MHD seismology of the solar corona

B. N. Dwivedi, A. Mohan and V. S. Pandey

The solar corona (see Figure 1) is the example, *par excellence*, of a plasma that is both structured (magnetically) and stratified (gravitationally). The magnetically dominated coronal plasma is an elastic medium which can support various kinds of waves. The relative importance of magnetic effects is provided by the plasma beta, β, defined by

$$\beta = \frac{\text{gas pressure}}{\text{magnetic pressure}}.$$

The Sun's interior is a region of high β because the gas pressure there is quite high. By contrast, the rapid decrease in gas pressure in the upper layers of the solar atmosphere suggests that β is of the order of unity or smaller there, and so magnetic effects are significant.

The idea of remote diagnostics of the Sun with observationally determined properties of waves has been successfully realized in helioseismology. Measurement of parameters of acoustic waves through various layers of the Sun's interior, makes it possible to reconstruct the physical conditions in these parts of the Sun which is non-observable by usual methods. By contrast, the solar corona is observable in the entire spectrum of electromagnetic radiation and particle emissions. However, the coronal physical conditions, for instance, rarefied, weakly collisional and almost ionized plasma, highly structured by the magnetic field, complicate the observational investigation of the corona. Some of the physical parameters such as magnetic field strength and transport coefficients, which are crucial to our understanding of 'how the Sun works', remains poorly revealed.

Despite considerable progress in coronal physics over the last several decades, some of the fundamental questions such as the existence of the corona and the acceleration of the solar wind, remain unanswered satisfactorily. All these questions require a detailed knowledge of physical conditions and parameters in the corona, which cannot yet be measured accurately. For instance, one vital piece of information that we are still unable to measure is the corona's magnetic field strength. We can measure, with considerable accuracy, the photospheric magnetic field, using instruments called magnetographs on solar telescope that work on the principle of Zeeman effect (magnetic splitting of the spectral lines). Although eventually infrared measurements may give important information, in practice, the only way at present in which the coronal magnetic field can be deduced is through extrapolations of the photospheric field through the assumption, for example, of a potential ($\nabla \times \mathbf{B} = 0$, i.e. current-free) or force-free ($\mathbf{J} \times \mathbf{B} = 0$) field. Also, the coronal transport coefficients, such as volume and shear viscosity, resistivity and thermal conduction are not known even within an order of magnitude.

Recent discovery of wave activity in the corona, in particular, longitudinal compressive waves in polar plumes[1,2], and coronal loops[3–5], and flare-generated decaying oscillations of coronal loops[6–8] (see Figure 2), provides us with a new diagnostic tool for the inference of the unknown parameters of the corona. This new diagnostic tool is known as *MHD seismology of the corona*. Measurement of properties of MHD waves and oscillations (periods, wavelengths, amplitudes, temporal and spatial signatures, characteristic scenario of the wave evolution), combined with a theoretical modelling of the wave phenomena (dispersion relations, evolutionary equations, etc.), can lead to the determination of the mean

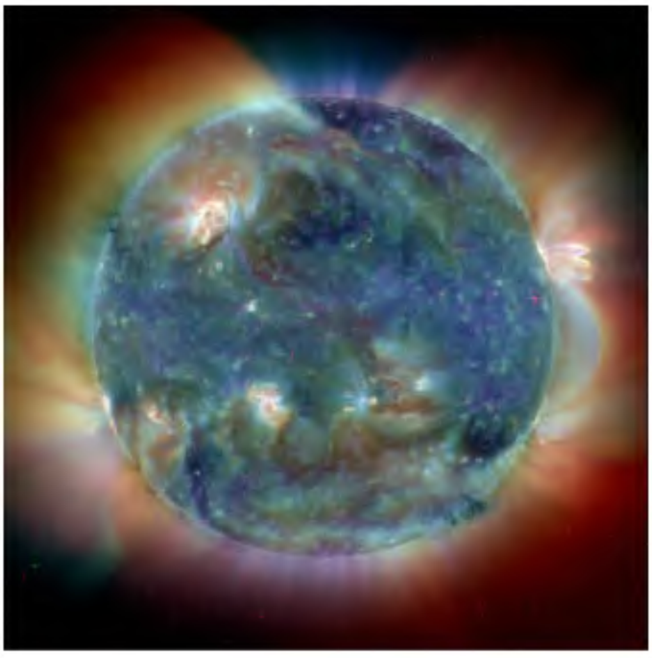

Figure 1. On 22 December 2002 at 01:14 UT, the Sun reached its southernmost point in planet Earth's sky, marking the final season change for the year 2002. This is the delightfully detailed, brightly coloured image of the active Sun. From the EIT (Extreme-ultraviolet Imaging Telescope) on board the space-based SOHO observatory, this tantalizing picture is a false-colour composite of three images, all in extreme-ultraviolet light. Each individual image highlights a different temperature regime in the upper solar atmosphere and was assigned a specific colour: red at 2×10^6 K, green at 1.5×10^6 K and blue at 10^6 K. The combined image shows bright active regions strewn across the solar disk, which would otherwise appear as dark groups of sunspots in visible light images, along with some magnificent plasma loops and an immense prominence at the right hand solar limb (Courtesy: EIT/SOHO consortium, ESA/NASA).

parameters of the corona, such as the magnetic field strength and transport coefficients. This approach is illustrated in Figure 3. The method is similar to the acoustic diagnostics of the Sun's interior, helioseismology. However, MHD coronal seismology is much richer as it is based upon three different wave modes, namely, Alfvén, slow and fast magnetoacoustic modes. These MHD waves have quite different dispersive, polarization and propagation properties, which makes this approach even more powerful[9]. The method of MHD coronal seismology was originally suggested long ago[10,11], and has recently been applied to obtain estimates of the coronal dissipative coefficients[7] and the magnetic field[12].

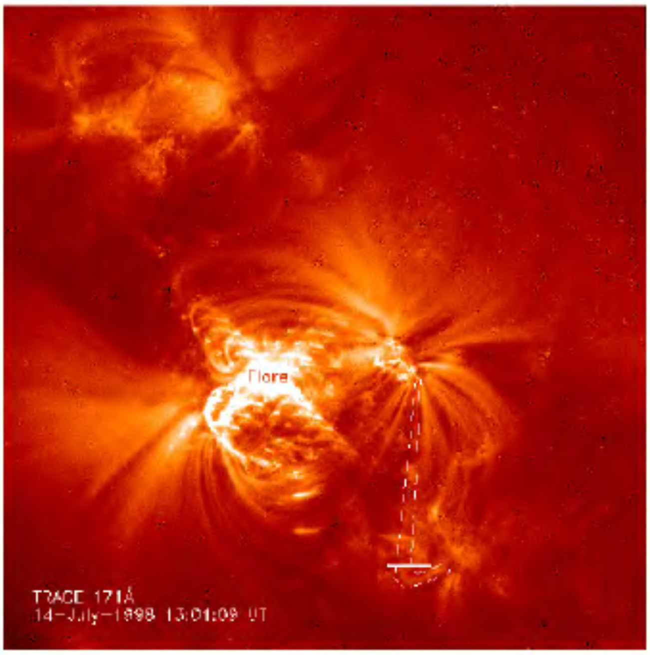

Figure 2. The coronal loop system observed with TRACE. The flare site is marked and the analysed oscillating loop is outlined. The box marks the location of the four cuts. The pointing of the image centre is (–284 arc s, – 363 arc s) from the Sun centre. The image size is 768 × 768 pixels, with a pixel size of 0.5 arc s (360 km). Courtesy: V. M. Nakariakov.

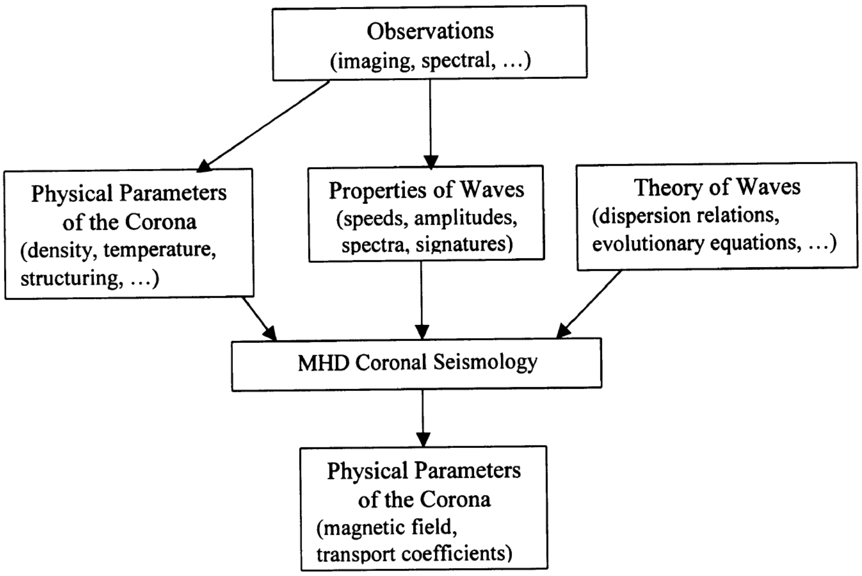

Figure 3. MHD seismology of the solar corona.

Corona's magnetic field strength

Analysing the landmark observations of flare-generated coronal loop oscillations on 14 July 1998 (cf. Figure 2) and on 4 July 1999 by the EUV imaging telescope on board the *TRACE* spacecraft in both 171 Å and 195 Å bandpasses, the displacement of the loop in time has been approximated by a harmonic function, ~ sin(t/P), where P is the period of oscillations. These phenomena have been interpreted as standing kink fast magnetoacoustic modes[7]. The loop footpoints prescribe the nodes of the mode. Consequently, the loop plays a role of the resonator for the mode. The length of the loop L determines the resonant period P of the standing modes. Neglecting the effects of the corona stratification and loop curvature, and assuming the loop cross-section to be circular, the period of the global mode is given by

$$P \approx 2L / C_{\mathrm{k}},$$

where

$$C_{\mathrm{k}} = \left(\frac{2}{1 + \rho_{\mathrm{o}}/\rho_{\mathrm{i}}} \right)^{1/2} C_{\mathrm{A}},$$

is a so-called kink speed, C_{A} is the Alfvén speed inside the loop and ρ_{i} and ρ_{o} are plasma densities inside and outside the loop respectively. Measuring the periods of the loop oscillations and the loop lengths, one can estimate the kink speed. The kink speed is proportional to the Alfvén speed C_{A} with a factor of about $\sqrt{2}$, because normally $\rho_{\mathrm{o}}/\rho_{\mathrm{i}}$ is small. Thus we can determine the Alfvén speed in the corona. For $P \approx 265$ s and $L \approx 130$ Mm (14 July 1998 event), the kink speed C_{k} is 1020 ± 132 km/s, which gives the Alfvén speed of $C_{\mathrm{A}} = 777 \pm 100$ km/s in the loop[7]. A similar estimate can be made for the event of 4 July 1999. For the period of oscillations 360 s and the loop length 186 Mm, the kink speed is $C_{\mathrm{k}} = 1030 \pm 410$ km/s and the Alfvén speed is about 780 km/s. The determination of the Alfvén speed in the loop allows the determination of magnetic field in the corona as

$$B = \pi\rho_i^{\;\Box\Box} C_A$$

$$= \frac{\sqrt{\Box}\,\pi^{3/2} L}{P}\sqrt{\rho_{/\!/}\Box + \rho_{/\!/}/\rho_i)}\,.$$

The determination of the magnetic field is weakly sensitive to errors in the determination of the plasma density in the loop, because the magnetic field is proportional to the square root of the density. For a quite wide range of plasma number densities, from 10^9 to $6 \times 10^9\ cm^{-3}$, the value of the magnetic field is in the range from 4 to 30 G. Using *TRACE* 171 Åand 195 Åimages of the loop, taken on 4 July 1999 to determine the plasma density, the magnetic field in the loop was estimated to be 13 ± 9 G (ref. 12). It is to be noted, however, that improved diagnostics of the loop length, the oscillation period, and the plasma density in the loop will significantly improve the method's precision.

The Reynolds number

The observed dissipation of the resonant global mode may be due to viscous and resistive dissipation that have a similar effect on the wave dissipation. The dependence of the wave amplitude decay rate on the resistive dissipation coefficient is well-known. Viscous dissipation in a fluid is expressed in terms of the dimensionless Reynolds number R. Similarly, the magnetic diffusion coefficient gives rise to the dimensionless magnetic Reynolds number (or the Lundquist number) S.

Applying the numerically determined scaling laws[7] which connect the oscillation decay time and the Reynolds R and Lundquist S numbers, the values of $R = 10^{5.3-6.1}$ and $S = 10^{5.0-5.8}$ have been estimated. The Reynolds number deduced from the observations is eight to nine orders of magnitude smaller than the classical value of $R = 10^{14}$. Likewise, the Lundquist number is seven to eight orders of magnitude smaller than the commonly quoted classical value of $S = 10^{13}$ for coronal plasma. And making use of these modern values, the possibility of heating the corona by MHD waves has been investigated[13] (Dwivedi and Pandey, unpublished).

In conclusion, the new method of MHD coronal seismology, based on high resolution observations of the coronal wave activity, can become a powerful tool for the inference of physical parameters in the solar corona.

1. DeForest, C. E. and Gurman, J. B., *Astrophys. J.*, 1998, **501**, L217–L220.
2. Ofman, L., Nakariakov, V. M. and DeForest, C. E., *Astrophys. J.*, 1999, **514**, 441–447.
3. Berghmans, D. and Clette, F., *Solar Phys.*, 1999, **186**, 207–229.
4. DeMoortel, I., Ireland, J. and Walsh, R. W., *Astron. Astrophys.*, 2000, **355**, L23–L26.
5. Nakariakov, V. M., Verwichte, E., Berghmans, D. and Robbrecht, E., *Astron. Astrophys.*, 2000, **362**, 1151–1157.
6. Aschwanden, M. J., Fletcher, L., Schrijver, C. J. and Alexander, D., *Astrophys. J.*, 1999, **502**, 880–894.
7. Nakariakov, V. M., Ofman, L., DeLuca, E. E., Roberts, B. and Davila, J. M., *Science*, 1999, **285**, 862–864.
8. Schrijver, C. J. and Brown, D. S., *Astrophys. J.*, 2000, **537**, L69–L72.
9. Nakariakov, V. M., in *Dynamic Sun* (ed. Dwivedi, B. N.), Cambridge University Press, Cambridge, 2003, pp. 314–334.
10. Uchida, Y., *Pub. Astron. Soc. Jpn*, 1970, **22**, 341–364.
11. Roberts, B., Edwin, P. M. and Benz, A. O., *Astrophys. J.*, 1984, **279**, 857–865.
12. Nakariakov, V. M. and Ofman, L., *Astron. Astrophys.*, 2001, **372**, L53–L56.
13. Dwivedi, B. N. and Pandey, V. S., *Solar Phys.*, 2003, in press.

The authors are in the Department of Applied Physics, Institute of Technology, Banaras Hindu University, Varanasi 221 005, India. For correspondence, e-mail: bholadwivedi@yahoo.com

COMMENTARY

Linking of major rivers of India—Bane or boon?*

B. P. Radhakrishna

Water shortage is going to be the most serious problem that the country will be facing in the 21st century. Painting a grim picture of water shortage in Karnataka, the Chief Minister of the state recently declared that the only solution to the problem of water shortage is the linking of rivers. The state is presently facing a severe drought. Instead of taking up measures to alleviate distress and reduce the hardship of farmers, the Chief Minister was only projecting a mirage promising better days ahead with plenty of water to be brought from the north by linking major rivers. He had obviously no clear conception of how this magic could be achieved.

It is not just the Chief Minister of Karnataka alone, but the Chief Ministers of other states of India are also repeating the same *mantra*. The Prime Minister of India, too, has joined in the chorus and has announced in the Parliament massive financial support for implementing such a scheme. The cost of the project is estimated to be a staggering sum of Rs 560,000 crores or Rs 56,000 crores a year, if it has to be completed in a decade.

The Central Government appears to be quite serious about implementing the project in spite of serious deficiencies in the information base. Suresh Prabhu, a former minister, has been made the Chairman of the Task Force for Linking Rivers and has been given Cabinet rank. Former Water Resource Secretary C. B. Thatte is made the Member Secretary and a new Ministry is in the offing. The scheme envisages effecting 30 river links in the next two years. Construction of over 1000 km of link canals is envisaged and 10,000 mW of electricity for lifting 11,000 cusecs of water would be required. No less than

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