Seismic Emission from Solar Flares

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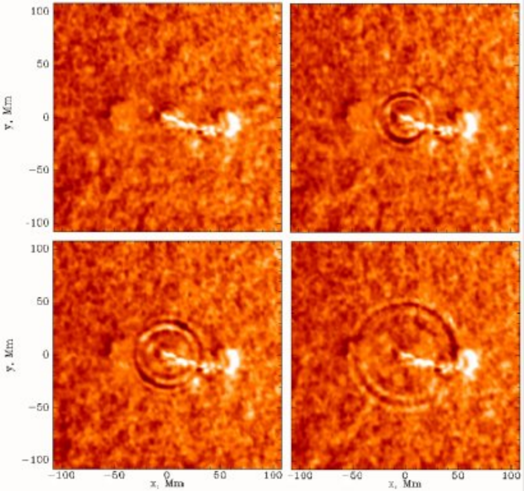
What is THIS?



Oscillation Modes

l=1,m=0 l=1,m=1 l=3,m=0

l=3,m=1 l=3,m=2 l=3,m=3

History on the go

first indications of solar oscillations were detected by Plaskett (1916) observed fluctuations in the solar surface Doppler velocity in measurements of the solar rotation rate

Hart (1954, 1956) established the origin of these fluctuations to be caused by the Sun

precise observations of oscillations of the solar surface by Leighton et al. (1962) T$\sim$300s

A confirmation of the initial detection of the oscillations was made by Evans and Michard (1962)

Claverie et al. (1979) identification of modal structure of five-minute oscillations in Doppler-velocity observations in light integrated over the solar disk

Claverie et al. (1979) identified lower wavenumber oscillations with the same period $\rightarrow$conclusive evidence of global modes of oscillation within the Sun

At present, solar oscillations are detected by the Global Oscillation Network Group (*GONG+* http://gong.nso.edu/), *SOHO-MDI* (Scherrer et al., 1995) and *HINODE (SOLAR-B)* (Kosugi et al., 2007)

Global Oscillations

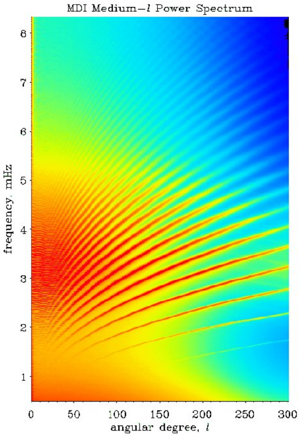
The normal modes of oscillation p-modes, f-modes, or g-modes
each mode – spherical harmonic degree & radial order

g- gravity – internal gravity waves (primary restoring force is buoyancy) are almost totally confined to the deep solar interior

f- fundamental (n=0) – surface gravity wave with amplitude that decays exponentially with depth away from the solar surface
dispersion relation is similar to that for deep water waves, $\omega^2 = gkh$
ω – angular temporal frequency of the wave
g = 274 $\mathrm{m\,s^{-2}}$ – gravitational acceleration at the Sun's surface
$k_h = \sqrt{l(l+1)}/R_\odot$ – horizontal wave-number
$R_\odot = 696$ Mm – solar radius

p- pressure – gravity-modified acoustic waves (pressure is the primary restoring force)

Discrete mode pattern – consequence of the existence of a resonant cavity with reflecting boundaries



Local Oscillations

Global modes do not distinguish between the Northern and Southern hemispheres

Local helioseismology – goal to interpret the full wave field observed at the surface

Zhugzhda and Locans (1981) – filter property of the sunspot

Bogdan (1987) – the sunspot was a scatterer of acoustic waves

Braun et al. (1987) (Hankel analysis) – sunspots absorb as much as 50% of the incoming acoustic waves

Braun et al. (1992) and subsequent papers (Fourier-Hankel decomposition) further studied the properties of scattering and absorption

Lindsey and Braun (2005a,b) (phase-sensitive holography) – showerglass effect (direct dependence of control-correlation phase signatures on the line-of-sight)

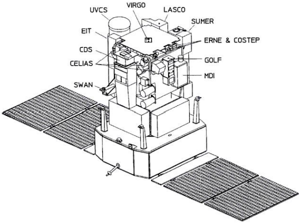
Schunker et al. (2005) – there is a clear cyclic variation of the ingression phase with azimuthal angle within a sunspot penumbra, and the line-of-sight direction The magnetic field of the sunspots affects the acoustic waves passing through

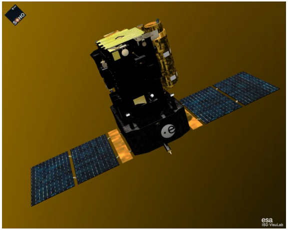
Schunker and Cally (2006) – frequency dependency of waves in sunspots Schunker et al. (2007) – In regions of stronger field strengths, corresponding to the inner penumbrae, acoustic waves at 5 mHz are affected more by the magnetic field Schunker et al. (2008) – inclined magnetic field in sunspot penumbrae may convert primarily vertically-propagating acoustic waves into elliptical motion

Special techniques:ring-diagrams, antipodal imaging and helioseismic holography, time-distance helioseismology and the holography formalism

Brief History

“a brieferuption of intense high-energy radiation from the Sun’s surface" first solar flare observed in 1859 – a localized brightening in a sunspot group by two independent observers Carrington (1859) and Hodgson (1859) – a white light event followed by a geomagnetic storm, telegraph wires shorted out in the USA and Europe and extraordinary auroras around the globe (visible even in the Carribean!)
1936 – emission line of Hα
1962 – ultraviolet and soft X-ray from outer space with the “Orbiting Solar Observatory"(*OSO*)
1975 – launch of the first Geostationary Operational Environmental Satellite *GOES-1*
Past&Present: Ulysses(1990); Yohkoh (1991); SOHO (1995); ACE (1997); TRACE(1998); RHESSI(2002); HINODE/Solar-B (2006); Stereo (2006); SDO (2010); etc.
Future: IRIS(2012); MMS(2014)





Solar Flares

occur when the magnetic energy that has built up in the solar atmosphere is suddenly released

Radiation – virtually the entire electro-magnetic spectrum

Classification:

- H classification scheme (1930s)

  S (subflare) 1, 2, 3, 4 (successively larger flares) – flare size & letter: f (faint), n (normal), b (bright)
  $\rightarrow$ most outstanding flares 4b / smallest and faintest Sf

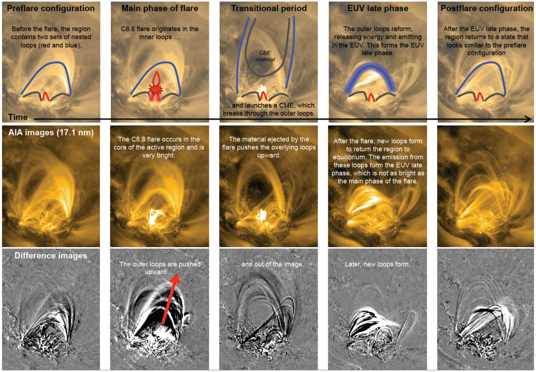
- based on soft X-ray (the integrated flux in the 1–8 Å band) – 1970: size of the flare is given by the peak intensity (on a logarithmic scale) of the emission.

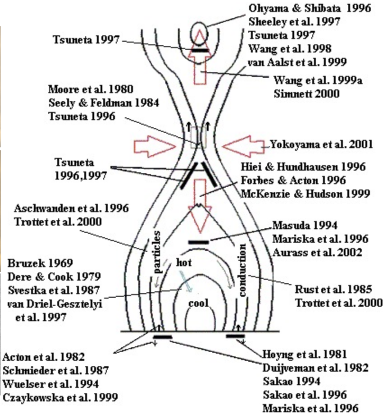
  a letter (A, B, C, M or X-class) and a number (1–9) that acts as a multiplier

	I
A	$< 10^{-7}$ W/m^2 (10^{-4}erg/cm^2/s)
B	$10^{-7} \leq I < 10^{-6}$ W/m^2
C	$10^{-6} \leq I < 10^{-5}$ W/m^2
M	$10^{-5} \leq I < 10{-}4$ W/m^2
X	$\geq 10^{-4}$ W/m^2 (10^{-1}erg/cm^2/s)

July 28-29 2012

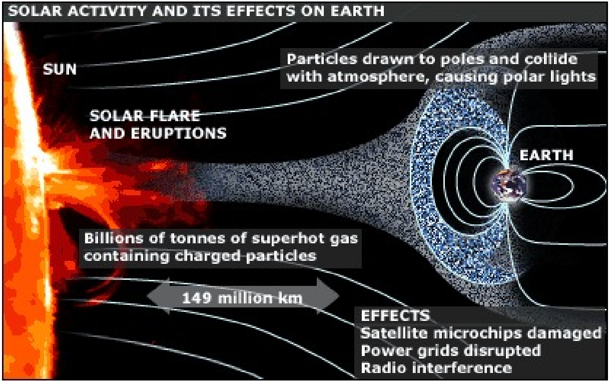
Observations/Scenarios





Flare & Consequences

Solar flares/CME/ Filament eruptions/ SEPs/etc
$\Rightarrow$
Space Weather



Computational Helioseismic Holography

Roddier (1975) as a principle of generating an acoustic hologram of the solar surface

The main computations in helioseismic holography: “ingression" and “egression"

the ingression (H_-) is an assessment of the observed wave-field converging upon the focal point egression (H_+) is an assessment of waves diverging from that point obtained from the wave-field at the surface, ψ, through theoretical Green's functions

$$\text{Egression:} \quad \hat{H}_+(\mathbf{r},\ \omega) \ = \int_{pupil} \hat{G}_+(\mathbf{r},\ \mathbf{r}',\ \omega)\ \hat{\psi}(\mathbf{r}',\ \omega)\ d^2\mathbf{r}' \tag{1}$$

where $\hat{G}_+(\mathbf{r},\ \mathbf{r}',\ \omega)$ is a Green's function that expresses the disturbance at the focus

The relation between the complex amplitude, $\hat{\psi}(\mathbf{r},\ \omega)$, of frequency and the real acoustic field, $\psi(\mathbf{r},\ t)$, representing the surface acoustic field in the *MDI* observations

$$\psi(\mathbf{r},\ t) \ = \ \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} e^{i\omega t}\ \hat{\psi}(\mathbf{r},\ \omega)\ d\omega \tag{2}$$

The same applies to the acoustic egression:

$$H_+(\mathbf{r},\ t) \ = \ \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} \hat{H}_+(\mathbf{r},\ \omega) e^{iwt}\ d\omega \tag{3}$$

$$\text{“Egression power”} \quad P(\mathbf{r},\ t) \ = \ |H_+(\mathbf{r},\ t)|^2 \tag{4}$$

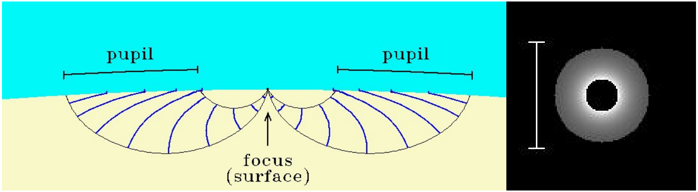


image acoustic sources reconstructs phase-coherent acoustic waves to render stigmatic images of subsurface sources given rise to the surface disturbance

a pupil defined as an annulus with radius 15–45 Mm, to image the focus a considerable distance away

natural acceleration as the ripples propagate outwards (Kosovichev and Zharkova, 1998)

The helioseismic holography technique is applied to (*SOHO-MDI*) 1 minute cadence Dopplegrams (Scherrer et al., 1995)

Normal data resolution of 2 arcsec/px
High resolution data 0.6 arcsec/px resolution

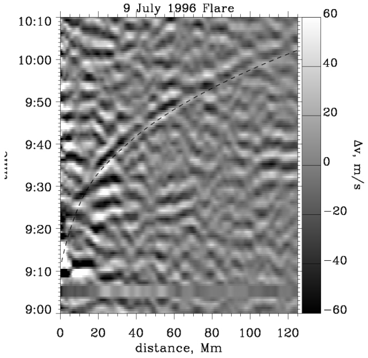
Kosovichev and Zharkova (1998) constructed seismograms (maps of distances traveled by the wave front) of the solar flare by remapping the *SOHO-MDI* Doppler images into polar coordinates centred at the point of the initial velocity impulse, and then applying a Fourier transform with respect to the azimuthal angle (Kosovichev and Zharkova, 1998, See Fig. 1d)

Seismogram – the record of an earth tremor made by a seismograph ⇒ analog concept for the solar quake

July 9, 1996 (X2.6 solar flare) the seismic wave was so powerful that is was even seen in simple differences of Dopplergrams as ridges (began about 18 Mm from the flare site *rightarrow* about 120 Mm)

used to show the wave front moving in time

usually the ripple is difficult to see. in individual Dopplergrams



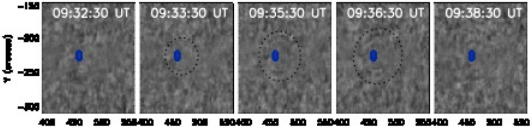
Credits: Valentina Zharkova

Brief History

- "high-order modes of solar oscillation to interesting amplitudes" suggested by Wolff (1972)
- Haber et al. (1988a) possible excitation of acoustic modes within the Sun, but found that power bridges may be influenced by the poor data quality
- first attempt at computing radial propagating waves using Doppler velocities (Haber et al., 1988b) – suggested that the flare may have excited outgoing waves
- Braun and Duvall (1990) “unable to detect an excess of oscillatory power in the vicinity of the active region following a large flare", but did not rule out the existence of sun quakes
- The first known sun quake – Kosovichev and Zharkova (1998)
- First application of helioseismic holography to detect a seismic source Donea et al. (1999)

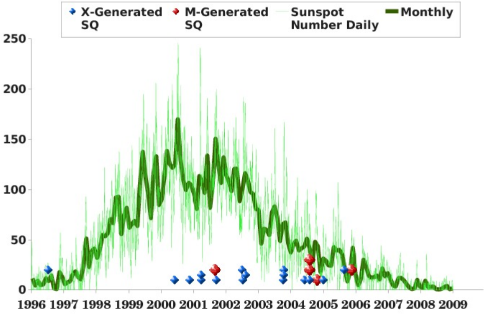
“sun quake"

a roughly circular surface ripple seen accelerating outwards from the site of an impulsive flare 20–60 minutes after the impulsive phase



9 July 1996

Known SunQuakes



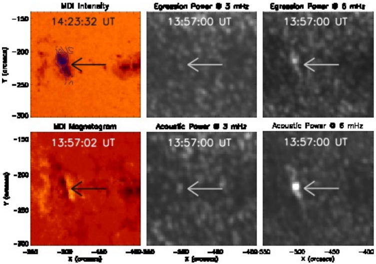
"SunQuakes"

as spreaded on SC23

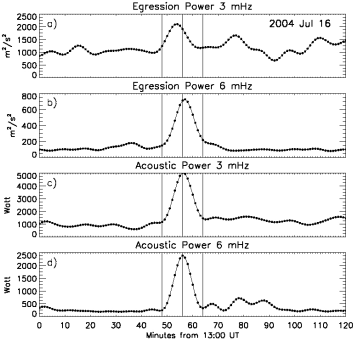
SunQuakes from flare as weak as M6.7

(Martinez-Oliveros et al., 2008)

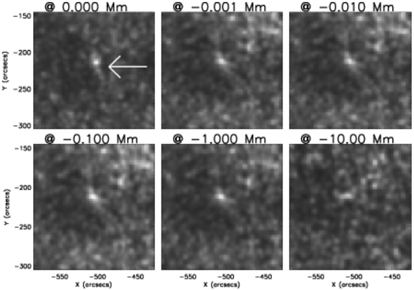
16 July 2004



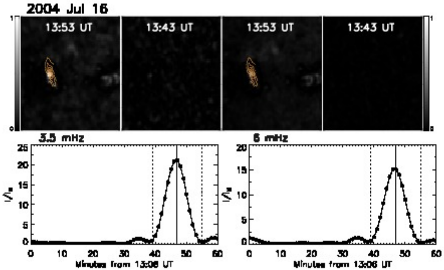
General view of AR 10649



Time profiles of specified measures

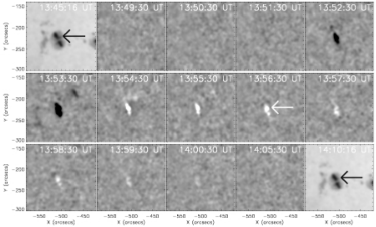


Smeared Egression Power at different depths

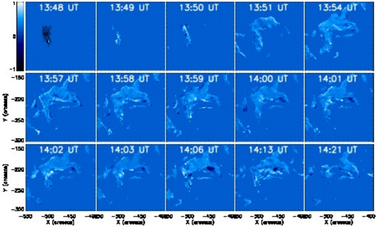


Acoustic Power at specified frequencies

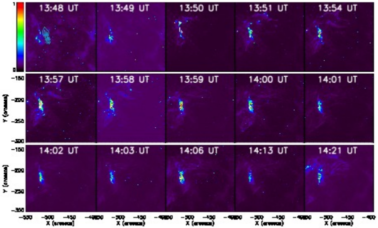
MultiWaveLength



White Light Differences



Hα Doppler Maps



TRACE @ 171Å

To Take Home

- the Sun has many oscillation modes

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- a new type of oscillation detected

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- the Sun has many oscillation modes
- a new type of oscillation detected
- seismic emission difficult to detect
- solar flares are responsible for triggering acoustic transients
- seismic emission fits best the “back-warming" model

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