SMALL-SCALE DISSIPATIVE PROCESSES IN STELLAR ATMOSPHERES

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ABSTRACT

The outer atmospheres of stars must be heated by some non-thermal energy flux to produce chromospheres and coronae. We discuss processes which convert the non-thermal energy flux of organized, macroscopic motions into random, microscopic (thermal) motions. Recent advances in our description of the chromosphere velocity field suggest that the acoustic waves observed there transmit very little energy, and hence are probably incapable of heating the upper chromosphere and corona. The apparent failure of this long held mechanism and the growing appreciation of the importance of strong magnetic fields in the chromosphere and corona have led to hypotheses of heating by the dissipation of currents (both oscillatory and quasi-steady). This follows discoveries in laboratory and ionospheric plasmas and work on solar flares, that instabilities can concentrate currents into thin high current density filaments where they dissipate rapidly.

INTRODUCTION

The major advances in understanding the Sun and other stars during the second half of this century have resulted from our appreciation of violations of the paradigm: stellar structure (both interior and atmospheric) is determined by thermal energy transport (i.e., radiation, convection and to a much lesser extent conduction). It now appears that the outer atmospheres of virtually all stars are substantially hotter than radiative equilibrium would have predicted and that stellar winds are important energy losses for the outer atmosphere. The conventional wisdom has become: a thermodynamic engine converts internal, thermal energy (maintained by thermal energy transport) to external, macroscopic energy which then propagates, or is transported, with little interaction with the material through which it propagates, upwards into the corona. Generally, production of propagating energy is not very efficient, $\lesssim 10^{-3}$. However, where the bulk of the total outward energy flux escapes from the star, i.e., within the outer several

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photon mean free paths, the macroscopic energy now represents a substantial proportion of the energy density, and dissipation of this energy can substantially change the temperature structure. In addition, the mechanical energy density directly contributes to the momentum balance, and hence structure, of the overlying atmosphere. Dissipation of the macroscopic energy results from microscopic processes (viscosity, conductivity and resistivity) which reduce gradients and increase random internal motions; i.e., increase entropy. By dissipation, we understand the ultimate transformation of macroscopic, organized energy to microscopic disorganized ones, and we don't discuss the transformation of one propagation mode to another, which "dissipates" the mode, but not the non-thermal energy.

We shall discuss the wave modes (acoustic, internal gravity and Alfven) which have been considered, and the role they appear to play in the Sun, as well as the less fully studied hypothesis of heating by current dissipation. We do not discuss the generation of this propagation energy here, and the reader is referred to Stein and Leibacher (1979, 1980).

Finally, we should point out that the identification of the various candidates for propagating the required non-thermal energy flux has proceeded from observations of the time dependent, horizontally inhomogeneous structure of the Sun. The Sun is where we learn the physics to understand the stars. On the other hand, the variation of non-thermal heating with stellar type provides a stringent test for all generation, propagation and dissipation theories. We should note several recent reviews of heating mechanisms: Cram (1977), Cram and Ulmschneider (1978), Rosner, Tucker and Vaiana (1978)—particularly the Appendix—and Wentzel (1978).

ACOUSTIC (PRESSURE) WAVES

Propagating pressure fluctuations were the first non-radiative flux suggested to account for the corona's high temperature. These steepen to form discontinuities due to the dependence of their propagation speed on temperature: the upwardly moving, hotter part of the wave propagates faster than the downwardly moving cooler part. The steepening is accelerated in a stellar atmosphere, since the wave amplitude increases as the density decreases, to keep the energy flux constant in the absence of dissipation and refraction. When the steepening progresses to the point that the wave changes appreciably over a collision mean-free-path, diffusion (viscosity and conductivity) acts against further steepening, converting the organized motion of the wave into thermal motions, and a shock wave is said to exist. In stellar coronae, the high thermal conductivity of the hot plasma is generally more important than viscosity. As the pressure jump across the wave increases, the dissipation (or entropy increase) grows very rapidly: initially as the third power of the pressure jump. It is important to note that it is the sharp gradient, or discontinuity, produced by the wave which produces the dissipation;

the existence of large velocities (comparable with the sound speed) is not sufficient. In particular, long period vertical motions will raise and lower the atmosphere more or less in phase, with the velocity varying exponentially—not sinusoidally with height—and even at large amplitudes "phase" is not propagated vertically. Radiative exchange (losses from hot, compressed gas and gains by the cool, rarefied gas) also will dissipate the flux of an acoustic wave.

Short period waves (10 - 100 seconds), created by turbulent motions in the convection zone, should be capable of providing the heating required near and immediately above the temperature minimum (Ulmschneider, Schmitz, Kalkofen and Bohn 1978, and references therein). However, they rapidly dissipate their energy and do not appear capable of any heating higher up. These waves lose a very substantial part of their energy by radiative damping in the photosphere before forming shock waves. Thus, the flux available for heating is a small number which is the difference of two large numbers (the generation and radiative damping), a situation which amplifies numerical as well as physical uncertainties.

Although the dissipation of these waves is fairly well understood, the total power emitted and its temporal spectrum remains uncertain. Extrapolations to other stars have been suggested (Renzini, Cacciari, Ulmschneider and Schmitz, 1978), but the predicted, very rapid increase in the chromospheric emission with luminosity for solar type stars does not appear to occur (Linsky and Ayres, 1979). Short period waves remain "unobservable" because their wavelengths are comparable to the widths of the regions emitting the spectral lines used as diagnostics, however they do contribute to the non-thermal width of spectral lines.

Longer period acoustic waves are seen as spatially resolved displacements of photospheric and chromospheric lines. Theory and observation have achieved rare agreement in the description of the "five minute oscillations" as acoustic waves trapped within certain ranges of temperature (Leibacher, 1977; Zirker, 1979). These standing waves transmit virtually no energy: neither in the cavity where upward and downward propagating waves, of equal flux, interfere constructively, nor outside the reflecting boundaries of the cavity where the mode may continue to exist by "tunneling" as an evanescent wave. Thus, although the velocity amplitudes may be substantial, since pressure and velocity vary nearly in quadrature, little energy would be propagated. In addition, since there is no vertical phase propagation, the large vertical gradients required for diffusive dissipation do not occur.

The radiative losses of the upper chromosphere and corona appear to exceed the most optimistic estimates of the acoustic flux (Athay and White, 1978; Bruner, 1979): assuming that the total non-thermal width of chromospheric lines is due to acoustic waves propagating upwards at the maximum possible energy propagation (group) velocity. For other stars, the situation is likely to be similar: short period waves lose a majority of their flux by radiation and dissipate the remainder in a relatively short distance. Longer period waves develop substantial amplitudes only if they are trapped, and propagate little energy.

INTERNAL GRAVITY (BUOYANCY) WAVES

Buoyancy restoring forces, in a convectively stable atmosphere, will drive predominantly horizontal motions known as internal gravity waves (IGW). These waves are abundant in the earth's atmosphere, and will be generated by slow motions, such as penetrative convection, and velocity shear, such as that associated with the variation of the supergranulation velocity with altitude. Because of their short vertical wavelengths, they are not prominent in the observed macroscopic motions of the Sun, but they presumably make a significant contribution to the unresolved, "microscopic" velocity field. Dissipation through ordinary viscosity and conductivity will occur, and as they propagate upwards and their amplitude grows, the waves will "break" and produce shorter wavelength IGW turbulence along their fronts—like whitecaps. Large amplitude waves can drive mean flows, and conversely IGW's can be absorbed by a steady flow whose velocity equals the wave's phase velocity. The wave energy goes into the mean flow, and it is not dissipated in the sense of returning to thermal energy. Radiative damping tends to make a wave isothermal, which destroys the buoyancy driving force, and hence is particularly effective in dissipating IGW's.

The energy propagation speed for IGW's is $\lesssim$ the sound speed, so the arguments of Athay and White (1978) for the energy flux carried if the excess line broadening were all taken as propagating mechanical energy, also apply for IGW's. However, because their velocity is primarily horizontal, only a small part of their amplitude contributes to line broadening at disk center.

MAGNETIC FIELDS (CURRENTS)

Recent observations have vastly increased our appreciation of the importance of magnetic fields on the Sun, and hence other stars. Strong fields have been found away from active regions: the super-granulation network consists of strong (greater than 1000 gauss), concentrated (less than a magameter horizontal extent) fields, and flux emerges at all latitudes. X-ray observations indicate that the corona consists almost entirely of filamentary and loop structures which have been identified as magnetic flux tubes. The role of magnetic fields in heating solar and stellar flares has long been known, as has their importance in maintaining the enhanced emission of active regions. While the important physical processes are becoming clearer, we are still far from an accepted model for these phenomena (Spicer and Brown, 1980). Nonetheless, as the difference between a spherically symmetric, one dimensional chromosphere or corona and reality becomes more obvious, the idea that the magnetic field plays an essential role in the transport of mechanical energy to the corona away from active regions and its dissipation there, has become increasingly attractive. While it is tempting to consider coronal models that are scaled down analogs of flare models where energy is released gradually, we should recall that it has been the requirement of rapid energy release that has driven the search for flare mechanisms, and that processes which are too slow to describe flares, and have been discarded, may be relevant for the quasi-steady heating of the corona.

Although we are not discussing generation mechanisms here, we should point out that the observed fields are roughly in equipartition with the kinetic energy density at the top of the convection zone (Peckover and Weiss, 1978). The seed field for amplification by the convective motions presumably results from the dynamo interaction between rotation and convection in deeper layers. Thus, the magnetic field associated heating will vary with the spindown time of a star, which in general will be unrelated to the evolutionary time scale determined by nucleosynthesis.

In the convection zone β(= gas pressure/magnetic pressure) is large and convective velocities move the magnetic lines of force with little resistance. Magnetic fields provide (at least) three broad mechanisms for transmitting energy from the convection zone to the corona: 1) waves propagating along lines of force, 2) currents induced in the corona by waves, twists and motions of the magnetic foot points, and 3) emerging flux carrying stored energy upwards. Dissipation of magnetic energy occurs primarily as the dissipation of induced currents. Although, where the magnetic energy is in the form of Alfven waves, viscous damping and wave mode coupling also occur.

Alfven Waves

The field may serve (more or less passively) as a medium for transmitting the shaking or twisting of field lines (Wentzel, 1978; Uchida and Kaburaki, 1974; Hollweg, 1980). Twisting or jiggling of a magnetic line of force can be produced directly by convective motions or by thermal over-stability in the convectively unstable layer. The disturbance will then propagate away as a wave, or if slow enough, as a quasi-static change in the field. Several magneto-acoustic-gravity wave modes exist. One can understand the essence of magnetic waves by considering only Alfven waves. Their restoring force is magnetic tension, so they act like waves on a string—the magnetic field line—with motion transverse to the field. The temperature, density, pressure and magnetic field strength ($\underset{\sim}{B}_o + \delta\underset{\sim}{B}$) are constant. Energy propagates along the field at the Alfven speed

$$a = B/\sqrt{4\pi\rho}.$$

Because of its density dependence, the Alfven speed increases by a factor of 10^3 between the photosphere and the corona, so that substantial reflection of Alfven waves will occur. Since the magnetic field in the corona is inhomogeneous, the internal Alfven waves will be slightly modified and propagate as surface waves with the average

Alfven speed. Where the local Alfven speed equals this average Alfven speed a resonance occurs, at which the transverse velocity and electric field become large.

The Alfven speed is independent of Alfven wave amplitude, since the density and magnetic field remain constant. Hence, Alfven waves do not steepen and shock. However, they can dissipate by microscopic processes (viscosity and resistivity). The damping lengths for both viscous and Joule heating increase as the cube of the magnetic field and the square of the wave period.

Viscous damping is more important than Joule heating in the corona and vice versa in the photosphere and chromosphere. In the corona the problem is turned around. The damping lengths are so long that dissipation is very small and attention has focussed on coupling to other modes which dissipate more rapidly. Surface Alfven waves have very large amplitudes at their resonant point, so most of their energy will be dissipated by Joule and viscous dissipation in the thin resonant layer. The damping rate is determined by the rate at which energy can propagate into the resonant layer. Mode coupling occurs when the Alfven wave amplitude becomes large, and a compressible, sound wave is formed which can dissipate efficiencly (Derby, 1978). Coupling also occurs in the presence of inhomogeneities, by producing an uncertainty in the wave number, of the order of the reciprocal of the inhomogeneity scale size. For two waves of the same frequency and wavenumbers differing by Δk, the coupling will be of order

$1/L|\Delta k|$ (Melrose, 1974).

In particular, Alfven waves propagating nearly along the field can couple efficiently to fast mode waves.

Current Dissipation

Slow motions of the magnetic foot points in the convection zone may force flux tubes against one another in the corona, which will induce currents between them perpendicular to the field direction. If the magnetic fields are oppositely directed, a neutral sheet will be produced. Buffeting of magnetic flux tubes in the photosphere by granule and supergranule motions will produce twists and Alfven waves which propagate up into the corona and induce currents there. Emerging magnetic fields may also carry energy stored as twists ($\underset{\sim}{J} \times \underset{\sim}{B} \neq 0$) up into the corona, where β is small. Any unbalanced magnetic force ($\underset{\sim}{J} \times \underset{\sim}{B}$) will cause the tube to move and relax (Parker, 1974). Field aligned currents can remain in the relaxed coronal flux tube (Parker, 1974; Hollweg, 1980).

Current or magnetic field dissipation is a diffusive process due to single or collective particle collisions. The heating rate is $Q = \eta J^2$, where J is the current density and η is the resistivity. The characteristic resistive diffusion time scale is $\tau_R = 4\pi L^2/\eta c^2$.

For typical coronal parameters $\tau_R \sim 10^4$ yrs; too long to be significant. This Joule dissipation time can be reduced either by reducing the width L of the region through which the currents flow or by increasing the resistivity by increasing the effective collision rate. To get significant current dissipation by any mechanism, the dissipation must occur in such small volumes that the transfer of the resulting heat to the rest of the corona is a serious problem.

Tearing Instability

The size of the current region can be reduced by the tearing instability in a sheared magnetic field. Parallel currents attract one another and tend to clump. The clumping of current produces a fluid flow that forces the sheared magnetic field into X-type neutral points Filamented currents are produced with small enough length scales so that the classical Coulomb collision resistive diffusion time becomes small and the magnetic field can tear and reconnect, and the currents can dissipate (Drake and Lee, 1977; Bateman, 1978, chapter 10).

This mechanism has been invoked for the violent energy release in flares. (See Spicer and Brown, 1980.) However, short wavelength tearing modes release less energy than the long wavelength instability thought to occur in flares, and so may produce a more tranquil heating appropriate for coronal flux tubes. The shorter wavelength modes distort the field lines more, which produces a greater restoring force, and also have a smaller volume of magnetic energy they can release. The tearing instability has a lower threshold than the current driven instabilities which lead to anomalous resistivity (discussed below).

Thermal Instability

Thermal instabilities can also reduce the size of the current region by producing current filamentation, because Coulomb resistivity decreases with increasing temperature. Hence, Joule heating will increase the temperature, which reduces the resistivity, which increases the current density, which leads to enhanced heating. Current filaments parallel to $\underset{\sim}{B}$ result. This instability can act as a trigger for other instabilities.

Anomalous Resistivity

When the current density, $J = n_e \, e \, V_{drift}$, becomes large enough that the drift velocity approaches the electron thermal velocity, then substantial numbers of electrons will tend to run away and generate several different types of electrostatic waves. These waves bunch the ions, so that the electrons collide with the electric field of a large collective charge rather than that of a single ion. This scattering of electrons by the waves increases the effective collision rate, the rate of momentum transfer and hence the resistivity. The enhanced resistivity due to electron scattering by plasma waves is called "anomalous resistivity", and since it occurs in conjunction with current filamentation will shorten the resistive diffusion time tremendously (Papadopolous, 1977; Rosner, Golub, Coppi and Vaiana, 1978).

CONCLUSIONS

Short period acoustic waves (period < acoustic cut-off period) still appear to be the most satisfactory mechanism for heating the low chromosphere. These waves shock before reaching the corona, so increasing their flux only increases the temperature of the low chromosphere. Longer period waves are trapped by temperature gradients, and although their amplitudes can increase by constructive interference, they transmit little energy.

Internal gravity waves are probably present in stellar atmospheres, and while they may be important dynamically (line broadening, acceleration of steady flows), they probably do not contribute directly to heating.

Magnetic fields have recently received a great deal of interest, largely as a result of the discovery of very strong fields and the inhomogeneous structure of the corona. Progress has proceeded by invoking mechanisms previously considered for solar active regions and flares: Alfven waves dissipating motions excited by convective buffeting of flux tubes, anomalous resistivity dissipating field aligned currents induced by twisting of the field in and below the photosphere, and reconnection of field lines in regions of strong field gradients produced by the flux tube twisting and relative motions of different flux tubes.

For the new, magnetic field associated heating mechanisms, even more than the older, wave heating mechanism, small spatial structures are of fundamental importance and we must rely on solar observations and theory to lead the way to applications to other stars.

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