Coronal Oscillations above Sunspots?

J.G. Doyle
Armagh Observatory, College Hill, Armagh BT61 9DG, N. Ireland

E. Dzifčáková
Astronomical Institute, Faculty of Mathematics, Physics and Informatics, Comenius University, Mlynská dolina, 842 48 Bratislava 4, Slovakia

M.S. Madjarska
Armagh Observatory, College Hill, Armagh BT61 9DG, N. Ireland
now at: Mullard Space Science Laboratory, University College London, Holmbury St Mary, Dorking, Surrey RH5 6NT

Abstract. Observational data clearly indicate the presence of 3 min oscillations in sunspots in spectral lines covering a vast temperature range from the low chromosphere to those lines normally associated with coronal temperatures. We show that after folding in the sunspot plume emission measure distribution, the contribution functions for lines normally formed just below 1×10^6 K are shifted to lower temperatures. For example, the Fe IX 171 Å line is shifted to 6×10^5 K for a Maxwellian distribution and to less than 5×10^5 K with a non-Maxwellian distribution. Other lines such as Mg IX 368 Å will also be effected. This then questions some previous work regarding the suggested detection of 3 min oscillations in the corona above sunspots.

Keywords: Sun: Transition region–Ultraviolet: SoHO–Sun: Sunspots: coronal oscillations: Non-Maxwellian: Kappa distribution.

1. Introduction

Using ultraviolet data from the Solar Maximum mission for emission lines formed at temperatures of 7×10^4 K to 1.3×10^5 K, Gurman *et al.* (1982) observed transition region oscillations in sunspots with frequencies in the range of 5.8-7.8 mHz. Their in-phase intensity and velocity oscillations lead them to interpret the oscillations in terms of upward propagating acoustic waves. Thomas *et al.* (1987) detected simultaneously umbral oscillation at different heights, starting from the chromosphere through to the transition region.

With the launch of SoHO there has been renewed interest in the study of umbral oscillations. Fludra (1999, 2001) investigated 3 min intensity oscillations with the Coronal Diagnostic Spectrometer (CDS) by observing the chromospheric line He I and several transition region lines. He concluded that the 3 min umbral oscillations can occur both in sunspot plumes and in the lower intensity plasma closely adjacent to the plumes. He found the spectral power to be contained in the 5.55-6.25 mHz range.

SUMER observations (in both intensity and velocity) have confirmed that the sunspot oscillations are prominent in transition region lines above the umbra (Maltby *et al.* 2001). Support for the acoustic wave hypothesis was presented by Brynildsen *et al.* (1999a,b). They observed oscillations in intensity and velocity to test the hypothesis and found the oscillations to be compatible with upwardly propagating waves.

More recently O'Shea *et al.* (2002) and Brynildsen *et al.* (2002) have both presented joint observations of the 3 min umbral oscillations with TRACE and CDS. O'Shea *et al.* (2002) found oscillations at all temperatures from the temperature minimum, as observed in the TRACE 1700 Å filter up to the upper corona, as measured by the Fe XVI 335 Å line with CDS. Both these papers report that the oscillation amplitude above the umbra increases with increasing temperature, reaches a maximum in the transition region and decreases for higher temperature lines, although O'Shea *et al.* (2002) finds evidence for another increase in amplitude for lines formed above 1 MK. No oscillations were detected by Fludra (1999,2001) in the Mg IX 368 Å line, suggesting that the 3 min oscillation did not propagate into the corona in this particular sunspot.

O'Shea *et al.* (2002) interpreted their observations in terms of slow magneto-acoustic waves propagating upwards (as confirmed from their time delays) along magnetic field lines. However, O'Shea *et al.* (2002) noted that in one particular instance their Mg IX data suggested a downward propagation while the higher temperature lines of Mg X 625 Å and Fe XVI 335 Å again suggested upward propagation. Maltby *et al.* (2000) noted the presence of 3 min. oscillations in TRACE 171 Å data. These oscillations were at the 2% level and the authors concluded that the O VI 173 Å lines were not sufficiently strong to be the source of the variability and that the oscillations were from the sunspot plume and were coronal in origin. It is therefore clear from the observational database that sunspots show a 3 min. oscillation in the spectral lines, including those normally associated with coronal temperatures. The question we wish to address is whether some of these hotter lines are formed in the corona or may they be formed at transition region temperatures.

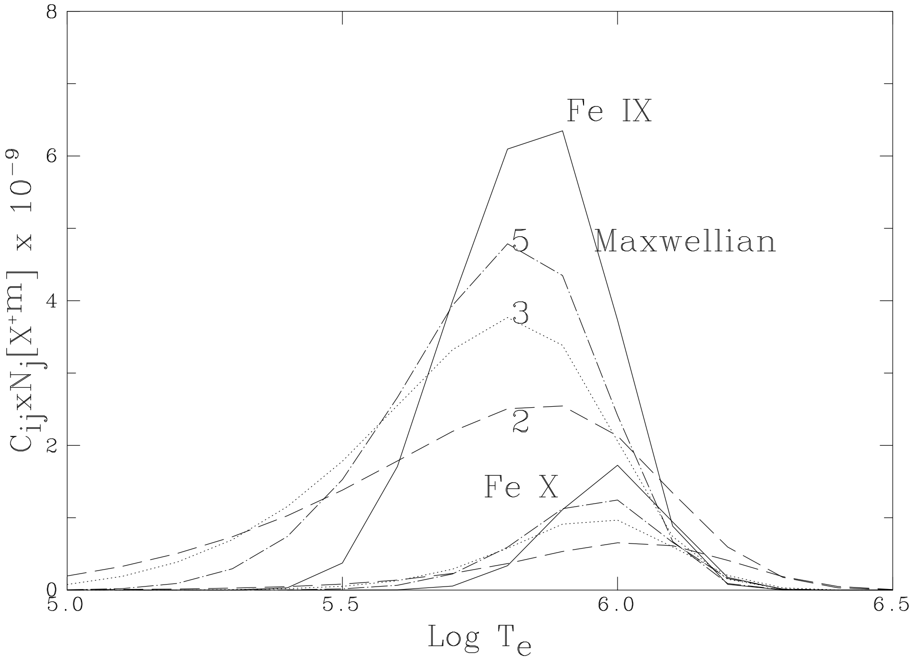

Figure 1. The contribution function (i.e. ionization fraction times the electron excitation rate) for Fe IX 171 Å and Fe X 174 Å for a Maxwellian electron velocity distribution (solid line) and for a Non-Maxwellian with $\kappa = 2$ (dashed line), 3 (dotted line) & 5 (dashed-dotted line).

2. Non-Maxwellian Electron Distributions

Under ideal thermal equilibrium conditions the electron distribution in a plasma follows a Maxwellian distribution as commonly assumed in the analysis of most solar spectroscopic data. However, non-Maxwellian distributions with an enhanced high-energy tail can occur as a result of high temperature gradients or particle concentration (Owocki & Scudder 1983, Scudder 1992). Both of which is possible in the solar transition region and/or between cool loops and the surrounding hot coronal plasma.

A convenient parameterization of a non-Maxwellian distribution is the so-called Kappa distribution,

$$f_\kappa(E) = \frac{2\sqrt{E}}{\sqrt{\pi}(kT)^{3/2}} A_\kappa / \left(1 + \frac{E}{(\kappa - 3/2)kT}\right)^{\kappa+1} \tag{1}$$

where T is the temperature, k the Boltzmann constant and A_κ is given in terms of Gamma functions so that

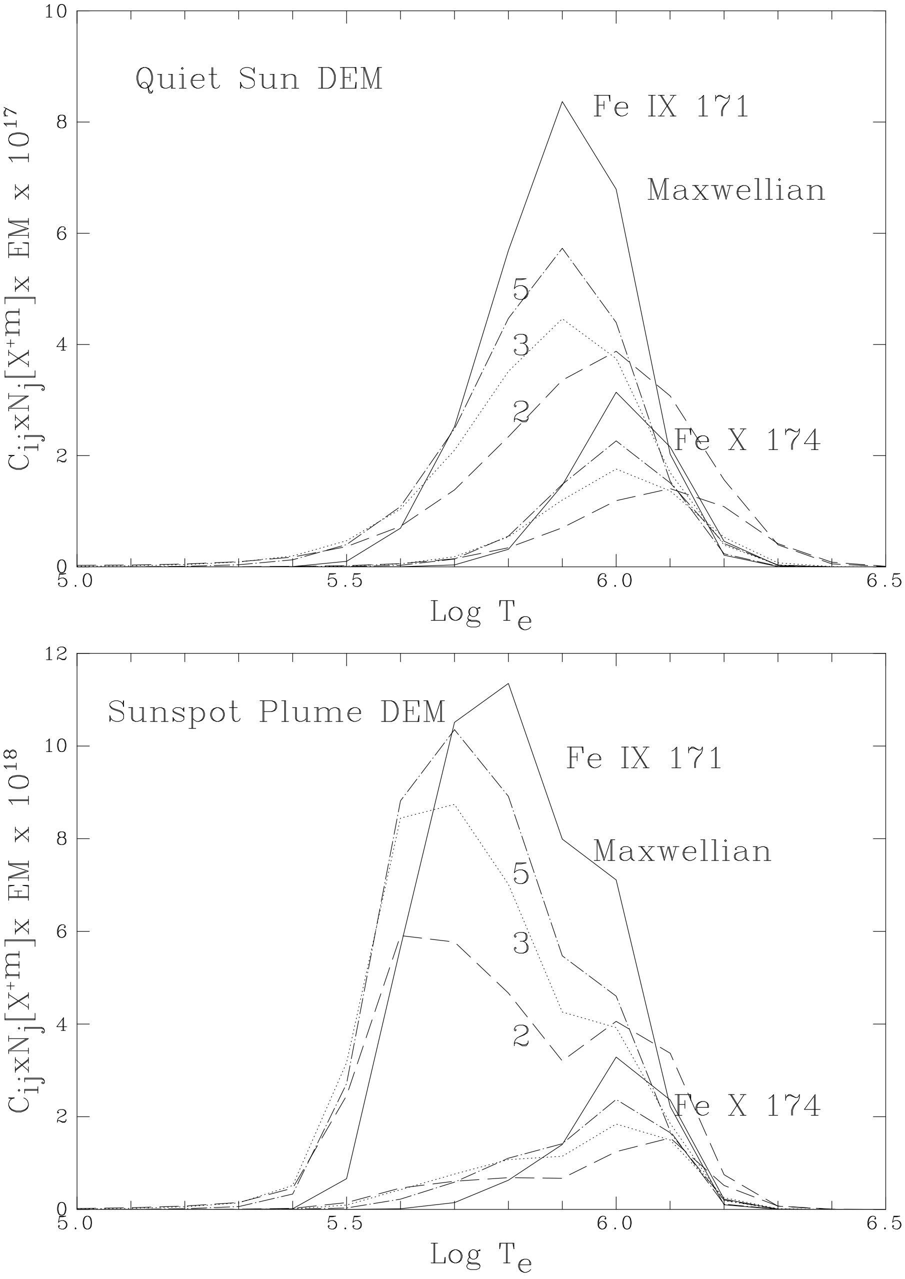

Figure 2. The contribution function (i.e. ionization fraction times the electron excitation rate times the emission measure curve) for the quiet sun and for a sunspot plume) for Fe IX 171 Å and Fe X 174 Å for a Maxwellian electron velocity distribution (solid line) and for a Non-Maxwellian with $\kappa = 2$ (dashed line), 3 (dotted line) & 5 (dashed-dotted line).

$$A_\kappa = \frac{\Gamma(\kappa+1)}{\Gamma(\kappa-1/2)(\kappa-3/2)^{3/2}}. \tag{2}$$

This parameterization represents the Maxwellian distribution at low energy while the parameter κ controls the steepness of the power-law tail, hence, as $\kappa \to \infty$, the overall distribution becomes Maxwellian.

Using this distribution function, Dzifčáková (2002) presented ionization fractions for several Fe ions while Wannawichian *et al.* (2003) give ionization fractions for all ions from C up to Ni.

In Fig. 1 we plot the contribution functions (i.e. the product of the ionization fraction times the electron excitation rate coefficient) for Fe IX 171 Å and Fe X 174 Å. We can clearly see from this figure that with a non-Maxwellian distribution, a fraction of the Fe IX 171 Å line and to a lesser extent, Fe X 174 Å, is formed at transition region temperatures. In the next section, we look at the effect of introducing a suitable sunspot emission distribution.

3. Discussion

Various authors (e.g. Noyes *et al.* 1985, Doyle *et al.* 1985, Brynildsen *et al.* 2001) have all shown that the transition region lines and hence the emission measure from this region is enhanced by an order of magnitude in sunspot plumes. Thus with the contribution functions shown in Fig. 1, a large fraction of the Fe IX 171 Å line (and other lines normally formed just below 1 MK) may be shifted to much lower temperatures. In Fig. 2 we show the effect of folding in the quiet sun emission measure distribution of Raymond & Doyle (1981) compared to using the sunspot plume emission measure distribution of Doyle *et al.* (1985). Here, we see that the Fe IX 171 Å line is shifted to 6×10^5K for a Maxwellian distribution and to less than 5×10^5K with a non-Maxwellian distribution. The Fe VIII lines around 168 Å will also be significantly enhanced. For the sunspot EM used here, this amounts to a factor of ≈30 enhancement. However, this will have a minimum effect in the TRACE 171 Å filter as the sensitivity drops significantly at these wavelengths.

This then questions whether all of the observed oscillations seen in TRACE 171 Å data (Maltby *et al.* 2000) and Mg IX 368 Å (O'Shea *et al.* 2002) is actually coronal in origin. In a dataset analyzed by O'Shea *et al.* (2002), they noted that at a particular location, the time delay between Mg IX and Mg X changed dramatically, indicating at first sight a downward propagating wave in contrast to all other spectral lines, which indicated upward propagation. We suggest that this is because the Mg IX line at this location has both a transition region and a coronal contribution. This therefore means that in order to investigate the propagation of waves, one should have a large selection of spectral lines covering a very wide temperature range. This does not mean that all coronal lines are effected in a similar manner, for example, O'Shea *et al.* (2002) have shown the existence of oscillations in higher temperatures lines (e.g. Mg X 625 Å and Fe XVI 335 Å) which would not be shifted to transition region temperatures with either a non-Maxwellian velocity distribution or due to the shape of the emission measure distribution in the transition region, and thus are coronal in origin.

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