PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

The Energy and Pressure Balance in the Corona

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The energy and pressure balance in the corona

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This paper reviews theoretical models for the solar corona based on energy and pressure calculations. Processes included in these calculations are:
(*a*) heating of the outer corona by mechanical waves;
(*b*) convective out-flow of gas giving rise to the solar wind;
(*c*) thermal conduction;
(*d*) radiated power loss.
Possible observations to help answer some of the outstanding questions about the energy balance are suggested.

1. Introduction

In this paper we present a brief review of studies related to the energy balance in the solar atmosphere above the chromosphere. The main characteristics of this part of the atmosphere are illustrated in the upper part of figure 1 which shows the steep temperature rise in the transition region from the top of the chromosphere (*ca.* 8000 K) to the corona (*ca.* 2×10^6 K). The problem is to understand why the corona is so hot. Recent studies have included some or all of the processes illustrated in the lower half of figure 1. These are:

(*a*) heating, by the dissipation of mechanical waves generated in the lower atmosphere;
(*b*) convective out-flow of the atmosphere giving rise to the solar wind;
(*c*) thermal conductivity;
(*d*) radiated power loss.

Papers dealing with this subject fall into two groups depending on whether they concentrate on the mechanical heating problem (*a*) or the other three (*b*), (*c*) and (*d*) of which the physics is better defined and which lead to the development of specific models. These may be compared with, or constrained to fit, observational data.

Much of the recent data emphasizes the importance of complex spatial structures in this part of the atmosphere as well as temporal variations. Relatively minor attempts have been made to take account of these in the work that we discuss here and the models cannot therefore be expected to reproduce these detailed observations. The object rather is to produce a broad view of the salient features. We start by discussing the four processes listed above and make particular reference to our own work (McWhirter, Thonemann & Wilson (1975)) which was done in association with P. C. Thonemann of the University College of Swansea.

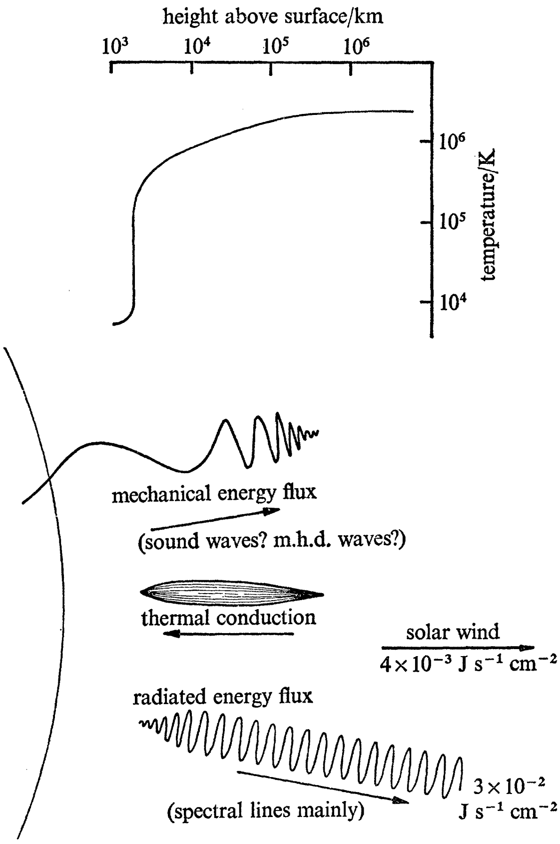

FIGURE 1. The temperature distribution and processes contributing to the energy balance of the solar corona.

2. MECHANICAL WAVES

Heating by mechanical waves is now universally accepted as the primary energy source for heating the corona. Progress in understanding this part of the problem is bedevilled with the difficulties associated with the propagation and damping of waves in an atmosphere whose temperature changes abruptly by about a factor of 100, is in a gravitational field and is threaded by a complex magnetic field. Most authors have assumed some form of acoustic shock heating but Osterbrock (1961) and others consider Alfven waves. It is generally agreed that only long period waves (> 100 s) reach the outer atmosphere so that the distance between their heights of formation and dissipation is only a few wavelengths. This is illustrated schematically on figure 1 where the 300 s acoustic waves of our model are shown to the length scale of the upper part.

Direct experimental evidence for these mechanical waves is slender and consists of the observation of excessive Doppler broadening of spectral lines emitted from the transition region. Papers by Boland, Engstrom, Jones & Wilson (1973), Boland *et al.* (1975) describe some such measurements and discuss their analysis. The resulting estimates of mechanical energy flux are uncertain by almost a factor 10 and are in the region of 10^{-2} J cm^{-2} s^{-1}. The results of Boland *et al.* (1975) are plotted in figure 2 for spherically symmetric, and a network, model described later (§ 5). They include some measurements in the chromosphere ($T <$ *ca.* 10^4 K) not relevant to the present paper. It is not possible from these observations to distinguish between acoustic and m.h.d. modes of propagation.

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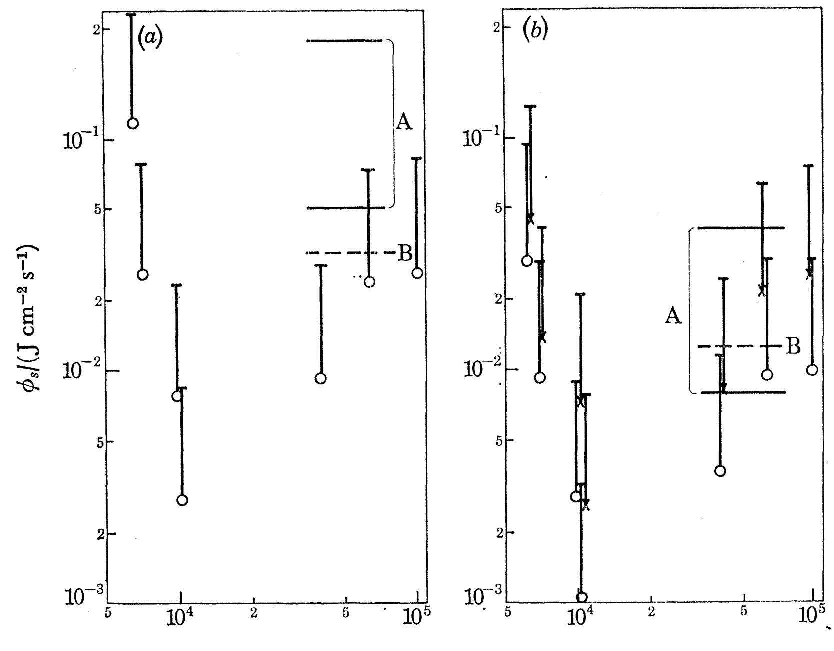

FIGURE 2. The mechanical energy flux measured by Boland *et al.* (1975). (*a*) spherical; (*b*) network.

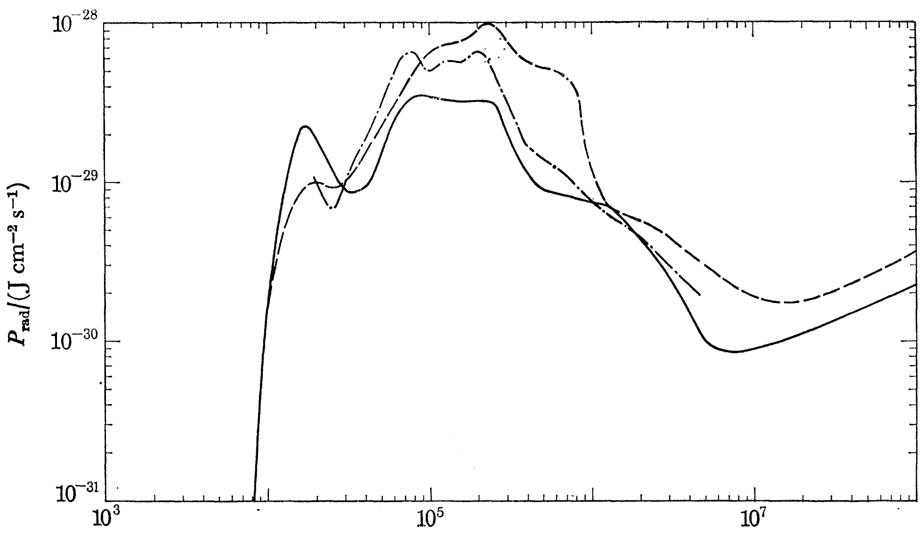

FIGURE 3. The total radiated power loss function for the solar corona. —·—, Pottosch (1965); ———, Cox & Tucker (1969); ——, McWhirter (to be published).

3. CONVECTION, CONDUCTIVITY AND RADIATION

The other three processes contributing to the energy balance are often taken together to derive solar models constrained by some authors to also fit observational data. On the grounds that it is only a small component, convective out-flow is neglected in some calculations. Earlier attempts to include it to achieve an energy balance gave rise to out-flows of gas that were up to 600 times greater than the particle flux required for the solar wind (Ulmschmeider 1967, Lantos 1972).

Recently Chiuderi & Riani (1974) have produced a model that includes out-flow that is consistent with the requirements of the solar wind which has an energy of about $4 \times 10^{-3}\,\mathrm{J\,cm^{-2}\,s^{-1}}$ In none of these papers is a physical mechanism proposed for the propulsion of the out-flowing gas. Kuperus & Athay (1967) get closer to a mechanism in proposing that some of the energy conducted to the chromosphere goes to producing the spicules.

All the recent energy balance models include thermal conductivity and radiated power. These are now both well understood physical processes amenable to fairly accurate calculation and they constitute the essential basis of most model calculations. Some of the earlier attempts to derive models suffered through the use of wrong values for the coefficients representing these processes. This was particularly true for the radiated power loss for which some authors used coefficients that were between 1/10 and 1/100 of values currently accepted. Recent work is usually based on the calculations of Cox & Tucker (1969) although we repeated these for our own model and found substantial agreement. The results are compared in figure 3 together with an earlier calculation by Pottosch.

4. Overall energy balance

Partly as a result of using wrong coefficients it was concluded from earlier calculations that it was not possible to balance the conducted flux with the total radiated power. This belief still persists today. However, it was shown by Moore & Fung (1972) that an overall balance of the total conducted and radiation energy fluxes in the transition region is possible. This conclusion is confirmed by our own work which gives rise to a relation between the pressure in the transition region and the energy flux that it is capable of radiating. This is shown in figure 4 where the curves are an analytical result (McWhirter *et al.* 1975) and the points are the result of detailed computer calculations. There is good agreement with Moore & Fung (1972) who point out that the conducted flux at the top of the chromosphere ($T \approx 8000\,\mathrm{K}$) must be less than $10^{-5}\,\mathrm{J\,cm^{-2}\,s^{-1}}$ otherwise there would be a substantial thermal gradient at this level.

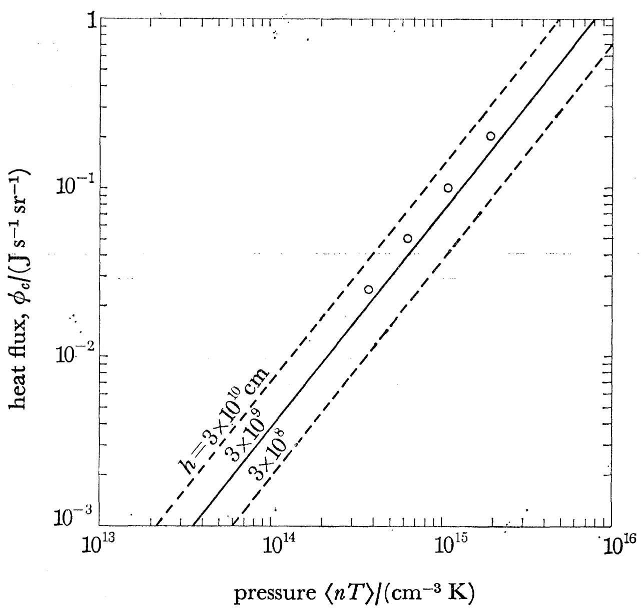

Figure 4. Relations between the pressure in the transition zone and the heat flux the atmosphere can radiate.

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Observational support for the overall balance of radiated and conducted energy is afforded by Athay's (1966) estimate that the total energy radiated by the corona is about 3×10^{-2} J cm^{-2} s^{-1}. This was based on an assessment of observed X.u.v. intensities. It is consistent with the estimates of Boland *et al.* (1973, 1975) for the mechanical energy flux and that required by some energy balance models including ours.

The temperature dependence on height of a selection of energy balance models is shown in figure 5. The similarities between these indicates how insensitive the temperature distribution is to the various assumptions of the models. Over most of the height range it is determined essentially by the balance between conductive dissipation and radiative loss.

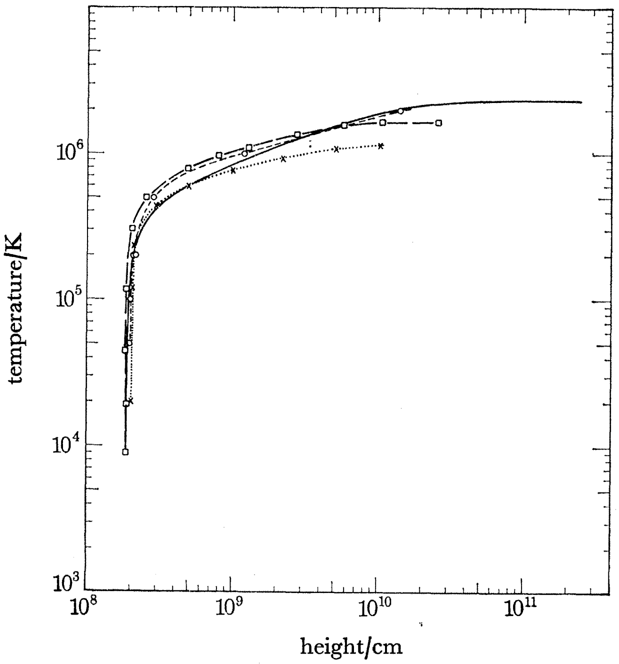

FIGURE 5. Comparisons of the temperature distributions found by various authors who have published energy balance models: ---○---, Athay (1966) 5×10^{-2} J cm^{-2} s^{-1}; —□—, Ulmschneider (1971); ···×···, Chiuderi & Riani (1974); ——, McWhirter, Thoneman & Wilson (1975) 3×10^{-2} J cm^{-2} s^{-1}.

5. Channelling of the conducted heat

All these models assume a stratified atmosphere either in plane parallel geometry or spherical symmetry. In an attempt to take some account of the solar magnetic field Kopp & Kuperus (1968) introduced the idea of the channelling of the conducted heat flux along the field lines. By this idea the conducted heat is limited to a fraction of the total surface.

In their paper the authors concluded that the regions of low magnetic field would be bright in the transition region spectral lines and that in those regions there could be a balance of radiated and conducted energy. However, in a later paper Kopp (1972) revises this opinion and presents a model that is bright in these lines in the network (high magnetic field) regions. In this it is qualitatively consistent with observation. By constraining his model to fit the observed spatially averaged intensities of the X.u.v. lines Kopp concludes that direct mechanical heating plays an important part in the energy balance of the transition region. A similar model (but without direct mechanical heating) was used by Boland *et al.* (1975) in analysing their measurements of line widths and give rise to the results presented on the right hand diagram (*b*) of figure 2. For this our model was modified to include the idea of magnetic field channelling (see also the following paper by Gabriel).

6. Pressure balance

Another assumption of all these models, including Kopp's, is that the atmosphere is in hydrostatic equilibrium although constant pressure was deemed adequate by some authors. However, it has been pointed out that a flux of mechanical waves also carries momentum which modifies the pressure balance. For our model we show that this pressure, due in our case to acoustic waves, is greater than the hydrostatic pressure in the transition region (McWhirter *et al.* 1975). An attempt to include this term in the model resulted in a failure to find a solution since it so increased the density of the atmosphere that the radiated power exceeded that available from the acoustic flux. That existing models do not include the mechanical wave pressure represents an important failing.

7. Current problems

Recent and forthcoming solar observations from satellites provide unique opportunities to study some of these problems. It may therefore be useful in a review of this nature to try to identify some of the outstanding questions whose answers will make a significant advance in understanding the energy balance.

Undoubtedly the area in which there is least knowledge concerns the nature of the mechanical waves. Are they acoustic, or m.h.d.? The possibility of observing spectral profiles with good spatial and spectral resolution may make it possible to distinguish between these. An acoustic wave propagating towards the observer has an asymmetric profile such as that shown in figure 6 for C IV 2s–2p. These profiles are also modulated with respect to time and this would be a measure of the wave frequency. Pure Alfven waves produce symmetric profiles.

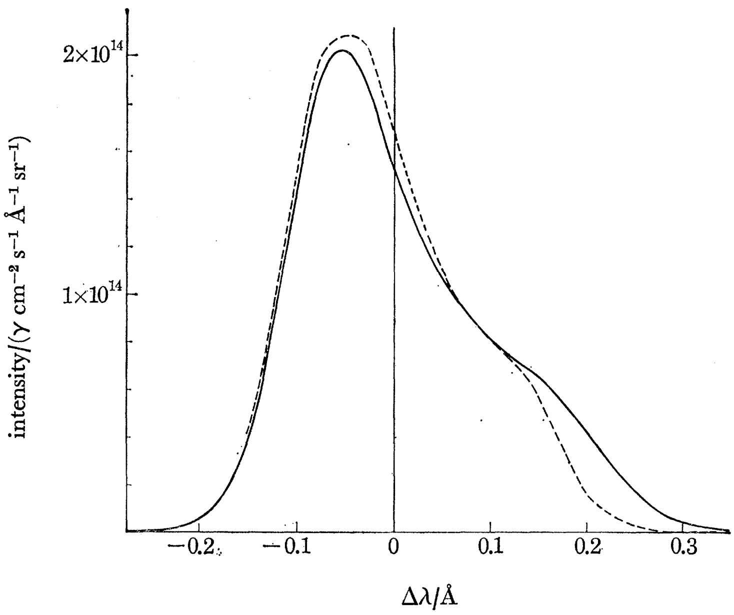

Figure 6. The predicted profile of the C IV 2s–2*p* spectral line from an atmosphere carrying an acoustic wave. ——, isothermal $\gamma = 1$; ----, adiabatic $\gamma = \frac{5}{3}$; 3.0×10^{-2} J cm^{-2} s^{-1}.

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It is also very desirable to improve the accuracy and range of the measurements of mechanical flux such as those made by Boland *et al.* (1973, 1975). By extending these measurements into the corona it may be possible to establish the height at which damping takes place and the contribution of direct mechanical heating to the energy balance in the transition region.

The existence of an additional term in the pressure balance equation due to the momentum flux of the mechanical waves means that it is important to try to measure directly the hydrostatic pressure at various levels in the atmosphere. Spectroscopic methods of simultaneously measuring density and temperature could be very helpful here.

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