Astrophysical Implications of Magnetoacoustic Autowaves in Thermally Unstable Plasmas

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Abstract

The formation and evolution of magnetoacoustic autowaves in thermally unstable plasmas is discussed, with particular reference to solar and stellar flares. The competition of thermal overstability, thermal conductivity and radiative losses leads to self-organisation of weakly nonlinear magnetoacoustic perturbations into dissipative structures with the parameters independent of the initial perturbation. This evolution is modelled in terms of the extended Burgers equation. The properties of the autowaves are expressed through the plasma parameters such as the magnetic field, plasma temperature and density. The autowaves are saw-tooth shaped waves, with an eventual amplitude that depends upon the balance between the amplification due to radiative losses and decay due to thermal conductivity. Increased dissipation due to thermal conductivity or stronger non-linearity leads to a lower amplitude, while stronger thermal instability leads to a higher final amplitude. X-ray, white light and radio band observations and numerical simulations of flaring loops show quasi-periodic pulsations during the flares. These pulsations are standing acoustic waves (primarily the second harmonic) and show little decay over a number of periods despite the large theoretically predicted damping due to thermal conductivity. It is suggested that these waves are magnetoacoustic autowaves.

1 Introduction

An autowave is a wave that has some properties (amplitude, period, velocity) which are determined not by the excitation mechanism but by the properties of the medium through which it propagates. The extended Burgers Equation can be derived from the MHD equations which predicts the existance of autowaves as the result of competition between amplification due to thermal instability and damping due to thermal conductivity. The amplitude of these oscillations is determined by the relative strengths of the thermal conductivity and radiative loss terms.

Long period intensity oscillations have been observed in association with solar and stellar flares. X-Ray observations show long period oscillations in the range of 20s to 25 minutes. Examples can be seen in Harrison (1987), McKenzie and Mullan (1997) and Terekhov et al. (2002). Similiar periodicities have been reported in the decimeter and microwave bands. For example, Wang and Xie (2000) observed oscillations with periods of around 50 s in at 1.42 and 2 GHz. Mathioudakis et al. (2003) studied a Solar Flare on Peg II and reported an intensity oscillation with a period of 220 s. It is possible that that the 160 s oscillation observed on Ad-Leonis reported by Houdebine et al. (1993) and the 26 s and 13 s oscillations reported by Zhilyaev et al. (2000) have the same nature.

Nakariakov et al. (2004) performed numerical studies of flaring coronal loops. It was shown that the observed oscillations could be interpreted as second harmonic standing acoustic waves. This paper extends the work done in that study, and discusses the evidence that the oscillations seen in simulated loops are auto-oscillations.

2 Magnetoacoustic Autowaves

Given the MHD equations including terms for thermal conductivity and radiative losses an extended Burgers Equation can be derived. This is an evolutionary equation. The derivation is given by Kelly and Nakariakov (2004) and the equation is

$$\frac{\partial V_z}{\partial \tau} + \mu V_z + \nu \frac{\partial^2 V_z}{\partial \xi^2} + \epsilon V_z \frac{\partial V_z}{\partial \xi} = 0. \tag{1}$$

The three coefficients μ, ν and ϵ in the equation represent the amount of radiative losses, thermal conductivity, and non-linearity respectively. ν is negative, ϵ is positive and μ can be either positive or negative. $\nu < 0$ corresponds to a thermal instability. A phase diagram of the ordinary differential equation

$$\nu \frac{d^2 V_z}{d\xi^2} + \epsilon V_z \frac{dV_z}{d\xi} + \mu V_z = 0, \tag{2}$$

shows the existance of closed loops (stationary solutions) when ν is less than zero. Physically these are solutions for which amplification, damping and non-linearity balance and the wave does not change. Numerical studies show that an arbitrary sine wave will evolve to one of these solutions. The amplitude of the selected solution does not depend upon the input wave, but upon the values of the three coefficients.

3 Simulations of Flaring Loops

A flaring loop is modelled numerically using a one-dimensional hydrodynamic simulation. The simulation domain consists of a corona of hot, low density plasma with dense sources cool material at each end. The model includes the effects of gravitational stratification, thermal conduction, radiative losses, added external heat input, the presence of helium, non-linearity and Braginskii bulk viscosity. The radiative loss function is that given by Rosner et al. (1978) extended to a wider temperature range.

A flare is modelled using the external heat input function. When heat is applied the loop draws plasma from the foot points, and then as the loop cools the plasma falls back down. Oscillations are observed in the loop during this process. Figure 1 shows time series and wavelet transform for a 333 second flare. The wavelet transform shows two phases, in the first

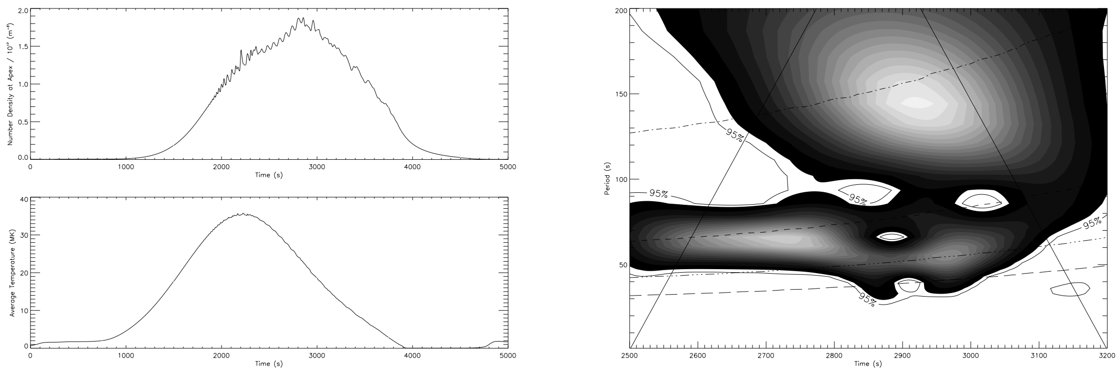

Figure 1: (left) The evolution of density at the loop apex and average temperature. (right) A wavelet transform of the density at the apex timeseries showing various harmonics.

the second harmonic is dominant and then later the first and third harmonics are seen. This is one example from a range of simulation results. The second harmonic is the most commonly observed mode.

The oscillations are seen to persist over several periods with no significant damping. However, the theoretically predicted effect of thermal conductivity should be to damp the oscillations very quickly. It appears that some other effect is acting to balance the damping. When the radiative loss term is switched off the oscillations do not appear. With an increased loss term the amplitude is larger. This shows that thermal instability is responsible for balancing thermal conductivity, exactly as predicted by autowave theory. The final piece of evidence is that oscillations disappear suddenly after a certain time. This can be understood as the instability is switched off below a certain temperature.

4 Conclusions

Long period oscillations observed during stellar and solar flares may be explained in terms of acoustic oscillations of coronal loops, with the second harmonic being the dominant mode. In order to explain the observed absence of strong damping it is necessary to invoke an autowave interpretation. This properties of the oscillations fit this interpretation well. However, the theory developed for propagating waves cannot be applied directly to standing waves, and more theoretical work is necessary to fully explain these oscillations.

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