X-RAY QUASI-PERIODIC PULSATIONS IN SOLAR FLARES AS MAGNETOHYDRODYNAMIC OSCILLATIONS

C. Foullon¹, E. Verwichte¹, V.M. Nakariakov¹, and L. Fletcher²

¹Department of Physics, University of Warwick, Coventry CV4 7AL, UK
²Department of Physics and Astronomy, University of Glasgow, Glasgow G12 8QQ, UK

ABSTRACT

In Foullon et al. (2005), we reported the first observation at high spatial resolution of long-period (8-12 min) quasi-periodic pulsations (QPP) of X-ray radiation during solar flares, made possible with the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI), supported by complementary data at other wavelengths from space-based and ground-based telescopes. Evidence for the presence of a transatorial loop possibly responsible for the detected periodicity connected with its kink mode is found. Our findings suggest that QPP can be interpreted as a periodic pumping of electrons in a compact flaring loop, modulated by oscillations in a magnetically linked and larger loop acting as a long-period magnetohydrodynamic resonator.

Key words: Sun: corona – flares – oscillations – X-rays, gamma rays.

1. INTRODUCTION

Solar flares with ‘quasi-periodic pulsations’ (QPP) in their emissions have been known since the early 1970s. With RHESSI, we can now investigate the origin of QPP in X-rays with better spatial and temporal resolution than ever achieved before.

QPP have periods ranging from fractions of seconds to several minutes. In the 80s, the coarse images from the Hard X-ray Imaging Spectrometer on the Solar Maximum Mission indicated that long periods (12-29 min) were seen to originate at the foot of, or below, large-scale coronal loops (Švestka et al. 1982; Harrison 1987). Similar phenomena exist in stellar flares, where no spatial resolution is available.

Figure 1. QPP on February 5-6 2003: a) QPP1 and b) QPP2. Full disk measurements in X-rays from GOES-8 (1-8 Å and 0.5-4 Å) and RHESSI (3-6 keV, 6-12 keV and 12-25 keV). The vertical dashed lines indicate the peak times of the flares, as seen by GOES 1-8 Å.
2. FIRST OBSERVATIONS OF LONG PERIODS AT HIGH SPATIAL RESOLUTION

On February 5-6 2003, two sequences of QPP of large-amplitude and with periods around 8-12 min were recorded by RHESSI (see Fig. 1). These new events were investigated by Foullon et al. (2005); see also Foullon (2005). Supported by complementary data at other wavelengths from space-based and ground-based telescopes, they give us a number of extra clues to understand what is happening.

Each of the two sequences of QPP originates from the top of a small flaring loop. But the two sequences do not originate from the same region. Two principal active sources are present: one in the Northern hemisphere (first QPP), and one in the Southern hemisphere (second QPP).

3. POSSIBLE MHD RESONATOR: TRANSEQUATORIAL LOOP

The quasi-periodic variations may be interpreted as some periodic pumping, or other energisation, of electrons in the flaring loop, modulated by MHD oscillations (Roberts et al. 1983, 1984). The length-scale of the loop, though, cannot explain such long periods as the largest period of a wave that could be sustained by one of the flaring loops in either region A or region B, the fundamental period of a slow magnetoacoustic standing mode, would not exceed 100 s (with a loop length of up to 22 Mm and temperature of 10 MK). Therefore we suppose that the modulation of the flaring emission is due to MHD oscillations in a magnetically linked, larger resonating loop. Several clues suggest the presence of a large-scale transequatorial loop connecting the two oscillating regions:

- the long periods, explained in terms of magneto-hydrodynamic (MHD) oscillation modes of a large-scale loop;
- the similarity of periodicities found at opposite sites;
- for each QPP, some aperiodic sympathetic activity observed in the oppositely located and quieter region;
- evidence of the transequatorial loop in the EUV.

4. MOST LIKELY CANDIDATE: FAST MAGNETO-AcouSTIC MODE

Several aspects are consistent with fast magneto-acoustic modes observed by the Transition Region And Coronal Explorer (TRACE) instrument (Aschwanden et al. 1999; Nakariakov et al. 1999; Verwichte et al. 2004):

- the phase speeds (between 1400 and 2500 km/s for a loop length estimated to be 500-600 Mm and periods found of 8-12 min);
- the weak damping;
- the response to a dynamic event (flare, filament eruption and CME).

The fast magnetoacoustic kink mode is also an attractive option, as it perturbs the magnetic field lines in the transverse direction, and in turn may compress the field lines of the flaring loop (see Fig. 2). In turn, the periodic oscillations of magnetic field causes the plasma in the flaring loop to be successively compressed and expanded, modulating the particle acceleration process. Magnetic pumping (also called betatron acceleration) is one possible mechanism (Brown & Hoyng 1975).

Finally, the monotonic change of the periods in the QPP might be accounted for by changes in the coronal environment immediately after or before the eruptions. In a long wavelength and cold plasma approximation, the period of the fast magnetoacoustic kink fundamental mode
is (Edwin & Roberts 1983)

\[ P \sim \frac{2L}{C_k} \sim \frac{\sqrt{2(\rho_0 + \rho_e)\mu_0}}{B_0} L, \]  

(1)

for a loop of length \( L \) modelled as a straight cylinder, with internal magnetic field \( B_0 \) and density \( \rho_0 \) and external density \( \rho_e \); \( C_k \) is the kink speed and \( \mu_0 \) is the magnetic permeability. An increase in period would either indicate a decrease in magnetic field strength, an increase in density or an increase in oscillating loop length, and vice-versa. Any of these changes in the transequatorial loop associated with a large-scale coronal eruption are plausible.

5. OTHER POSSIBILITY: SLOW STANDING MODE?

If the observed modulations were caused by another MHD mode, the slow magnetoacoustic mode, then the transequatorial loop would need to have an unrealistic temperature for a quiescent coronal loop. It is conceivable that medium-size loops might be the acoustic resonators providing the periodicities in question.

Similar long periods have been observed off the solar limb, in 27 flare-like events, with periods between 7 and 31 min, in the coronal emission lines Fe XIX (6.3 MK) and Fe XXI (8.9 MK) from the Solar Ultraviolet Measurements of Emitted Radiation (SUMER) spectrograph on SOHO (Wang et al. 2003). However the causal configuration in SUMER events, where the initial injection of hot flows at one footpoint from a magnetically connected small flaring loop excites the slow mode waves in a bigger loop (Wang et al. 2005), is the exact inverse of the present situation (i.e. something drives externally the small flaring loop). Besides, it is not clear how a basically longitudinal mode present in the large loop could modulate the emission of the smaller, flaring loop.

However, in the absence of spectroscopic and high-cadence EUV imaging data, we had to draw conclusions indirectly, based upon the observed loop structures, oscillation characteristics, wave theory and phenomenology. As a result other interpretations involving in particular the slow standing MHD mode cannot be entirely ruled out.

6. CONCLUSIONS

These findings suggest that QPP can be interpreted as a periodic pumping of electrons in a compact flaring loop, modulated by oscillations in a magnetically linked and larger loop acting as a long-period MHD resonator.

This study links together solar flare pulsations and a MHD kink oscillation that has been widely exploited in recent years through coronal seismology. Such studies, resolving QPP on the solar disk with RHESSI, combined with complementary data at other wavelengths, in particular high-resolution EUV images from instruments such as TRACE or the future EIS/Solar-B, have the potential to provide remote diagnostics of solar plasma and broaden our understanding of physical processes operating in solar and stellar flares.

ACKNOWLEDGMENTS

C.F. gratefully acknowledges the organisers for the financial support offered to attend the Chromospheric and Coronal Magnetic Fields workshop, and the hospitality and support from the Space and Astrophysics Group at the University of Warwick. E.V. acknowledges UK Particle Physics and Astronomy Research Council (PPARC) support. V.M.N. acknowledges the support of a Royal Society Leverhulme Trust Senior Research Fellowship. L.F. acknowledges the support of a PPARC Short-Term Research Visitor Grant.

REFERENCES

Foullon, C. 2005, RHESSI and quasi-periodic pulsations, RHESSI Science Nuggets, 05.08.16, URL: http://sprg.ssl.berkeley.edu/~tohban/nuggets/