Flare global waves of three kinds

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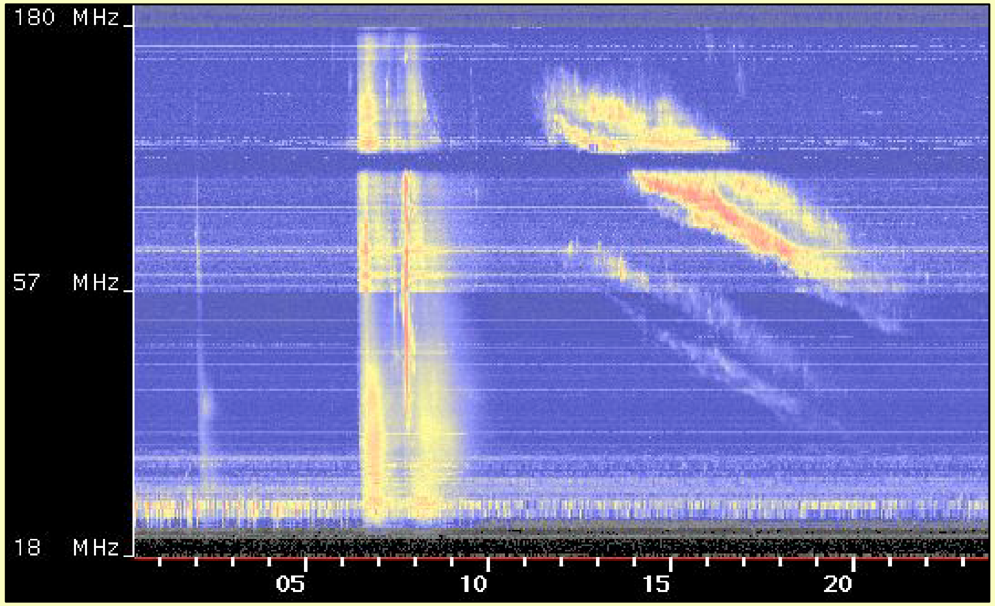
Abstract

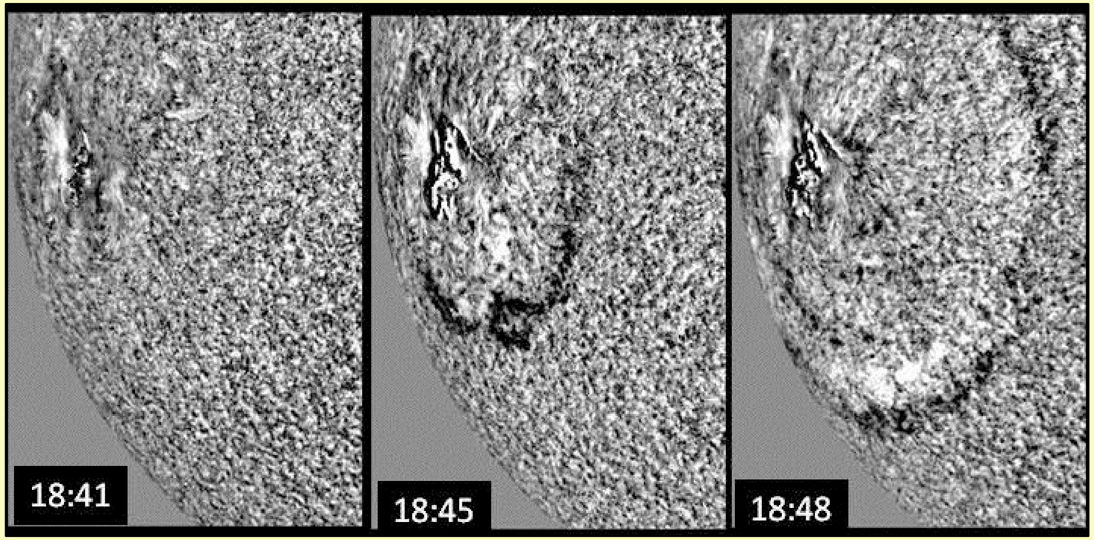
Flares produce at least three kinds of global waves: coronal (metric type II; coronagraphic), chromospheric (Moreton) and interior ("sunquakes"). In addition, EIT waves, coronal dimmings, and CMES may also have wave-like properties. Each of the three types of global wave begins at the impulsive phase of a flare. This is also the time of sudden stepwise change in the photospheric line-of-sight field, and the time of the CME acceleration phase. We review the observational material, starting with the published seismic events, and ask whether or not a common origin is consistent with the physical parameters in the likely region of origin.

Morphology I



Type II burst:
- slow drift ~10^3 km/s
- onset delayed
- radiant @ early impulsive phase

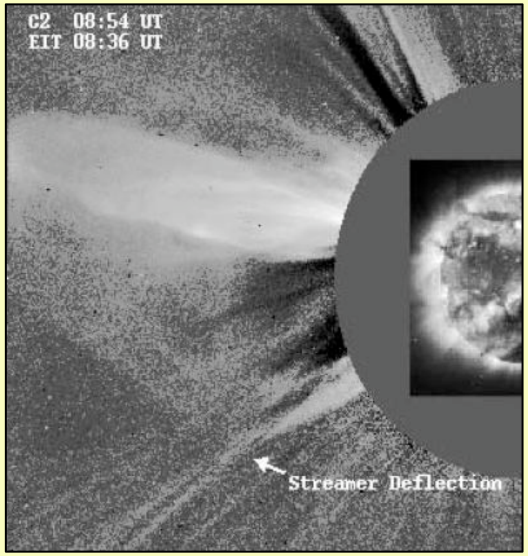
(Culgoora file image)

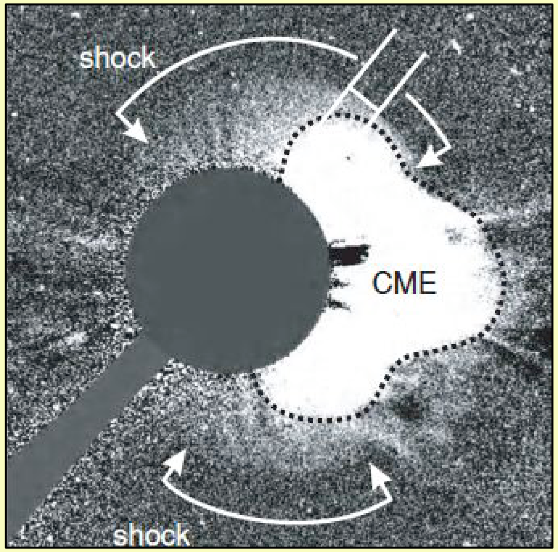


Moreton wave:
- chromospheric signatures
- speed ~10^3 km/s
- radiant @ early impulsive phase

(Balasubramaniam et al. 2010; from 2002 Dec. 6 “tsunami”)

Morphology II

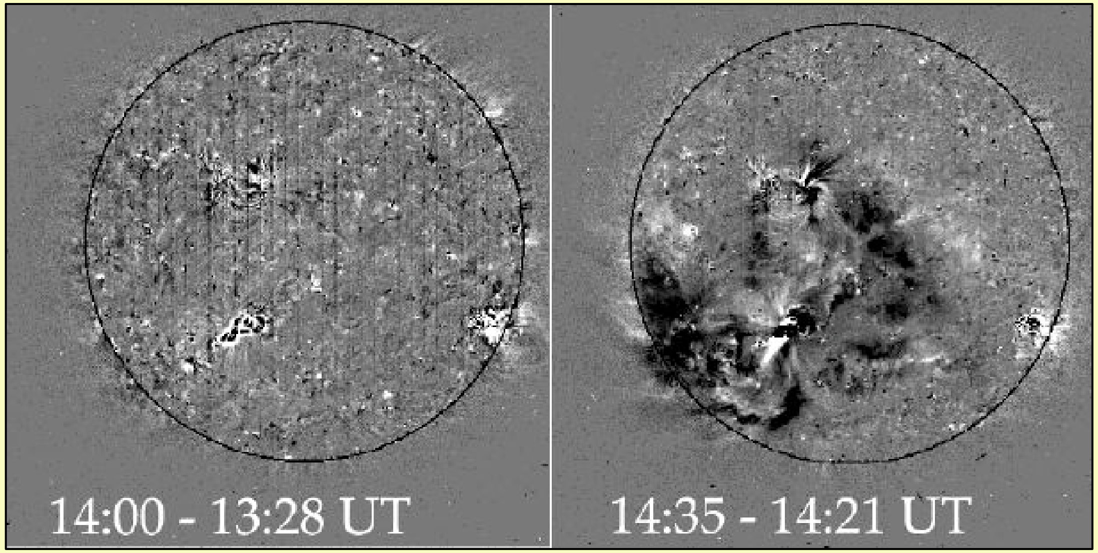




Coronagraphic shock:

- flanks may be important
- consistent with RH
- common feature (now)

(Vourlidas 2003; Ontiveros & Vourlidas 2009)

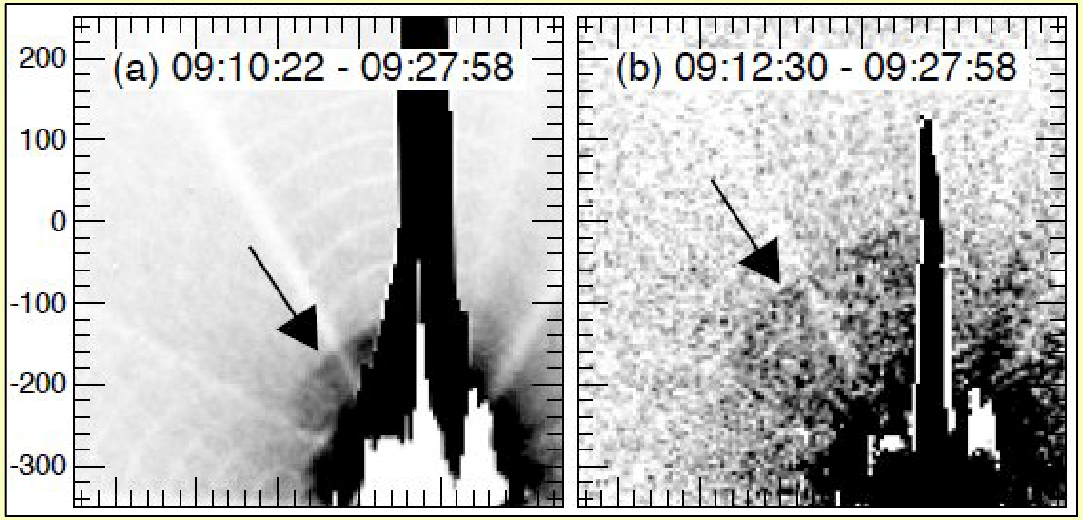


EIT “wave”:

- heterogeneous sources
- speed usually <10^3 km/s
- clear magnetic deflections
- radiant @ impulsive phase

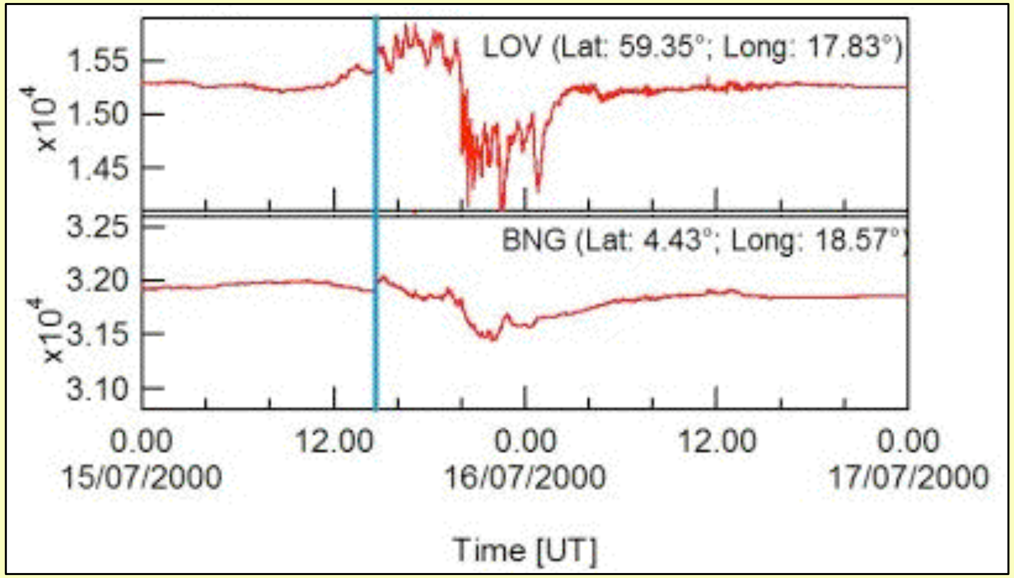
(Thompson et al. 1999)

Morphology III



Soft X-ray wave:
- speed ~10^3 km/s
- radiant @ impulsive phase
- suggests low Mach number
- ignore many artifacts!

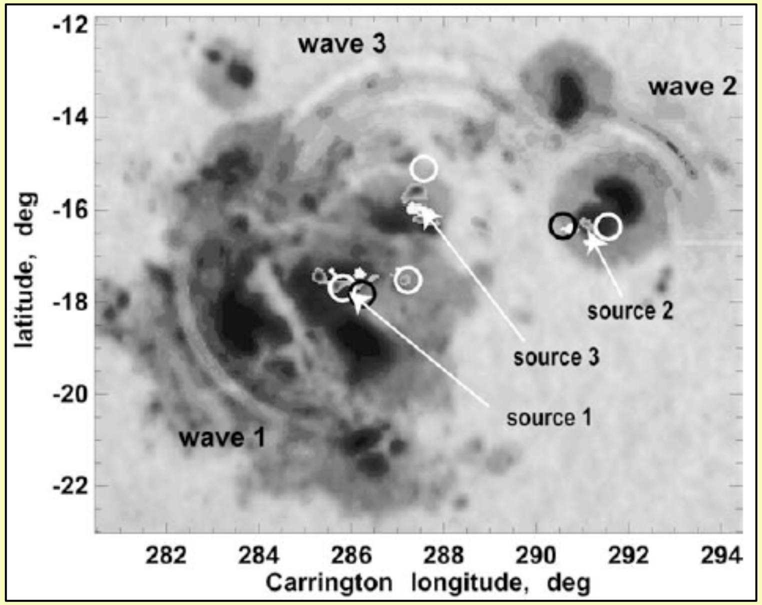
(Khan & Aurass 2002; Hudson et al. 2003)



Storm commencement (SI)
- geomagnetic signature
- global magnetospheric effect
- 1859 Carrington flare
- interplanetary shock wave
- ICME association

(Source INGV)

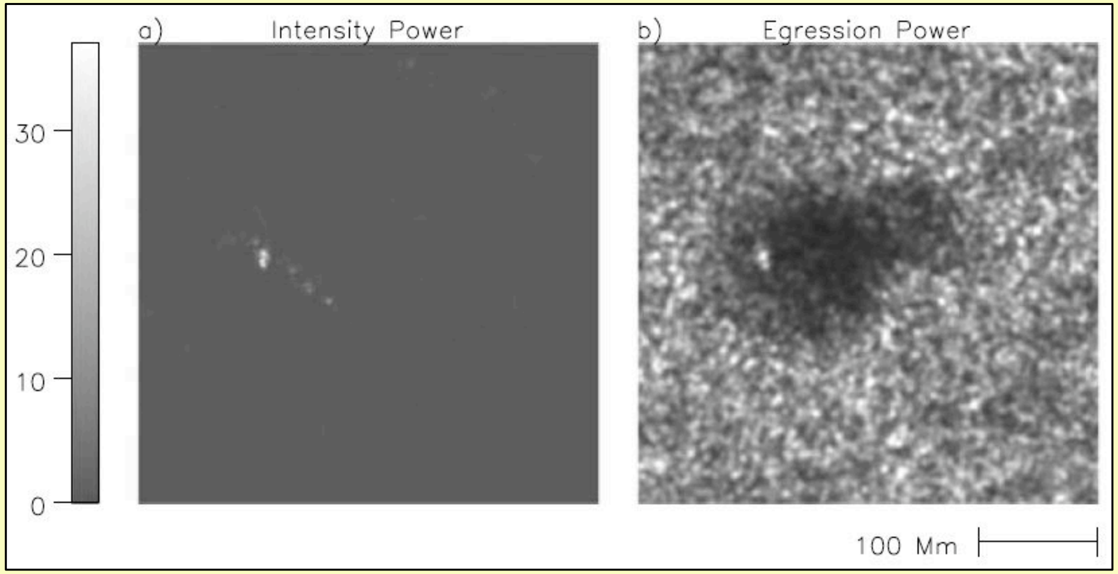
Morphology IV



Seismic wave:

- example of 28-Oct-03
- multiple radiant points
- HXR association
- now many examples

(Kosovichev 2007)



Acoustic source:

- holographic imaging
- WLF (left) matches source
- "egression power" (right) easier to see in umbra

(Source Lindsey & Donea 2008)

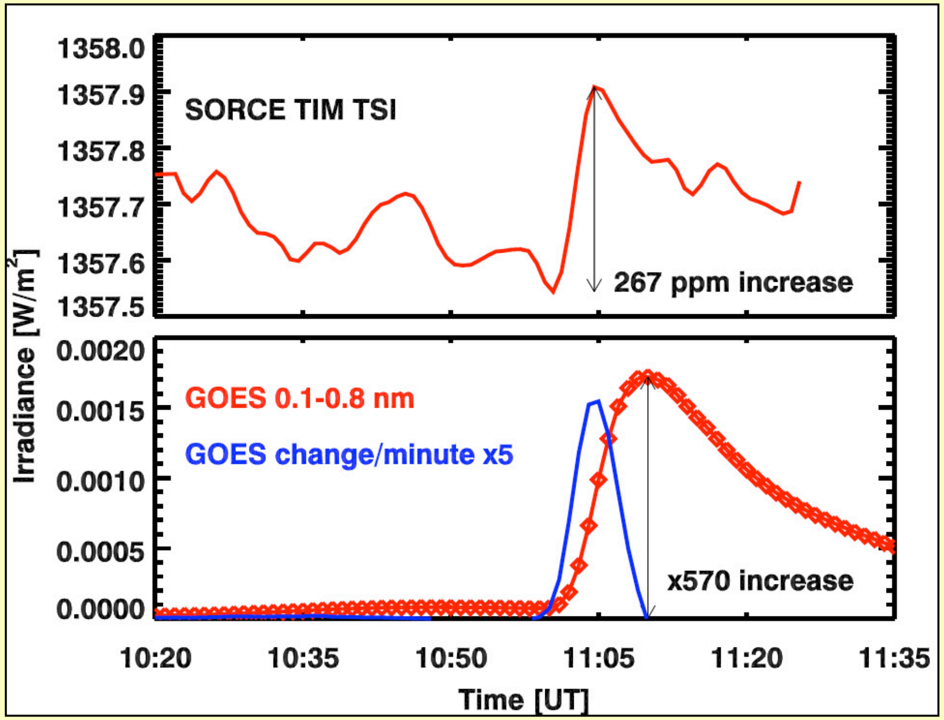
Energies of global waves

- IP shock: ~ 0.1 (Mewaldt et al. 2008)
- Moreton wave: $>10^{-6}$ (Gilbert et al. 2008)
- Seismic wave: $\sim 10^{-4}$ (Lindsey & Donea)
- CME ~1[a] (Emslie et al. 2005)

[a] (if present)

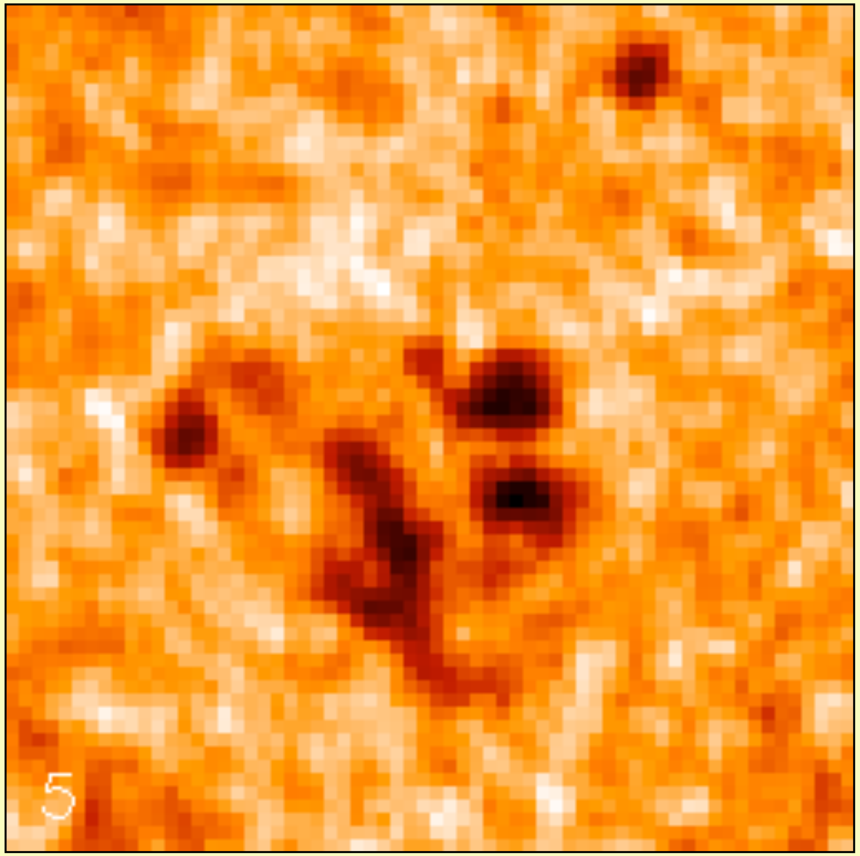
Flare energy

Short-lived[1]



Woods et al 2004

Small-scale[2]

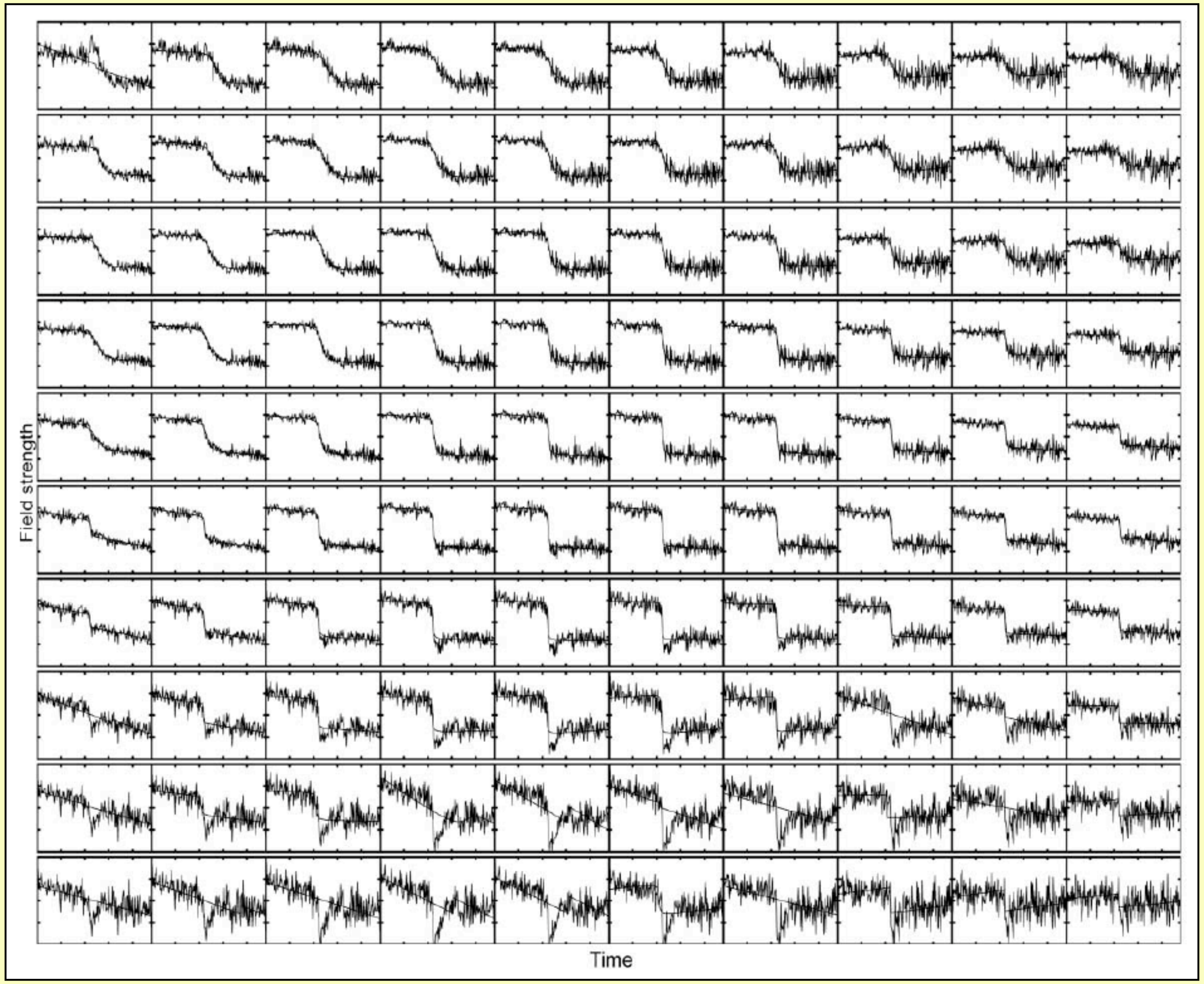


Hudson et al 2006

[2]TSI impulsive phase, flare SOL20031028T11:05

[2]TRACE 0.5" pixels, flare SOL20040722T00:30

Magnetic changes during flares



“Confusogram” legend:
10x10 2.5” pixels;
240 minutes time base;
500 G magnetic range;
SOL20031102T17:03
(X8.3 flare)

(Sudol & Harvey 2005)

Energetic inferences

• Flare energy scales are consistent with wave energies, except possibly that of the IP wave

• Flare energy sources are compact and brief, and can excite coronal waves via the Lorentz force

• Seismic wave excitation may require an intermediary atmospheric shock wave, or radiative coupling, or Alfvénic coupling

Significance of low β

- In the active-region corona, except possibly for small inclusions, β is low. Thus gas pressure is explicitly unimportant.

- At low β all visible structures are mere tracers and can't be dynamically important.

- This also applies to the sunspot regions where seismic waves are launched.

- In the solar wind, β increases and so these observations do not necessarily apply.

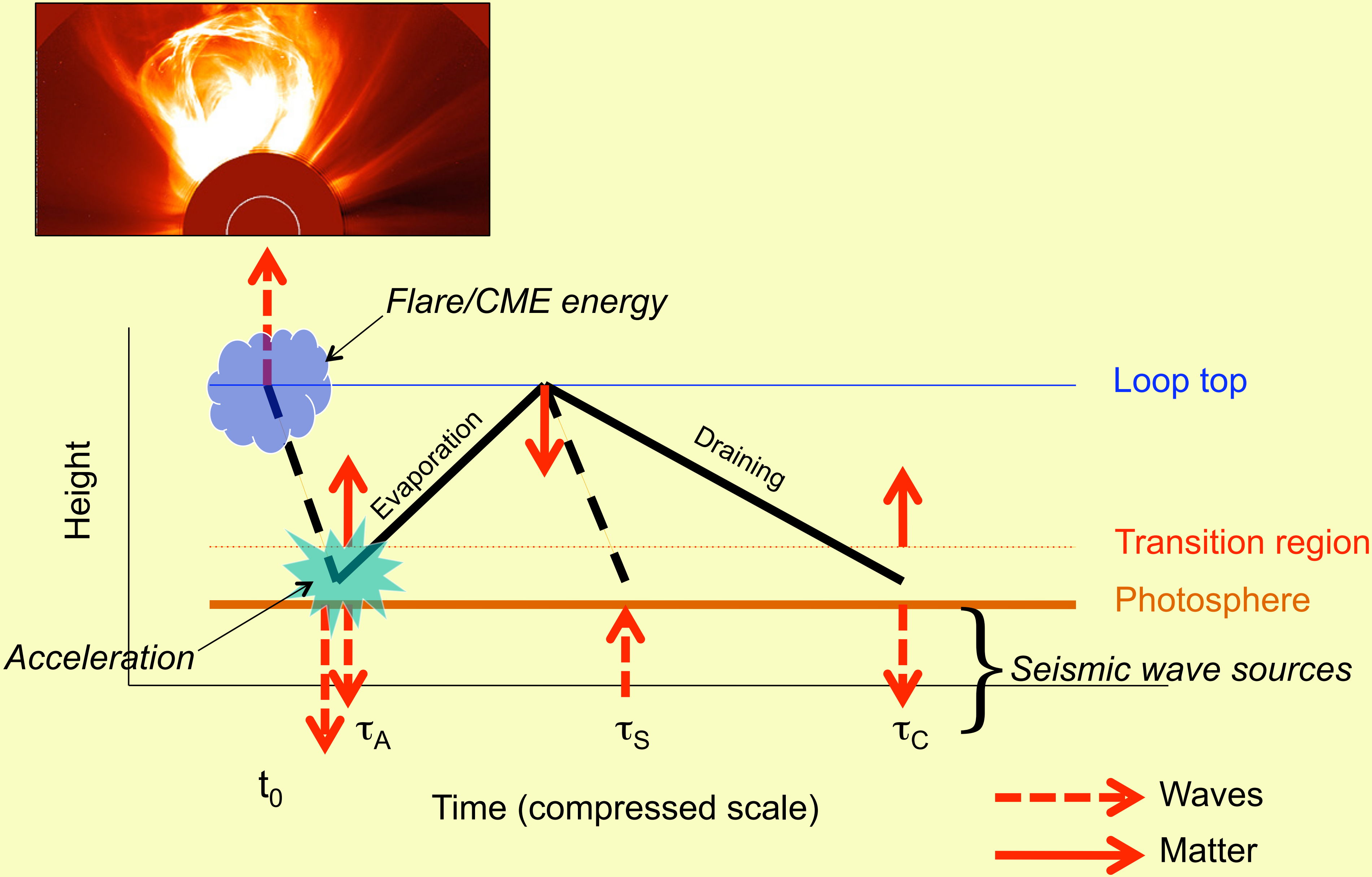
Momentum for seismic wave[1]

Phenomenon	Mass g	Velocity km/s	Δt s	Momentum gm cm/s
Surge/jet[a]	2×10^{15}	500	$\sim$300	1.1×10^{23}
CME[b]	10^{16}	1000	100?	10^{24}
Evaporation[c]	2×10^{15}	500	30	1×10^{23}
Trapping[b]	2×10^{15}	500	30	-1×10^{23}
Draining	2×10^{15}	10	$\sim 10^4$	2×10^{21}
Seismic wave[d]		40	20-50	2.5×10^{22}

[a]Bain and Fletcher (2009); [b]rough estimate; [c]Canfield et al. (1987); [d]10^{29} erg

[1]Scaled to X1

Flare Momentum Conservation



Momentous inferences

• There is sufficient momentum in either CME or evaporative flows to explain the seismic wave

• The mismatch in detail probably reflects spectral selection (ie, different timescales)

• CME excitation predicts one pulse, evaporative excitation two of opposite sign

• These considerations suggest that flares without CMEs will have weaker seismic signatures

The Lorentz force in context

"…an enormous amount of magnetic energy…seems to be annihilated during the flare. This should cause a subsequent relaxation of the entire field structure…moving large masses…"

- Wolff 1972

"The magnetic force applied to the photosphere…1.2 x 10^{22} dyne…"

- Anwar et al. 1993 (McClymont)

"Magnetic forces should be of particular significance… where the magnetic field is significantly inclined from vertical."

- Donea & Lindsey 2005

"Our estimates suggest that the work done by Lorentz forces in this back reaction could supply enough energy to explain observations of flare-driven seismic waves."

- Hudson et al. 2008 ("Jerk")

Conclusions

- Several kinds of global wave are commonly excited during a major solar flare
- The radiant points of these global waves strongly tend to coincide with the impulsive phase, both spatially and temporally
- Heating, shock dynamics, or the Lorentz force may each play a role
- But ultimately it is the restructuring of the magnetic field that must supply the energy and momentum because plasma β is low

B. Anwar, L.W. Acton, H.S. Hudson, M. Makita, A.N. McClymont, S. Tsuneta, Rapid Sunspot Motion during a Major Solar Flare. Solar Phys. **147**, 287–303 (1993). doi:10.1007/BF00690719

H.M. Bain, L. Fletcher, Hard X-ray emission from a flare-related jet. Astron. Astrophys. **508**, 1443–1452 (2009). doi:10.1051/0004-6361/200911876

K.S. Balasubramaniam, many co-authors, Tsunami HO! Journ. Geophys. Res., (2010)

A. Donea, C. Lindsey, Seismic Emission from the Solar Flares of 2003 October 28 and 29. Astrophys. J. **630**, 1168–1183 (2005). doi:10.1086/432155

A.G. Emslie, B.R. Dennis, G.D. Holman, H.S. Hudson, Refinements to flare energy estimates: A followup to "Energy partition in two solar flare/CME events" by A. G. Emslie et al. Journal of Geophysical Research (Space Physics) **110**, 11103 (2005). doi:10.1029/2005JA011305

H.R. Gilbert, A.G. Daou, D. Young, D. Tripathi, D. Alexander, The Filament-Moreton Wave Interaction of 2006 December 6. Astrophys. J. **685**, 629–645 (2008). doi:10.1086/590545

H.S. Hudson, G.H. Fisher, B.T. Welsch, Flare Energy and Magnetic Field Variations, in *Subsurface and Atmospheric Influences on Solar Activity*, ed. by R. Howe, R. W. Komm, K. S. Balasubramaniam, & G. J. D. Petrie . Astronomical Society of the Pacific Conference Series, vol. 383, 2008, p. 221

H.S. Hudson, C.J. Wolfson, T.R. Metcalf, White-Light Flares: A TRACE/RHESSI Overview. Solar Phys. **234**, 79–93 (2006). doi:10.1007/s11207-006-0056-y

H.S. Hudson, J.I. Khan, J.R. Lemen, N.V. Nitta, Y. Uchida, Soft X-ray observation of a large-scale coronal wave and its exciter. Solar Phys. **212**, 121–149 (2003). doi:10.1023/A:1022904125479

J.I. Khan, H. Aurass, X-ray observations of a large-scale solar coronal shock wave. Astron. Astrophys. **383**, 1018–1031 (2002). doi:10.1051/0004-6361:20011707

A.G. Kosovichev, Properties of Flares-Generated Seismic Waves on the Sun. Solar Phys. **238**, 1–11 (2006). doi:10.1007/s11207-006-0190-6

A.G. Kosovichev, V.V. Zharkova, X-ray flare sparks quake inside Sun. Nature **393**, 317–318 (1998). doi:10.1038/30629

C. Lindsey, A. Donea, Mechanics of Seismic Emission from Solar Flares. Solar Phys. **251**, 627–639 (2008). doi:10.1007/s11207-008-9140-9

R.A. Mewaldt, C.M.S. Cohen, J. Giacalone, G.M. Mason, E.E. Chollet, M.I. Desai, D.K. Haggerty, M.D. Looper, R.S. Selesnick, A. Vourlidas, How Efficient are Coronal Mass Ejections at Accelerating Solar Energetic Particles?, in *American Institute of Physics Conference Series*, ed. by G. Li, Q. Hu, O. Verkhoglyadova, G. P. Zank, R. P. Lin, & J. Luhmann . American Institute of Physics Conference Series, vol. 1039, 2008, pp. 111–117. doi:10.1063/1.2982431

V. Ontiveros, A. Vourlidas, Quantitative Measurements of Coronal Mass Ejection-Driven Shocks from LASCO Observations. Astrophys. J. **693**, 267–275 (2009). doi:10.1088/0004-637X/693/1/267

J.J. Sudol, J.W. Harvey, Longitudinal Magnetic Field Changes Accompanying Solar Flares. Astrophys. J. **635**, 647–658 (2005). doi:10.1086/497361

B.J. Thompson, J.B. Gurman, W.M. Neupert, J.S. Newmark, J. Delaboudinière, O.C. St. Cyr, S. Stezelberger, K.P. Dere, R.A. Howard, D.J. Michels, SOHO/EIT Observations of the 1997 April 7 Coronal Transient: Possible Evidence of Coronal Moreton Waves. Astrophys. J. (Lett.) **517**, 151–154 (1999). doi:10.1086/312030

A. Vourlidas, S.T. Wu, A.H. Wang, P. Subramanian, R.A. Howard, Direct Detection of a Coronal Mass Ejection-Associated Shock in Large Angle and Spectrometric Coronagraph Experiment White-Light Images. Astrophys. J. **598**, 1392–1402 (2003). doi:10.1086/379098

C.L. Wolff, Free Oscillations of the Sun and Their Possible Stimulation by Solar Flares. Astrophys. J. **176**, 833 (1972). doi:10.1086/151680

T.N. Woods, G. Kopp, P.C. Chamberlin, Contributions of the solar ultraviolet irradiance to the total solar irradiance during large flares. Journal of Geophysical Research (Space Physics) **111**, 10 (2006). doi:10.1029/2005JA011507

Momentum Conservation