

On Sunday 1 November 1755 a strong earthquake accompanied by a tsunami devastated the city of Lisbon and left 70 000 inhabitants dead. This dramatic event triggered a new approach in understanding the forces of the Earth: seismology. In more general terms, seismology is the remote diagnostics of media by means of waves. Seismology has become a well-developed technique in various applications; as well as seismology of the Earth's interior, there are ultrasound scans of the human body and marine acoustics (sonars), and a less familiar but important application in laboratory plasma spectroscopy. The first implementation of this technique in solar physics – helioseismology – is connected with solar surface oscillations, discovered by Robert Leighton in the early 1960s. These oscillations were interpreted in terms of acoustic-gravitational waves and now provide unique information about the solar interior, its structure and differential rotation – and even about the far side of the Sun (see discussion by Thompson, this issue p4.21–4.25). Now seismology can be applied to a different, but significant, part of the Sun: the solar corona.

The corona is the uppermost part of the solar atmosphere, an almost fully ionized hot plasma where the temperature exceeds a million K. This high temperature makes the corona emit in the EUV and X-ray bands, so it is best observed from space, rather than from Earth. Furthermore, it is believed that the high temperature is intricately connected to the solar magnetic field that dominates the coronal plasma and is responsible for structuring the corona into loops. An insight into the physical processes operating in the corona is important to understand the relationship between the Sun and the Earth's environment (space weather). Moreover, the corona is a natural plasma laboratory, providing a huge variety of plasma equilibrium configurations and dynamical events to study. This knowledge is vital for research in controlled fusion, which holds the promise of an essentially limitless and environmentally clean source of energy. In short, it is impossible to underestimate the importance of solar coronal physics.

But the observational study of the hot and rarified plasma of the corona is not a trivial task, and several important physical parameters of the corona remain closed to direct observations. Because of strong thermal broadening of coronal emission lines, the magnetic field cannot be measured by the techniques based upon the Zeeman effect. This is where the application of seismological techniques to the corona comes into its own.

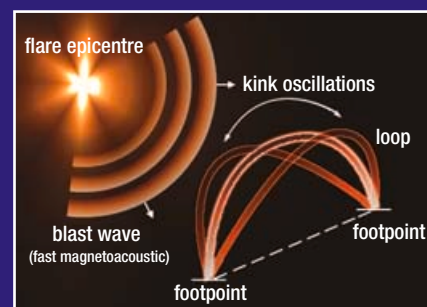
The corona supports a family of waves called magnetohydrodynamical (MHD) waves, which combine magnetic with plasma acoustic effects. In 1970 Yutaka Uchida proposed the mechanical diagnosis of coronal magnetic structures by

# Seismology of the corona of the Sun

V M Nakariakov and E Verwichte put seismology to work in the study of the solar corona, the hot atmosphere of the Sun.

## Abstract

Seismology now includes study of the Sun's corona, a promising research target both in its own right and for its role in the relationship between the Sun and the Earth and its links to the solar magnetic field. In addition, the corona, as a natural plasma, is itself an objective for fundamental physics. Observations using spacecraft such as SOHO and TRACE highlight the interrelationship between the magnetic field and corona.



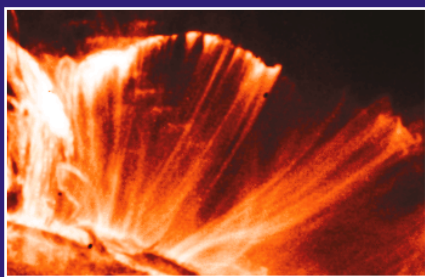
1. A possible mechanism for excitation of fast magnetoacoustic kink oscillations of coronal loops by a solar flare.

the use of flare-associated MHD propagating disturbances – the then-hypothetical coronal component of the chromospheric Moreton wave. Later on, in 1983, the identification of fast magnetoacoustic wave trains in solar radio observations inspired Bernie Roberts (St Andrews) and colleagues to propose the use of these wave trains to probe coronal magnetic structures, dubbing the method “MHD coronal seismology”. However, the lack of reliable high-resolution observational evidence of coronal waves and oscillations did not allow the practical implementation of MHD coronal seismology until the late 90s. Nevertheless, that embryonic period of MHD coronal seismology allowed the coronal wave research community to establish the theoretical groundwork of the method. The standard theoretical model for a coronal loop was a straight magnetic cylinder. It was concluded that there could be four main types of MHD wave modes in this structure: kink, sausage, torsional and longitudinal. These modes have different properties: if the kink and torsional modes are practically incompressible, the longitudinal mode is well-nigh the familiar acoustic wave. The sausage mode is compressive as well, but in contrast to the longitudinal mode, it produces significant perturbations in the magnetic field. Another distinguishing property is that kink and sausage modes are highly dispersive, while longitudinal and torsional are virtually dispersionless. Furthermore, the modes also have quite different propagation speeds, which are determined by the *sound* speed,

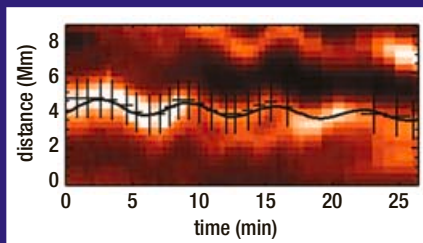
connected with plasma temperature, and the Alfvén speed, given by the root of the ratio of the magnetic tension and the plasma density.

## Breakthrough

The breakthrough in the observational study of coronal wave activity is associated with the launches of the Solar and Heliospheric Observatory (SOHO) in 1995 and the Transition Region and Coronal Explorer (TRACE) in 1998. The unprecedented combination of spatial and temporal resolution has led to the confident identification of several kinds of MHD modes in coronal structures and made the practical implementation of MHD coronal seismology feasible. In 1999 Markus Aschwanden (LMSAL) and co-authors and Valery Nakariakov (Warwick) and co-authors reported the first identification of kink oscillations of coronal loops in EUV TRACE data. Kink oscillations, the quasi-harmonic displacements of the loop as a whole, can be seen with an imaging telescope if the plane of the oscillations is perpendicular to the line of sight. The Bastille Day flare on 14 July 1998 generated several oscillating loops around the flare epicentre (figure 1 shows a possible excitation mechanism). They oscillated with different periods, all of about several minutes, with all segments of the loop oscillating in phase. It was concluded that the oscillations were produced by a standing wave with the wavelength equal to double the length of the loop. As both the period of the oscillations and the wavelength



2: A post-flare loop arcade in NOAA active region 9415 on the SW solar limb, seen by the TRACE instrument on 15 April 2001 at 22:11 UT in the 171 Å bandpass. Due to an erupting prominence to the north, the loops are made to oscillate as a fast magnetoacoustic kink mode.



3: A time-space diagram of one of the loops in the previous figure, showing the kink oscillation.



4: A series of difference images of a fan of loops emanating from NOAA active region 8218 taken by the TRACE instrument on 13 May 1998 in the 171 Å bandpass. The images show slow magnetoacoustic wave packets that propagate outwards along the loops. The circle follows one such wave-packet.

are observationally determinable, one may estimate the phase speed of the waves, which is connected with the Alfvén speeds inside and outside the loop. In its turn, it makes possible the estimation of the magnetic field – vital for coronal physics. According to the study of Nakariakov and Leon Ofman (NASA/GSFC), the magnetic field strength in an oscillating EUV loop was about 13 G, with wide error bars, about 9 G. The main source of the error was uncertainty in the measurement of the plasma density. As this quantity can be estimated separately, the precision of the method can be significantly improved. Very recently, Erwin Verwichte (Warwick) and co-authors applied this method to kink oscillations observed with TRACE at an off-limb EUV arcade and found that the arcade magnetic field was in the range of 4 to 30 G. Figures 2 and 3 show observational signatures of kink oscillations.

The kink oscillations decay very quickly, in just a few oscillation periods. This raises several important issues. In particular, it may indicate the significant enhancement of the shear viscosity in the coronal plasma. In fact, estimations show that the shear viscosity is several orders of magnitude higher than its theoretically predicted value and is of the same order as bulk viscosity. If so, this must be connected with plasma micro-turbulence.

The encouraging start of MHD coronal seismology occurred at the same time as the identification of another MHD mode, a longitudinal or slow magneto-acoustic one, in the corona,

stimulating the further development of the method. Propagating longitudinal waves (figure 4 shows an example) observed simultaneously either with TRACE and the SOHO Extreme Ultraviolet Imaging Telescope (EIT) by Eva Robbrecht and co-authors or in two different EUV bandpasses of TRACE by Damian King (Warwick) and co-authors, have been used to deduce a subresolution structuring of coronal active region. The logic of this conclusion is fairly simple: if the same coronal loop is observed in two different bandpasses, for example 171 Å and 195 Å, corresponding to emission coming from plasmas at different temperatures, it may indicate the presence of plasma threads of different temperatures at the same location. The transverse scale of the threads is smaller than the pixel size of the image. (The pixel size of TRACE images is about 360 km on the solar disk.) Supporting this reasoning, Robbrecht *et al.* (2001) and King *et al.* (2003) have detected the decorrelation of longitudinal waves in different bandpasses while propagating along the same structure. Longitudinal waves propagate at the local sound speed, corresponding to the local temperature. Waves propagating along the same path at different speeds will gradually decorrelate, exactly as is observed. Consequently, the observed decorrelation is consistent with the hypothesis of the coronal plasma filamentation. The seismological methods provide us with an exclusive chance to study unresolved structuring!

The seismological ideas and approaches

mentioned above can be considered as *local*, associated with a particular coronal structure or a small group of them. In 1998 the analysis of EIT data by Barbara Thompson (NASA/GSFC) and co-authors discovered a *global* EUV coronal disturbance, propagating radially from an epicentre and occupying a significant part of the solar disk. This phenomenon was interpreted as a fast magnetoacoustic mode, because it is the only MHD wave, which can propagate across the magnetic field. Consequently, it is quite likely to be the coronal counterpart of the Moreton wave. Currently, this mode is intensively studied both observationally and theoretically as a possible candidate for *global* coronal seismology, aiming to produce global maps of the magnetic field, density and temperature.

Another interesting development of this method may be connected with study of the moss on the bright upper transition region, where Bart De Pontieu (LMSAL) and Robert Erdélyi (Sheffield) have found strong (up to 15%) EUV intensity oscillations. These oscillations are possibly associated with magnetoacoustic waves. Seismological methods will help to understand the physical processes operating in the transition region – crucial for the solution of the enigmatic problem of coronal heating (discussed by Erdélyi on p4.34–4.37 of this issue).

A number of other wave and oscillatory phenomena recently discovered in the corona are still awaiting their seismological utilization. These are global acoustic oscillations of coronal loops, resembling resonant oscillations of organ pipes; flare-generated longitudinal oscillations – sudden attacks of shivering experienced by overheated loops; propagating fast magnetoacoustic wave trains with characteristic “tadpole” period modulation, carrying information about the loop density profile; global sausage modes – periodic contractions and expansions of loops, which are well-known for solar radio observers, and many, many others. Furthermore, in the future new space instruments such as Solar-B, STEREO, the Solar Dynamical Observatory and the Solar Orbiter, with improved resolution and different view points, will markedly improve the quality of coronal MHD wave observations. Clearly the prospects of MHD coronal seismology are looking bright indeed. ●

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