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HEATING AND MASS TRANSFER IN SOLAR AND STELLAR ATMOSPHERES BY TURBULENT ALFVĒN WAVES

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ABSTRACT: We examine the possibility that turbulent Alfvēn waves, created in the upper transition region or lower corona, can be the principal source of the heating of solar and stellar coronae, and the origin of solar and stellar winds. The model avoids the general problem of energy transfer of waves through the photosphere and chromosphere. We show that energy fluxes of $\sim 10^6$ ergs/cm^2-s and power law spectra in phase space $W(k) \propto k^{-\beta}$ for the turbulent Alfvēn waves ($\beta \sim 0$ (white noise) to $\beta \sim 3.5$ (Kolmogorov spectra)), and reasonable values for the density and magnetic fields for the atmosphere, produce observed coronal temperatures ($\sim 10^6$ K) and ejection velocities ($\gtrsim$ 100 km/s). When the heating is impulsive, as in solar flares, the predicted time interval between the hard X-ray burst and the microwave burst is $\sim$0.1 - 1 second, as observed.

Key words: solar and stellar atmosphere, Alfvēn waves, turbulence

I. INTRODUCTION

It is well known that the solar corona has a temperature of the order of 1 million degrees, and that magnetic fields play an important role in the heating of the corona (Vaiana and Rosner 1978). One of the main mechanisms of energy input to the chromosphere and corona is generally assumed to be the dissipation of MHD or acoustic waves (Withbroe and Noyes 1977). Recent evidence on the heating of stellar coronae and the production of stellar winds indicate the possible importance of Alfvēn waves.

Already energy fluxes of the order of 10^5 ergs/cm^2-s in the solar corona imply nonlinear waves in the photosphere and lower chromosphere and these waves should be strongly damped in these regions (Osterbrock 1961; Parker 1960). It is thus probable that an energy flux of more than 10^5 ergs/cm^2-s

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(which is required to heat the solar corona) cannot be transported upward from the photosphere or chromosphere and must arise, at least in part, from the generation of waves in the transition region or the lower corona (Leer et al. 1982).

It is generally assumed that the addition of energy to the solar wind above the coronal base is required to accelerate the wind to speeds of more than 600 km/s at 1 A, and a prime candidate for this are Alfvēn waves (Leer et al. 1982). It has also been suggested that Alfvēn waves might play an important role in driving winds in late-type giant and supergiant stars, that frequently exhibit cool massive stellar winds (Cassinelli 1979). Similarly, Alfvēn waves have also been suggested for driving winds in hot stars (Underhill 1983).

Alfvēn waves can also possibly be responsible for the observed delay in solar flares of the microwave pulse with respect to the X-ray pulse $\lesssim 1$ second (Hoyng et al. 1981; Marsh and Hurford 1980; Marsh et al. 1980; Kundu et al. 1981; Kundu et al. 1982; Kundu 1983).

We investigate here the effects of turbulent Alfvēn waves on coronal heating and mass ejection in stellar and solar atmospheres, and the energy transfer in solar flares. In the model, a quasi-continuous production of turbulent Alfvēn waves, with a power law spectrum, is responsible for the heating of the corona and mass ejection, while an impulsive production of turbulent Alfvēn waves produces flares.

We evaluate the increase in temperature ΔT as a function of: 1) the distance S from the turbulent source; 2) the value of the spectral index β; 3) the magnetic field and its gradient in the arc; and 4) the density and its gradient. We apply the model to mass transfer in open field lines (e.g. coronal holes) and evaluate the velocity $\bar{V}$ of the ejected matter as a function of the distance S from the source of the turbulent Alfvēn waves.

In section II we discuss some general properties of turbulence and in section III possible sources of turbulent Alfvēn waves. In section IV we describe the simplified models used and give our results.

II. TURBULENCE

Theoretical analysis of turbulence indicate that the spectrum of turbulent Alfvēn waves has a power law dependence in phase space

$$W(k) \propto k^{-\beta}$$

where k is the Alfvēn wave number, β is the spectral index, and

$$\int W(k)\ 4\pi k^2\ dk$$

is the energy density of turbulent Alfvēn waves.

The value of the spectral index β is determined by the type of turbulence. For a time-independent noise source which reaches steady-state with damping processes, the value $\beta = 2$ was obtained by De Groot and Katz (1973) and $\beta = 0$, a white noise spectrum, was obtained by Kainer et al. (1972).

A different turbulent Alfvēn wave spectrum, which can be called "eddy-turbulent Alfvēn waves", is produced if the origin of the Alfvēn waves are eddies. For large Reynolds numbers ($R_e \sim 10^5 - 10^6$) we have energy transfer from large to small eddies (Kolmogorov 1941; Cantwell 1981). The cascade extends down from the Taylor scale $l_T \simeq l_o (15/R_e)^{1/2}$, which is the transition from large-scale ordered turbulence to small scale disordered motion (Cantwell 1981), where l_o is the dimension of the turbulent region and R_e is the Reynolds number. For eddies of dimension $l < l_T$ we have the energy spectrum $W(\kappa) = \kappa^{-m}$ where $\kappa = 2\pi/l$. For Kolmogorov (1941) turbulence we have $m = 5/3$. The eddies generate Alfvēn waves (Kulsrud 1955; Kato 1972) similar to the production of sound waves (Lighthill 1952) with $\beta = 3.5$ for the Kolmogorov spectrum, for example. For this type of turbulence the value of β is between $\sim 2 - 3.5$ (Kolmogorov 1941; Cantwell 1981; Eilek and Henriksen 1984; Kulsrud 1955; Kato 1972).

III. SOURCES OF TURBULENT ALFVEN WAVES

There are various possible sources of turbulent Alfvēn waves in the corona. Some of them are shown in Figs. 1, 2 and 3. In Fig. 1 we see a result of the constant twisting of magnetic field lines. Alfvēn and Falthammer (1963) showed that this configuration is unstable. The magnetic lines in the loops eventually form magnetic islands by the tearing mode instability, and then annihilate. Recent observations indicate the existence of this process (Kundu et al. 1982; Velusamy and Kundu 1982). In general, the formation of magnetic islands and magnetic field annihilation are associated with the formation of turbulent regions and these regions can produce Alfvēn waves.

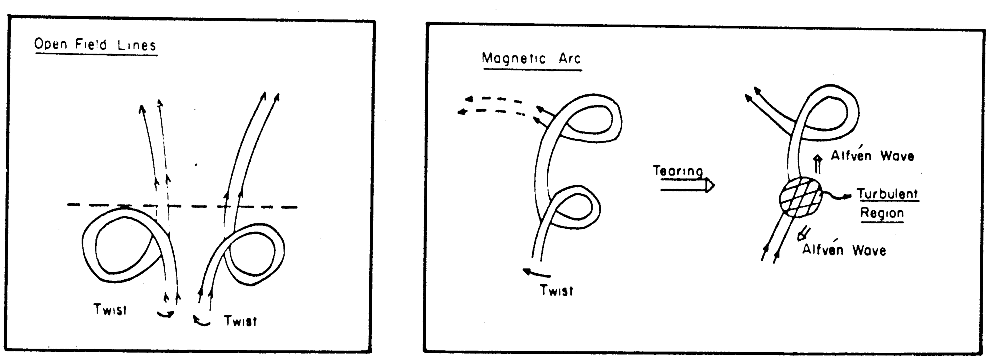

Fig. 1 Instability of Twisted Field Lines

In Fig. 2 we have the encounter of an emerging magnetic dipole with an overlying older magnetic arc of opposite direction (e.g. Kundu et al. 1982; Kundu et al. 1984) as a possible source of turbulent Alfvēn waves.

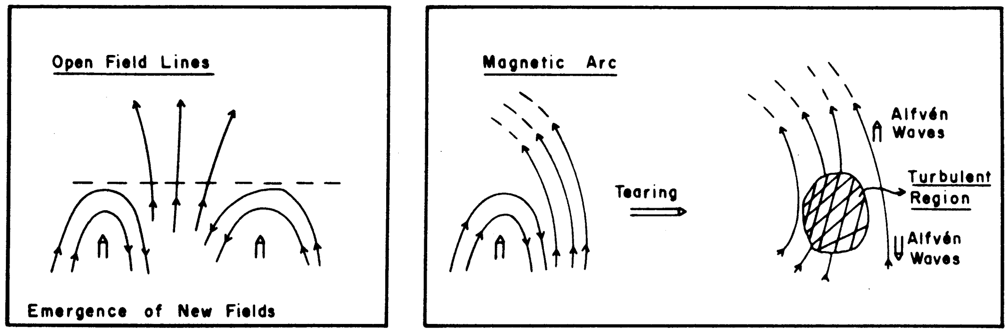

Fig. 2 The Emergence of New Fields

In Fig. 3 we have the commonly called "Petschek Mechanism" as another possible source of turbulent Alfvēn waves.

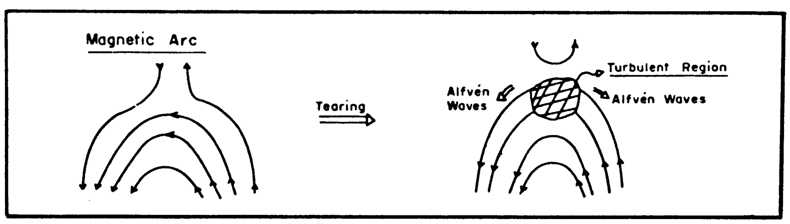

Fig. 3 The Petschek Mechanism

IV. SIMPLIFIED MODELS AND THE RESULTS

In our simplified heating model, (Fig. 4), we evaluate the increase in temperature ΔT as a function of the distance S from the source of the turbulent Alfvēn waves.

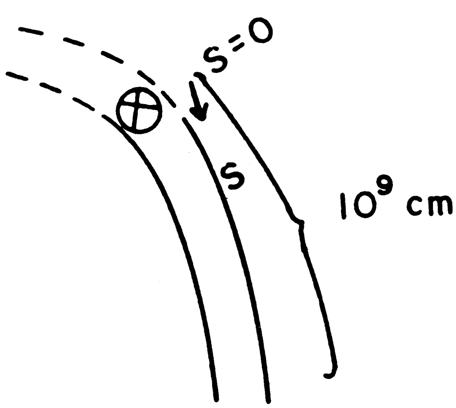

Fig. 4 The Heating Model

We assume that the turbulent Alfvēn waves have a power law spectrum in phase space, with the spectral index $0 \leq \beta \leq 3.5$. We use an average flux of turbulent Alfvēn waves $\sim 10^6$ ergs/cm^2-s. The source of turbulent Alfvēn waves is at S = 0 and while they are propagating towards the feet of the arc they are absorbed by the plasma, which is consequently heated. This kind of structure, where the top of the arc is not necessarily the hottest point, is in agreement with recent observations (Shevgaonkar and Kundu 1984). The damping of turbulent Alfvēn waves is due to collisions (Kaplan and Tsytovich 1973) and Landau damping (Krall and Trivelpiece 1973). We have

$$\gamma(\text{absorption}) = \gamma(\text{coll. e, i, n}) + \gamma(\text{Landau})$$

where γ(coll. e, i, n) is the damping rate due to collisions between electrons, ions and neutral atoms. The best available data was used to evaluate γ(coll. e, i, n). The maximum possible wave number of a turbulent Alfvēn wave is ω_{ci}/V_A, where ω_{ci} is the ion cyclotron frequency and V_A is the Alfvēn velocity. The minimum wave number for "eddy turbulence" ($2 \leq \beta \lesssim 3.5$) is $2\pi/l_T$, where $l_T \simeq l_o \times (15/R_e)^{1/2}$. Using $l_o \sim 10^7$ cm and $R_e \sim 5\times10^5$ we obtain typical values of $\sim 1/4 \times \omega_{ci}/V_A$. For "noise turbulence" ($0 \leq \beta \leq 2$) we use the minimum wave number $2\pi/10^7$.

For a flare, we assume a pulse of turbulent Alfvēn waves of duration Δt much smaller than the characteristic cooling time. We use a flux of Alfvēn waves $F = 10^6$ ergs/cm^2-s and a pulse duration $\Delta t = 1$ second. Since the increase in temperature ΔT is proportional to $F\Delta t$, our results in Figs. 5 - 8 for ΔT can be scaled by the factor $F\Delta t(s)/10^6$.

Our simple model is applied to the steady state conditions of a corona by assuming that the corona consists of a network of magnetic arcs in which the heating of the magnetic arc studied represents average physical conditions of the corona. Then the average ΔT of the magnetic arc studied is the average temperature of the corona. For steady state conditions we assume an average flux of $F = 10^6$ ergs/cm^2-s and an average cooling time $\tau \simeq 1$ second. The average ΔT of Figs. 5 - 8, $\overline{\Delta T} \sim 10^6$ K, is then the average temperature of the corona. Since $\overline{\Delta T}$ is proportional to $F\tau$, the average ΔT in our model is found to be $\overline{\Delta T} \simeq F\tau$.

The simple model of a flare used is the following. The turbulent regions in Figs. 1 - 3 produce $\sim$ relativistic electrons and turbulent Alfvēn waves. The $\sim$ relativistic electrons travel along the magnetic arc near the speed of light, c, and produce the X-ray pulse at the feet of the arc. The turbulent Alfvēn waves travel at the slower Alfvēn velocity, V_A, heat the arc, and produce the microwave pulse. The time delay between the X-ray and microwave pulses is $\sim L(V_A^{-1} - c^{-1}) \simeq L/V_A$, where L in our model is $\sim 10^9$ cm.

For the density and the magnetic field of the arc, and their gradients, we use the expressions

$$n(S) = n_T \left[1 + (k_n/L)\, S\right]$$

where n_T is the density near the source of turbulent Alfvēn waves and L is the total height of the arc. We use $n_T = 10^8$ cm^{-3}, $L = 10^9$ cm, and

$$B(S) = B_T \left[1 + (k_B/L)\, S\right] ,$$

where B_T is the magnetic field near the source of turbulent Alfvēn waves.

For different values of k_n/L and k_B/L, we evaluate the increase in temperature as a function of S. The results are shown in Figs. 5 and 6. We also evaluate the time of arrival of Alfvēn waves. In Figs. 5 and 6 we note the time of arrival t_A at $S = 10^9$ cm.

We note that the VLA array of radio telescopes, in particular, is highly sensitive and has a spatial resolution sufficient to observe the propagation of pulses of turbulent Alfvēn waves described above. If it would operate with a time resolution ~ 0.1 seconds, it would then be capable of observing ΔT as a function of S and t in a solar flare, which could be then compared with the predictions of this paper.

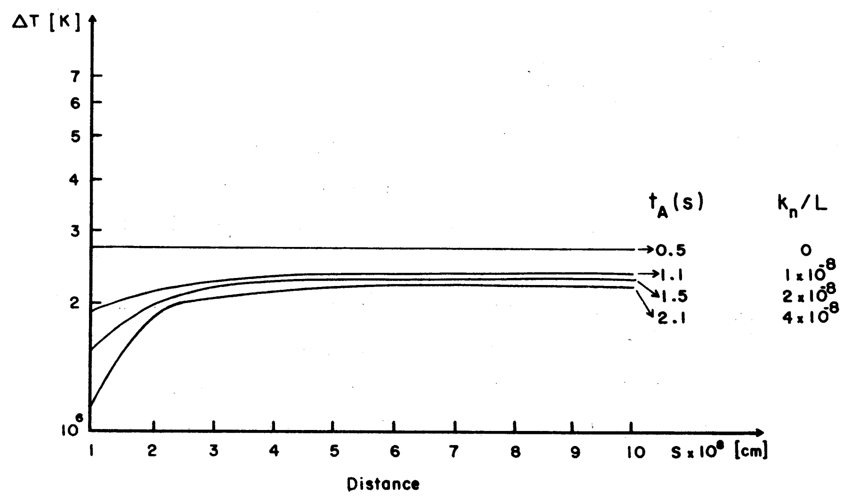

Fig. 5 The increase in temperature as a function of S for different values of density gradient.

From Fig. 5 we see that larger gradients in density produce lower temperatures near the source. From Fig. 6 we note that larger gradients in magnetic field produce lower temperatures away from the source.

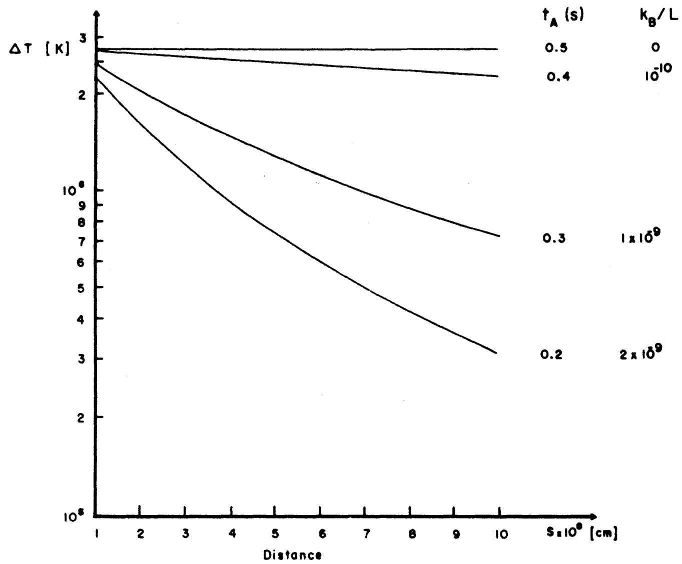

Fig. 6 The increase in temperature as a function of S for different values of magnetic field gradient.

In Fig. 7 we have the increase in temperature as a function of the spectral index β. We note that higher β produce lower temperatures.

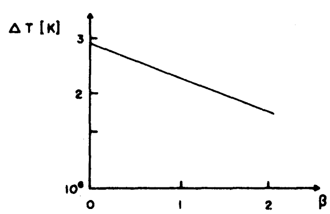

Fig. 7 The increase in temperature as a function of the index β.

In Fig. 8 we have the increase in temperature as a function of the magnetic field. We see that larger magnetic fields produce lower temperatures.

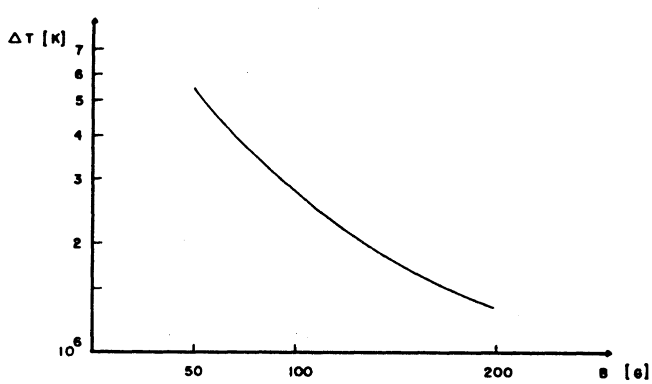

Fig. 8 The increase in temperature as a function of the magnetic field.

We use a very simple model of mass ejection assuming a steady flux of 10^6 ergs/cm^2-s and that the gain in momentum of the plasma is equal to the loss of momentum of the Alfvēn waves. Since the ejection velocity $\bar{V}$ is proportional to the flux F, the ejection velocities obtained can be scaled by the factor $F/10^6$. The model, applied to open field lines, is shown in Fig. 9. The source of turbulent Alfvēn waves can be, for example, the encounter of the open field lines with magnetic dipoles of opposite direction as shown in Fig. 2, or the twisting of the open field lines as shown in Fig. 1.

We evaluated the velocity $\bar{V}$ of the ejected matter as a function of the distance S from the source of the turbulent Alfvēn waves over a limited range of parameters.

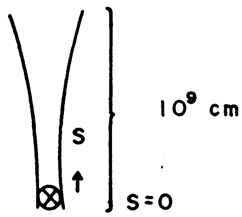

Fig. 9 The Mass Ejection Model

We examined $\bar{V}$ only over the small distance $S \sim 10^9$ cm and varied only the parameters of the density and its gradients. For the density we used the expression

$$n(S) = n_T \exp(-2 \times 10^{-9}\ S)$$

where n_T is the density near the source of turbulent Alfvēn waves.

One example of our results is shown in Fig. 10.

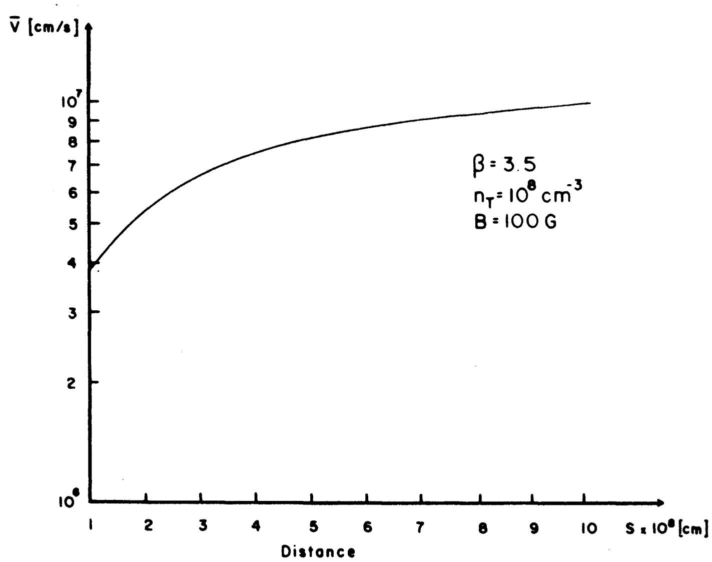

Fig. 10 The velocity of ejection $\bar{V}$ as a function of S.

From Fig. 10 we find that for reasonable values of β, densities and nagnetic fields, we obtain velocities of $\sim$100 km/s in the relatively short distances $\sim 10^9$ cm.

V. CONCLUSIONS

We analysed the heating of a magnetic arc by a turbulent Alfvēn wave spectrum $W(k) \propto k^{-\beta}$ and assumed that the primary heating of a corona is due to the absorption of turbulent Alfvēn waves in magnetic arcs. We showed: 1) An average flux of turbulent Alfvēn waves $\sim 10^6$ ergs/cm^2-s created in a corona can heat it to coronal temperatures; 2) For solar flares, where the heating is due to a pulse of Alfvēn waves, we obtained time delays $\sim$0.1 - 1 second for the microwaves with respect to the X-rays; and 3) We evaluated the velocity $\bar{V}$ of the ejected matter as a function of the distance S from the source of the turbulent Alfvēn waves and showed that for reasonable stellar parameters, turbulent Alfvēn waves are capable of creating stellar wind velocities $\gtrsim$ 100 km/s.

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