Review of Coronal Oscillations - An Observer’s View

Markus J. Aschwanden (aschwanden@lmsal.com)
Lockheed Martin Advanced Technology Center, Solar & Astrophysics Laboratory,
Dept. L9-41, Bldg.252, 3251 Hanover St., Palo Alto, CA 94304, USA

Abstract. Recent observations show a variety of oscillation modes in the corona. Early non-imaging observations in radio wavelengths showed a number of fast-period oscillations in the order of seconds, which have been interpreted as fast sausage mode oscillations. TRACE observations from 1998 have for the first time revealed the lateral displacements of fast kink mode oscillations, with periods of $\approx 3-5$ minutes, apparently triggered by nearby flares and destabilizing filaments. Recently, SUMER discovered with Doppler shift measurements loop oscillations with longer periods ($10-30$ minutes) and relatively short damping times in hot (7 MK) loops, which seem to correspond to longitudinal slow magnetoacoustic waves. In addition, propagating longitudinal waves have also been detected with EIT and TRACE in the lowest density scale height of loops near sunspots. All these new observations seem to confirm the theoretically predicted oscillation modes and can now be used as a powerful tool for “coronal seismology” diagnostic.

1. Introduction

Some 30 years ago, solar radio astronomers discovered a host of solar radio events with periodic or quasi-periodic pulses, with typical periods in the range of $P \approx 0.5 - 5$ s (e.g. Rosenberg 1970). The evidence for coronal oscillations was entirely based on the periodicity observed in time profiles of the fluctuating radio flux, which occurred at decimetric frequencies and thus were known to originate in the corona. Imaging observations of such pulsating radio events were largely not available, or only in form of 1-dimensional brightness maps with poor spatial resolution. Nevertheless, these radio observations stimulated some theoretical work on MHD oscillations (e.g. Roberts et al. 1984) and the observed period range of $P \approx 0.5 - 5$ s was correctly identified in terms of fast sausage mode oscillations. However, little progress has been made over the next 20 years, mainly because of the lack of high-resolution imaging observations.

Some 3 years ago, when high-resolution imaging observations on sub-arcsecond scale became available with the Transition Region and Coronal Explorer (TRACE), the transverse motion of fast kink MHD mode oscillations in coronal loops was for the first time spatially resolved (Aschwanden et al. 1999). Additionally, the Solar Ultraviolet Measurements of Emitted Radiation (SUMER) instrument onboard the Solar and Heliospheric Observatory (SoHO) discovered recently...
Doppler shifts of slow mode MHD oscillations in coronal loops (Wang et al. 2002a,b). All these instrumental capabilities permit us now to measure the periods, damping times, spatial displacements, velocities, and loop geometries in great detail, which rekindled theoretical work on MHD oscillations and waves to a great deal. It opened up the new field of "coronal seismology" (Roberts et al. 1984), which is expected to reveal fundamental physical properties of the solar corona with similar sensitivity as the discipline of "helioseismology" provides for the solar interior.

2. Coronal Oscillations in Radio

The physical mechanisms of radio pulsation events can be subdivided into three categories: (1) MHD eigen-mode oscillations, (2) limit cycles of nonlinear dissipative systems, and (3) modulation by a quasi-periodic particle acceleration or injection mechanism (for a review, see Aschwanden 1987a). In Table I-III we compile radio observations of coronal oscillations in three different period ranges (Table I: fast periods $P < 0.5$ s; Table II: short periods $0.5 < P < 5$ s; Table III: long periods $P > 5$ s). The subdivision into these three period ranges is a little bit arbitrary, but is believed roughly to separate three (or more) different physical processes. We list in Tables I-III the observed periods $P$, the radio frequencies $\nu$, and the spatial scale (either the measured spatial source size or the instrumental resolution).

2.1. Very Fast Radio Oscillations

In Table I we compile radio observations with very fast (sub-second) periods, measured down to 50 ms. Such short periods are most likely not produced by a MHD mode of an oscillating coronal loop, but rather by the nonlinear dynamics of small-scale phenomena. If we assume a typical Alfvén speed of $v_A \approx 1000$ km s$^{-1}$ in the solar corona, time periods of $P \approx 0.05 - 0.5$ s would require spatial scales of $L \approx P \times v_A \approx 50 - 500$ km, which are way below diameters of typical active region loops observed in EUV and soft X-rays. However, such small spatial scales have been estimated from the spectral bandwidth of decimetric millisecond spikes, which are believed to be a manifestation of fragmented energy release (Benz 1985). Moreover, elementary time structures of hard X-ray emission have similar sub-second time scales (Aschwanden et al. 1995a), which are believed to reflect the spatially and temporally intermittent acceleration and injection of electrons from dynamic current sheets operating in a bursty magnetic reconnection mode (LeBoef et
Table I. Coronal oscillations observed in radio (very fast periods: \( P < 0.5 \) s)

| Observer                     | Frequency | Period | Spatial Scale |
|------------------------------|-----------|--------|---------------|
| Droege (1967)                | 240, 460  | 0.2-1.2|               |
| Elgaroy and Sveen (1973)     | 500-550   | 0.1-0.3|               |
| Tapping (1978)               | 140       | 0.06-5 |               |
| Pick and Trottet (1978)      | 169       | 0.37   | 5'-7' (Nançay) |
| Gaizauskas and Tapping (1980)| 10,700    | 0.4    | 2.7' (Algonquin)|
| Takakura et al. (1983)       | 22,000, 44,000 | 0.25-0.33|               |
| Costa and Kaufmann (1986)    | 90,000    | 0.15   |               |
| Kaufmann et al. (1986)       | 90,000    | 0.06   |               |
| Elgaroy (1986)               | 305-540   | 0.05-0.15|               |
| Li et al. (1987)             | 327       | 0.3    |               |
| Fu et al. (1990)             | 5380-6250 | 0.16-0.18|               |
| Kurths et al. (1991)         | 234-914   | 0.07-5.0|               |
| Fleishman et al. (1994)      | 2500, 2850| 0.07-0.08|               |
| Chernov et al. (1998)        | 164-407   | 0.2    | 5'-7' (Nançay) |
| Makhmutov et al. (1998)      | 48,000    | 0.2-0.5| 1.9' (Itapetinga)|

al. 1982; Priest 1985; Tajima et al. 1987; Kliem 1988, 1995). Numerical MHD simulations have shown that non-steady reconnection operates in quasi-periodic cycles of tearing mode filamentation and coalescence (Tajima et al. 1987; Karpen et al. 1995; Kliem et al. 2000). Recent physical models of sub-second pulsations inferred from radio observations therefore deal with quasi-periodic particle acceleration and injection (Takakura et al. 1983; Costa & Kaufmann 1986; Kaufmann et al. 1986; Fleishman et al. 1994; Kliem et al. 2000).

Alternative interpretations, mostly published earlier, deal with a pulsating regime of ion beam instabilities (Zaitsev 1971), a pulsating regime of loss-cone instabilities (Chiu 1970; Zaitsev & Stepanov 1975; Aschwanden & Benz 1988), modulation of gyro-synchrotron emission by propagating whistler wave packets (Tapping 1978; Li et al. 1987; Chernov 1989), modulation by torsional Alfvén waves (Tapping 1983) caused by repetitive collapses of double layers (Tapping 1987), bounce times of trapped electrons (Elgaroy 1986), or modulation of gyrosynchrotron emission by radial (fast-sausage) MHD mode oscillations (Gaizauskas & Tapping 1980). What is common to most of these dynamic scenarios is that the pulsating regime corresponds to the limit cycle in phase space (e.g. Weiland & Wilhelmsson 1973) of a nonlinear dissipative system, and thus may show minor (for linear
disturbances) or larger (for highly nonlinear conditions) deviations from strict periodicity. The nonlinear properties of such systems have been explored by measurements of the strange attractor dimension (Kurths & Herzel 1986, 1987; Kurths et al. 1991) and the bifurcation of periods on the (Ruelle-Takens-Newhouse) route to chaos (Kurths & Karlicky 1989). Strange attractor dimension analysis of radio pulsation events yielded \( D \approx 2.5 - 3.5 \), which means that a coupled equation system of about 3-4 independent physical parameters is needed to describe the nonlinear dissipative system (Kurths et al. 1991).

Very fast oscillations with periods of \( P < 0.1 \) s could also result from heating and acceleration of minor ions by dissipation of high-frequency (10-10^4 Hz) ion-cyclotron waves, as they have been employed to explain the large perpendicular ion temperature anisotropies (\( \approx 10^8 \) K) inferred from the excessive line broadening of O VI lines by SoHO/UVCS (Kohl et al. 1997, 1999). These signatures, however, have been observed in coronal holes, while fast radio pulsations are generally associated with flares, occurring at low latitudes.

2.2. SHORT-PERIOD RADIO OSCILLATIONS

Radio pulsations with periods of order seconds are most common. In Table II we compile a list of some 32 papers that contain observations of radio pulsations with periods of \( 0.5 < P < 5.0 \) s, detected at metric, decimetric, and centimetric frequencies. Examples of such observations are shown in Figs.1 and 2. Fig.1 shows the first detection of radio pulsations that have been interpreted in terms of (fast-sausage) MHD modes (Rosenberg 1970). The time profile shown in Fig.1 shows not only the fundamental period of \( P_1 = 3.0 \) s, but also subpulses at the harmonic

\[ \text{Figure 1. Microphotometric tracing of radio pulsations observed on February 25, 1969, 09.55 UT, in the frequency range of } \nu = 160 - 320 \text{ MHz at the Utrecht radio observatory. Note that besides the fundamental period of } P_1 \approx 3 \text{ s, there are also subharmonic pulse structures with periods of } P_2 \approx 1 \text{ s visible (Rosenberg 1970).} \]
Table II. Coronal oscillations observed in radio (short periods: $0.5 \leq P \leq 5$ s)

| Observer                        | Frequency $\nu$ [MHz] | Period $P$ [s] | Spatial Scale |
|---------------------------------|------------------------|----------------|---------------|
| Droege (1967)                   | 240, 460               | 0.2-1.2        |               |
| Abrami (1970, 1972)             | 239                    | 1.7-3.1        |               |
| Gotwols (1972)                  | 565-1000               | 0.5            |               |
| Rosenberg (1970)                | 220-320                | 1.0-3.0        |               |
| De Groot (1970)                 | 250-320                | 2.2-3.5        |               |
| McLean et al. (1971)            | 100-200                | 2.5-2.7        |               |
| Rosenberg (1972)                | 220-320                | 0.7-0.8        |               |
| McLean and Sheridan (1973)      | 200-300                | 4.20±0.01      |               |
| Kai and Takayanagi (1973)       | 160>1.0                | 17' (Nobeyama) |               |
| Achong (1974)                   | 18-28                  | 4.0            |               |
| Abrami and Koren (1978)         | 237                    | -              |               |
| Tapping (1978)                  | 140                    | 0.06-5         |               |
| Pick and Trottet (1978)         | 169                    | 0.37, 1.7      | 5'-7' (Nançay) |
| Elgaroy (1980)                  | 310-340                | 1.1            |               |
| Bernold (1980)                  | 100-1000               | 0.5-5          |               |
| Trottet et al. (1981)           | 140-259                | 1.7±0.5        | 5' (Nançay)   |
| Slottje (1981)                  | 160-320                | 0.2-5.5        |               |
| Sastry et al. (1981)            | 25-35                  | 2-5            |               |
| Kattenberg and Kuperus (1983)   | 5000                   | 1.5            | 0.15' (Westerbork) |
| Wiehl et al. (1985)             | 300-1000               | 1-2            |               |
| Aschwanden (1986, 1987b)        | 300-1100               | 0.4-1.4        |               |
| Aschwanden and Benz (1986)      | 237, 650               | 0.5-1.5        |               |
| Correia and Kaufmann (1987)     | 30,000, 90,000         | 1-3            |               |
| Kurths and Karlicky (1989)      | 234                    | 1.3, 1.5       |               |
| Chernov and Kurths (1990)       | 224-245                | 0.35-1.3       |               |
| Zhao et al. (1990)              | 2840                   | 1.5            |               |
| Kurths et al. (1991)            | 234-914                | 0.07-5.0       |               |
| Aschwanden et al. (1994)        | 300-650                | 1.15, 1.8      |               |
| Qin and Huang (1994)            | 9375                   | 1.0-3.0        |               |
| Qin et al. (1996)               | 2840, 9375, 15,000     | 1.5            |               |
| Makhmutov et al. (1998)         | 48,000                 | 2.5-4.5        | 1.9' (Itapetinga) |
| Kliem et al. (2000)             | 600-2000               | 0.5-3.0        |               |
period, which has a period ratio of $P_1/P_2 = 5.3/1.8 = 3.0$ based on the first-order Bessel function that characterizes the eigen-modes of radial oscillations in a cylindrical fluxtube. Fig.2 shows a very periodic pulsation with a period of $P = 4.20 \pm 0.01 \text{ s}$ and a relatively long damping time that corresponds roughly to 10 pulse periods (McLean & Sheridan 1973).

Radio pulsations with periods of order $0.5 < P < 5.0 \text{ s}$ have generally been interpreted in terms of the fast sausage MHD mode, which is a standing wave of a cylindrical fluxtube with radial cross-section variations. The period of the fast sausage mode corresponds to the Alfvénic wave propagation across the loop cross-section $a$ (Roberts et al. 1984),

$$P_{\text{fast-sausage}} = 4\pi^{3/2}a\left(\frac{\rho_0 + \rho_e}{B_0^2 + B_e^2}\right)^{1/2} \approx \frac{2\pi a}{v_A}$$

where $v_A$ is the Alfvén speed, $\rho_0 = \mu m_p n_0$ and $\rho_e = \mu m_p n_e$ are the mass density interior and exterior to the flux tube, $a$ is the flux tube radius, and $B_0$ and $B_e$ are the magnetic field strengths interior and exterior to the fluxtube.

In Fig.3 we show the observed period ranges $P$ versus the radio frequency $\nu$, as tabulated in Table II. Let us estimate what relation between these two parameters is expected for the fast sausage mode. We consider coronal loops within a height range of $h = 2, ..., 500 \text{ Mm}$ ($h/r_\odot = 0, ..., 0.7$). The electron density in this height range can be estimated from the Baumbach-Allen model, which is in this height
Figure 3. Measurements of radio pulsation periods $P$ as function of frequency $\nu$ (rectangle and bars) and expected theoretical periods of the fast sausage mode as function of the plasma frequency (see model in text). Note the tendency that the periods become longer at low frequencies.

\[ n(h) = 2.99 \times 10^8 \left( \frac{1}{1 + h/r_\odot} \right)^{16} q_n \ [cm^{-3}] \ , \quad (2) \]

where $q_n = 10, \ldots, 100$ is a typical over-density ratio for active region loops, compared with the background corona. We assume that radio pulsations are emitted at a frequency near the local plasma frequency $\nu_p$, which is a strict function of the local electron density $n_e$,

\[ \nu \approx \nu_p = 8980 \sqrt{n_e [cm^{-3}]} \ [Hz] , \quad (3) \]

in cgs-units, and yields frequencies of $\nu \approx 20 - 1000$ MHz for our coronal loop densities. For the fast sausage mode, the loop cross-section $a$ is needed, which we assume to scale proportionally to the loop height $h$, say

\[ a = 0.2 \times h \ . \quad (4) \]
Using then a canonical value for the coronal Alfvén speed of \( v_A \approx 1000 - 2000 \text{ km s}^{-1} \), we find periods of

\[
P = \frac{2\pi a}{v_A} \approx 0.1 - 5.0 \text{ s} , \tag{5}
\]

In Fig.3 we show the functions \( P(\nu) \) expected for two values of the Alfvén velocity (\( v_A = 1000 \text{ km s}^{-1} \), and 2000 km s\(^{-1} \)) and for two over-density factors \( q_n = 10, \) and 100, which roughly bracket the observed values \( P(\nu) \). We see a tendency that the periods become longer for low (metric) frequencies, which probably belong to large-scale loops in the upper corona. All in all, the fast sausage MHD mode seems to explain the observed periods in the range of \( 0.5 < P < 5 \) s satisfactorily in the observed frequency range of \( \nu \approx 25 - 1000 \text{ MHz} \).

The fast sausage MHD mode is a radial oscillation of the flux tube radius \( a(t) \), and thus the cross-sectional area varies as \( A(t) = \pi a^2(t) \), and the loop density varies reciprocally, i.e. \( n_e(t) = n_0 * A_0 / A(t) \propto a^{-2}(t) \).

Since the magnetic flux \( \Phi(t) = B(t)A(t) = B_0A_0 \) is conserved, the magnetic field varies as \( B(T) \propto A^{-1}(t) \propto a^{-2}(t) \). This way, the density and magnetic field variations will modulate any radio emission that is related to the plasma frequency or gyrofrequency. Rosenberg (1970) interpreted the radio emission in terms of gyro-synchrotron emission, in which case the emissivity scales as

\[
I(t) \propto n_e(t)B^2(t) \propto a^{-6}(t) . \tag{6}
\]

Therefore, the gyro-emissivity amplifies diameter variations by the sixth power, which is perhaps the reason why radio detection of fast sausage modes are commonly detected. The magnetic field variation due to the sausage mode modulates also the loss-cone angle, which can then modulate any type of (coherent) radio emission that is driven by a loss-cone instability. Imaging observations in radio have still insufficient resolution to determine the exact source location, but the observations are consistent with gyro-synchrotron sources near flare loop footpoints and with plasma emission from type III-emitting electron beams above flare sites. Thus, fast sausage MHD mode oscillations can modulate the emissivity of nonthermal electrons in manifold ways, but progress in modeling can only be obtained with high-resolution imaging in many radio frequencies, such as with the planned future FASR instrument (Bastian et al. 1998).

2.3. Long-Period Radio Oscillations

There are also reports of radio oscillations with significantly longer periods (Table III), up to periods of an hour. Such longer periods are
more likely to be produced by standing modes that result from wave reflections in longitudinal direction (forth and back) a coronal loop, either with Alfvénic speed (fast kink mode), or with slow magneto-acoustic speed (slow modes). The period of the fast kink mode, which corresponds to a harmonic transverse displacement of a loop, is (Roberts et al. 1984)

\[ P_{\text{fast-kink}} = \frac{2L}{j c_k} = \frac{4\pi^{1/2}L}{j} \left( \frac{\rho_0 + \rho_e}{B_0^2 + B_e^2} \right)^{1/2} \approx \frac{2L}{j v_A} \quad (7) \]

where \( c_k \) is the phase speed, \( L \) is the full loop length, and \( j \) the node number (\( j = 1 \) for fundamental harmonic number). Thus, for typical loop lengths of \( L = 50 - 500 \) Mm and an Alfvén speed of \( v_A = 1000 \) km s\(^{-1}\) we expect kink mode periods of \( P = 100 - 1000 \) s, or \( P = 1.4 - 14 \) minutes. The fast kink mode represents just a lateral displacement of the loop position, so it does not change the magnetic field or electron density in first order, and thus it cannot easily be understood how it modulates radio emission. There is indeed a paucity of detected radio periods in the range of \( P = 100 - 1000 \) s (Table III). There are essentially only three observations that report periods in this range, which seem to be clustered around 3 and 5 minute oscillations (Chernov et al. 1998; Gelfreikh et al. 1999; Nindos et al. 2002), which seem to be related to sunspots and thus might be explained in terms of modulation by penumbral waves or global p-mode oscillations.

The slow mode, which corresponds to a bounce time of a disturbance with the sound speed, has a period of (Roberts et al. 1984)

\[ P_{\text{slow}} = \frac{2L}{j c_T} = \frac{1.2 \times 10^{-4}L}{j T_0^{1/2}} \left( 1 + \frac{c_0^2}{v_A^2} \right)^{1/2} \approx \frac{2L}{j c_0} \quad (8) \]

where \( c_T \) is the tube speed, which is close to the sound speed \( c_0 \). Thus, for a coronal temperature of \( T_0 = 2 \) MK and loop lengths of \( L = 50 - 500 \) Mm we expect periods of \( P = 420 - 4200 \) s, or \( P = 7 - 70 \) minutes. We see that the periods of the slow mode covers the largest observed radio periods in Table III (Kaufmann 1972; Kobrin & Korsunov 1972), and thus may serve as potential interpretation for these cases. An acoustic wave propagating forth and back a coronal loops modulates the density, and thus is able to modulate plasma emission as well as gyro-synchrotron emission.
Table III. Coronal oscillations observed in radio (long periods: $P > 5$ s)

| Observer                        | Frequency $\nu$ [MHz] | Period $P$[s] | Spatial scale       |
|---------------------------------|------------------------|---------------|---------------------|
| Janssens and White (1969)       | 2700-15400             | 17, 23        |                     |
| Parks and Winckler (1969)       | 15400                  | 16            |                     |
| Janssens et al. (1973)          | 3000                   | 10-20         |                     |
| Kaufmann (1972)                 | 7000                   | 2400          |                     |
| Kobrin and Korshunov (1972)     | 9670, 9870             | 1800-3600     |                     |
| Tottet et al. (1979)            | 169                    | 60            | 6' (Nançay)         |
| Aurass and Mann (1987)          | 23-40                  | 44-234        |                     |
| Aschwanden et al. (1992)        | 1500                   | 8.8           | 0.2'-0.9' (VLA, OVRO) |
| Zlobec et al. (1992)            | 333 MHz                | 9.8-14.2      | 0.7'-1.5' (VLA)     |
| Baranov and Tsvetkov (1994)     | 8500-15,000            | 22, 30, 34    | 3.6'-6.0' (Crimea)  |
| Qin et al. (1996)               | 2840, 9375, 15,000     | 40            |                     |
| Wang and Xie (1997)             | 1420, 2000             | 44, 47        |                     |
| Chernov et al. (1998)           | 164-407                | 180           | 5.7' (Nançay)       |
| Gelfreikh et al. (1999)         | 17,000                 | 120-220       | 0.2' (Nobeyama)     |
| Nindos et al. (2002)            | 5000, 8000             | 157, 202      | 1.1''-5.7'' (VLA)   |
| Klassen et al. (2001)           | 150, 260               | 3-15          |                     |

Table IV. Coronal oscillations observed in optical and $H_{\alpha}$

| Observer                        | Wavelength $\lambda$ [Å] | Period $P$[s] | Instrument            |
|---------------------------------|---------------------------|---------------|-----------------------|
| Koutchmy et al. (1983)          | 5303                      | 43, 80, 300   | Sac Peak              |
| Pasachoff and Landman (1983)    | 5303                      | 0.5-2 (?)     | Hydrabad (eclipse)    |
| Pasachoff and Ladd (1987)       | 5303                      | 0.5-4 (?)     | East Java (eclipse)   |
| Jain and Tripathy (1998)        | $H_\alpha$                | 180-300       | Udaipur               |
| Pasachoff et al. (2000)         | 5303                      | -             | Chile (eclipse)       |
| Pasachoff et al. (2002)         | 5303                      | -             | Romania (eclipse)     |
| Williams et al. (2001, 2002)    | 5303                      | 6             | Bulgaria (eclipse)    |
| Ofman et al. (1997)             | 360, 1200-3000            | SOHO/UVCS, WLC|                      |
| Ofman et al. (2000a)            | 400, 625                  | SOHO/UVCS, WLC|                      |

3. Coronal Oscillations in Optical

The detection of coronal oscillations in optical wavelengths (Table IV) seems to be rather difficult due to the sky fluctuations in the Earth atmosphere, but several searches were conducted, motivated by the theoretical possibility of coronal heating by waves. Koutchmy, Zugzda, and
Locans (1983) analyzed Fe XIV green line (5303 Å) spectra recorded above the solar limb and did not found any significant period in intensity, but discovered quite significant power in the Doppler shift signal at periods of 43, 80, and 300 s, the latter being coincident with global p-mode oscillations. Koutchmy et al. (1983) suggested that the Doppler velocity oscillations could be due to resonant Alfvén waves. Then there were searches for high-frequency oscillations \( (P = 0.5 - 10\) s) performed in a number of total solar eclipse observations (Pasachoff & Landman 1983; Pasachoff & Ladd 1987; Pasachoff et al. 2000, 2002), but none or only a marginal excess (at the \( \lesssim 1\% \) level) was found in power spectra of the 5303 Å green line. Analysis of similar eclipse data in the same wavelength with a different instrument (SECIS), however, provided evidence for oscillations at a period of \( P = 6\) s (Williams et al. 2001, 2002). Williams et al. (2001) identified the location of the coronal oscillation in a small-scale loop (with a length of \( L \approx 50\) Mm), and measured a propagation speed of \( v_A \approx 2000\) km s\(^{-1}\) at the location of the oscillating signal. Based on these observables they interpret the phenomenon as an impulsively generated fast mode wave that is generated at one footpoint of the loop and propagates along it.

For completeness we mention also a detection of intensity oscillations in Hα wavelengths (Jain and Tripathy 1998). They found prominent 5- and 3-minute modes in flares, which seem to be linked to global p-mode oscillations. However, they find frequency deviations of about 300 \( \mu\)Hz between the coronal and chromospheric oscillation periods, which they attribute to differences in the magnetic field and flare plasma temperature.

Quasi-periodic brightness fluctuations were also measured in polarized brightness time series in coronal holes at heights of \( \gtrsim 2R_\odot\) with the white-light channel of UVCS onboard SOHO, exhibiting significant peaks in the Fourier power spectrum at \( P \approx 6 - 10\) min, and possibly at \( P \approx 20 - 50\) min (Ofman et al. 1997, 2000a). These oscillation have been interpreted in terms of slow magnetosonic waves propagating in coronal plumes (Ofman et al. 2000b).

4. Coronal Oscillations in EUV

The great breakthrough in detecting coronal oscillations came with the availability of sub-arcsecond images in EUV, as provided by the Transition Region And Coronal Explorer (TRACE) since 1998. A compilation of EUV detections of coronal oscillations and modeling studies is given in Table V.
Table V. Coronal oscillations observed in EUV

| Observer            | Wavelength λ [Å] | Period P[s] | Instrument     |
|---------------------|------------------|-------------|----------------|
| Chapman et al. (1972) | 304, 315, 368    | 300         | OSO-7          |
| Antonucci et al. (1984) | 554, 625, 1335  | 141, 117    | Skylab         |
| DeForest and Gurman (1998) | 171           | 600-900 (prop.) | SoHO/EIT     |
| Aschwanden et al. (1999) | 171, 195       | 276±25      | TRACE          |
| Nakariakov et al. (1999) | 171           | 256         | TRACE          |
| Berghmans and Clette (1999) | 195          | (prop.)     | SoHO/EIT      |
| De Moortel et al. (2000)     | 171          | 180-420 (prop.) | TRACE         |
| Nakariakov and Ofman (2001)  | 171, 195      | 256, 360    | TRACE          |
| Robbrecht et al. (2001)      | 171, 195      | (prop. waves) | TRACE, EIT    |
| Schrijver et al. (2002)       | 171, 195      | -           | TRACE          |
| Aschwanden et al. (2002a)     | 171, 195      | 120-1980    | TRACE          |
| De Moortel et al. (2002a,b)   | 171, 195      | 282±93 (prop.) | TRACE         |

The ultimate proof of coronal loop oscillations was produced by direct imaging of their spatial displacements, while all previous reports merely were inferred from the periodicity in time profiles (without imaging observations). After the 1998 July 14, 12:55 UT, flare, a number of at least five loops in the flaring active region were discovered to exhibit periodic transverse displacements, with an average period of $P = 280 \pm 30$ s (Aschwanden et al. 1999). The transverse displacement (with an amplitude of $A = 4100 \pm 1300$ km) amounted only to a few percent of the loop lengths ($L = 130,000 \pm 30,000$ km). The standing wave could be identified as a fast kink MHD mode in the fundamental eigenmode, based on the characteristics of fixed nodes (near the footpoints of the loop) and the lateral displacements (near the apex of the loop). Moreover, the observed period $P$ matched the theoretical expression for the fast kink mode $P_{\text{fast-kink}} \approx 2L/v_A$ (Eq.7), based on the observed loop lengths $L$ and estimated Alfvén speeds $v_A$. In Fig.4 we show the probabilities for different MHD modes based on physical parameters $(L, n_e, B)$ that were measured from similar loops (Aschwanden et al. 1999). However, although the notion of fast kink MHD mode oscillations may be correct in first order, observations often show substantial deviations from a nice symmetric kink mode oscillation, asymmetric excitation, and systematic eigen-motion trends superimposed on the oscillatory displacements (Aschwanden et al. 2002a).

Another interesting property is the strong damping, which brings loops oscillations to a halt after a few periods. For instance, the damping time of an oscillating loop with a period of $P = 261$ s (Fig.5) was
Figure 4. Probability distributions of four different MHD periods calculated for densities, magnetic fields, and altitudes that are typical for EUV loops observed in the temperature range of $T_e = 1.0 - 1.5$ MK (e.g. with TRACE or SOHO/EIT 171 Å). The probabilities are normalized for period bandwidths covering a factor of 2, i.e. per $\log(dT)=0.3$. Note that the fast kink MHD mode has the highest probability of coinciding with the 5-minute period [Aschwanden et al. 1999].

measured to $t_D = 1183$ s (Aschwanden et al. 2002a), and independently as $P = 256 \pm 8$ s and $t_d = 870$ s (Nakariakov et al. 1999), so it corresponds only to about 3 oscillation periods. A larger statistics of some 26 loops confirmed the general trend of strong damping, with an average of $t_D/P = 4.0 \pm 1.8$ periods. There are at least five different theories considered for the loop damping: (1) nonideal effects (viscous and ohmic damping, optically thin radiation, thermal conduction), (2) wave leakage through the sides of the loops, (3) wave leakage at the footpoints, (4) phase mixing, and (5) Alfvénic resonant absorption. The first two damping effects are considered to be too inefficient to explain the observed loop damping (Roberts 2000). Wave leakage at footpoints (DePontieu et al. 2001) is a too weak damping force for standard chromospheric scale heights (Ofman 2002), say $\lambda_H \approx 500$ km, but could account for slightly extended chromospheric scale heights, say a factor of $\approx 2$ (Aschwanden et al. 2002a). Evidence for the existence of an extended (spicular) chromosphere is supported by sub-mm radio observations of the solar limb (Ewell et al. 1993) as well as by recent RHESSI observations (Aschwanden, Brown, and Kontar 2002b). Phase mixing (Heyvaerts & Priest 1983), which provides a viscous damping mechanism due to the differences in Alfvén speeds in an inhomogeneous medium, was found to yield a scaling law of the damping time with
Table VI. Average and ranges of physical parameters of 26 oscillating EUV loops.

| Parameter                        | Average     | Range            |
|----------------------------------|-------------|------------------|
| Loop half length $L$             | 110 ± 53 Mm | 37-291 Mm        |
| Loop width $w$                   | 8.7 ± 2.8 Mm| 5.5-16.8 Mm      |
| Oscillation period $P$           | 321 ± 140 s | 137-694 s $^2$   |
|                                  | 5.4 ± 2.3 min| 2.3-10.8 min$^2$|
| Decay time $t_d$                 | 580 ± 385 s | 191-1246 s$^3$   |
|                                  | 9.7 ± 6.4 min| 3.2-20.8 min$^3$|
| Oscillation duration $d$         | 1392 ± 1080 s| 400-5388 s      |
|                                  | 23 ± 18 min | 6.7-90 min       |
| Oscillation amplitude $A$        | 2200 ± 2800 km| 100-8800 km     |
| Number of periods                | 4.0 ± 1.8   | 1.3-8.7          |
| Electron density of loop $n_{loop}$ | (6.0 ± 3.3)×10^8 cm$^{-3}$ | (1.3 – 17.1)×10^8 cm$^{-3}$ |
| Maximum transverse speed $v_{max}$ | 42 ± 53 km/s | 3.6-229 km/s    |
| Loop Alfvén speed $v_A$          | 2900 ± 800 km/s | 1600-5600 km/s  |
| Mach factor $v_{max}/v_{sound}$  | 0.28 ± 0.35 | 0.02-1.53        |
| Alfvén transit time $t_A$        | 150 ± 64 s  | 60-311 s         |
| Duration/Alfvénic transit $d/t_A$| 9.8 ± 5.7   | 1.5-26.0         |
| Decay/Alfvénic transit $t_d/t_A$ | 4.1 ± 2.3   | 1.7-9.6$^3$      |
| Period/Alfvénic transit $P/t_A$  | 2.4 ± 1.2   | 0.9-5.4$^2$      |

$^1$ All Alfvénic speeds and times are calculated for a magnetic field of $B = 30$ G.

$^2$ An extreme period of $P = 2004$ s is excluded in the statistics.

$^3$ Only the 10 most reliable decay times $t_d$ are included in the statistics.

loop period that is consistent with observations, if the length scale of inhomogeneity is assumed to be proportional to the loop length (Ofman & Aschwanden 2002). On the other side, Alfvénic resonant absorption (Ionson 1978; Rae & Roberts 1982) provides also an efficient damping mechanism if the cross-sectional density gradient at the loop edges is sufficiently flat (Ruderman & Roberts 2002; Goossens, Andries, & Aschwanden 2002). Nakariakov et al. (1999) concluded that the coronal value of the viscous and resistive dissipation coefficient could be 8-9 orders of magnitude larger than the classical value. Such high Reynolds numbers are actually in line with fast reconnection rates estimated in the corona (Dere 1996). So the jury is still out which physical mechanism is dominant in the strong loop damping.

The exciter mechanism of loop oscillations is another interesting topic. In virtually all cases there seems to be a flare or a filament destabilization involved (Schrijver et al. 2002). Moreover, the local magnetic field topology at the footpoints of oscillating loops seems...
to have a preference for magnetic separatrices, which would explain the amplification of oscillatory excitations (Schrijver et al. 2002) and was simulated with magnetic field models (Schrijver & Brown 2000). The exciter mechanism has severe consequences for the geometry and dynamics of the loop oscillations. An asymmetric exciter hits a loop
Table VII. Coronal oscillations observed in Soft X-rays

| Observer                  | Wavelength $\lambda$ | Period $P$ [s] | Instrument                  |
|---------------------------|----------------------|----------------|-----------------------------|
| Jakimiec and Jakimiec (1974) | 1-8 Å                | 200-900        | SOLRAD 9                    |
| Harrison (1987)           | 3.5-5.5 keV          | $>1440$        | SMM/HXIS                    |
| Thomas et al. (1987)      | 2-8, 8-16 Å          | 1.6            | OSO-7                       |
| Svestka (1994)            | 0.5-4, 1-8 Å         | 1200           | GOES                        |
| McKenzie and Mullan (1997) | 3-45 Å               | 9.6-61.6       | Yohkoh/SXT                  |
| Wang et al. (2002a,b)     | (Fe XIX) 1118 Å      | 660-1860       | SoHO/SUMER                  |

First at some location away from the midpoint, and thus can excite higher harmonic nodes or a combination of multiple modes (sausage, kink, torsional, slow mode). Because strong damping occurs, the loops do not have enough time to settle into an eigen-frequency, and thus phase shifts of propagating waves and complicated patterns of multiple modes occur that are difficult to analyze.

A summary of observed physical parameters is given in Table VI, quantifying also the ratios of periods, damping times, and durations of observed oscillations. If we use a canonical value of $B \approx 30$ G to estimate the Alfvén speed, we find that the observed periods exceed the expected kink mode period by a factor of 2.4 in the average. It is not clear whether the magnetic field in the oscillating loops is lower (i.e., $B = 13 \pm 9$ G; Nakariakov & Ofman 2001) than expected from standard coronal models, or whether the fast-kink mode period needs to be corrected for propagating (impulsively generated) wave modes or for a combination of multiple modes. Nevertheless, the high-quality images of TRACE provide a substantial number of physical parameters for the oscillating loops that translate into quite rigorous constraints for theoretical models of MHD oscillations and waves.

5. Coronal Oscillations in Soft X-Rays

There were only very few reports on oscillating loops in soft X-rays in the past (Table VII), one with a very fast period (Thomas et al. 1987), and some with very long periods (Jakimiec & Jakimiec 1974; Harrison 1987; Svestka 1994). A systematic search for oscillating loops in soft X-rays with Yohkoh/SXT data was conducted by McKenzie and Mullan (1997), but only 16 out of 544 cases were found to exhibit significant periodicities, with periods in the range of $P = 9.6 - 61.6$ s. These oscillations were derived from fluctuations in the soft X-ray
Table VIII. Coronal oscillations observed in Hard X-rays

| Observer                  | Wavelength $\lambda$ [Å] | Period $P$ [s] | Instrument       |
|---------------------------|---------------------------|----------------|------------------|
| Parks and Winckler (1969) | 16                        |                | Balloon          |
| Lipa (1978)               | 10-100                    |                | OSO-5            |
| Takakura et al. (1983)    | 0.3                       |                | Hinotori         |
| Kiplinger et al. (1982)   | 0.4, 0.8                  |                | SMM/HXRBS        |
| Kiplinger et al. (1983)   | 8.2                       |                | SMM/HXRBS        |
| Desai et al. (1987)       | 2-7                       |                | Venera           |
| Terekhov et al. (2002)    | 143.2±0.8                 |                | GRANAT           |
| Asai et al. (2002)        | 6.6 s                     |                | Yohkoh/HXT       |

Flux time profiles, which are proportional to the emission measure (or squared density). Density modulations could be most easily explained in terms of the fast sausage MHD mode (Fig.4), because the fast kink MHD mode does not cause density modulations in first order. Also, the required Alfven speeds appear to be unusually high for the fast kink MHD mode interpretation, as it was suggested by McKenzie and Mullan (1997).

A renaissance of loop oscillations in soft X-rays was initiated with recent SUMER/SoHO observations. Searches for waves in SUMER data were performed with both line width measurements (Erdelyi et al. 1998) as well as with Doppler shift measurements (Wang et al. 2002a, b). As for the case of optical observations, oscillatory signals were detected more pronounced in Doppler shifts than in line intensity. A total of 17 loop oscillation events have been detected with SUMER in Fe XIX Doppler shifts, at temperatures of $T > 6$ MK, although the majority were not associated with flare-like activity. The Doppler oscillations have periods of $P = 14 - 18$ minutes and exponential decay times of $\tau_D = 12 - 19$ minutes, so the ratio is only $\tau_D/P \approx 1$. The long periods (compare with Fig.4) as well as the measurements of Doppler shifts support an interpretation in terms of slow MHD modes (Eq.8). We suspect that a flare or filament destabilization causes a pressure disturbance at one side of a loop, which propagates as a slow mode magnetosonic (acoustic) wave in longitudinal direction along the loop and becomes reflected at the opposite side (Nakariakov et al. 2000). The rapid damping of the propagating wave seems to be caused by thermal conduction, as simulated with an MHD code (Ofman & Wang 2002).
6. Coronal Oscillations in Hard X-Rays

Reports of oscillation detections in hard X-ray wavelengths are listed in Table VIII. Because it has been shown that radio pulsations are often correlated with the hard X-ray flux (Correia and Kaufmann 1987; Aschwanden, Benz, and Kane 1990; Kurths et al. 1991), it is likely that the hard X-ray flux is modulated by the same quasi-periodic acceleration mechanism that produces the radio-emitting nonthermal electrons (Aschwanden et al. 1994; 1995b). Therefore, the same interpretation may hold for fast hard X-ray pulsations (e.g. Takakura et al. 1983) as for fast radio pulses (Sections 2.1 and 2.2). In general, however, much less fast (sub-second) pulses were detected in hard X-rays (e.g. Kiplinger et al. 1982) than in radio, because of the poorer sensitivity of earlier hard X-ray instruments. For the 7 recurrent hard X-ray pulses (with a mean period of 8.2 s) observed during the 1980 June 7 flare (Kiplinger et al. 1983), a detailed dynamic model of an oscillating current sheet was developed by Sakai & Ohsawa (1987) and Tajima et al. (1987). In this scenario, a current sheet undergoes oscillatory dynamics driven by pressure balance oscillations between the lateral plasma inflow and the internal currents that cause the current sheet collapse. This model even reproduced the observed double-peak substructure of the quasi-periodic pulses. On the other side, large flares always show long arcades of postflare loops, which suggests that a spatial fragmentation of the energy release (or intermittent bursty reconnection along the neutral line) causes a temporal sequence of quasi-periodic or random-like hard X-ray pulses, which is difficult to reconcile with the oscillatory dynamics of a single compact current sheet. So we have to await better spatial information in hard X-rays, such as with RHESSI, to sort out whether quasi-periodic hard X-ray pulses come from spatially separated structures or from the same compact region.

The fast sausage MHD mode causes a cross-sectional vibration of the flare and modulates in this way the density and magnetic field. Brown & McClymont (1976) (and similarly Zaitsev and Stepanov 1982) suggested a betatron acceleration model in a vibrating flare loop and explained in this way an observed correlation between the electron flux and spectral index in one event. Such a model can explain quasi-periodic hard X-ray emission with periods amenable to the fast sausage MHD mode (e.g. Parks and Winckler 1969; Lipa 1978; Kiplinger et al. 1983; Desai et al. 1987).

For the longest periods reported in hard X-rays (e.g. P=143 s, Terekhov et al. 2002), we might envision an interpretation in terms of slow MHD modes, such as for the SUMER/SoHO observed cases of Doppler shift oscillations.
The detection of oscillations and waves has grown exponentially over the last few years, especially with space-borne EUV telescopes, which were equipped with improved sensitivity, higher spatial resolution, and with faster cadences. Not only the volume of observations increased, but also progress was advanced in the physical interpretation. The observations show evidence for a variety of MHD oscillation modes, which roughly can be discriminated by their characteristic period range for coronal conditions (see Fig.4): fast sausage MHD mode ($P \approx 0.5-5$ s), fast kink MHD mode ($P \approx 3-7$ minutes), and slow (acoustic) modes ($P \approx 10-30$ minutes). The fastest MHD mode, i.e., the sausage mode, could only be detected in radio so far, and in optical perhaps (Williams et al. 2002), where sufficiently high (sub-second) time resolution is available, but it could not have been detected with TRACE or SUMER because of the insufficient time cadence (in the order of minutes). The fast kink mode has definitely been detected with TRACE in EUV, based on the lateral displacements and expected periods. The full picture, however, may be more complicated because of asymmetric excitation and propagating waves. The slow (acoustic) mode seems to be detected with SUMER, based on the periods ($P \approx 10-30$ minutes) and Doppler velocities.

The observations of oscillating systems in the solar corona raise interesting questions about their exciting and quenching mechanisms. The excitation of loop oscillations seems to be accomplished by nearby flares or destabilizing filaments, with a preference near magnetic separatrices. Asymmetric excitation may excite multiple modes, higher harmonics, and superimposed eigen-motion of the loop centroids. The damping of loop oscillations is strong ($t_D/P \approx 1-3$). Viable physical mechanisms are chromospheric leakage (for an extended chromosphere), phase mixing (for inhomogeneous loops), and Alfvénic resonance absorption (if the loop cross-sectional density profile has a “smooth” edge).

Besides the regular oscillations that is an intrinsic characteristic of MHD modes, there are also aperiodic or quasi-periodic phenomena which call for a different interpretation. Quasi-periodic oscillations observed in radio and hard X-rays do not have the regular periodicity as MHD oscillations and are likely to be produced by oscillatory regimes (limit cycles) of nonlinear dissipative systems, e.g. in the magnetic reconnection and particle acceleration region.
Acknowledgements

Part of this work has been supported by NASA contracts NAS5-38099 (TRACE) and NAS8-00119 (Yohkoh/SXT). Support by the NATO Science Programm for participation at the Advanced Research Workshop is acknowledged. The author thanks Bernie Roberts, Robertus Erdélyi, Valery Nakariakov, Leon Ofman, Tongjiang Wang, Werner Curdt, and the referee for instructive and helpful discussions and comments.

References

Abrami, A.: 1970. Solar Phys. 11, 104.
Abrami, A.: 1972. Nature 238/80, 25.
Abrami, A. and Koren, U.: 1978. Astron. Astrophys. Suppl. Ser. 34, 165.
Achong, A.: 1974. Solar Phys. 37, 477.
Antonucci, E., Gabriel, A. H., and Patchett, B. E.: 1984. Solar Phys. 93, 85.
Asai, A., Shimojo, M., Isobe, H., Morimoto, T., Yokoyama, T., Shibasaki, K., & Nakajima, H.: 2001, Astrophys. J. 562, L103.
Aschwanden, M. J.: 1986. Solar Phys. 104, 57.
Aschwanden, M. J.: 1987a. Solar Phys. 111, 113.
Aschwanden, M. J.: 1987b. PhD Thesis Pulsations of the radio emission of the solar corona, ETH Zurich, 173p.
Aschwanden, M. J., Bastian, T. S. and Gary, D. E.: 1992. Bull.Amer.Astron.Soc. 24/2, 802.
Aschwanden, M. J. and Benz, A. O.: 1986. Astron. Astrophys. 158, 102.
Aschwanden, M. J. and Benz, A. O.: 1988. Astrophys. J. 332, 466.
Aschwanden, M. J., Benz, A. O., and Kane, S. R: 1990. Astron. Astrophys. 229, 206.
Aschwanden, M. J., Benz, A. O., Dennis, B. R., and Kundu, M. R.: 1994. Astrophys. J. Suppl. Ser. 90, 631.
Aschwanden, M. J., Benz, A. O., Dennis, B. R., and Schwartz, R. A.: 1995a. Astrophys. J. 455, 347.
Aschwanden, M. J., Brown, J. C., and Kontar, E. P.: 2002b. Solar Phys. (in press).
Aschwanden, M. J., DePontieu, B., Schrijver, C. J., and Title, A.: 2002a. Solar Phys. 206, 99.
Aschwanden, M. J., Fletcher, L., Schrijver, C., and Alexander, D.: 1999. Astrophys. J. 520, 880.
Aschwanden, M. J., Montello, M. L., Dennis, B. R., and Benz, A. O.: 1995b. Astrophys. J. 440, 394.
Aurass, H. and Mann, G.: 1987. Solar Phys. 112 359.
Baranov, N. V. and Tsvetkov, L. I.: 1994. Astronomy Letters 20, No.3, 327.
Bastian, T. S., Gary, D. E., White, S. M., and Hurford, G. J.: 1998. SPIE Conf.Proc. 140, 563.
Benz, A. O.: 1985. Solar Phys. 96, 357.
Berghmans, D. and Clette, F.: 1999. Solar Phys. 186, 207.
Bernold, T. E. X.: 1980. Astron. Astrophys. Suppl. Ser. 42, 43.
Brown, J. C. and Mc Clymont, A. N.: 1976. Solar Phys. 49, 329.
Chapman, R. D., Jordan, S. D., Neupert, W. M., and Thomas, R. J.: 1972, Astrophys. J. 174, L97.
Chernov, G. P.: 1989, Sov. Astron. 33(6), 649.
Chernov, G. P. and Kurths J.: 1990, Sov. Astron. 34(5), 516.
Chernov, G. P., Markeev, A. K., Poquerusse, M., Bougeret, J. L., Klein, K. L., Mann, G., Aurass, H., and Aschwanden, M. J.: 1998, Astron. Astrophys. 334, 314.
Chiu, Y. T.: 1970, Solar Phys. 13, 420.
Correia, E. and Kaufmann, P.: 1987, Solar Phys. 111, 143.
Costa, J. E. R. and Kaufmann, P.: 1986, Solar Phys. 104, 253.
DeForest, C. E., and Gurman, J. B.: 1998, Astrophys. J. 501, L217.
De Groot, T.: 1970, Solar Phys. 14, 176.
De Moortel, I., Hood, A. W., Ireland, J., and Walsh, R. W.: 2002a, Solar Phys. 209, 61.
De Moortel, I., Ireland, J., and Walsh, R. W.: 2000, Astron. Astrophys. 355, L23.
De Moortel, I., Ireland, J., Walsh, R. W., and Hood, A. W.: 2002b, Solar Phys. 209, 89.
De Pontieu, B., Martens, P. C. H., and Hudson, H. S.: 2001, Astrophys. J. 558, 859.
Dere, K. P.: 1996, Astrophys. J. 472, 864.
Desai, U. D., Kouveliotou, C., Barat, C., Hurley, J. M., Niel, M., Talon, R., Vedrenne, G., Estulin, I. V., and Dolidze, V. C.: 1987, Astrophys. J. 319, 567.
Droge, F.: 1967, Z. Astrophys. 66, 200.
Elgaroy, O.: 1980, Astron. Astrophys. 82, 308.
Elgaroy, O.: 1986, Solar Phys. 104, 43.
Elgaroy, O. and Sveen, O. P.: 1973, Solar Phys. 32, 231.
Erdélyi, R., Doyle, J. G., Perez, M. E., and Wilhelm, K. 1998, Astron. Astrophys. 337, 287.
Ewell, M. W. Jr., Zirin, H., Jensen, J. B. and Bastian, T. S. 1993, Astrophys. J. 403, 426.
Fleishman, G. D., Stepanov, A. V. and Yurovsky, Y. F.: 1994, Solar Phys. 153, 403.
Fu, Q. J., Gong, Y. F., Jin, S. Z., and Zhao, R. Y.: 1990, Solar Phys. 130, 161.
Gaizauskas, V. and Tapping, K. F.: 1980, Astrophys. J. 182, 337.
Gotwols, B. L.: 1972, Solar Phys. 25, 232.
Harrison, R. A.: 1987, Astron. Astrophys. 182, 337.
Heyvaerts, J. and Priest, E. R.: 1983, Astron. Astrophys. 117, 220.
Ionson, J. A.: 1978, Astrophys. J. 226, 650.
Jain, K. and Tripathy, S. C.: 1999, Solar Phys. 181, 113.
Jakimiec, J. and Jakimiec, M.: 1974, Astron. Astrophys. 34, 415.
Janssens, T. J. and White, K. P. III: 1969, Astrophys. J. 158, L127.
Janssens, T. J., White, K. P. III, and Broussard, R. M.: 1973, Solar Phys. 31, 207.
Kai, K. and Takayanagi, A.: 1973, Solar Phys. 29, 461.
Kattenberg, A. and Kuperus, M.: 1983, Solar Phys. 85, 185.
Karpen, T., Antiochos, S. K., and DeVore, C. R.: 1995, Astrophys. J. 450, 422.
Kaufmann, P.: 1972, Solar Phys. 23, 178.
Kaufmann, P., Correia, E., Costa, J. E. R., and Zodi Vaz, A. M.: 1986, Astron. Astrophys. 157, 11.
Kiplinger, A. L., Dennis, B. R., Forst, K. J. and Orwig, L. E.: 1982. in Proc. Hinotori Symposium on Solar Flares, (eds. Y. Tanaka et al.), Tokyo, Japan: ISAS, p.66.

Kiplinger, A. L., Dennis, B. R., Frost, K. J. and Orwig, L. E.: 1983, Astrophys. J. 273, 783.

Kliem, B.: 1988. ESA SP-285, 117.

Kliem, B.: 1995. Lecture Notes in Physics 444, 93.

Kliem, B., Karlicky, M., and Benz, A. O.: 2000. Astron. Astrophys. 360, 715.

Klassen, A., Aurass, H., and Mann, G.: 2001. Astron. Astrophys. 370, L41.

Kohl, J. L., Gardner, L. D., Fineschi, S., Raymond, J. C., Noci, G., Romoli, M., Antonucci, E., Tondello, G., Nicolosi, P., and Huber, M. C. E. 1997, Adv. Space Res. 20, 3.

Kohl, J. L., Fineschi, S., Esser, R., Ciavarella, A., Cranmer, S. R., Gardner, L. D., Suleiman, R., Noci, G., Modigliani, A. 1999, Space Science Reviews 87, 1/2, 233.

Kobrin, M. M. and Korshunov, A. I.: 1972. Solar Phys. 25, 339.

Koutchmy, S., Zhugzhda, Ia. D., and Locans, V.: 1983. Astron. Astrophys. 120, 185.

Kurths, J., Benz, A. O. and Aschwanden, M. J.: 1991. Astron. Astrophys. 248, 270.

Kurths, J. and Herzel, H.: 1986. Solar Phys. 107, 39.

Kurths, J. and Herzel, H.: 1987. Physica Scripta 25D, 165.

Kurths, J. and Karlicky, M.: 1989. Solar Phys. 119, 399.

LeBoef, J. N., Tajima, T., and Dawson, J. M.: 1982. Phys. Fluids 25, 784.

Li, H. W., Messerotti, M., and Zlobec, P.: 1987. Solar Phys. 111, 137.

Lipa, B.: 1978. Solar Phys. 57, 191.

Makhmutov, V. S., Costa, J. E. R., Raulin, J. P., Kaufmann, P., Lagrotta, P. R., Gimenez de Castro, C. G., Magun, A., and Arzner, K.: 1998. Solar Phys. 178, 393.

McKenzie, D. E. and Mullan, D. J.: 1997. Solar Phys. 176, 127.

McLean D. J., Sheridan, K. V., Steward, R. T., and Wild, J. P.: 1971. Nature 234, 140.

McLean D. J. and Sheridan K. V.: 1973. Solar Phys. 32, 485.

Nakariakov, V. M. and Ofman, L.: 2001. Astron. Astrophys. 372, L53.

Nakariakov, V. M., Ofman, L., DeLuca, E., Roberts, B., Davila, J. M.: 1999. Science 285, 862.

Nakariakov, V. M., Verwichte, E., Berghmans, D., and Robbrecht, E.: 2000. Astron. Astrophys. 362, 1151.

Nindos, A., Aliessandakis, C. E., Gelfreikh, G. B., Bogod, V. M., and Gontikakis, C.: 2002. Astron. Astrophys. 386, 658.

Ofman, L., Ofman, L., Romoli, M., Poletto, G., Noci, G., and Kohl, J. K.: 1997, Astrophys. J. 491, L111.

Ofman, L., Romoli, M., Poletto, G., Noci, G., and Kohl, J. L.: 2000a, Astrophys. J. 529, 592.

Ofman, L., Nakariakov, V. M., and Sehgal, N.: 2000b, Astrophys. J. 533, 1071.

Ofman, L.: 2002. Astrophys. J. 568, L135.

Ofman, L. and Aschwanden, M. J.: 2002. Astrophys. J. 576, L153.

Ofman, L. and Wang, T. J.: 2002. Astrophys. J. Lett. (in press).

Pasachoff, J. M., Babcock, B. A., Russell, K. D., McConnachie, T. H., and Diaz, J. S.: 2000. Solar Phys. 195, 281.

Pasachoff, J. M., Babcock, B. A., Russell, K. D., and Seaton, D. B.: 2002. Solar Phys. 207, 241.

Pasachoff, J. M. and Landman, D. A.: 1993. Solar Phys. 90, 325.

Pasachoff, J. M. and Ladd, E. F.: 1987. Solar Phys. 109, 365.
CORONAL OSCILLATIONS

Pick, M. and Trottet, G.: 1978. *Solar Phys.* **60**, 353.
Priest, E. R.: 1985. *Rep. Prog. Phys.* **48**, 955.
Qin, Z.H. and Huang, G. L.: 1994. *Astrophys. Space Sci.* **218**, 213.
Qin, Z.H., Li, C., and Fu, Q.: 1996. *Solar Phys.* **163**, 383.
Rae, I.C. and Roberts, B.: 1982. *Astrophys. J.* **256**, 761.
Robbrecht, E., Verwichte, E., Berghmans, D., Hochedez, J. F., Poedts, S., and Nakarikov, V. M.: 2001. *Astron. Astrophys.* **370**, 591.
Roberts, B.: 2000. *Solar Phys.* **193**, 139.
Roberts, B., Edwin, P. M., and Benz, A. O.: 1984. *Astrophys. J.* **279**, 857.
Rosenberg, H.: 1970. *Astron. Astrophys.* **9**, 159.
Rosenberg, H.: 1972. *Solar Phys.* **25**, 188.
Ruderman, M. S., and Roberts, B.: 2002. *Astrophys. J.* **577**, 475.
Sastry, Ch. V., Krishan, V., and Subramanian, K. R.: 1981. *J. Astrophys. Astron.* **2**, 59.
Schrijver, C. J., Aschwanden, M. J., and Title, A.: 2002. *Solar Phys.* **206**, 69.
Svestka, Z.: 1994. *Solar Phys.* **152**, 505.
Takakura, T., Kaufmann, P., Costa, J. E. R., Degaonkar, S. S., Ohki, K., and Nitta, N.: 1983. *Nature* **302**, No. 5906, 317.
Tajima, T., Sakai, J., Nakajima, H., Kosugi, T., Brunel, F., and Kundu, M. R.: 1987. *Astrophys. J.* **321**, 1031.
Tapping, K. F.: 1978. *Solar Phys.* **59**, 145.
Tapping, K. F.: 1983. *Solar Phys.* **87**, 177.
Tapping, K. F.: 1987. in *Rapid Fluctuations in Solar Flares*, NASA CP-2449. 445.
Terekhov, O. V., Shevchenko, A. V., Kuz’min, A. G., Sazonov, S. Y., Sunyaev, R. A., and Lund, N.: 2002. *Astronomy Letters*, (in press).
Williams, D. R., Phillips, K. J. H., Rudaway, P., Mathioudakis, M., Gallagher, P.T., O’Shea, E., Keenan, F.P., Read, P., and Rompolt, B.: 2001, *Mon.Not.R.Astron.Soc.* **326**, 428.
Zaitsev, V. V.: 1971. *Solar Phys.* **20**, 95.
Zaitsev, V. V., and Stepanov, A. V.: 1975. *Astron. Astrophys.* **45**, 135.
Zhao, R. Y., Jin, S. Z., Fu, Q. J., and Li, X. C.: 1990. Solar Phys. 130, 151.
Zlobec, P., Messerotti, M., Dulk, G. A., and Kucera, T.: 1992. Solar Phys. 141, 165.

\footnote{Aschwanden, M. J.: 2003. \textit{Review of Coronal Oscillations - An Observer's View}, in \textit{Turbulence, Waves, and Instabilities in the Solar Plasma}, NATO Advanced Research Workshops, 16-20 Sept 2002, Budapest, Hungary, (eds. R. von Fay-Siebenburgen, K. Petrovay, B. Roberts, and M.J. Aschwanden).}