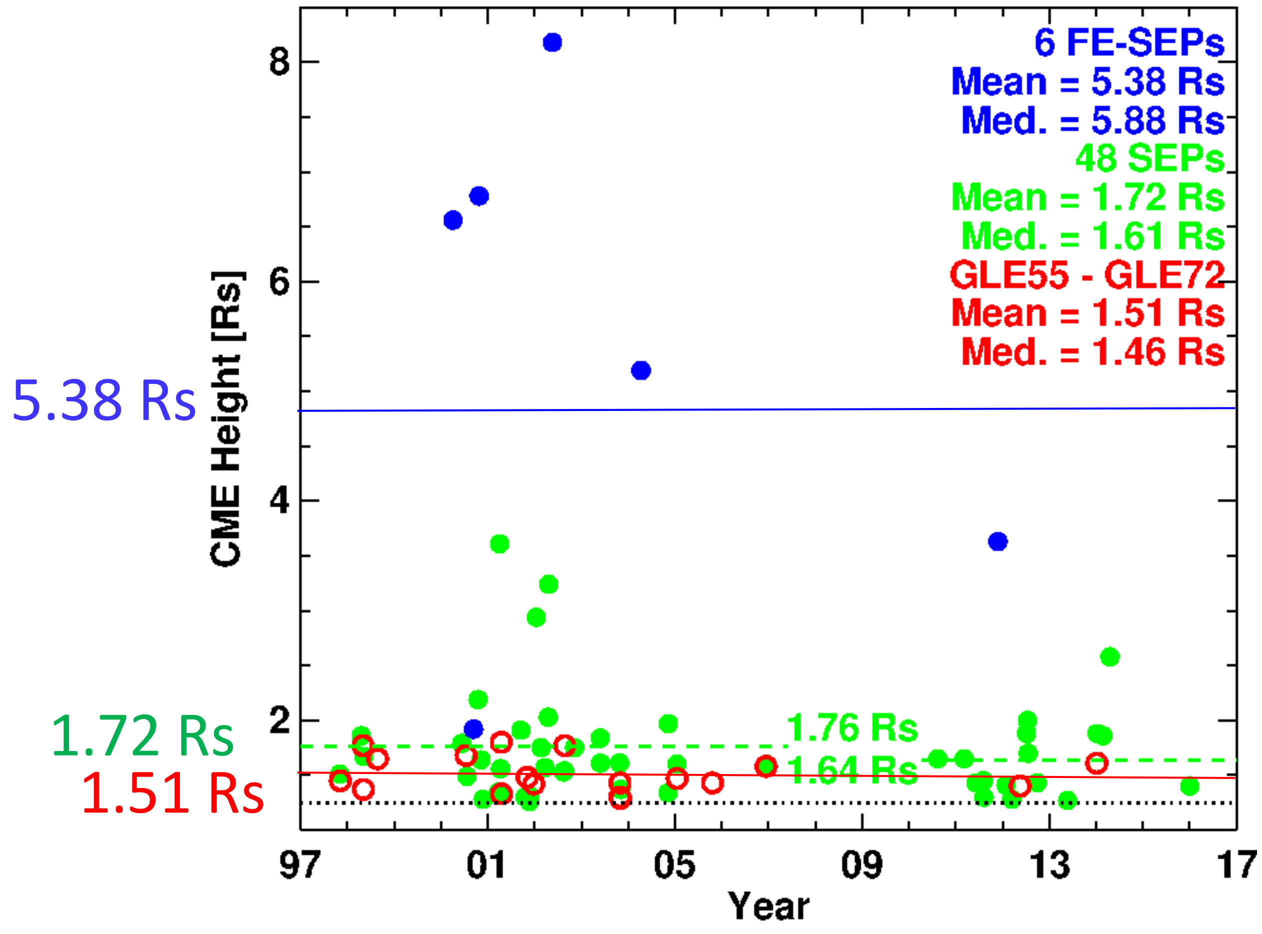
CME height at SPR & Type II Onset



- Type II onset < 2 Rs (mean value ~1.5 Rs). Flat as a function of longitude
- CME height at solar particle release (SPR) depends on the source longitude because
- the shock has to cross the Sun-Earth field line
- The shock has to travel by about a solar radius before releasing high-energy SEPs. For a 2000 km/s CME, this corresponds to an acceleration time of ~ 700 s or 12 min

Gopalswamy et al. 2012 Space Sci Rev., See also Reames, 2009

Shock Formation Height of FE SEP, Regular SEP and GLE Events



Gopalswamy et al. 2009; 2013; Mäkelä et al. 2015

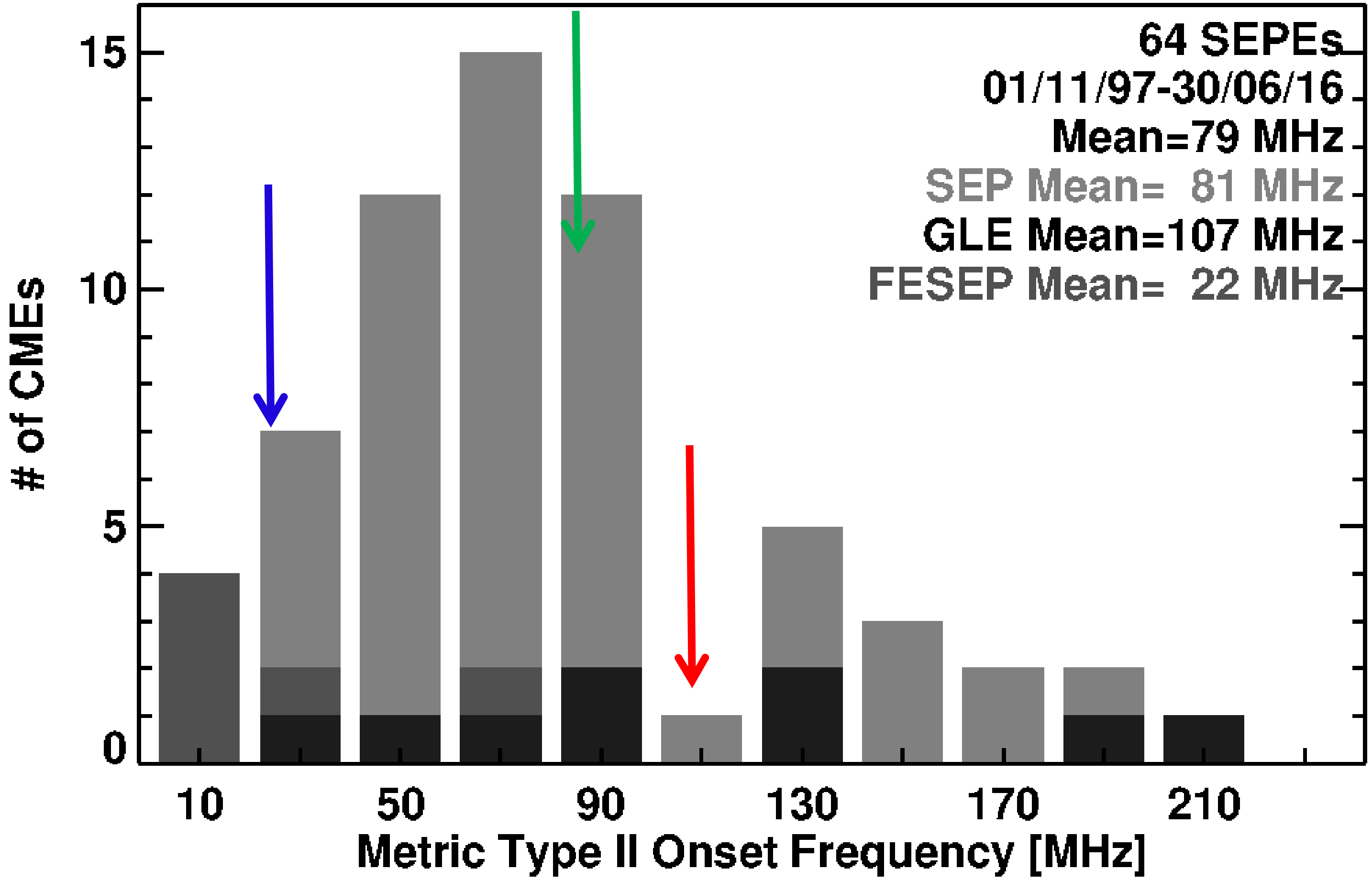
Height of the CME/shock at the onset time of the type II radio burst

For FE SEP events, the type II burst onset is determined from Wind/WAVES dynamic spectra

For **regular SEP** events and GLE events, the type II burst onset is from ground based radio telescopes

Shock formation height increases as one goes from GLE to **regular SEP** to **FE SEP** events

Starting Frequencies for FE SEP, Regular SEP, and GLE Events

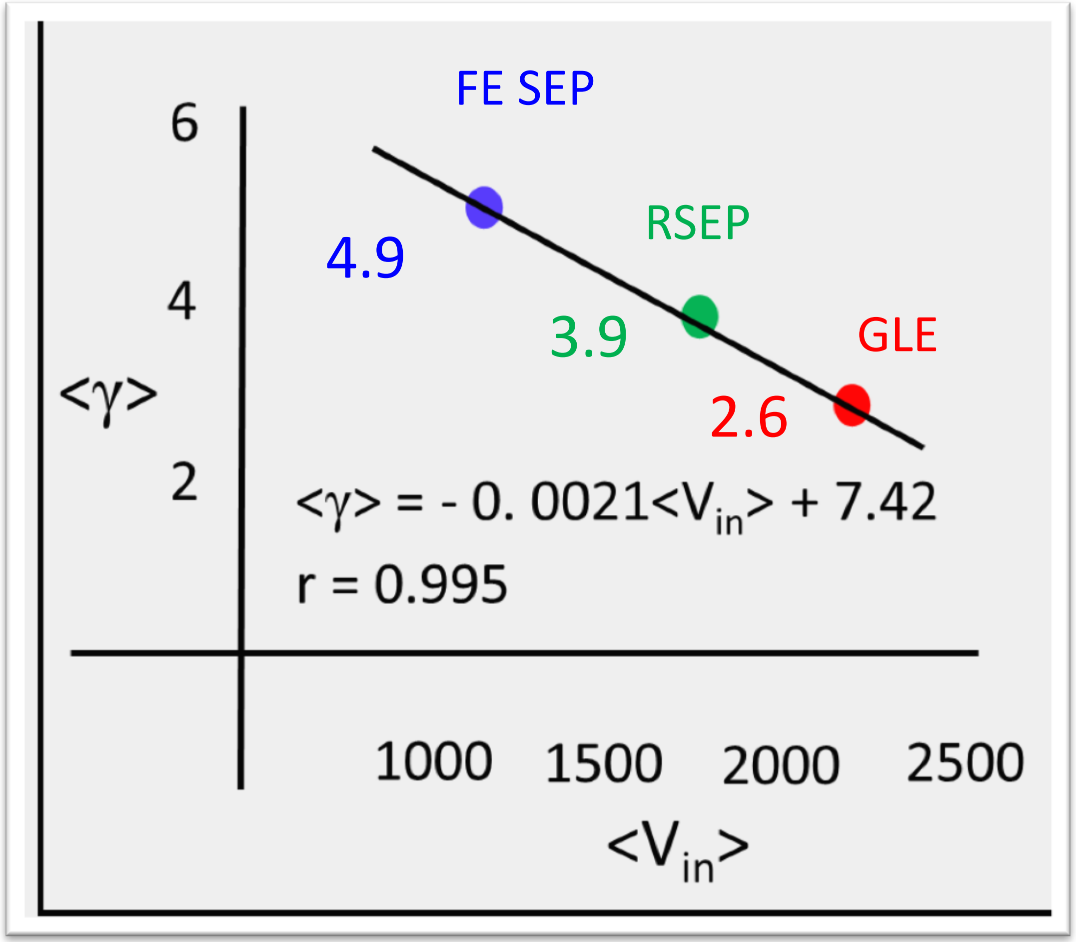


Type II bursts start at a higher frequency in GLE events compared to regular SEP events and FE SEP events

This translates into shock formation closer to the Sun for GLE events and far from the Sun in FE SEP events

Shock formation closer to the Sun alone is not sufficient because the shock needs to survive for ~10 min to accelerate particles to high energies

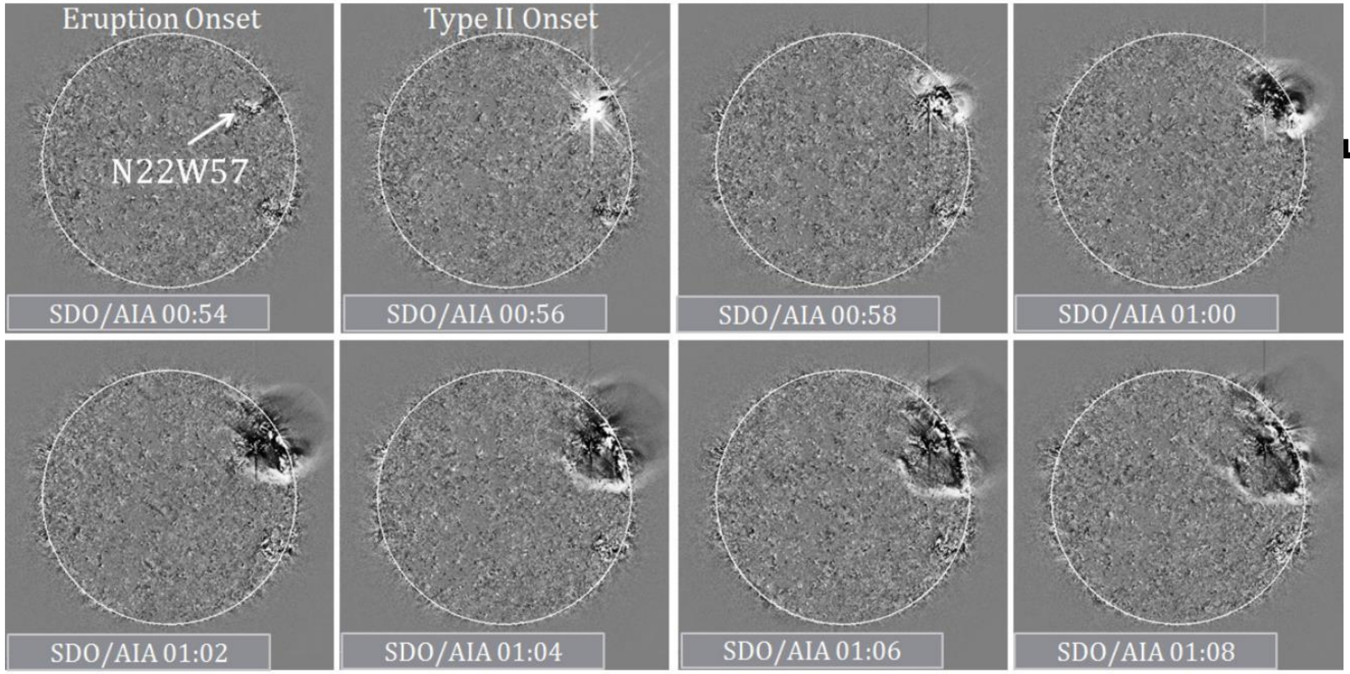
Fluence Spectral Index of SEP Events

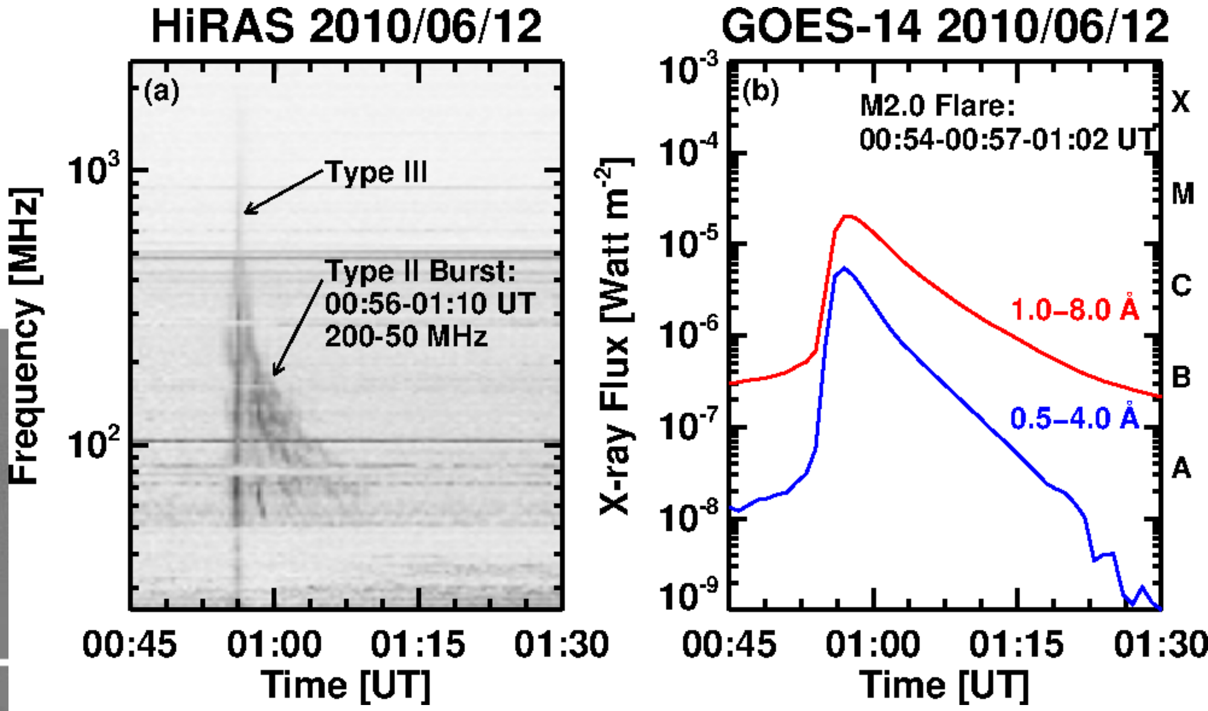


- Fluence Spectra of SEP events are organized by the initial acceleration of CMEs (propelling force)
- GLE, regular SEP, and FE SEP events are distinguished by their initial acceleration and hence the height of shock formation (indicated by the starting frequency of type II bursts)
- The close connection between SEP spectra and CME properties are consistent with the idea that the particles in large SEP events are accelerated by CME-driven shocks

2010 June 12 Event

- Metric type II with the highest frequency ~400 MHz (harmonic emission) observed by Hiraiso Radio Spectrograph (HiRAS).
- GOES M2.0 flare has a short duration ~ 8 mins.
- EUV wave observed by SDO/AIA



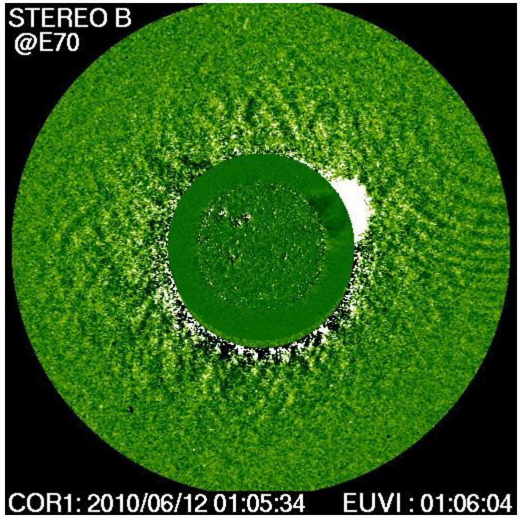


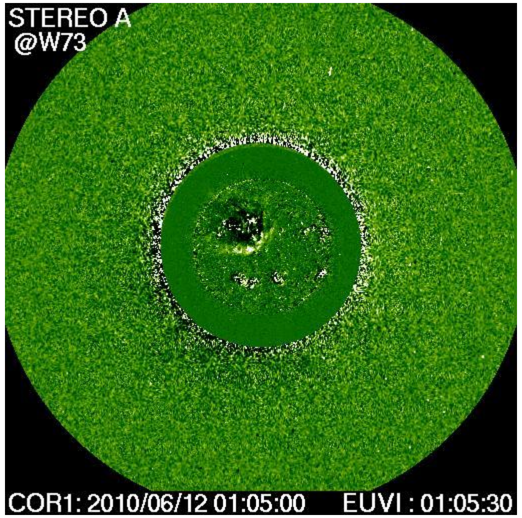
Metric type II radio burst started when the leading edge of the wave was at the limb in projection (actual height ~1.20 Rs).

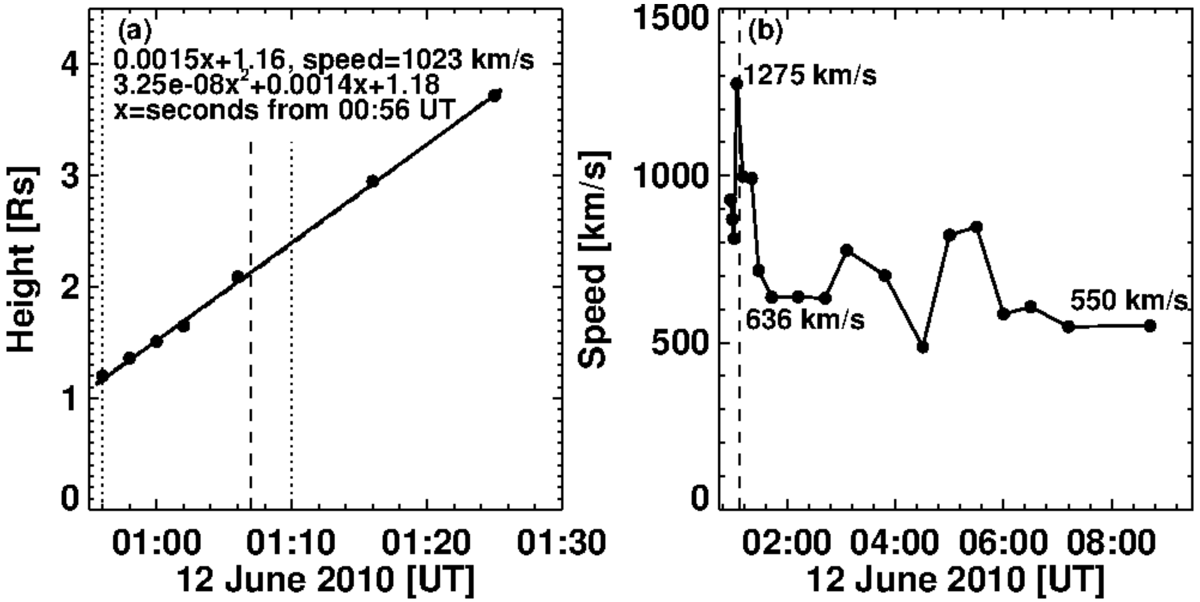
Empirical formula: $f = 308.17r^{-3.78} - 0.14$ gives $r \approx 1.13$ Rs for $f = 200$ MHz

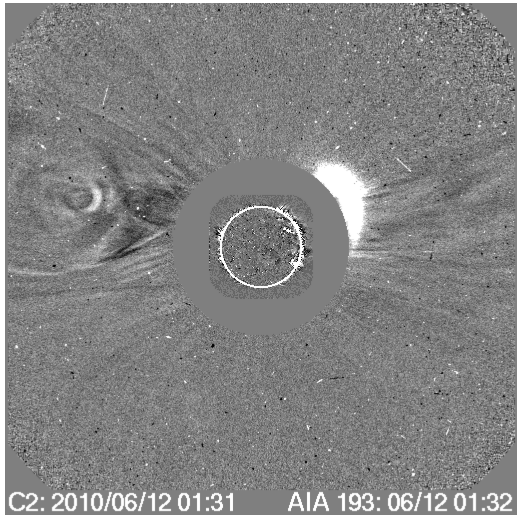
2010 June 12 CME

- Type II burst start: CME leading edge speed of ~900 km/s.
- CME speed increased to a maximum value of ~1275 km/s and dropped back to ~1000 km/s when the type II ended.
- No IP type II burst. Shock died or was too weak to produce type II emission.



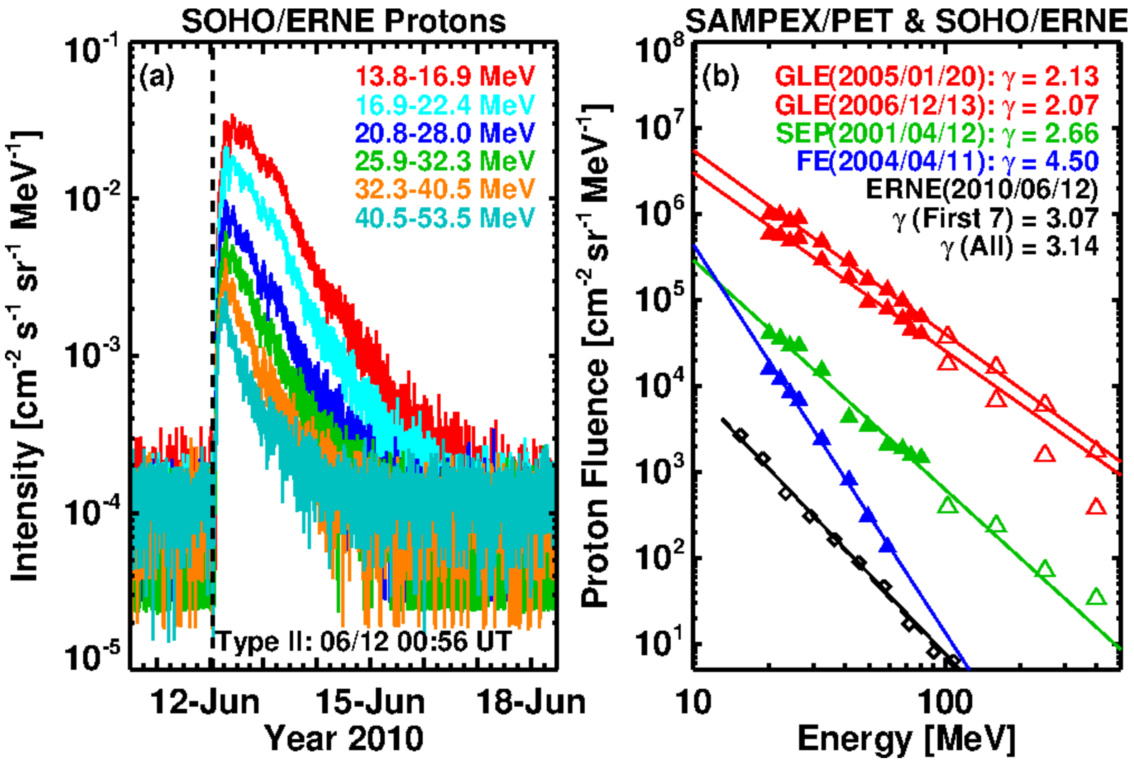






2010 June 12 SEP

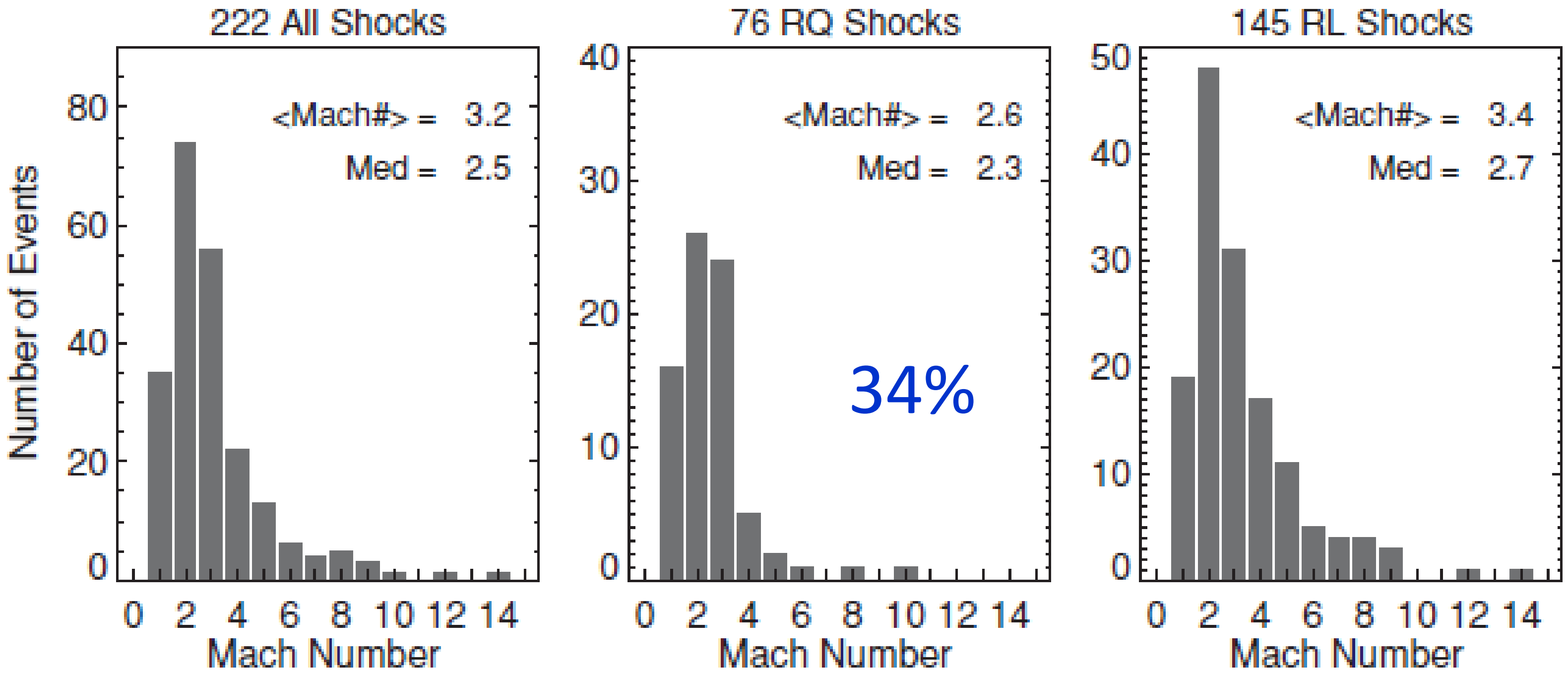
- SOHO/ERNE 13.8 – 16.9 MeV energy channel 0.3 particles per (cm^2 s sr MeV) .
- GOES >10 MeV channel peak 1.21 particles per (cm^2 s sr)



- electromagnetic emissions becomes 01:07 UT.
- Type II burst 00:56-01:10 UT, so the SEP acceleration took ~ 10 mins, which is a typical value.

- The fluence spectrum resamples those of regular SEP events. The spectral index (3.14) lies between the 2001 April 12 regular SEP event and the 2004 April 11 FE SEP event.
- In addition to high initial acceleration, the CME speed needs to be high to produce an intense event

Radio Technique cannot be used for some shocks

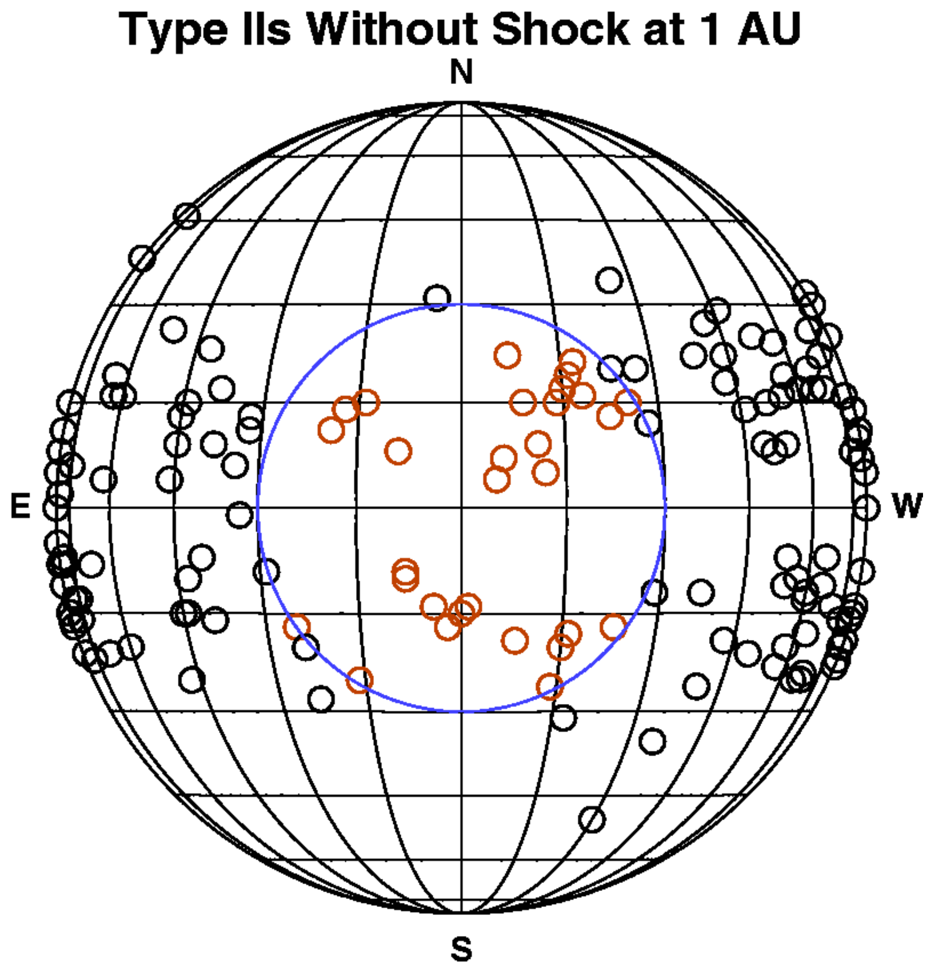


- About a third of IP shocks are radio-quiet (no type II)
- These are due to slowly accelerating CMEs forming shocks at large distances from the Sun
- Fortunately, these shocks are not important for space weather

Gopalswamy et al. 2010 JGR

Some shocks observed near the Sun do not arrive at 1 AU

- Type II bursts from limb CMEs generally do not produce a shock signal at 1 AU (black circles)
- However, some disk-center CMEs with type II bursts do not produce a shock signal at 1 AU (red circles)
- No large SEP events, only minor SEP events (intensity <10 pfu). Consistent with type II bursts near the Sun
- These CMEs are generally slow (<V>~640 km/s) and the type II bursts occur over a narrow spectral range (above 1 MHz)
- CME interaction can lead to the disappearance of one of the shocks
- CMEs can be deflected away from the Sun-Earth line by nearby coronal holes



Gopalswamy et al. 2012

Summary

- Type II radio bursts provide an early warning of CME-driven shocks
- Shock propagation up to a heliocentric distance of 2 Rs can be observed from ground (e.g., using CALLISTO) that can be verified using CME observations
- The shock formation height can be derived from the starting frequency of type II bursts, a good reference for SEP release height
- The type II starting frequency (and hence the shock formation height) is also indicative of the spectral hardness of the associated SEP events.