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Chromospheres, Transition Regions, and Coronas

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As long as total solar eclipses have been observed, people have seen the extended region around the sun, called the corona, which gives off a dim ghostly light during the total eclipse. The corona is not homogeneous but has a radial structure, or streamers (see Fig. 1). The resemblance to a crown gave it its name. The total amount of light emitted by the corona is only about one millionth of the light emitted by the solar disk itself, that is, photospheric spectrum. Analysis of the coronal light reveals that it consists of three parts:

1) The Fraunhofer corona, which consists of photospheric light scattered by "dust" particles at large distances from the sun.

2) The continuum corona, which is also due to photospheric light, but scattered by rapidly moving electrons in the solar corona. Because of the very rapid motions of the scattering particles, the Fraunhofer lines are washed out by the Doppler effect.

3) Some fairly strong emission lines, which differ so much from the photospheric spectrum that they cannot be scattered photospheric light but must originate in the corona itself. In discussing the coronal spectrum in this article, I mean this emission line spectrum of the corona proper. The coronal line at wavelength $\lambda = 5303$ Å can be seen in Fig. 2.

During the first seconds of a total solar eclipse, when the solar disk is just covered by the moon, another kind of spectrum, the "flash" spectrum, is visible (see Fig. 2). This emission occurs in a layer just above the photosphere. Its brightness is about 10 to 100 times that of the total corona, but it remains visible only for a few seconds, indicating that it is emitted by a layer whose vertical extent is of the order of 10,000 km. As shown in Fig. 1, the extent of the corona is several solar radii (the solar radius is 700,000 km). The layer that emits the colorful flash spectrum is called the chromosphere.

Summary. The increase in temperature outward from the surface of a stellar photosphere can be understood by looking at the local energy balance. The relatively high-density stellar photosphere is cooled effectively by radiative energy loss penetrating the optically thin corona. For the low-density chromosphere and corona, if the energy input cannot be balanced by radiative energy losses, the temperature will rise steeply, possibly up to 1 million degrees or more. Coronal heating and emission appear to be strongly influenced by magnetic fields, leading to large differences in x-ray emission for otherwise similar stars. Comparatively small variations are seen in the overall chromospheric emission of stars. Chromospheres are probably mainly heated by shock-wave energy dissipation, modified by magnetic fields.

Observed Temperature Stratification in the Outer Layers of the Sun

The corona. The source of the coronal emission line spectrum remained a mystery for many years until Grotrian (*1*) and Edlén (*2, 3*) identified most of the observed corona lines with transitions in very highly ionized heavy elements. The identification of the lines implied that some elements had to be ionized 15 times. Removal of the last electron would require energies of about 500 eV. Such energies cannot be supplied by the photospheric radiation field; they can only be supplied from the kinetic energy of particles. Grotrian inferred that the corona must have temperatures of the order of 1 million degrees, which came as a big surprise. It led to questions of how such high temperatures can be sustained above the solar photosphere, which has an average temperature of 5800 K and a surface temperature of about 4500 K; how the photosphere can remain cool in between the hot solar interior and the hot corona outside; and whether this contradicts the second law of thermodynamics. In fact, if the very high coronal temperatures had not been so difficult to believe, they might have been discovered much earlier from the large Doppler effects implied by the washed out Fraunhofer lines of the continuous corona.

Modern x-ray observations confirm the high coronal temperatures. Figure 1b shows a photomontage of an x-ray picture of the sun on the disk of the moon occulting the sun. The structure in the x-ray picture of the corona reflects the magnetic field strength and also the topology of the field lines. X-ray dark regions, the so-called coronal holes, coincide with regions where the magnetic field lines are "open" (this means that they close at very large distances from the sun). Bright coronal regions coincide with regions where the magnetic field lines are closed in the corona. Loop structures can often be seen (Fig. 3).

The chromosphere. Studies of emission line strengths and degree of ionization can also be used to determine the temperature in the chromosphere. The chromospheric line emission is mainly due to elements that are ionized only once, indicating a much lower temperature. For a quantitative determination of the temperature it is necessary to study how much of the energy needed for the ionization and light emission comes from absorption of photospheric radiation and how much must ultimately come from collisions (including the reabsorbed energy from chromospheric emission).

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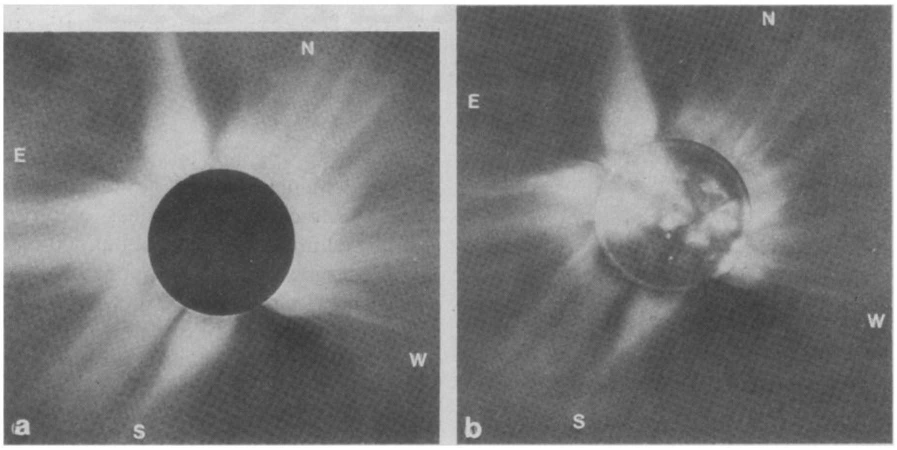


Fig. 1. (a) The solar corona on 7 March 1970 during total solar eclipse [from Gibson (*40*)]. (b) X-ray picture of the solar disk, taken shortly after the eclipse, photomontaged on the disk of the moon.

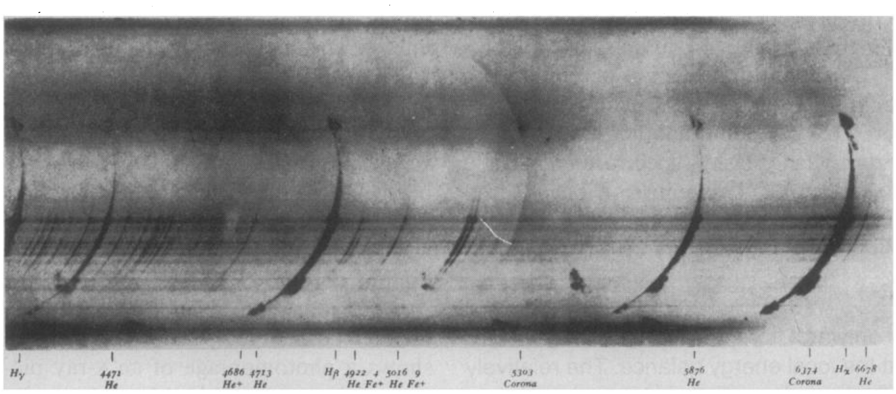


Fig. 2. Slitless solar flash spectrum taken 14 January 1926 by Davidson and Stratton (*41*). The emission spectrum shows lines of hydrogen, helium, and ions of the heavy elements. The curved solar limb is seen in the light of the different lines. A coronal emission line is seen at 5303 Å. [From Unsöld (*42*); courtesy of Springer-Verlag]

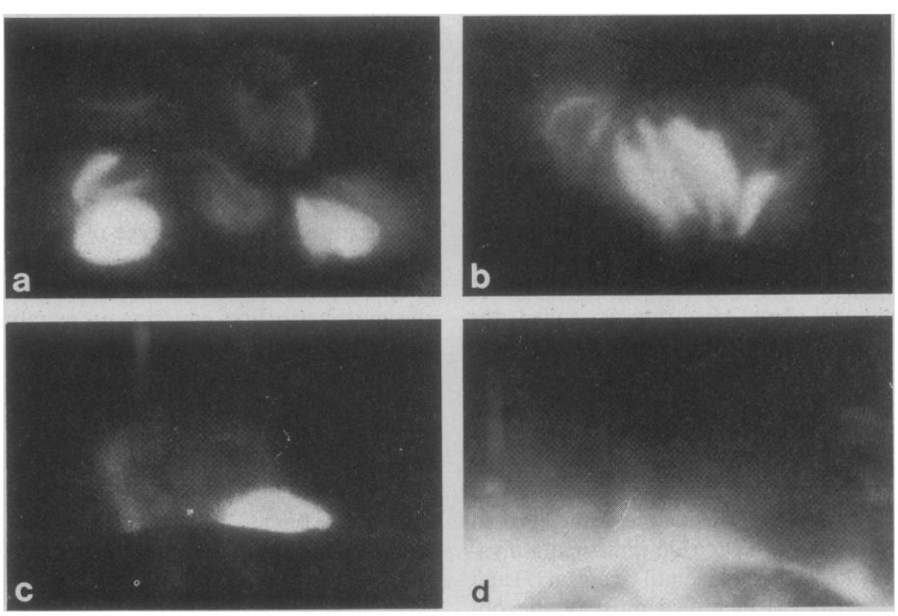


Fig. 3. X-ray pictures of the solar corona. Loop structure is often seen in the x-ray emission, outlining the geometry of the magnetic lines of force. [From Rosner *et al.* (*10*); courtesy of *Astrophysical Journal*]

From such a study we can, in principle, determine the temperature necessary to give the observed chromospheric spectrum, but many of the details of the processes involved are still under investigation.

Solar eclipse observations can show directly the stratification of temperature and density. During a total solar eclipse, a few seconds before the disk becomes visible again, the light comes mainly from the highest chromospheric layers. As the eclipse progresses, successively deeper layers contribute to the light. Using the observations of the highest layers first, we can see how much light is added for successively deeper layers. It is generally found that in the chromosphere the temperature increases slowly outward to about 8500 K; thereafter it increases somewhat more rapidly to about 20,000 K.

The transition region. Since the corona has temperatures of about 2 million degrees and the chromosphere temperatures up to 20,000 K, there must be a layer with temperatures between 20,000 and 1 million degrees. This layer is called the transition region. Woolley and Allen (*4*) pointed out on theoretical grounds that the transition layer might be very thin, and the temperature might rise from 20,000 to 500,000 K over a distance of only 5000 km.

With the availability of rocket and satellite observations in the far ultraviolet ($\lambda < 1700$ Å), new ways of observing chromospheres and transition layers have been opened up. In the far ultraviolet the photospheric radiation of the sun is so reduced that the intensities of the emission lines of the chromosphere and transition layer are greater than the intensity of the photospheric light even when there is no eclipse. Figure 4 shows part of the solar ultraviolet spectrum. From such observations it is found that the temperature increase is even steeper in the lower transition region than suggested by Woolley and Allen (*4*). Figure 5 shows the temperature stratification as derived by Böhm-Vitense (*5*).

Understanding the Temperature Stratification

How can a temperature stratification such as that shown in Fig. 5 be maintained in nature? How can the temperature minimum at the surface of the photosphere ($h = 0$ in Fig. 5) be maintained between the hot solar interior and the hot corona? Keeping in mind that outside the solar corona there is the cool interstellar medium, we should ask instead how the corona can be maintained at a temperature between 1 million and 2 million degrees in between the relatively cool photosphere and the cold interstellar medium. This is the question addressed below.

The observational fact that the solar photosphere maintains its temperature in spite of its radiative energy loss at the surface is very important for understanding the photospheric temperature stratification. If the photosphere does not cool off, it must be heated from below at the same rate at which it loses energy at the surface. Such a heat flow requires a decreasing temperature outward. How can the photospheric heat flow go from the cool photosphere to the hot corona?

Actually, it does not go to the corona, it only goes through the corona. There is so little material in the corona (about 10^{-5} g in a column of 1 cm^2, compared to 1 g/cm^2 in the photosphere) that the corona is transparent to the photospheric radiation, and the photosphere can cool off in spite of the hot corona.

Furthermore, the hot corona transports very little heat into the photosphere to increase its temperature because the radiation from the corona is about one millionth of the photospheric radiation. Absorption of that much radiation by the photosphere results in heating that is negligible compared with the radiative loss from the photosphere. In addition, heat conduction is not important. The conductive heat flow downward is about one ten-thousandth of the photospheric radiation loss. In essence, the photosphere does not notice the corona; it barely notices the chromosphere.

Energy Balance in the Outer Layers of the Sun

Similar considerations apply in trying to understand the high temperatures of the outer layers of the sun. The chromosphere and corona are also constantly losing energy by radiation and by heat conduction. In order to stay hot, they also must constantly be supplied with energy. The amount of energy a hot gas loses by radiation can be calculated, and at least that much energy must be supplied to keep the gas hot.

For light to be emitted electrons must be excited into a higher energy level. In the outer solar layers excitation occurs mainly through collisions between electrons and atoms or ions. Photon emission therefore drains kinetic energy from the gas. Higher densities mean more frequent collisions and excitations and larger energy losses by radiation. Locally, energy losses increase with the square of the density. At very low densities the gas finds it hard to get rid of its energy.

With increasing temperature, electrons can be excited to higher energy states, from which they can emit more energetic photons. Radiative energy losses increase with increasing temperature up to about 10,000 K. At higher temperatures other effects become important. Hydrogen ionizes around 10,000 K. Helium ionizes above 20,000 K the first time and above 40,000 K the second time. Heavier atoms become fully ionized at higher temperatures. Complete ionization of abundant elements reduces radiative energy losses, since no electrons are left to be excited.

Several authors have calculated radiative energy losses [for instance, Cox and Tucker (*6*)]. Figure 6 shows the results of McWhirter *et al.* (*7*), Pottasch (*8*), and

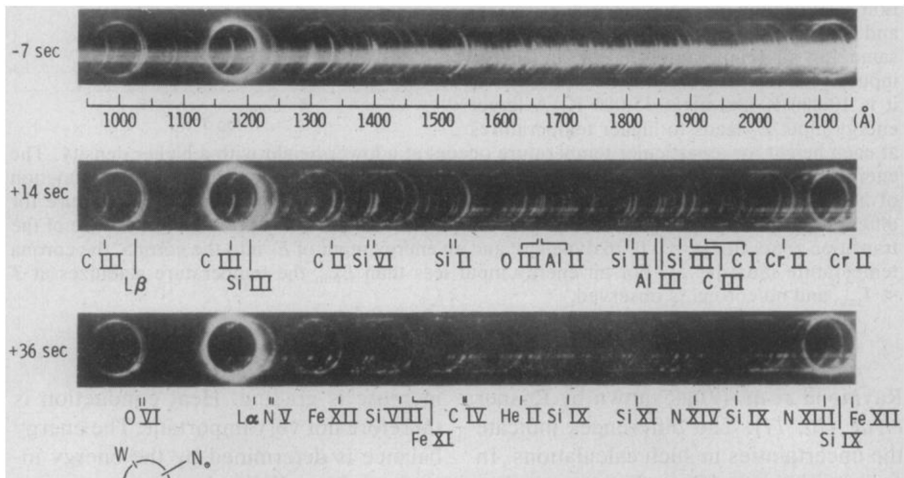


Fig. 4. Slitless ultraviolet spectrum of the transition layer taken from a rocket during total solar eclipse. Images of the solar limb are seen for the different spectral lines. The ions responsible for the line emission are indicated. [From Gibson (*43*); courtesy of National Aeronautics and Space Administration]

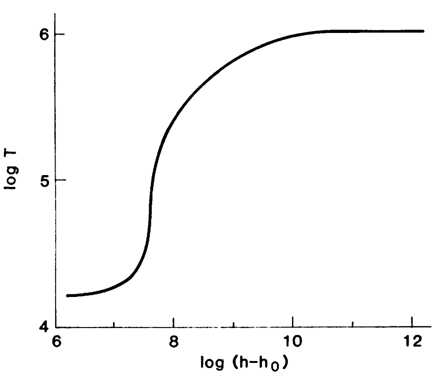


Fig. 5. Temperature stratification in the transition layer derived from the ultraviolet emission line spectrum by Böhm-Vitense (*5*). The height h is measured in centimeters and the temperature in kelvins; h_0 refers to a point in the upper photosphere and is chosen arbitrarily.

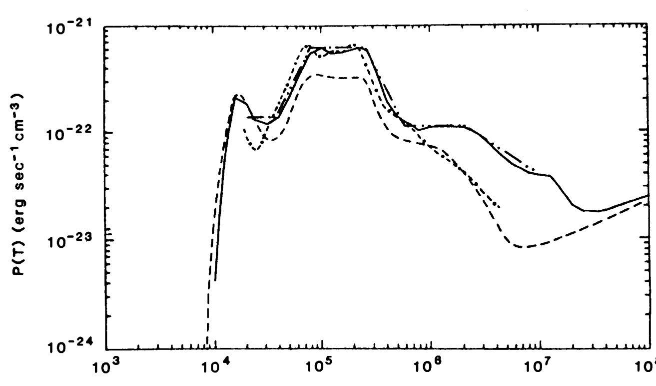
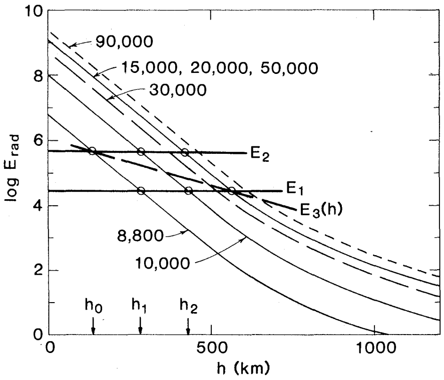


Fig. 6. Radiative energy loss as a function of temperature for a given density according to Pottasch (*8*) (.---.), McWhirter *et al.* (*7*) (----), Raymond (*9*) (——), and the approximation of Rosner *et al.* (*10*) (-...-). [From Rosner *et al.* (*10*); courtesy of *Astrophysical Journal*]



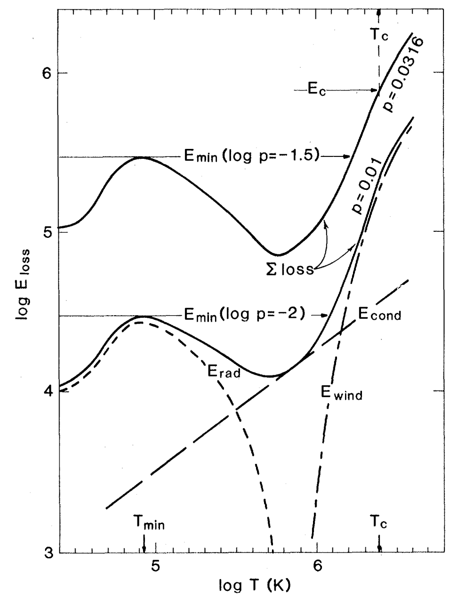


Fig. 7 (left). Radiative energy loss at different temperatures as a function of height (h) in the solar chromosphere. [The density and ionization stratification is from Vernazza *et al.* (*44*) and is assumed, for this discussion, to be the same for all temperatures.] For an energy input E_1 the temperature at h is 8,800 K. At h_2 it is 10,000 K and at h_3 15,000 K. A larger energy input E_2 leads to higher temperatures at each height, or a particular temperature occurs at a lower height with a higher density. The energy input as a function of height, for instance $E_3(h)$, determines the temperature as a function of height. Fig. 8 (right). Total energy loss of a corona as a function of temperature for different pressures in the corona. The pressure is determined by the pressure at the base of the transition zone. For p = 0.0316 dyne/cm^2 and an energy input of E_c into the corona, the corona temperature must be T_c. For an energy input less than E_{min} the temperature stabilizes at $T < T_{min}$ and no corona is observed.

Raymond *et al.* (*9*) as shown by Rosner *et al.* (*10, 11*). The differences indicate the uncertainties in such calculations. In a qualitative sense they all agree on some basic features. At constant density and a given chemical composition radiative losses increase with increasing temperature up to about 15,000 K. At higher temperatures hydrogen ionizes and the losses drop until helium becomes important and the losses increase again. When helium ionizes, heavier elements become responsible for the energy loss. At temperatures above 200,000 K the material is highly ionized and radiative losses drop finally, at least up to 6 million or 7 million degrees.

Energy Balance in the Chromosphere

In the following discussion we consider the density stratification as equal to the observed one. Clearly, a temperature increase in deeper layers will increase the density scale height and thereby increase the density in higher layers, and vice versa, but this is only a secondary effect resulting from the temperature changes. Our main concern here is to understand the temperature increase outward, which is the primary effect for the creation of the chromosphere and corona. Starting with the resulting density stratification permits us to consider the energy balance locally.

In the chromosphere the temperature increase is gradual. Heat conduction is therefore not very important. The energy balance is determined by the energy input and the radiative losses.

Suppose we start with a star whose temperature is as expected from our discussion of the photosphere: cool at the outside with the temperature increasing inward. In radiative equilibrium the amount of radiative energy absorbed in each layer is equal to the amount of energy reemitted. If we now put additional energy into the outer layers (assuming for simplicity that the energy input into each cubic centimeter is independent of height), the additional energy leads to an increase in temperature, T. For $T <$ 15,000 K this leads to increased emission. When the increase in emission equals the increase in energy input, the heating stops. A new equilibrium temperature is reached. Figure 7 shows the radiative energy loss per unit volume for different temperatures as a function of height in the solar chromosphere (*12*). With increasing height the radiative losses per unit volume decrease approximately in proportion to the square of the density. We start out with a cool chromosphere, say 4300 K. At this temperature photon absorption and emission balance. We now put an additional amount of energy E into the chromosphere such that the total energy input per cubic centimeter is E_1 at each layer. At height h_1 the temperature now stabilizes at 8800 K because the energy loss for this temperature equals the energy input E_1. At height h_2 the temperature keeps rising until it is 10,000 K, and at height h_3 it stabilizes only at 15,000 K. For a given energy input we obtain a temperature increasing outward because the radiative energy losses decrease with decreasing density.

Suppose we now increase the energy input to the higher value E_2. The temperature now rises everywhere, and a particular temperature is now found at a lower depth with a higher density. For instance, 8000 K is now found at the lower depth h_0, where we have a larger density; we find 10,000 K at h_1 and 15,000 K at h_2. The density of the chromosphere at a given value of T tells us how large the energy input is.

So far, it has been assumed that the energy input is independent of height. Figure 7 also shows the case where the energy input $E_3(h)$ per cubic centimeter decreases with height. In this case we find a smaller temperature gradient dT/dh, but still temperatures increasing outward, as long as $dE_3(h)/dh < dE_{loss}/dh$, that is, as long as the energy input decreases more slowly with height than the energy loss for a constant temperature. The temperature gradient in the chromosphere can tell us how the energy input depends on height.

Energy Balance in the Transition Layer

Figures 6 and 7 show that at temperatures just above 20,000 K the energy loss decreases with increasing temperature. If energy balance cannot be achieved at a temperature less than 20,000 K, the temperature keeps rising until about 50,000 K is reached. This leads to a steep temperature increase. At a slightly greater height an energy input E_1 is even larger than the energy loss at 90,000 K. Beyond this temperature the energy loss finally decreases with increasing temperature, as seen in Fig. 6. The assumed energy input E_1 is now larger than the radiative energy loss at any temperature. The temperature keeps rising and the energy loss keeps falling, which makes the temperature increase even more. A runaway temperature increase occurs, building up the transition layer. The temperature increase stops only when additional energy losses become important. An energy input $E_2 > E_1$ would already surpass the energy loss at higher densities, and the transition layer would occur at higher densities.

A steep temperature gradient leads to heat conduction in the direction of decreasing temperature. In the case of the transition layer this constitutes energy transport back to the photosphere, which means that it drains energy from this layer. In the chromosphere the temperature gradient is modest, but in the transition layer it becomes so steep that the temperature stratification is determined essentially by heat conduction. The conductive flux through the transition layer serves to drain the surplus energy from the corona. Such transition layer stratifications were first discussed by Woolley and Allen (*4*) and by Unsöld (*13*).

Energy Balance in the Corona

When studying the corona we must look at yet another energy loss mechanism. Observations of comet tails led Biermann (*14, 15*) to conclude that a wind must be blowing from the direction of the sun with particle velocities of several hundred kilometers per second. Parker (*16*) clarified the physical processes that lead to the solar wind: at a distance of several solar radii gravitation becomes too weak to keep hot gas bound. If hot coronal gas extends to such large distances, the pressure forces make the gas escape at high speeds. (For low temperatures the density at such distances would be too low to cause any noticeable wind.) The pressure forces increase with increasing temperature, causing a rapidly increasing energy loss. For high coronal temperatures the solar wind is a very efficient cooling agent. The same considerations apply to other stars.

In the following discussion I will assume a spherically symmetrical homogeneous corona of constant temperature. This is a grossly simplified picture, as seen from Fig. 1, but it helps in understanding the major effects. For such a schematic corona, Hearn (*17*) gave approximate equations for calculation of the total energy loss.

Figure 8 shows the energy loss of a corona by radiation, E_{rad}, and by heat conduction, E_{cond}, plotted as a function of coronal temperature, assuming that the stratification in the transition layer is determined by heat conduction. The energy loss due to the stellar wind, E_{wind}, is also plotted as a function of temperature. Curves are drawn for different pressures in the corona. As discussed in the preceding section, the density in the transition zone, and therefore also in the corona, is determined by the energy input at the base of the transition zone. For a given energy input, E_c, into the corona, the temperature is determined by the equilibrium condition $E_c = E_{wind} + E_{cond} + E_{rad}$. The larger the energy input the larger the temperature. The increase in temperature with increasing energy input is, however, very small, since the energy loss due to the stellar wind increases so steeply with temperature.

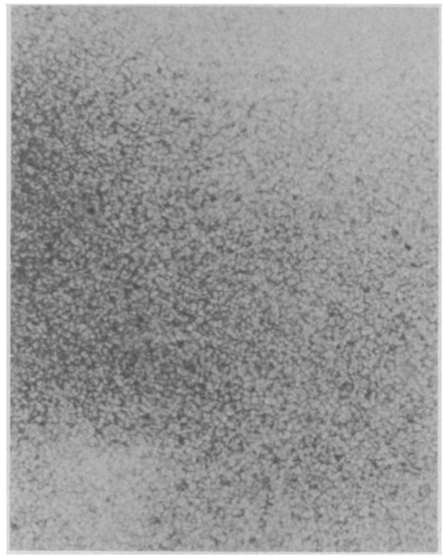


Fig. 9. High-resolution image of the solar surface showing solar granulation. Bright regions are moving upward, dark areas downward. [From Gibson (*45*); courtesy of the National Aeronautics and Space Administration]

In Fig. 8 we see that for a given pressure the total coronal energy loss has a minimum at a temperature, T_{min}, which depends on the density. There have been discussions in the literature, starting with a paper by Hearn (*17*), whether coronal density and temperature would adjust in such a way as to obtain this temperature of minimum energy loss for a coronal density which would adjust according to the energy input. I do not see how it could. If the energy input equaled the energy loss at this minimum, the corona would actually stabilize at the lower temperature T_0. However, T_{min} is a lower limit to the actual temperature. It appears that the actual coronal temperature cannot be very much higher, since the energy loss increases so steeply with temperature.

Energy Input into the Chromosphere

The discussions above show how we can understand the temperature stratification in the outer layers by considering the equilibrium between energy loss and energy input. We must still consider what causes the energy input. It cannot be radiation alone, because if it were the chromosphere would be in radiative equilibrium, which would generally give a temperature decreasing outward. Also, there can be no other kind of heat transport from the cool photospheric gas to the hotter chromosphere and corona. The only way to create a hot layer of gas within a cool surrounding is by heating the gas with mechanical energy (for instance, by acoustic waves or shock waves) or with some form of magnetohydrodynamic energy. A goal of modern studies of chromospheric and coronal temperature stratifications is to try to decide which of these mechanisms is the more important one. The next question is how such energies can be created in a hot ball of gas like the sun.

Mechanical or kinetic energy can be generated by means of temperature differences. There is a natural temperature gradient in a star due to the heat transport from the inside out. In layers where the radiative conductivity is very small, a very steep temperature gradient is required to transport the energy by radiation. This leads to convection. In the sun, the radial temperature gradient leads to rising and falling gas streams, which we can see in the photosphere as the solar granulation (see Fig. 9). The bright granules appear to rise. The dark areas generally fall, as can be seen from the Doppler shifts of the spectral lines in the different regions. Velocities up to 7000 km/hour are observed; for comparison, the velocity of sound in the photosphere is about 18,000 km/hour. At such high velocities large amounts of noise (acoustical waves) are generated (*18*). Some of these are absorbed in the photosphere, but a not very well-determined fraction of the acoustic waves are able to travel outward into the low-density chromosphere, where they steepen to form shock waves. We know from experience that shock waves dissipate their energy rapidly and generate large amounts of heat, which may possibly heat the chromosphere (*19*). If this is indeed the main source of energy for heating the chromosphere, then stars with larger convective velocities than the sun may be expected to have stronger chromospheric emission than the sun. This can be tested by observation.

If convection alone causes chromospheric heating, we may expect stars with outer convection zones to have chromospheres, while those without outer convection zones do not. Overall, stellar properties are best visualized in the Hertzsprung-Russell diagram (Fig. 10), where stars are entered according to their temperature and luminosity, or intrinsic brightness. In the H-R diagram most stars fall along the main sequence. Larger and hence brighter stars are called giants or supergiants. Stars to the right of the solid line in Fig. 10 are expected to have outer convection zones; stars to the left, which have higher temperatures, are not. The change is expected to be quite abrupt (*20*).

Since the launching of the International Ultraviolet Explorer (IUE) satellite (*21*), chromospheres of many cool stars have been observed. It was confirmed that stars with outer convection zones have chromospheres, while for stars without outer convection zones no chromospheric emission lines were visible. In fact, chromospheric emission decreases rather abruptly at the boundary line for outer convection zones (*22*). As expected theoretically, it is generally observed to increase for stars with increasing convective velocities, although there are still quantitative disagreements between theory and observations (*23*). There are, however, many stars with enhanced chromospheric emission, referred to as stars with active chromospheres, which shows that other effects are also important.

Stars may inherit a magnetic field at birth from the interstellar medium. At the photospheres and outer convection zones of stars these magnetic fields are expected to decay within 100 million to 1 billion years. Older stars with surface magnetic fields, like our sun, must have regenerated their fields. It is generally thought that convective mass flows, subject to Coriolis forces on a rotating star, in combination with differential rotation (the sun rotates faster at the equator than at the pole) can result in a dynamo action which builds up a magnetic field in the surface layers of a star. In the case of the sun, this turns out to be a periodically varying magnetic field leading to the 22-year sunspot cycle. More rapidly rotating stars, possibly with stronger differential rotation, might be expected to have stronger magnetic fields than the sun, but fields still too weak to be measured on a distant star.

Weak chromospheric emission lines can be found in the solar spectrum in the center of the strong Fraunhofer line due to the calcium ion (the Ca II *K* line) and also in the ultraviolet lines of the magnesium ion (the Mg II *h* and *k* lines). Wilson (*24*) made extensive observations of stellar Ca II *K* lines. Based on these observations, Skumanich (*25*) concluded that for ages up to the age of the sun, 4.5×10^9 years, chromospheric emission for stars of a particular type decreases with increasing age of the stars. Stellar rotation also decreases with increasing age of the stars. Satellite observations of the Mg II *h* and *k* lines con-

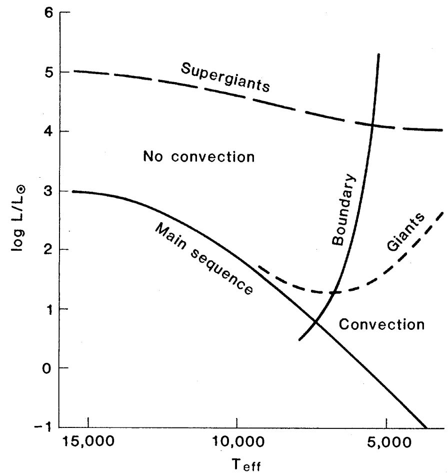


Fig. 10. Schematic diagram of luminosity versus T_{eff}, showing the positions of the main sequence, the giants, and the supergiant branches. Cool stars have a surface convection zone; hot ones do not. The dividing line between convective and nonconvective stars is shown as a solid line labeled *Boundary*. Stars to the right of this line show chromospheric emission lines; stars to the left do not.

firmed that young stars show greater emission than older stars (*26*).

Solar observations also showed that the Ca II *K* emission is stronger in regions of stronger magnetic fields (*27*), indicating that either more energy is fed into the chromosphere in regions of stronger magnetic fields, or the energy is preferentially dissipated in regions of stronger magnetic fields. Since the overall Ca II *K* emission increases at sunspot maximum, when large magnetic fields occur at the solar surface, it appears that more energy is delivered to the chromosphere if the magnetic field is stronger. Calculations indicate that more acoustic noise will be generated in regions with increased magnetic fields.

With this in mind, Skumanich concluded that the observed decreasing chromospheric emission with increasing stellar age is probably caused by a decreasing magnetic field due to decreasing rotation. In the case of young stars, a decreasing magnetic field may also be due to decay of the inherited fossil field.

Observations of the Ca II *K* line (*28*) and the Mg II *k* line (*29*) also indicate enhanced emission for close binary stars, which probably means that they too have enhanced magnetic fields due to either rapid rotation or tidal interaction.

The Ca II *K* line emission has been observed only for stars cooler than about 6500 K. These stars generally are slow rotators. For hotter stars, which are frequently rapid rotators, the Mg II *h* + *k* lines have been observed. Such observations show that for very rapid rotation the emission does not increase further with increasing rotation (*26*). Perhaps stronger magnetic fields can reduce the convective motions, thereby reducing the acoustic wave energy output. Further studies will be needed to answer this question.

If magnetic fields and rotation decrease with increasing age, then chromospheric emission from very old stars should be very weak. Observations of star clusters show that very old stars have lower abundances of heavy elements. Turning this around, we can say that stars with a low abundance of heavy elements are very old, which appears to be the case for stars in our galaxy. Observations indicate that for such old stars the total chromospheric emission probably decreases little, if at all, with increasing age, where age is measured by decreasing heavy element abundance (*30*). It seems that once the fossil magnetic field has decayed, after about 10^9 years, the magnetic fields decrease very slowly, or perhaps for very weak fields the field strength becomes unimportant for chromospheric heating. Further studies are needed to confirm this result.

In conclusion, acoustic noise generation in stellar outer convection zones appears to be necessary for the heating of solar-type chromospheres. Some additional mechanism, probably related to magnetic fields, may enhance chromospheric energy input, except possibly for very weak and very strong fields.

Heating of the Corona

Since the corona loses less energy than the chromosphere, it needs much less energy to stay hot. Nevertheless, the heating of the corona poses more difficult problems to the theoreticians. Shock waves appear to dissipate their energy in the chromosphere and have no energy left by the time they reach the corona. In addition, the steep temperature and density gradient in the transition zone would reflect acoustic waves. Nevertheless, the convection zone seems to be very important for heating of the corona.

I pointed out earlier that it has been possible to take x-ray pictures of the solar corona. It is not possible to take similar x-ray pictures of other stars, but the Einstein satellite, equipped with an x-ray telescope, has been able to measure the total x-ray emission of many stars (*31*). Surprisingly, x-ray emission was observed for almost all kinds of stars close enough to us that the flux was not too much diluted by distance. Only for cool, large stars—the giants and supergiants, with temperatures less than about 4000 K—has x-ray emission not yet been detected (*32*).

For the problem of the heat source of the corona, it is a significant observation that the x-ray emission of normal single stars increases abruptly by a factor of about 10 as the stellar temperature decreases from about 8000 to about 7500 K. The much higher x-ray emission of the cooler stars shows that they have a well-developed corona, while the hotter stars have either a low-temperature or a low-density corona. Stars with surface temperatures $T \leq 7800$ K are expected to have strong outer convection, while stars with $T \geq 8000$ K are not (Fig. 10). The abrupt increase in x-ray flux in this temperature range shows the importance of convection for coronal heating.

On the other hand, the fact that stars with higher temperatures also emit some x-rays shows that hot regions may also exist in the outer layers of stars that do not have an outer convection zone. In fact, for stellar surface temperatures above 8000 K the x-ray emission increases with increasing surface temperatures. The strong x-ray flux from hot stars is one of the many unsolved puzzles presented by the data from the Einstein observatory.

Why the cool giants and supergiants do not seem to have coronas in spite of their strong convection is another puzzle which astronomers are trying to solve. Observations by Simon *et al.* (*33*) showed that for these stars lines originating in transition regions cannot be seen either. It was suggested that this might be due to cooling by a very strong stellar wind. But in the absence of a hot corona, what would drive such a strong wind? No satisfactory solution has been found yet for the winds blowing from the cool luminous stars, though radiative acceleration due to photon absorption in the hydrogen Lyman alpha line (*34*) and Alfvén wave pressure (*35*) have been discussed.

A look at the x-ray picture of the sun shows rays (or streamers) and loops with enhanced x-ray emission. The only explanation of these streamers and loops is that they outline the direction of the magnetic lines of force in the corona. The loops appear to be confined by magnetic flux tubes. X-ray emission is enhanced along these structures which apparently outline stronger magnetic fields. Regions above sunspot groups with strong magnetic fields also show enhanced x-ray emission. Studies of line intensities indicate that these regions of enhanced x-ray emission are regions of higher temperature or density than their surroundings (*36*). Stronger magnetic fields appear to lead to higher radiative energy losses, which probably indicates higher energy input.

If it is correct that stellar magnetic fields are constantly regenerated by the interaction of convection and rotation, then we might expect the x-ray emission to increase with increasing stellar rotation for otherwise similar stars. Pallavicini *et al.* (*37*) observed increasing x-ray emission with increasing rotation, but their sample did not contain any stars rotating faster than 35 km/sec (actually, only the product $v_{rot} \sin i$ can be measured, where v_{rot} is the equatorial rotational velocity and i is the angle of inclination between the rotation axis and the line of sight). For stars with $T \gtrsim 7500$ K and rotational velocities larger than 50 km/sec, no further increase was found with increasing rotational velocity (*30*). Again, there seems to be a saturation effect.

Strongly enhanced x-ray emission is also observed for close binaries. Walter and Bowyer (*38*) and Walter (*39*) observed an increasing x-ray flux with decreasing separation of the two stars. Coronal temperatures appear to increase presumably due to increasing magnetic fields for close binaries either due to increasing rotation, expected for close binaries, or due to increasing tidal effects. More observations will be needed to determine which effect causes the increased emission and presumably an increased magnetic field.

In any case, these observations show a strong dependence of coronal x-ray emission on effects that are unrelated to convection and acoustic waves. The coronal structures seen in x-ray emission indicate the importance of magnetic fields. On the other hand, the observations also show that the presence of convection also increases coronal emission.

The variation in chromospheric emission from different stars is rather small, about a factor of 4, compared to the variation in x-ray flux, which can amount to a factor of 10^4. The range in chromospheric energy output can easily be explained in terms of the expected range of acoustic noise generation; in fact, we would expect larger variations. But the large increase in x-ray emission from some stars must be due to a much more efficient means of transporting energy into the corona. For strong x-ray emitters, a large fraction of the generated mechanical energy must be transformed into a form of energy that can reach the corona and heat it.

At present we do not know the mechanism of heating of the corona. We do not even know whether the heating takes place mainly in the loops. It is not possible here to discuss this in detail, but I would like to point out one possible mechanism for heating of the corona.

As discussed above, any acoustic energy reaching the chromosphere is dissipated rapidly in the chromosphere and cannot reach the corona. The rapid convective motions in the photosphere and chromosphere may, however, displace and distort the magnetic fields. This would generate magnetohydrodynamic waves (Alfvén waves), which are damped very little and can therefore travel along the lines of force into the corona. But this presents another problem: since the waves are not damped they will not dissipate their energy in the corona either. In fact, satellite observations have shown that Alfvén waves exist in the solar wind, and thus they may persist to very large distances from the sun. Looking at the corona, we see that only near the poles do the streamers indicate magnetic field lines that go almost radially outward. In most areas the field lines are bent with rather small radii of curvature. In such curved and tangled magnetic fields, Alfvén waves could regenerate waves related to acoustic waves (fast and slow modes, which may also form shocks), which can dissipate their energy in the corona. It is possible that Alfvén waves are the vehicle for transporting energy into the corona, where dissipation may occur due to shocks generated through fast and slow modes [for example, see (*15*) and (*20*)]. However, at present this suggestion is only speculative.

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Human Physiology at Extreme Altitudes on Mount Everest

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Summary. Extreme altitude presents an enormous physiological challenge to the human body because of severe oxygen deprivation. The American Medical Research Expedition to Everest was specifically designed to study man under these conditions, and successfully obtained physiological data above 8000 meters, including a few measurements on the summit itself. The results show that man can tolerate the extreme hypoxia only by an enormous increase in ventilation, which results in an alveolar partial pressure of carbon dioxide of 7.5 torr on the summit and an arterial *p*H of over 7.7. Even so, the arterial partial pressure of oxygen is apparently less than 30 torr, and maximum oxygen uptake is about 1 liter per minute. Additional measurements of ventilation, blood physiology, and metabolic and psychometric changes clarified how man responds to this hostile environment.

High altitude has always intrigued physiologists because of the remarkable ability of man and other animals to adapt to the hostile environment. When we ascend to elevations where the inspired partial pressure of oxygen (PO_2) falls to low levels, a whole series of compensatory changes take place in a process known as acclimatization. The changes include an increase in pulmonary ventilation, polycythemia, a rightward shift of the oxygen dissociation curve, an increase in the number of capillaries in peripheral tissues, and changes in oxidative enzymes within cells (*1*). As a result of these changes, lowlanders can spend extended periods of time at altitudes up to about 5300 m. This altitude also marks the highest habitation of permanent high-altitude dwellers, and such people, as in the South American Andes, show physiological changes that are in some ways similar to those of acclimatized lowlanders, although there are important differences (*1*).

Extreme altitudes, say above 6000 m, have evoked special interest in the past few years. A major milestone was the first ascent of Mount Everest (altitude 8848 m) without supplementary oxygen in 1978 by Messner and Habeler (*2*). Many physiologists thought that this feat could never be achieved, and the event was responsible for a surge of interest in the effects of extreme hypoxia on human physiology.

The American Medical Research Expedition to Everest in fall 1981 was designed to make the first measurements of human physiology above 8000 m. Data were successfully obtained above this altitude, and a few measurements were made on the summit itself. In addition, two laboratories were set up at 6300 and 5400 m, and a wealth of new information about man at extreme altitudes was obtained.

American Medical Research Expedition

There are two ways of studying the human response to prolonged exposure to low oxygen. One is to use a low-pressure chamber, but this has several disadvantages. For example, it is not clear whether subjects can tolerate confinement under reduced pressures for several weeks and remain physically fit. In addition, the psychological consequences of such confinement might complicate the results (*3*). Such an exposure is necessary to develop the acclimatization required in order to tolerate the low oxygen pressures that exist near the summit of Mount Everest.

A better solution is to use the natural laboratory of the mountain itself. However, it is difficult to accomplish scientific objectives on a regular mountaineering expedition, so the American Medical Research Expedition to Everest had an unusual design. The expedition had six highly experienced Himalayan climbers, including John P. Evans, climbing leader. Next, there was a group of six "climbing scientists," all of whom were strong climbers, but each was a doctor of medicine with an interest in high-altitude physiology. Their responsibility was to carry out the measurements at extreme altitudes. Finally, there was a third group of eight physiologists who worked

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