

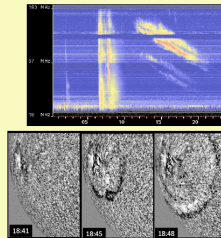
Flares and global waves, including seismic

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Abstract

Solar flares are closely associated with large-scale waves or other global signatures in the corona (type II bursts, EIT waves, and CMEs). Global waves also appear in the chromosphere (Moreton), and in the interior ("sunquakes"). The morphology of these phenomena suggests that all begin in compact sources at low altitudes in the solar atmosphere, and that their excitation is closely related to the impulsive phase of the associated flare. For the coronal and chromospheric signatures, the effects cannot now be observed close to their radiant points. The seismic signature is most conspicuous 5-60 Mm away from the source, and 30-60 minutes after the impulsive phase. We discuss the morphology and energetics of these global effects. We argue that the magnetic restructuring involved in flare energy release ultimately must excite each of them. This process may involve intermediary steps that are in most cases not well understood.

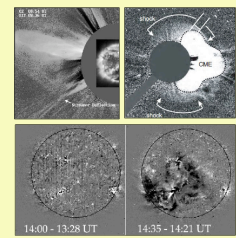
Morphology I



Type II burst:
 • slow drift ~10³ km/s
 • onset delayed
 • radiant @ early impulsive phase (Culpoora file image)

Moreton wave:
 • chromospheric signatures
 • speed ~10 km/s
 • radiant @ early impulsive phase (Balasubramanian et al. 2010; from 2002 Dec. 6 "tsunami")

Morphology II



Coronal shock:
 • flanks may be important
 • consistent with RH
 • common feature (now) (Vourlidas 2003; Ontiveros & Vourlidas 2009)

EIT wave:
 • heterogeneous sources
 • speed usually <10 km/s
 • clear magnetic deflections
 • radiant @ impulsive phase (Thompson et al. 1999)

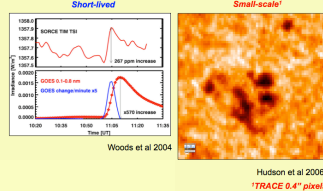
Energies of global waves

- IP shock: ~0.1 (Mewaldt et al. 2008)
- Moreton wave: >10⁻⁶ (Gilbert)
- Seismic wave: ~10⁻⁴ (Lindsey)
- CME: ~1⁹ (Emslie et al. 2005)

* (if present)



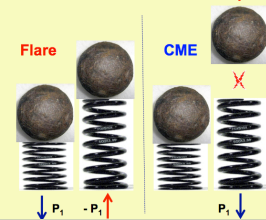
Flare energy



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

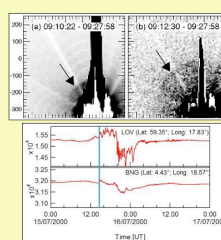
Momentum Conservation



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 (i.e. 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

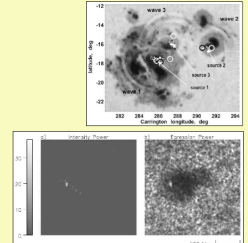
Morphology III



Soft X-ray wave:
 • speed ~10³ km/s
 • radiant @ impulsive phase
 • suggests low Mach number (Khan & Aurass 2002; Hudson et al. 2003)

Storm commencement (SI)
 • geomagnetic signature
 • global magnetospheric effect
 • 1859 Carrington flare
 • intermediary shock wave
 • ICME association (Source INGV)

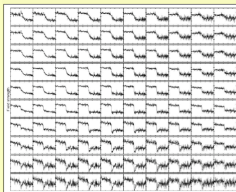
Morphology IV



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
 • "regression power" (right) easier to see in umbra (Source Lindsey & Donea 2008)

Magnetic changes during flares



"Confusogram" legend:
 10x10 2.5 pixels
 240 minutes time base
 500 G magnetic range

(Sudol & Harvey 2005)

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.

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..." - Wolf 1972

"The magnetic force applied to the photosphere... 1.2 x 10²² 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")

Momentum for seismic wave¹

| Phenomenon | Mass g | Velocity km/s | Δt s | Momentum gm cm/s |
|---------------------------|----------------------|---------------|------------------|------------------------|
| Surge/jet ^a | 2 × 10 ¹⁵ | 500 | ~300 | 1.1 × 10 ²³ |
| CME ^b | 10 ¹⁶ | 1000 | 1007 | 10 ²⁴ |
| Evaporation ^c | 2 × 10 ¹⁵ | 500 | 30 | 1 × 10 ²³ |
| Trapping ^d | 2 × 10 ¹⁵ | 500 | 30 | -1 × 10 ²³ |
| Draining | 2 × 10 ¹⁵ | 10 | ~10 ⁴ | 2 × 10 ²¹ |
| Seismic wave ^d | | 40 | 20-50 | 2.5 × 10 ²² |

^aBain and Fletcher (2009); ^brough estimate; ^cCanfield et al. (1987); ^d10²⁰ erg

¹Scaled to X1

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



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