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IV. STELLAR CHROMOSPHERES AND CORONAE

The production of solar and stellar chromospheres and coronae

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Knowledge of the detailed field of turbulence in the solar granulation, and of the consequent photospheric mechanical flux, is one of the basic elements for understanding the solar chromosphere and corona. The other element is constituted by the structure and magnetic fields of the supergranular network, since the coarse mottles at the supergranular boundaries seem to yield a mechanical flux nearly an order of magnitude larger than that of the supergranular cell regions.

In the non-magnetic solar regions the upper photospheric mechanical flux is about 0.1 J cm^{-2} s^{-1}. This flux is equal to that emerging from the low-chromospheric vibrations; it seems not to be related to the observed microturbulent motions. Above such regions the chromosphere may be fairly thin, not exceeding 1000 or 2000 km. The precise thickness and detailed structure of the chromospheric layers can only be determined from a discussion of the interplay of the downward conductive flux with the dissipational losses of the up- and downward mechanical fluxes, and the radiative losses of the chromospheric matter. The greater apparent thickness of the chromosphere at the limb is due to the accumulated influence of the spicules seen from the side.

Lack of knowledge of stellar photospheric inhomogeneities and fields handicaps a reliable prediction of stellar chromospheres and coronae. Yet a few attempts have been made, and predicted X-ray fluxes from coronae of some nearby stars are given (table 3).

1. Generalities on the production of stellar coronae

The intriguing aspect of the solar corona is its high temperature, in contrast to the relatively low photospheric value. With the work of Biermann and Schwarzschild in 1948 it became clear that this apparent violation of the second law of thermodynamics can be explained by heating of the outer solar layers by viscous losses in outward travelling waves. Energy losses in sound waves are very small and mostly negligible, but waves propagating outward into the increasingly tenuous solar outer layers enhance their velocity amplitude, so that second-order terms become important in the wave equation, eventually leading to shock waves, which dissipate part of their energy by viscosity.

The main problems are therefore:

(*a*) Determination of the detailed velocity spectrum of the photosphere, including the influence of possibly existing magnetic fields.

(*b*) The generation of waves in the photospheric velocity field; computation of the mechanical energy flux.

(*c*) Determination of the absorption and reflexion coefficients for shock waves and establishment of the transfer equation for the mechanical flux.

(*d*) Computation of the coronal and chromospheric temperature and density from the transfer equation incorporating the influence of energy losses and gains by radiation, conduction, reflexion and convection.

Most of these problems have been discussed in recent years for the solar case; if one thing is clear it is that many uncertainties still occur in the various aspects of the problem. In particular the influence of magnetic fields and chromospheric fine structure is far from being solved. Yet it is gratifying that recent attacks on the problem have led to predicted coronal data that show a fair agreement with observations.

2. The non-magnetic solar case; mechanical flux at the base of the chromosphere

The mechanical flux is thought to be generated in the convective region. The convective velocity component in the uppermost part of the solar convection zone has been determined from observations (de Jager & Neven 1967, 1971) and was predicted theoretically (Böhm-Vitense 1958; De Loore 1970); both methods agree and yield values of about 2 km/s. Various theoretical expressions have been published for estimating the mechanical flux generated by these motions; the results depend greatly on the assumed spectrum of the motion field, and on the mechanism of generating acoustic waves. For instance Lighthill's (1952) generation efficiency, predicted on the basis of Proudman's (1952) mechanism, is about an order of magnitude smaller than Stein's (1967).

We therefore prefer to rely on the observations for an estimate of the mechanical flux. The best place to determine F_{mech} is the transition region between photosphere and chromosphere, where we are far enough above the convection zone to have a constant flux with height, and not yet high enough for F_{mech} to be seriously reduced by chromospheric absorption. Athay (1970) has shown that the small difference between the actual kinetic temperature and the predicted radiative equilibrium temperature at $\tau_5 = 10^{-4}$ shows that at that level $F_{mech} \lesssim 0.2\,\mathrm{J\,cm^{-2}\,s^{-1}}$. In detailed computations Ulmschneider (1970) found that at the base of the chromosphere $F_{mech} \approx 0.2\,\mathrm{J\,cm^{-2}\,s^{-1}}$. For this paper we shall use that value, which already allows us to draw a few important conclusions.

(a) *The mechanical flux does not show itself as 'microturbulence'*

It is normally assumed that the microturbulence of the chromosphere is the visible manifestation of the mechanical flux (see, for example, Unsöld 1970) and that actually the corona is heated by acoustic waves generated in the solar convection zone and propagating outward. These waves are then identified with the observed microturbulence. The variation of the vertical microturbulent velocity component ζ_t in the upper photosphere and low chromosphere has recently been determined by various authors, among them Athay & Canfield (1969) from NaD line studies, and De Jager & Neven (1971) on the basis of centre-limb observations of medium strong and strong infrared Fraunhofer lines.

We now make the conventional assumption that

$$F_{mech} = \theta \rho \zeta_t^2 v_s,$$

where θ is a number of the order unity, and v_s is the local velocity of sound. With ρ and v_s derived from the Bilderberg photospheric model (Gingerich & De Jager 1968) and ζ_t from De Jager & Neven (1970) and postulating $\theta = 1$, one finds

$\lg \tau_5$	$\zeta_t/\mathrm{km\,s^{-1}}$	$F_{mech}/\mathrm{J\,cm^{-2}\,s^{-1}}$
−2	1	30
−3	1.5	18
−4	2	8

These values of F_m are about two orders of magnitude larger than Athay's and Ulmschneider's empirical values which shows that the observed microturbulent velocities in the low chromosphere apparently stand in no relation to the mechanical energy flux since their energy seems not to be used for heating the chromosphere or corona. This result poses the problem of the character of the microturbulent motions and the way their energy is dissipated.

(b) *The energy of the outward propagating mechanical flux is equal to the energy of the vibrations of the low chromosphere*

The vibrations of the upper photosphere and low chromosphere have observed periods of the order of 200 to 300 s, and have a spatial correlation distance (mean size) of 3000 to 7000 km (Howard 1967; Deubner 1967; Appenzeller & Schröter 1968). From spectroscopic observations the latter authors derived power spectra of these vibrations; the average r.m.s. values are for the core of

$$\left.\begin{array}{l}\text{Fe } 5123.7\\ \text{Fe } 5123.2\end{array}\right\}: 0.14\,\text{km/s};$$

$$\text{Mg b}_2 \quad 0.26\,\text{km/s};$$

$$\text{Na D}_1 \quad 0.31\,\text{km/s}.$$

Since the cores of the Fe line and the Mg b_2 lines are estimated to be formed at about $\lg \tau_5 = -3$ or -4 and that of Na D_1 is formed higher up, it is the former values that should be used for computing the corresponding mechanical flux. This turns out to be for the Fe lines ($\lg \tau_5 = -3$): $0.2\,\text{J cm}^{-2}\,\text{s}^{-1}$ and for Mg b_2($\lg \tau_5 = -4$): $0.13\,\text{J cm}^{-2}\,\text{s}^{-1}$, very nearly equal to the mechanical flux at that level.

This numerical agreement suggests to us that the vibrations of the upper solar photosphere and low chromosphere may be identified as the manifestations of the outward propagating mechanical energy flux. In contrast to this postulate stands Ulmschneider's (1970) suggestion that the energy of the mechanical flux is mainly contained in a high frequency (10^{-1} Hz) component of the photospheric motion field.

Restriction. The above considerations apply only to the quiet parts of the solar low atmosphere, hence *not to the active regions*, and not even to the chromospheric mottles. They only apply to the supergranular *cells*, not to their boundaries where rather strong magnetic fields are known to occur at the places of the chromospheric mottles.

3. The mechanical flux in solar magnetic regions

Fairly strong magnetic fields occur at the boundaries of the solar supergranular cells, where they are manifested in the coarse mottles or rosettes. Similar fields occur also in the plages, the chromospheric active regions, away from the spots.

It is likely that the mechanical flux in these magnetic regions is different in intensity as well as in character from the flux in quiet regions. Osterbrock (1961) was the first to discuss the formation of the corona above magnetic regions. The restriction of Osterbrock's theory to magnetic or active regions has not always been appreciated by later authors, some of whom have applied his results to quiet regions too.

Recently Milkey (1970) applied an investigation of the energy transport by weak fast-mode hydromagnetic shock-waves to the magnetic chromospheric regions above supergranular cell boundaries, and predicted a local chromospheric temperature enhancement.

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From the observational side the ratio of the mechanical fluxes in magnetic and non-magnetic elements of the Sun was estimated by De Jager & De Loore (1970) on the basis of the observed coronal densities above active and quiet regions, using observed values of the relative coverage of these regions by magnetic elements, and by an application of De Loore's (1970) computations on the dependence of coronal densities on the mechanical flux in solar and stellar coronae. It is found that magnetic elements contain a mechanical energy flux about seven times that of non-magnetic regions (estimated logarithmic error: ± 0.2). Since active photospheric regions may consist of similar structures to the chromospheric mottles, but with a greater spatial density (estimated occupation factor ≈ 0.6 against ≈ 0.1 for the quiet regions), the average mechanical flux emerging from active regions is about three times the flux emerging from quiet solar regions (= regions outside faculae, but containing supergranular cells and their boundaries).

An important problem is, how the mechanical flux from supergranular boundaries is guided upward. It looks reasonable that it follows the magnetic field lines (cf. Milkey 1970). If these field lines diverge upward, in the way suggested by Athay & Kuperus (1967), to cover the lower corona homogeneously, then the supergranular boundaries would be visible in spectroheliograms of relatively low excitation lines, but not in those of coronal origin.

4. Structure of the solar chromosphere and corona

The mechanical energy flux at the base of the chromosphere being known, the computation of the structure of the chromosphere and corona is a matter of solving the transport equation for the mechanical flux, as was done by De Jager & Kuperus (1961) for non-magnetic regions, and by Osterbrock (1961) for magnetic regions. See the review paper by Kuperus (1969) and also the detailed computations by De Loore (1970).

We shall mainly discuss the non-magnetic regions. The computation for the magnetic regions is not fundamentally different, apart from the fact that magnetic fields apparently lead to structures like the spicules which consist of cool chromospheric matter piercing into the corona (see, for example, Kopp & Kuperus 1968). In such structures the computation of the chromospheric–coronal physical parameters is more intricate than in the non-magnetic regions.

Actually the parameters of the outer solar layers depend on, and define at the same time, the various fluxes in these regions. It is not too much of an oversimplification to state that while the structures of the subphotospheric and photospheric layers are mainly defined by the *convective* and *radiative fluxes*, the chromospheric and coronal structure is determined by the *mechanic al flux* Yet, further specification is necessary (see figure 1 and tables 1 and 2).

In the *transition region between the photosphere and the chromosphere*, up to a height of about 400 km above the solar limb (region V in figure 1), the temperature is still mainly defined by the radiative energy flux F_{rad}. There is some dissipation of mechanical energy but the consequent rise in temperature does not exceed 100 K (Athay 1970); the temperature still slightly *de*creases outward.

Higher up, the mechanical energy flux is continually reduced, by absorption, and by reflexion against the steep corona-ward temperature increase. Yet, at the level where the density is about $10^{9.1}$ electrons cm^{-3}, the energy dissipation in an overlying column of matter exceeds the emissive power of the gas (as first clearly stated by Unsöld 1960), and a stable configuration appears possible only for a gas temperature of the order of a million kelvins, where the dissipated energy of the mechanical flux (further reduced by reflexion) is lost by radiation and conduction. The plateau as shown in figure 1 could be called the main *corona*; region II. (Actually the idealized main corona, as shown in figure 1, and defined here as a region with a temperature *plateau*, hardly exists.)

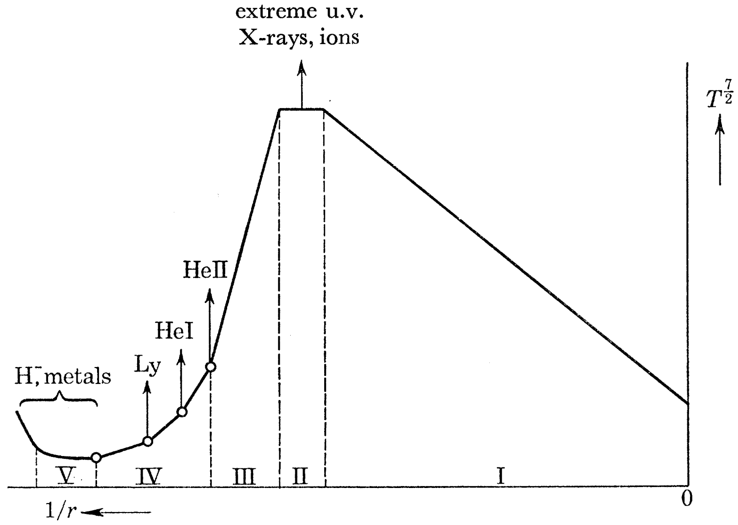

FIGURE 1. Schematic representation of the temperature distribution in the outer solar layers, and division of the outer solar atmosphere in five main regions. The arrows are meant to roughly indicate the influence of the main chromospheric emissions.

TABLE 1. MAIN CHARACTERISTICS OF THE FIVE REGIONS OF THE OUTER SOLAR ATMOSPHERE

region	name	main flux, and relation	contribution other fluxes
I	interplanetary gas	F^{+}_{cond}; equation (1)	F_{wind} (small)
II	corona	$F_{\text{diss}} = F_{\text{rad}}$	F_{wind} negligible
III	transition chromosphere-corona	F^{-}_{cond}; equation (1)	F_{rad}, $F_{\text{diss}} \ll F_{\text{cond}}$
IV	main chromosphere	$F_{\text{diss}} + F_{\text{cond}} \approx F_{\text{rad}}$	—
V	transition photosphere-chromosphere	F_{rad}	F_{diss} small but not negligible

TABLE 2. SOME REPRESENTATIVE VALUES OF THE FLUXES IN THE OUTER SOLAR ATMOSPHERE

The table gives logarithms of fluxes, in ergs cm^{-2} s^{-1}. The dissipated, radiative and reflected fluxes are estimated from the energy losses (cm^{-3} s^{-1}) integrated over the region considered. The values given here are orders of magnitude and have mainly illustrative significance.

region ...	V	IV	III	II	I
mechanical flux	6.3	5.8	—	5.3	small
dissipative	small	—	—	5	0
conductive	0	—	5	—	4
reflective	0	—	—	0	0
radiative	6.8	—	—	5.3	—
convective (wind)	0	0	0	small	small

The regions further outward are virtually without any dissipation; the temperature distribution in the interplanetary medium (region I) is defined by conduction; only a small fraction of the energy is converted into kinetic energy of the solar wind.

The most interesting parts are the regions between the corona and the solar limb region: the main *chromosphere* (region IV) and the transition region *chromosphere-corona* (region III). The latter is extremely thin; for temperatures above about 10^5 K its temperature distribution is almost exclusively governed by downward conduction of energy from the corona. Radiative losses and absorption of shock wave energy are small, due to the thinness of this region. Reflexion of shock wave energy is important in this part of the Sun.

In a region where conduction is the only mechanism for energy transport the temperature law is given by

$$\mathrm{d}T/\mathrm{d}r = -F_{\text{cond}}/4\pi r^2 K,$$

where F_{cond} is the conductive flux, and K the thermal conductivity $\approx AT^{\frac{5}{2}}$ c.g.s. for a completely ionized gas. Following Chapman (1957; see also Unsöld 1970) we write

$$\tfrac{8}{7}\pi A \frac{\mathrm{d}(T^{\frac{7}{2}})}{\mathrm{d}(1/r)} = F_{\text{cond}}.$$

The solution of this equation is

$$T^{\frac{7}{2}} = T_m^{\frac{7}{2}} + \frac{7F_{\text{cond}}}{8\pi A}\left(\frac{1}{r} - \frac{1}{r_m}\right), \tag{1}$$

where F is taken negative for an inward flux, and T_m is the maximum temperature; it occurs at r_m.

The linearity of $T^{\frac{7}{2}}$ versus $1/r$ has been proved experimentally by various authors (see, for example, Dupree & Goldberg 1967) for temperatures above 10^5 K. For lower temperatures deviations from linearity are found. This is for one part due to the chromospheric emission; for decreasing temperatures the chromospheric gas loses energy by radiation, successively from He II (mainly the resonance line at 30.4 nm, and the He II continuum), from He I (mainly the continuum at 50.4 nm and the 58.4 nm resonance line), and from the Lyman emissions of *H*. If these emissions occurred at sharply defined height levels, as suggested schematically in figure 1, the curve of $T^{\frac{7}{2}}$ against $1/r$ would consist of some linear parts with smaller and smaller slopes for increasing $1/r$, as shown in the figure. The actual situation is more complicated because the emissions take place in broad regions and since in these thicker layers absorption of shock waves is more important than in region III.

Detailed computations of the chromospheric structure along these lines have not yet been made, but numerical estimates show that in non-magnetic regions the 10^5 K region is reached already at a height of less than about 1500 km. Above magnetic regions where the flux is larger this level would be reached even earlier (Kopp & Kuperus 1968). Hence, the actual chromosphere, as the transition region between photosphere and corona, appears to be thinner than 2000 km. The reason why the solar chromosphere seen at the limb so much thicker is simply due to the summed up influence of the spicules seen from the side.

5. Stellar chromospheres and coronae

The prediction of stellar chromospheric parameters should be performed along analogous lines to those followed for the Sun, but the procedure is a very uncertain one, in particular when one is dealing with non-solar type stars. The fact that nothing is known yet about the fraction of stellar surfaces covered by magnetic elements is one of the main uncertainties of the problem. First estimates of stellar coronal parameters were produced already long ago by De Jager & Neven (1961) on the basis of rough computations of stellar convection, mechanical fluxes and coronal emission. Later, Kuperus (1965) and Biermann (1969) made estimates of the flux of stellar acoustic noise in the Hertzsprung–Russell diagram, expressed in units of the solar value, on the basis of homologous relations derived for the relevant atmospheric parameters. According to Biermann, the most intense coronal X-ray fluxes measured at the Earth's distance would be expected from α Cen, followed by Sirius and Procyon.

TABLE 3. PREDICTED INTEGRAL X-RAY PHOTON FLUXES FROM SOME STELLAR CORONAE (AFTER DE LOORE & DE JAGER 1970), AS COMPARED TO THE SUN'S OBSERVED FLUX (PHOTONS $cm^{-2} s^{-1}$ AT EARTH'S DISTANCE)

star		minimum flux	maximum flux
Procyon	F5	0.008	0.06
α Cen	G2	0.005	0.04
β Cas	F2	0.0006	0.004
Sun	G2	0.2×10^9	1.5×10^9

The detailed computations by De Loore (1970) of stellar convection zones agree reasonably well with similar, equally detailed but less complete calculations of Nariai (1969). Both authors computed lines of equal acoustic energy generation in the Hertzsprung–Russell diagram. Furthermore, De Loore, besides giving mechanical fluxes for eighty atmospheric models, presented computations of detailed coronal models for half a dozen stellar cases. In contrast to Biermann's estimate both Nariai and De Loore show the hottest and most dense coronae to occur around F2 III stars. On the basis of De Loore's work expected X-ray fluxes were computed by De Loore & De Jager (1970) and were compared with similar computations for the Sun. These show that Procyon (F5 IV–V) would be the first star from which coronal X-ray emission could be detectable (see table 3).

So far for stellar coronae. Stellar chromospheres would be detectable earlier than coronae, by their emission in strong lines in the visible and u.v. regions, and have actually already been found. Their production is qualitatively understandable on the basis of the considerations of § 4, but computations have not yet been made. It is expected that these will be produced in the years to come.

Many thanks are due to Dr Kuperus for interesting discussions.

REFERENCES (de Jager)

Appenzeller, I. & Schröter, E. H. 1968 *Solar Phys.* **4**, 131.
Athay, R. G. 1970 *Astrophys. J.* (in the Press).
Athay, R. G. & Canfield, R. 1969 *Astrophys. J.* **156**, 695.
Athay, R. G. & Kuperus, M. 1967 *Solar Phys.* **1**, 361.
Biermann, L. 1969 *Proc. Roy. Soc. Lond.* A **313**, 357.
Böhm-Vitense, E. 1958 *Z. Astrophys.* **46**, 108.
Chapman, S. 1957 *Smithsonian Contr. to Astrophys.* **2**, 1.
Deubner, F. L. 1967 *Solar Phys.* **2**, 133.
Dupree, A. K. & Goldberg, L. 1967 *Solar Phys.* **1**, 229.
Gingerich, O. & de Jager, C. 1968 *Solar Phys.* **3**, 5.
Howard, R. 1967 *Solar Phys.* **2**, 3.
De Jager, C. & Kuperus, M. 1961 *Bull. Astr. Insts Neth.* **16**, 71.
De Jager, C. & de Loore, de C. 1970 *Solar Phys.* **13**, 126.
De Jager, C. & Neven, L. 1961 In *Les spectres des astres dans l'ultraviolet lointain.* Liège Colloquium **20**, 552.
De Jager, C. & Neven, L. 1967 *Solar Phys.* **1**, 27.
De Jager, C. & Neven, L. 1971 *Solar Phys.* (in the Press).
Kopp, R. A. & Kuperus, M. 1968 *Solar Phys.* **4**, 212.
Kuperus, M. 1965 *Recherches Astron. Obs. Utrecht* **17** (1).
Kuperus, M. 1969 *Space Sci. Rev.* **9**, 713.

Lighthill, M. J. 1952 *Proc. Roy. Soc. Lond.* A **211**, 564.
De Loore, C. 1970 *Astrophys. Space Sci.* **6**, 60.
De Loore, C. & de Jager, C. 1970 In *Non-solar X and γ-astronomy* (ed. L. Gratton). *Symp. I.A.U.* **37**, 223.
Milkey, R. W. 1970 *Solar Phys.* **14**, 62.
Nariai, K. 1969 *Astrophys. Space Sci.* **3**, 150, 160.
Osterbrock, D. E. 1961 *Astrophys. J.* **134**, 347.
Proudman, I. 1952 *Proc. Roy. Soc. Lond.* A **214**, 119.
Stein, R. F. 1967 *Solar Phys.* **2**, 385.
Unsöld, A. 1960 *Z. Astrophys.* **50**, 57.
Unsöld, A. 1970 *Astron. Astrophys.* **4**, 220.
Ulmschneider, P. 1970 *Solar Phys.* **12**, 403.