Solar Physics
DOI: 10.1007/•••••-•••-•••-••••-•

An Estimate of P-Mode Damping by Wave Leakage

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Abstract High-cadence TRACE observations show that outward-propagating intensity disturbances are a common feature in large, quiescent coronal loops. Analysis of the frequency distribution of these modes show peaks at both three and five minute periods, indicating that they may be driven by the solar surface oscillations (p modes). The energy flux contained within the coronal intensity disturbances is of the order of $(1.1 \pm 0.4) \times 10^3$ ergs cm^{-2}s^{-1}. A simple order of magnitude estimate of the damping rate of the relevant p modes allows us to put an observational constraint on the damping of p modes and shows that leakage into the overlying coronal atmosphere might be able to account for a significant fraction of p-mode damping.

Keywords: MHD: oscillations - corona - activity

Received: 9 January 2007; Accepted 18 April 2007

1. Introduction

Since it was first understood that the complicated pattern of solar surface oscillations (Leighton, Noyes, and Simon, 1962) is in fact a superposition of millions of acoustic modes (Ulrich, 1970; Leibacher and Stein, 1971), many different candidate damping mechanisms for these p modes have been suggested. These are largely theoretically motivated and observationally unconstrained. At first sight, leakage of low-frequency p modes into the overlying atmosphere would appear to be one of the less likely damping mechanisms, as reflection of the chromosphere and transition region would effectively trap these modes near the solar surface. However, the appearance of p-mode-like frequencies (mainly three to five minutes), in a variety of solar structures, seems to indicate that at least part of the low-frequency p-mode energy penetrates into the atmosphere. For example, observations of slow modes in coronal loops (see review by De Moortel, 2006) give indications that they

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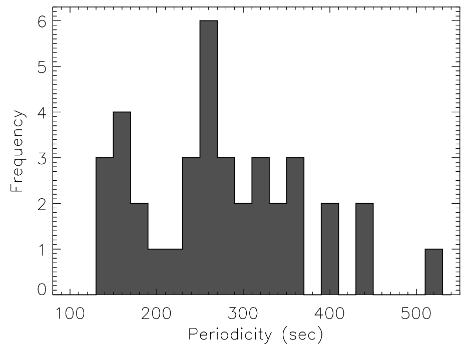

Figure 1. Distribution of the periodicities of the 38 propagating oscillations found from a wavelet analysis from 171 Å TRACE data (see De Moortel *et al.*, 2002b).

may be "leaking modes" from interior p-mode oscillations. Indeed, analysis of the frequency distribution of these modes shows peaks at both three and five minute periods (see Figure 1, taken from De Moortel *et al.*, 2002b). Both the theoretical and observational details and consequences of how these modes might propagate from the surface to the corona have recently been investigated by a variety of authors (*e.g.* De Pontieu, Erdélyi, and James, 2004; De Pontieu, Erdélyi, and De Moortel, 2005; McIntosh and Jefferies, 2006; Jefferies *et al.*, 2006; Bloomfield *et al.*, 2006; Vecchio *et al.*, 2007). However, another obvious question also arises, namely: is this observed leakage a significant component for the damping of solar p modes? In this paper, we explore this possibility, which offers one of the very few opportunities to constrain the damping mechanisms for p modes by direct observations.

This study aims to provide a conservative estimate of the lower bound on the damping of p modes by leakage into the overlying atmosphere. The manuscript is organised as follows: in the next section, we briefly summarise the relevant details of the observed coronal intensity perturbations. We then provide the details of estimating the p-mode energy budget (Section 3), and discuss the possible implications of our results (Section 4). Finally, we summarise our conclusions in Section 5.

2. Coronal Slow Waves

Within the past five years, it has become evident that the solar corona shows direct evidence for propagating slow modes, the origin of which is presumably much lower in the solar atmosphere (*e.g.* Berghmans and Clette, 1999; De Moortel, Ireland, and Walsh, 2000; De Moortel *et al.*, 2002a,b; Robbrecht *et al.*, 2001; King *et al.*, 2003; McEwan and De Moortel, 2006). In particular, De Moortel *et al.* (2002c) have shown that the frequency spectrum of these modes is rather narrow and is in fact peaked at three and five minutes (see Figure 1), strongly suggesting a relationship between these modes and solar p modes; indeed, it is not obvious why propagating coronal slow modes should be characterised by such a spectrum other than that this simply reflects the spectrum of the trapped acoustic modes of the solar interior. This would of course imply that what we are observing is "leakage" of these trapped modes into the overlying atmosphere.

For simplicity, we shall restrict our attention to those slow modes whose frequency spectrum peaks around five minutes; these modes are largely confined to coronal loop structures, not associated with sunspots. For these modes, the associated observed wave energy flux reported by De Moortel *et al.*, (2002a,b) and McEwan and De Moortel (2006) is of the order of $f_{obs} \sim 3.2 \times 10^2$ ergs cm^{-2}s^{-1}. However, this estimate is based on a general coronal density of $\rho = 5 \times 10^{-16}$ g cm^{-3} or number density $n = 3 \times 10^8$ cm^{-3} and more typical number densities for coronal loops are of the order of $n \sim 10^9$ cm^{-3} (Vaiana and Rosner, 1978; Aschwanden, 2004). For example, determining the magnetic-field strength from observed loop oscillations, Nakariakov and Ofman (2001) used number densities $n \approx 1 - 4 \times 10^9$ cm^{-3}. Recalculating the estimates of the observed energy flux in non-sunspot loops, using $n = 10^9$ cm^{-3}, we find values of the order of $f_{obs} \sim (1.1 \pm 0.4) \times 10^3$ ergs cm^{-2}s^{-1}, ranging from 507 - 2424 ergs cm^{-2} s^{-1} (see non-sunspot data in Table 4). However, for a coronal loop number density of $n = 4 \times 10^9$ cm^{-3}, the values could be up to four times higher. Additional uncertainty comes from the fact that the observed coronal perturbations are subject to damping, mainly due to thermal conduction (De Moortel and Hood, 2003, 2004), as they propagate along the loop footpoints. As we want to compare the observed coronal flux with the energy flux in the most likely driver of the perturbations, namely p modes, one could argue that the maximum amplitude should be used, to eliminate the effect of the "coronal" damping. Using these maximum values and a high coronal density of $n = 4 \times 10^9$ cm^{-3}, the estimated energy flux could be as high as $f_{obs} \sim (6.9 \pm 2.9) \times 10^3$ ergs cm^{-2}s^{-1} (range: $3 - 16 \times 10^3$ ergs cm^{-2} s^{-1}). To account for this range and uncertainty in both the perturbation amplitudes and coronal-loop densities, we will adopt an observed energy flux range of the order of

$$f_{obs} \sim 5 \times (10^2 - 10^3) \ \text{ergs cm}^{-2}\text{s}^{-1} . \tag{1}$$

Using this range for the observed energy flux, we can estimate the corresponding observed luminosity as

$$L_{obs} = 4\pi R_o^2 \, F \, f_{obs} \approx F \times 3 \times (10^{25} - 10^{26}) \ \text{ergs s}^{-1} , \tag{2}$$

(but with a possible range of $F \times (0.3 - 10.0) \times 10^{26}$ ergs s^{-1}, based on the maximum amplitude values in Table 4 and the range of coronal loop densities) where $R_o = 6.96 \times 10^{10}$ cm and F is a filling factor, denoting the fraction of the solar surface that is covered by magnetic flux tubes supporting five-minute oscillations, with $0 \leq F \leq 1$; thus, $F = 1$ corresponds to 100% of the solar surface covered by coronal structures supporting five-minute oscillations. Clearly, F is neither zero (as five-minute oscillations have been observed in coronal loops), nor one (for example, coronal loops above sunspots support three-minute oscillations). So what is a likely coronal value for F? In the photosphere, F is significantly less than one although, as pointed out by Jefferies *et al.* (2006), "magneto-acoustic" portals are expected to be abundantly present on the solar surface. Leakage of the five-minute p modes into the overlying atmosphere requires low-β, inclined flux tubes (magneto-acoustic portals), which are most likely to occur in plage and network regions and much, but not all, of the coronal field originates exactly from these regions. However, it is clear that the filling factor F (Equation (2)) in the corona will be significantly larger than it is in the photosphere, due to the expansion of the flux tubes. Additionally, Fontenla *et al.* (1993) find evidence for a considerable upward flux in quiet-Sun regions (associated with internetwork). So far, no five-minute oscillations have been observed in the quiet Sun but this might in part be due to the lack of sufficiently bright loops in quiet-Sun regions to allow observations of very low amplitude perturbations. Hence, it is likely that leaking p modes will be present in a large part of the solar atmosphere, although not all necessarily in the form of perturbations in coronal loops. For example, such leakage has also been suggested by observations of oscillations with similar periodicities (but slightly higher amplitudes) in moss by De Pontieu, Erdélyi, and de Wijn (2003), and has been associated with the formation of spicules (De Pontieu, Erdélyi, and James, 2004). So far, the exact value of the filling factor (F) in the corona is not known, and all we can say is that $0 \leq F \leq 1$.

In summary, the estimate of the observed coronal luminosity is subject to several uncertain input parameters, such as the filling factor, the perturbation amplitudes and the coronal-loop densities. Given the possible range of values described above, we will use a value of

$$L_{obs} \sim 10^{26} \ \text{ergs s}^{-1}\,, \tag{3}$$

in our comparison with the p-mode energy flux.

3. The *P*-Mode Energy Budget

3.1. Appropriate Modes

In order to compare the energy budget of the observed coronal perturbations with the p-mode energy budget, we first need to determine which p modes are relevant. In other words, which p modes could have contributed to the driving of the observed coronal slow modes? It is only those modes that the *observed* leakage could sensibly damp, and it is thus those modes whose energy budget we need to look at.

Now, a natural assumption is that only modes that are coherent across the "averaging scale", used in the determination of the observed coronal perturbations, can contribute. The reason underlying this assumption is that for small amplitudes of the coronal acoustic modes, the observed radiated energy flux scales linearly with $\delta\rho$, the coronal density fluctuation associated with the acoustic mode; hence line-of-sight averaging and averaging over the effective "pixel" will wash out density perturbations which are not coherent on at least the scale over which the observed intensities are averaged. For this reason, we assume that only modes with wavelength λ $(= 2\pi/k) \geq 2L$, where L is the averaging scale, contribute, as they will be coherent across the averaging scale. To obtain a signal-to-noise ratio sufficient to allow the detection of intensity perturbations about the background noise, De Moortel *et al.* (2002a,b) summed the intensities across loop strands which have average widths of the order of 8.1 ± 2.8 Mm (ranging from $3.9 - 14.1$ Mm). This is an average width, and the coronal loop footpoints are found to have minimum widths of 4.3 ± 1.5 Mm ($1.5 - 7.3$ Mm), which expand to 11.4 ± 4.4 Mm ($5.1 - 22.1$ Mm), so there is a large range of coronal averaging scales. However, these

Table 1. Wavelength of p modes of degree ℓ, based on Equation 4.

P-mode degree (ℓ)	Wavelength (λ_ℓ)	Total number of modes
96	45.3 Mm	9408
144	30.3 Mm	21024
215	20.3 Mm	46655
285	15.3 Mm	81795

scales were chosen to obtain intensity (density) perturbations that are statistically significant above the background level and hence, we can not automatically assume the wave packets actually remain coherent on the entire range of these scales.

Regardless of the actual value of the coronal scales, it is clear that this averaging will act as a “filter” and impacts the range of p-mode degrees that needs to be considered as “sources” for the observed coronal propagating modes. However, an added complication here is how to relate the *coronal* scales of the leaked p modes, which contribute to the observed coronal flux, to the original surface scales. As the fluxtubes expand strongly between the photosphere and corona, one can expect a certain amount of “expansion” of the surface scales. On the other hand, the p modes travel along the low-β fluxtubes as slow MHD waves, which are strongly field-guided, and hence, the rapid expansion of the fluxtubes will cause phasemixing, leading to a simultaneous reduction of the transverse scales. The combined effect of the fluxtube expansion and phasemixing of the slow modes is not easy to estimate and is far beyond the scope of our simple order of magnitude estimate. Additional processes such as mode coupling, gravitational stratification, loop inclination and non-linearities will complicate the picture even further and the exact relation between the photospheric and coronal scales is not at all obvious. Note that we are not claiming that p modes with wavelengths less than our chosen coronal averaging scales do not leak into the overlying atmosphere but merely that due to the averaging, these “small”-scale p modes do not contributed to the observed coronal energy flux and hence do not have to be included in our comparison.

Since we are primarily interested in a rough estimation of the possible damping effects that may result from leaking modes into the corona, a precise accounting is not critical. As a first-order estimate, we will basically assume that the coronal scale are of the same order as the surface scales. To account for the range of coronal averaging scales, we will estimate the number of contributing p modes for $L = 7.5, 10, 15, 22.5$ Mm, or in other words, we will look at p modes with wavelengths $\lambda > 15, 20, 30, 45$ Mm. If we use the relation

$$\lambda_\ell = \frac{2\pi R_o}{\sqrt{\ell(\ell+1)}} \tag{4}$$

connecting the mode wavelength with the p-mode degree (ℓ) (Christensen-Dalsgaard, Gough, and Toomre, 1985), then using the results shown in Table 1, we shall need the first 96, 144, 215 and 285 p modes, which have $\lambda_\ell > 15, 20, 30, 45$ Mm, respectively. Furthermore, for every degree (ℓ), there are $2\ell + 1$ modes with corresponding values of m $(-\ell, ..., 0, ..., \ell)$, leading to a total of $9408 - 81795$ modes to be accounted for. In our further accounting, we have for simplicity ignored the

Table 2. P-mode energy supply rate ($\times 10^{27}$ erg s^{-1}) from various authors and a range of p-mode wavelengths. The first set of values are based on the energy (E) divided by an appropriate damping time, whereas the second set are based on quoted values of the energy supply rate ($\mathrm{d}E/\mathrm{d}t$)

	$\lambda > 45$ Mm	$\lambda > 30$ Mm	$\lambda > 20$ Mm	$\lambda > 15$ Mm
no of modes:	*9408*	*21024*	*46655*	*81795*
Libbrecht (1988)	0.3 – 0.5	0.7 – 1.2	1.7 – 2.7	2.9 – 4.8
Chaplin *et al.* (1998)	0.5 – 1.1	1.1 – 2.4	2.3 – 5.4	4.1 – 9.5
Komm *et al.* (2000)	0.9 – 2.0	1.9 – 4.5	4.3 – 10.0	7.6 – 17.5
Chaplin *et al.* (1998)	0.8	1.8	3.9	6.9
Komm *et al.* (2000)	1.9	4.2	9.3	16.0
Baudin *et al.* (2005)	7.4	1.7	3.7	6.5
Average:	**1.7**	**2.2**	**4.8**	**8.4**

additional complication of accounting for modes with the same (ℓ, m), but different radial degree (n).

3.2. P-Mode Damping Rate

We now need to estimate the observed damping rate of those p modes that can be associated with the observed coronal slow modes, *i.e.*, those modes identified above which might be sensibly damped by leakage into the corona. The simplest way of establishing this damping rate is to estimate the energy per mode and the damping time. For example, if one considers the study of Komm, Howe, and Hill (2000), one finds that the energy per mode at a frequency $\nu = 3.3$ mHz is $E \sim 1.85 \times 10^{28}$ ergs (see their Table 2). To obtain a corresponding damping time (τ), we consider the discussion by Elsworth *et al.* (1990); while no values for τ are given at $\nu = 3.3$ mHz, they do quote values (see their Table 2) for τ at $\nu = 3.0$ mHz ($\tau = 2.3$ days $= 1.99 \times 10^5$ sec) and at $\nu = 3.4$ mHz ($\tau = 1.0$ days $= 8.6 \times 10^4$ sec). Hence, we obtain

$$\frac{\mathrm{d}E}{\mathrm{d}t} = \frac{E}{\tau} \sim 0.93 - 2.15 \times 10^{23} \ \text{ ergs s}^{-1} \, .$$

This value only depends on the frequency, not on the degree of the mode, and hence the total relevant observed damping rate is given by (when accounting for all of the modes that are relevant to the proposed leakage on a given scale), for example,

$$\left(\frac{\mathrm{d}E}{\mathrm{d}t}\right)_{tot} = \sum_{0}^{9408} \frac{\mathrm{d}E}{\mathrm{d}t} dl \approx 8.8 - 20.1 \times 10^{26} \ \text{ ergs s}^{-1} \, , \tag{5}$$

where we have used the number of modes with wavelengths $\lambda > 45$ Mm.

As an alternative, Libbrecht (1988) gives slightly different values for the energy per mode, with $E = 7.1 \times 10^{27}$ ergs at $\nu = 3.0$ mHz, and $E = 5.1 \times 10^{27}$ ergs at $\nu = 3.4$ mHz, respectively and Chaplin *et al.* (1998) give $E = 1.0 \times 10^{28}$ ergs at $\nu = 3.3$ mHz. Finally, Chaplin *et al.* (1998), Komm, Howe, and Hill (2000) and

Baudin *et al.* (2005) directly give values for $\mathrm{d}E/\mathrm{d}t$ per mode. For example, Chaplin *et al.* (1998) give an energy supply rate at $\nu = 3.3$ mHz of $\mathrm{d}E/\mathrm{d}t \sim 8.4 \times 10^{22}$ ergs s^{-1}. Summing over, for example, 9408 modes, we obtain

$$\left(\frac{\mathrm{d}E}{\mathrm{d}t}\right)_{tot} = 7.9 \times 10^{26} \text{ ergs s}^{-1} . \tag{6}$$

Incidentally, comparing the energy E and the energy supply rate $\mathrm{d}E/\mathrm{d}t$ given by Komm, Howe, and Hill (2000) and Chaplin *et al.* (1998), we find corresponding damping times of $\sim 1.1 - 1.4$ days, which is in good agreement with the damping times estimated by Elsworth *et al.* (1990). We also note here that the average values quoted by the various authors are based on p modes with different spherical harmonic degree ℓ. The values quoted by Libbrecht (1988), Chaplin *et al.* (1998), Komm, Howe, and Hill (2000) and Baudin *et al.* (2005) are for modes with degree $\ell \approx 20$, $\ell = 0$, $\ell = 90 - 150$ and $\ell = 1$, respectively. However, E and $\mathrm{d}E/\mathrm{d}t$ only depend on frequency, not on the degree of the mode (Komm, Howe, and Hill, 2000), and therefore, our estimates are not likely to be egregiously in error.

The results of the p-mode damping rates based on the values quoted by the different authors for the p-mode energy E and/or the energy supply rate $\mathrm{d}E/\mathrm{d}t$ are summarised in Table 2 for the range of p-mode wavelengths we discussed in Section 3.1. We find values ranging from 3×10^{26} ergs s^{-1} to 1.75×10^{28} ergs s^{-1}, with average values of the order of

$$\left(\frac{\mathrm{d}E}{\mathrm{d}t}\right)_{tot} \sim (2 - 8) \times 10^{27} \text{ ergs s}^{-1} , \tag{7}$$

and we shall adopt this number as an estimate of the *lower* bound on the p-mode damping rate in the frequency range of interest (since all alternative accounting techniques we are aware of lead to yet larger values for the damping rate). Compared to a coronal value of $L_{obs} \sim 10^{26}$ ergs s^{-1}, the observed coronal density perturbations could account for about $1.25 - 5\,\%$ of the p-mode damping rate. Using a combination of the maximum observed amplitudes, a high coronal density and a filling factor of $F = 1$, *i.e.* using $L_{obs} \sim 10^{27}$ ergs s^{-1}, compared to a p-mode damping rate of $(\mathrm{d}E/\mathrm{d}t)_{tot} = 8 \times 10^{27}$ ergs s^{-1}, this could be as high as $12.5\,\%$. This high value is based on quite an extreme combination of values but shows that leaking into the overlying atmosphere could account for a significant fraction of the p-mode damping.

4. Discussion

Although traditionally the five-minute solar surface oscillations were assumed to be evanescent in the overlying solar atmosphere, *i.e.* were thought to be fully reflected in the chromosphere and transition region, numerical simulations by De Pontieu, Erdélyi, and De Moortel (2005) confirmed that an inclination of the magnetic field lines reduces the effect of gravity sufficiently to allow the five-minute oscillations to tunnel through into the overlying coronal atmosphere, as suggested by Bel and Leroy (1977). A number of authors have recently confirmed this effect observationally; for example, McIntosh and Jefferies (2006), Jefferies

Table 3. Examples of p-mode amplitudes (percentage of background intensity) observed by various authors in the solar atmosphere. * Temperatures taken from Fludra (2001).

	He I	O V	Mg IX/TRACE 171Å
Temperature (K)*	2.0×10^4	2.2×10^5	9.5×10^9
O'Shea *et al.* (2002) A	4.3 – 4.8	9.9 – 14.9	4.8 – 6.9
O'Shea *et al.* (2002) B	0.8 – 1.4	6.0 – 9.2	2.9 – 9.1
Brynildsen *et al.* (2002)	2.5 – 6.0	7.0 – 16.0	≤3.0 – 5.0
Marsh *et al.* (2003)	**9.8**	**12.4**	**8.6**
Marsh and Walsh (2006)	2.0	4.0	3.0

et al. (2006), Bloomfield *et al.* (2006), and Vecchio *et al.* (2007) all found that propagating waves with frequencies below the traditional "cut-off" frequency exist in the solar atmosphere, with the appearance of the waves intrinsically linked to the value of the plasma β and the inclination of the magnetic field. Additionally, Fontenla *et al.* (1993) and Jefferies *et al.* (2006) point out that the energy flux carried by the observed low-frequency waves (< 5 mHz) is substantially higher than the energy flux contained in the high-frequency waves (> 5 mHz), which have recently been discounted as a heating mechanism for the quiet, internetwork, solar chromosphere (Fossum and Carlsson, 2006).

Clearly, at least part of the energy flux contained in the five-minute p modes makes its way into the overlying solar atmosphere. The estimate in Section 3.2 shows that the observed energy damping rate for five-minute p modes could be of a comparable order of magnitude as the energy flux associated with the observed coronal acoustic disturbances. This appears to corroborate the suggestion of Elsworth *et al.* (1990) and Jefferies *et al.* (1991) that low-degree p modes might experience additional damping (compared to their high-degree counterparts) due to leakage of the mode energy into the overlying atmosphere, by tunnelling through the region of the temperature minimum. Also, Fontenla *et al.* (1993) showed that in the $2-16$ mHz band, an upward energy flux exists in quiet-Sun regions of the order of 2×10^7 ergs cm^{-2} s^{-1} at a height of 50 km, which subsequently decreases to $\sim 1\times10^6$ ergs cm^{-2} s^{-1} at 150 km. Above this height, these authors suggest the energy flux decreases exponentially to $\sim 1\times10^5$ ergs cm^{-2} s^{-1} at 300 km. If we continue this exponential decay with height (taking the base of the corona as $3-4$ Mm), it would lead to a coronal energy flux several orders of magnitude smaller than the energy flux estimated by De Moortel *et al.* (2002a,b) in the lower part of coronal loops. This suggests that the upward energy flux in network regions (where the coronal loops are likely to be anchored) could be significantly higher than the 10^7 ergs cm^{-2} s^{-1} measured by Fontenla *et al.* (1993) in quiet-Sun (internetwork) regions. Indeed, Jefferies *et al.* (2006) find that, at a height of ∼400 km, slow waves travelling along low-β, inclined field lines at the boundaries of convective cells carry an energy of about 1.4×10^6 ergs cm^{-2} s^{-1}.

Unfortunately, very few observations exist of the amplitude of longitudinal perturbations with a periodicity of about five minutes as they propagate upward in the solar atmosphere. Table 3 gives a few examples of observed amplitudes in He I (top of chromosphere - $T\sim2\times10^4$ K), O V (TR - $T\sim2.2\times10^5$ K) and Mg IX or TRACE 171 Å (lower corona - $T\sim9.5\times10^5$ K). However, out of these examples, only Marsh *et al.* (2003) actually observed a five-minute periodicity. The other observations, given for comparison, are of three-minute oscillations observed above sunspots. Note that we have compiled simple averages of the amplitudes given by the various authors at the relevant frequencies ($\sim$ 5.5 mHz), without taking into account error bars or other uncertainties.

Following De Moortel *et al.* (2002a), we can estimate corresponding energy fluxes as

$$F = \rho[(\delta v)^2/2]c_s\,, \tag{8}$$

where the sound speed is taken as $c_s = 166\,T^{1/2}$ m s^{-1} (Priest, 1982), $\delta v = \sqrt{\delta I}$ (δI the observed intensity perturbation), and where the density has been taken as $\rho = 5 \times 10^{-13}$ g cm^{-3}, $\rho = 5 \times 10^{-14}$ g cm^{-3} and $\rho = 1.67 \times 10^{-16}$ g cm^{-3} for the chromosphere, transition region, and lower corona, respectively. At the top of the chromosphere (He I), the estimated energy fluxes are of the order of $(0.4-3.2)\times 10^3$ ergs cm^{-2} s^{-1}, reaching $(0.5 - 1.5) \times 10^4$ ergs cm^{-2} s^{-1} in the transition region (O V) before decreasing to $(1.06 - 3.04) \times 10^3$ ergs cm^{-2} s^{-1} in the lower corona (Mg IX/TRACE 171 Å). Given that the values are just simple averages, obtained by different authors, from observational data from different instruments and from both three and five-minute periods, there is a good (and even surprising!) order of magnitude agreement between the various studies. The flux carried by the three and five-minute perturbations (in sunspot and non-sunspot loops, respectively) are very similar. The coronal estimates of the different authors (Mg IX/TRACE 171 Å) are slightly higher (but of comparable order) than the values observed by De Moortel *et al.* (2002a) and McEwan and De Moortel (2006) (see Table 4). Hence, the comparison provided in this paper is based on coronal flux estimates which are on the lower side of the range of values observed by other authors, again reinforcing the conservative nature of our estimate. Note here that the above calculation is based on the assumption that the intensity perturbations $\delta I/I$ are directly related to $\delta v/c_s$. However, De Pontieu, Erdélyi, and de Wijn (2003) and De Pontieu, Erdélyi, and De Moortel (2005) showed that some of the periodicity seen in TRACE 171 Å (in moss) is due to a periodic obscuration of hot Transition-Region emission by neutral gas inside spicules. As both the He I and O V lines are below the ionisation edge of hydrogen, this periodic obscuration might also be present in the He I and O V measurements, possibly making the assumption that $\delta I/I \sim \delta v/c_s$ less reliable in those cases.

Table 4 gives an overview of the energy flux of various subsets of the data analysed by De Moortel *et al.* (2002a) and McEwan and De Moortel (2006). The data in Table 4 do not seem to show a solar-cycle dependence (solar maximum $\sim$ 2000 – 2001), but as they only cover about half a solar cycle, we cannot be entirely certain that a solar-cycle dependence is indeed absent; it would be instructive to analyse coronal data taken at solar minimum (2006 – 2007) to verify this. Chaplin *et al.* (2000) find that the p-mode energy supply rate ($\mathrm{d}E/\mathrm{d}t$) remains constant (at the level of precision of the observations) during the solar cycle. Komm, Howe, and Hill (2000) note that the solar-cycle variation in the supply rate is both smaller and less significant than the variations in other parameters such as the mode width and energy, suggesting the possibility that the small variations in $\mathrm{d}E/\mathrm{d}t$ could indeed be compatible with a zero change. Hence, the possible lack of a solar-cycle dependence in the estimated coronal fluxes seems to agree with the corresponding suggested lack of a solar-cycle dependence in the p-mode energy supply rate.

Table 4. Perturbation amplitudes (as % of the background intensity) and energy flux (in ergs $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$) for various subsets of the data given by De Moortel *et al.* (2002a) and McEwan and De Moortel (2006).

	Amplitude	Energy Flux $n = 10^9\ \mathrm{cm}^{-3}$
All Data *(av ampl)*	3.8 ± 1.4 $(1.8 - 8.6)$	1066 ± 407 $(507 - 2424)$
All Data *(max ampl)*	6.1 ± 2.5 $(2.8 - 14.6)$	1710 ± 701 $(789 - 4114)$
Sunspot Data *(av ampl)*	3.5 ± 0.9 $(2.3 - 4.9)$	992 ± 265 $(648 - 1395)$
Sunspot Data *(max ampl)*	5.5 ± 1.4 $(3.5 - 7.7)$	1550 ± 398 $(986 - 2170)$
Non-Sunspot Data *(av ampl)*	3.8 ± 1.5 $(1.8 - 8.6)$	1075 ± 419 $(507 - 2424)$
Non-Sunspot Data *(max ampl)*	6.1 ± 2.6 $(2.8 - 14.6)$	1733 ± 732 $(789 - 4114)$
2000 Data *(av ampl)*	3.1 ± 0.8 $(2.3 - 5.7)$	869 ± 228 $(648 - 1592)$
2000 Data *(max ampl)*	5.0 ± 1.4 $(3.5 - 9.4)$	1418 ± 396 $(986 - 2649)$
2001 Data *(av ampl)*	4.8 ± 1.5 $(2.7 - 8.4)$	1347 ± 420 $(747 - 2353)$
2001 Data *(max ampl)*	7.9 ± 2.6 $(3.8 - 14.6)$	2229 ± 743 $(1071 - 4114)$
2003 Data *(av ampl)*	3.4 ± 1.3 $(1.8 - 8.6)$	945 ± 350 $(507 - 2424)$
2003 Data *(max ampl)*	5.1 ± 2.0 $(2.8 - 13.4)$	1451 ± 556 $(789 - 3776)$

However, it is still possible that there might be a solar-cycle dependence of the filling factor used in Equation (2) which could lead to an observable solar-cycle dependence of the observed coronal slow-mode flux, giving independent confirmation that the observed coronal acoustic modes are a consequence of enhanced tunnelling resulting from inclined magnetic flux tubes.

Finally, Komm, Howe, and Hill (2002) find that the p-mode energy supply rate ($\mathrm{d}E/\mathrm{d}t$) does not show a correlation with magnetic activity (unlike the mode energy and lifetime), *i.e.* that the energy damping rates of p modes do not depend on the ambient magnetic field strength. Hence, one might also ask whether there is some dependence in the observed coronal energy fluxes on the magnetic field strength. De Moortel *et al.* (2002a) and McEwan and De Moortel (2006) did not estimate the magnetic field strength of the coronal loops supporting propagating intensity disturbances, and hence, it is not straightforward to evaluate the dependence of the coronal acoustic energy flux on the magnetic-field strength. However, if we assume that the field strength in a sunspot umbra is generally considerably higher than in an active region (and by inference – from simple potential-field extrapolation – that the corresponding coronal fields are substantially larger over sunspots than elsewhere), we might obtain a hint of a possible dependence by comparing the energy flux of perturbations found in sunspot and non-sunspot loops. Looking at both the average and range of values in Table 4 suggests that the energy flux is similar in both loop categories, although an additional complexity is introduced by the fact that the periodicities of these fluctuations are different. Also, we have singled out only one of the many difference between sunspot and non-sunspot regions, namely the magnetic-field strength, whereas in reality, the wave leakage is a complex process, depending on many different factors such as mode coupling, the field inclination, the plasma β,...).

5. Conclusions

In this study, we have determined a conservative estimate of a lower bound on p-mode damping by leakage into the overlying atmosphere. Our relatively simple analysis suggests that a significant (*e.g.*, of order 5%, but possibly more than 10%) fraction of p-mode damping could caused by leakage into the overlying coronal atmosphere. Since our analysis did not take into account the fact that significant energy loss is to be expected in the transition layers between the photosphere and the corona, this fraction may well be a very conservative estimate for the amount of energy drawn from p modes as a consequence of the "tunnelling" phenomenon resulting from the presence of (inclined) surface magnetic flux tubes. Indeed, De Pontieu, Erdélyi, and De Moortel (2005), De Pontieu *et al.* (2007) and Hansteen *et al.* (2006) show that the observed coronal perturbations are actually only remnants of chromospheric shocks (formed by leaking p modes), which drive fibrils or spicule-like jets. Hence, only a small fraction of the original p-mode energy reaches the corona, with other processes such as *e.g.* mode coupling, possibly reducing this fraction even further. The exact nature of the driving mechanism of the observed coronal perturbation is not important in our order of magnitude estimate as the observed coronal flux merely serves as a lower bound on the p-mode damping, but it does reinforce the conservative nature of our values. Additionally, our calculations of the coronal energy flux are based on the assumption of a single harmonic, again ensuring our estimate remains a conservative one, as is the fact that our values for the coronal energy flux are at the lower end of the range of values observed by several other authors.

The "filling" factor used in Equation (2) is unknown but as Jefferies *et al.* (2006) point out, favourable conditions allowing the necessary mode tunnelling might be present at a much larger portion of the solar surface than previously anticipated. As discussed above, the aforementioned "tunnelling" process leading to the observed coronal slow modes is expected to depend on the nature (*i.e.*, strength and inclination) of the ambient filamentary photospheric magnetic fields. Very high angular resolution imaging of these solar surface magnetic fields will in the future establish whether these characteristics have a solar cycle dependence; and if so, one would then expect to see a solar cycle dependence of the observed coronal slow modes. Thus, this line of research has the potential of further constraining the particulars of how the slow modes observed by TRACE in the solar corona are generated.

We also note that since damping of p modes by turbulence is the principal competing mechanism for limiting the amplitude of p modes, and since this type of damping cannot be constrained by direct observations, our analysis also provides a new constraint on turbulent damping not previously identified. Here again, as computational power increases and allows ever-more realistic modelling of turbulent damping, one will be able to invert this line of reasoning, and use computational constraints on turbulent damping to constrain the effects of damping by "tunnelling" (and thus provide an independent test of the tunnelling hypothesis).

Acknowledgements: The authors would like to thank W. Chaplin, B. De Pontieu, and R. Komm for valuable discussion. IDM acknowledges support of a Royal Society University Research Fellowship.

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