A SURVEY OF THE SOLAR ATMOSPHERIC MODELS*

K.D. Abhyankar
Centre of Advanced Study in Astronomy, Osmania University,
Hyderabad 500 007

INTRODUCTION :

A working model of the solar atmosphere is needed for several reasons : (1) to understand the observed distribution of energy in the spectrum of the quiet Sun ; (2) to find the abundances of elements in the Sun ; (3) to define the boundary conditions for the solar interior model ; and (4) to see how the fluctuations in the mean model could explain the solar phenomena. The model involves specifying essentially the run of temperature and the turbulent velocity parameter as a function of height. All other parameters such as pressure, excitation, ionisation, absorption coefficient etc. then follow from the equation of energy transfer, equation of hydrostatic equilibrium and the equation of state. The last equation includes the conditions of local thermodynamic equilibrium (LTE) or non-LTE as required.

It is the present practice to include in the atmosphere the whole region from the outer-most envelope of the body of the star to the boundary of the interstellar space. It is however convenient to distinguish between its parts viz., the photosphere below the optical depth of about .02 where the continuum and most of the dark Fraunhofer lines are formed ; the temperature minimum which is responsible for the infared spectrum from 10μ to 700μ and the UV spectrum around 1600A that is devoid of absorption lines ; the chromosphere which is characterised by emission lines ; the chromosphere-corona transition region indicating a sudden rise in temperature ; the corona with a kinetic temperature above one million degrees and finally the solar wind. The last region is obviously marked by the breakdown of hydrostatic equilibrium and the increased importance of the magnetic field. It will not be considered in this review which will be a sort of an historical account of how our ideas about the solar atmospheric model developed during the last 30 years. An excellent review of modern work is given by Eugene H. Avrett in the book 'The Solar Output and Its Variations', Ed. O.R. White, J.A. Eddy and D.F. Heath.

THE PHOTOSPHERIC MODEL :

The first model of the solar photosphere was constructed by Strömgren (1944) more than thirty years ago, which became possible at that time because : (i) it was firmly established that radiative transfer was the predominant mode of energy transport in the outer-most layers of the photosphere ; (ii) the Milne-Eddington solution of the equation of transfer for a grey atmosphere was found to be adequate for representing the observed limb darkening in white light ; and (iii) H^- was identified as the principal source of opacity and the first calculations of its absorption coefficient by Massey and Bates (1940) had become available. The main aim of Strömgren at that time was the determination of the hydrogen to metal ratio and abundances of certain other elements by making use of the theory of line formation.

Strömgren's was a theoretical model based on the Milne-Eddington solution, $B(\tau) = \frac{3F}{4\pi}\left(\tau + \frac{2}{3}\right)$, adjusted to the observed solar flux $F = \sigma T_e^4$, and the equation of hydrostatic equilibrium $\frac{dp}{d\tau} = \frac{g}{K}$. Here τ is the optical depth, T_e the effective temperature, g the surface acceleration to gravity and K the mass absorption coefficient. There was much progress on the theoretical side in the next few years. Chandrasekhar obtained the exact solution of the grey problem (1945) and calculated the correct eign-functions and absorption coefficient for H^- ion (1946). Also Münch (1946) was able to take into account the effect of line blanketting and bring the calculated and observed limb darkening in white light into fair agreement quite close to the limb. The net result was lowering of the boundary temperature to about 4600°K.

But in spite of the elegance of the theoretical methods, all later models of the solar photosphere were obtained empirically by making use of the observations of limb darkening in various wavelengths and the measurement of the intensity at the centre of the disk. The basic equation is

$$I_\lambda(0,\mu) = \int_0^\infty B_\lambda(\tau_\lambda)\, e^{-\tau_\lambda/\mu} \frac{d\tau_\lambda}{\mu} = B_\lambda\left\{\bar{\tau}_{\lambda_0}(\mu)\right\},$$

where $\mu = \cos\theta$ which varies from unity at the centre of the disc to zero at the limb. Since $\bar{\tau}_{\lambda_0}$ increases with increasing μ and decreasing absorption coefficient K, one can obtain the variation of temperature with optical depth at any wavelength and convert the results to the optical depth at a single wavelength λ_0 which is usually taken at λ 5000A and denoted by τ_{5000}. As $I_\lambda(0,\mu) = I_\lambda(0,1) \times [I_\lambda(0,\mu)/I_\lambda(0,1)]$ we need the intensity at the centre of the disc $I_\lambda(0,1)$ and the limb darkening $I_\lambda(0,\mu)/I_\lambda(0,1)$. These data are given for example by Minnaert (1953) and Goldberg and Pierce (1959) respectively. Combining these two sets of data we get $T(\tau_\lambda)$ for each wavelength. All results are then combined into one single model by converting the optical depths τ_λ to τ_{5000} through the known variation of absorption coefficient with wavelength ; cf Pierce and Waddell (1961).

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There are two limitations to this method of model making. At the centre of the disc we can look through to an optical depth of about unity which is thus the limit of our observations. However, the variation of the solar absorption coefficient as determined by Münch (1945) indicates that the atmosphere becomes more than twice as transparent at 1.6μ as at 5000A. Hence extension of observations to longer wavelengths allows us to extend the model to $\tau_{5000} = 2$–3. Below this optical depth we have to resort to theory. Here convection plays an important role in the transport of energy. Already at optical depths exceeding unity the radiative temperature gradient becomes larger than the adiabatic gradient due to inonization of hydrogen. This hydrogen convection zone extends to depths of thousands of kilometers because of the increase of absorption coefficient with temperature and later due to the first and second ionisation of helium as computed by Böhm-Vitense (1953). The theoretical models for the convection zone, which are based on the mixing length theory, can be confirmed to some extent by the study of the profiles of certain faint metal lines having contributions from these deep layers.

At the other extreme the difficulty of limb observations does not allow us to study the topmost layers of the solar atmosphere. The eclipse observations (Minnaert 1953) can take us to $\tau_{5000} \approx 0.01$. Hence, before the advent of rockets and satellites one had to depend on theory for extending the photospheric models to the surface.

The derived photospheric model of Minnaert (1953) along with Utrecht (Heintze et al, 1964), Bilderberg (Gingerich et al, 1968) and Harvard—Smithsonian (Gingerich et al, 1971) models are shown in Figure 1. The more recent results give higher temperature in deeper layers as compared to the model of Minnaert. The remaining differences, which are of the order of a few hundred degrees at optical depths near $\tau_{5000} \approx 10$ are actually an indication of the uncertainties in the mixing length theory of convection. However, the Harvard-Smithsonian model predicts quite well the accurate observations of I_λ (0,1) reported by Labs and Neckel (1968).

THE CORONA :

Next we shall discuss the corona, because in early fifties our knowledge of the corona was almost as complete as that of the photosphere, cf. van de Hulst (1953). Study of the eclipse photographs had allowed the separation of the false F corona, which is nothing but zodiacal light, from the true K corona which shows polarization and obliteration of Fraunhofer lines due to the scattering by fast moving electrons. The measured intensities could also be inverted to obtain the variation of electron density with height. The coronal emission lines were not only identified by Grotrian and Edlen but also photographed by Lyot with his coronograph. The radio emission of the corona was also observed and measured by the raido astronomers. All the various lines of research converged to produce a consistent picture in which the corona emerged as a more or less quiet isothermal atmosphere of high temperature plasma on which fluctuations are superimposed by the solar activity. The temperature was estimated to exceed one million degrees on several counts : (i) obliteration of Fraunhofer lines indicating high kinetic temperature; (ii) density gradient with a large scale height corresponding to a high temperature; (iii) large widths of emission lines caused by large thermal motions ; (iv) high degree of ionisation of atomic species like Fe, Ni and Ca ; and (v) radio brightness at meter wavelengths.

The energy required to maintain the corona at such a high temperature was supposed to be supplied by shock waves arising from the granulation and spicules, which were themselves the results of overshooting of the convection elements from the deeper layers of the photosphere.

This model of the corona is almost unchanged during the last twenty years although some details have been added in respect of coronal condensations, active regions and coronal holes. The presently accepted value of coronal temperature is 1.6×10^6 degrees.

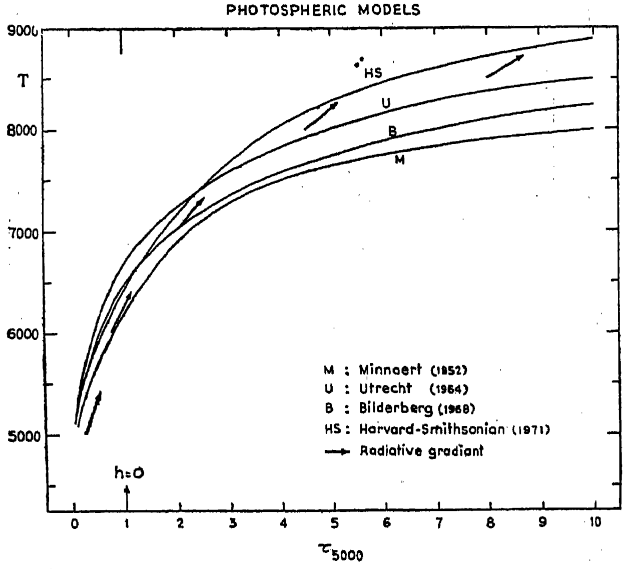

Fig. 1 : Solar photospheric models.

AN EARLY MODEL OF THE CHROMOSPHERE:

In contrast to corona our knowledge of the chromosphere and the transition regions towards the photosphere and corona was quite uncertain in the early fifties. This was so because the chromospheric flash spectrum can be observed only during total solar eclipses for brief moments before and after totality. Further the interpretation of the observed intensities and lengths of chromospheric arcs is quite involved and led to conflicting results. The radio data at centimeter and decimeter wavelengths gave some information and Piddington (1950) constructed a model based on it. But the model was not unambiguous as shown by Woolley and Allen (1950).

I would like to divide the evolution of our ideas about the chromospheric structure into three periods: The early period represented by the work of Wooley and Allen, an intermediate period represented by the researches of Thomas and Athay (1961), and the modern period spanning the last decade. The models representing these three periods are shown in Figure 2 from which it can be seen that the boundary of the lower chromosphere has been progressively brought lower from 6000km in Wooley-Allen model to about 2000 km in the most recent models.

Wooley and Allen (1950) were the first to construct a model of the chromosphere consistent with all available

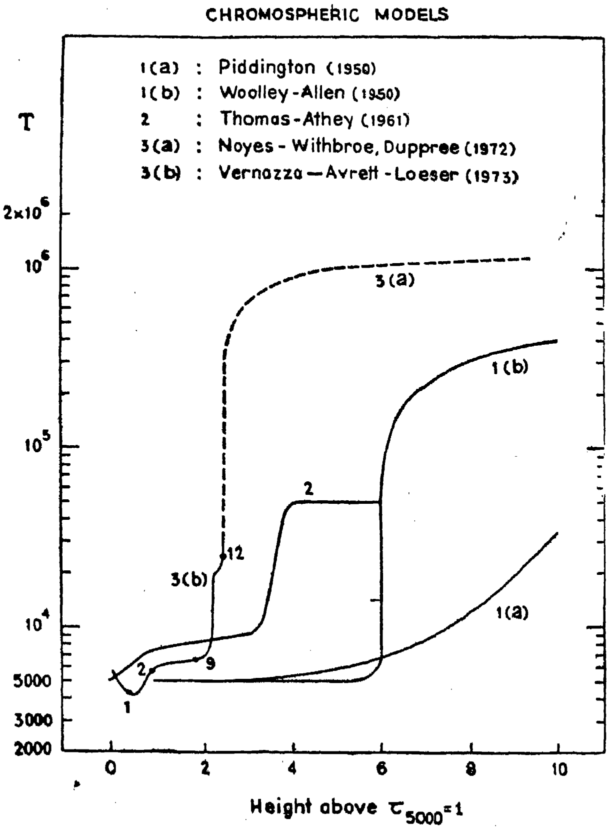

Fig. 2 : Solar chromospheric models in the three representative periods, the height is in thousand kilometers.

data. They gave particular attention to the requirements of ultra-violet flux necessary for the formation of the ionosphere. The chromosphere was divided into two parts separated by a thin transition zone at about 6000 km height. The lower chromosphere was assumed to be in radiative equilibrium with the photospheric temperature of 5040°K. In this region the hydrogen was neutral and the scale height was superthermal in conformity with observations. The lower temperature was preferred because it was consistent with: (i) radio noise data, (ii) condition of excitation and ionisation of metals as revealed by the flash spectrum, (iii) the absence of forbidden lines and absorption lines of helium, (iv) the observed intensity distribution in the Balmer continuum and the Balmer jump, and above all, (v) it did not give rise to too much UV emission in the Lyman continuum which would have been inconsistent with ionospheric requirements. The evidence which pointed to a high temperature of the chromosphere was discarded for the following reasons: the larger widths of H and He lines could be attributed to turbulence; the measured scale heights obtained from line intensities could be explained partly by self absorption and partly again by turbulence : and lastly the emission of He lines was attributed either to superexcitation by coronal radiation or to lateral inhomogenities.

The transition zone at a height of 6000 km, where hydrogen was half ionised, produced most of the Lyman radiation. This region had to be narrow to keep the number of Lyman quanta low enough for the requirements of the ionosphere. Hence above 6000 km the temperature was made to rise suddenly to 10^6 degrees due to the energy supplied by the corona. The pressure in these upper chromospheric layers was taken to be constant and the electron density and temperature were adjusted so as to transport enough energy from the corona downwards by conduction.

Wooley and Allen did not take into account the density scale heights of strong Balmer lines because of the difficulty of calculating the populations of the lower hydrogen states under non-LTE conditions, the importance of which was brought out by Giovanelli (1948) shortly before. In spite of the tentative nature of the Wooley-Allen model, and the later refutation of the low temperature of the lower chromosphere, the idea that there is a sharp rise in the temperature between the lower and the upper chromosphere has survived to this day.

THE TRANSITION PERIOD :

The main obstacle in constructing a satisfactory model of the chromosphere stemmed from the lacuna of direct observations of the ultra-violet and infrared radiations emitted by the lower chromosphere. The UV observations began to be made in 1946 through the use of rockets, but significant results of high spectral resolution could not be obtained until the beginning of sixties. Hence in the intervening period attempt was made to push to the limit the interpretation of the eclipse observations of the chromospheric spectrum. The 1952 total solar eclipse expedition to Khartoum was particularly successful. In an analysis of that data Thomas and Athay (1961) challenged the Wooley-Allen model. They showed that the observed emission intensities in the continuum at 4700A, which is mainly due to H^- and the Paschen continuum of hydrogen and at 3646A due to the Balmer continuum, required a rise of temperature to 6100°K i.e. about 1500 degrees in the first 500 kilometers and a further rise to about 8000°K up to a height of 1500 km. The temperature between 1500 km and 4000 km was found to be uncertain as the the line intensities required an inhomogeneous chromosphere with hot and cold regions. However, at 1500 km a plateau of temperature rising to 10-20 thousand degrees was indicated. This is the region where hydrogen gets rapidly ionised. Then again at 4000 km we have another rise to about 10^5 degrees as helium gets ionised.

A consideration of non-LTE conditions prevalent in the chromosphere showed that the higher temperatures in the low chromosphere were not inconsistent with observed excitation of atomic species. The non-LTE calculations indicated that T_{exc} for them would be in the range of 4000° to 5500°K in spite of the higher kinetic temperatures. Similarly the populations of the lower hydrogen states will be increased with respect to their thermodynamic values. The ionisation of hydrogen would also be cut down and Lyman quanta will be prevented from escaping from the lower chromosphere. In this way there will be no conflict with the ionospheric data, because the UVquanta responsible for ionising the ionospheric layers will again come from the narrow region where the temperature rises sharply to more than 50000°K.

The work of Thomas and Athay brought sharply into focus the need to include non-LTE effects in the chromosphere. Results of several investigations were compiled by de Jager (1959). His conclusion was that the effective temperature T_e increases from about 4000°-4500°K at h = 0 to about 6000°K at h = 3000 km, but the data on hydrogen lines indicate the presence of hotter elements with $T_e = 10^4$. Beyond this height the temperature rises to 1-2 × 10^4 degrees and between 4000 to 5000 kms it rises to coronal values. These temperatures are not sufficient to maintain the observed density gradients in the chromosphere. The necessary support comes from turbulent pressure. The turbulent velocity increases with height as indicated by the widths of H, Ca and He lines from a few km/sec at h = 0 to about 15 km/sec at h = 3000 kms.

THE NEW OBSERVATIONS :

The uncertainty about the conditions in the lower chromosphere started clearing up when reliable observations of the vital ultraviolet solar spectrum started coming in the early sixties. These observations have formed the basis of more realistic semi-empirical models of the chromosphere. The extreme UV observations were reviewed by Tousey (1964) in his George Darwin lecture. An inspection of the solar spectrum from 1200A to 2000A published therein reveals the following characteristics ;

(i) In the region longward of 1683 A corresponding to a silicon absorption edge, we can see the dark Fraunhofer lines as also the phenomenon of limb darkening. This radiation therefore arises from the photosphere. Heavy absorption by Fe, Si and CO in this region restricts our view to the topmost layers whose brightness temperature drops from 5000°K at 2000A to as low as 4600 at the silicon edge.

(ii) Below 1680 A, absorption lines are virtually absent and further in the reigon 1520-1680A the continuum shows neither limb darkening nor limb brightening. This means that we have reached the temperature minimum.

(iii) Below 1520 A limb brightening is observed, so this radiation is coming from the lowest portion of the chromosphere where the temperature has started rising with height.

The observed and computed energy distribution in the solar spectrum below 4000 A are compared by Gingerich et al (1971). We find that the brightness temperature decreases from 6000°K at 4000A to 5000°K at 2000A with stepwise drops due to the atomic continua of Mg, Al and Si. According to Tarafdar and Vardya (1972) the discrepancy in the observed and computed intensities may be alleviated by taking into account the opacities of abundant molecules like CO and H_2.

The lowest temperature reached in the 1600A region is found to be about 4300°K. This is confirmed by the infrared observations at 300μ by Eddy et al (1969) and Gay (1970) . The temperature minimum is placed at a height of about 575 km above the level $\tau_{5000} = 1$, corresponding to log $\tau_{5000} = 10^{-4}$.

At shorter wavelengths, the contribution to which arises from higher and higher layers, the brightness temperature again increases, reaching a value of 6600°K at $\lambda \leq$ 900A beyond the Lyman limit. The emission lines in this and the X-ray region give information about still higher layers of the chromosphere where the temperature increases steeply from 10^4 to 10^6 degrees.

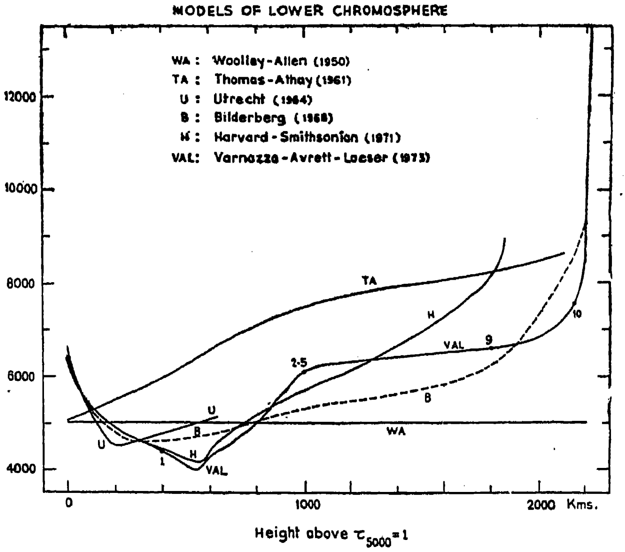

Fig. 3 : Models of the lower chromosphere. Numbers on the curve for VAL-model represent V_t in km/sec.

THE COMPREHENSIVE MODEL :

With the accumulation of a large amount of data about the solar spectrum in the normally inaccessible UV and IR regions during the last 10-15 years, particularly with the advent of Orbiting Solar Observatories, it has become possible to construct comprehensive models of the whole solar atmosphere from the deep photospheric layers to the top of the corona. The first such attempt was made at Utrecht (Heintze et al 1964). Since then new models have appeared at the intervals of every 3-4 years, e.g. the Bilderberg model of 1968 (Gingerich et al 1968), the Harvard-Smithsonian model of 1971 (Gingerich et al 1971) and the more recent models due to Vernazza, Avrett and Loeser (1973, 1976). They are shown in Figure 3 for the lower chromospheric heights.

The Utrecht model was based on the earlier photospheric models with 2 or 3 streams—hot, cold and average—in the convective layers, which were extended through the temperature minimum of 4500°K at 200 km height to the lowest layers of the chromosphere with T = 5000°K at h = 600 km. From this time onwards the convention of measuring chromospheric heights from the layer with $\tau_{5000} = 1$ was established.

The Bilderberg model broadened the temperature minimum set at 4600°K to 500 km and made the temperature rise first slowly to 6000°K at 1700 km and then rapidly to 9000°K at 2200 km. In the Harvard-Smithsonian model the minimum temperature was somewhat arbitrarily taken to be 4100°K at 575km, and the temperature rise was similar but steeper than the Bilderberg model reaching 9000°K at 1800 kms only where the steep rise to coronal temperature was expected to occur.

The most recent model of the lower chromosphere is that due to Vernazza, Avrett and Loeser (1973,1976).

The VAL-model is based on the simultaneous solution of the equations of statistical equilibrium and line transfer for all important atomic species along with the Lyman continuum equation including the calculation of electron density number and the equation of hydrostatic equilibrium. The parameters T_e and the turbulent velocity V_t were adjusted by a process of iteration until the observed solar spectrum was satisfactorily reproduced in the range from 700A to about 2 cm.

In the VAL-model, the temperature rises from the minimum of 4100°K at $h = 550$ km where $V_t = 1$ km/sec rapidly to 6000°K at $h = 1000$ km where $V_t = 2.5$ km/sec. Thereafter the increase of temperature is slow while that of V_t is steep upto $h = 2000$ km where $T_e = 7000$°K and $V_t = 10$ km/sec, in this region the density gradient is supported to a considerable extent by the turbulent pressure. Then follows the rapid rise of T_e to 20000°K at 2200 km where it forms a small plateaux before rising again rapidly to 35000°K at $h = 2400$ km with $V_t = 12$ km/sec. This is the beginning of the final rise to the coronal temperature of 1.6×10^6 degrees.

The total number density of hydrogen varies rather uniformly from $10^{17} / \text{cm}^3$ at $h = 0$ to $10^{10} / \text{cm}^3$ at $h = 2400$ km, all the ionisation occuring near the steep temperature rise at 2200 km. The non-LTE departure coefficient b_1 which is unity at $h = 0$ drops to 0.1 in the temperature minimum region and then rises with temperature to 100 at 1200 km, remains roughly constant through the first broad temperature plateaux, and then reaches values of one million and above during the fast temperature rise at 2200 km.

The fit with the observed intensities is quite good in the ranges 700A to 1700A and 10μ to 2 cms. The fit in the region longward of 1700A was still poor. Originally Vernazza et al (1973) had obtained a forced fit between 1700A and 1900A by introducing an opacity multiplier which was supposed to compensate for the missing opacity source and the effect of line blanketing. Kohl and Parkinson (1973) have recently measured the neutral-aluminum photoionisation cross section which seems to remove the discrepancy near the Al I edge at 2100A. In their most recent model Vernazza et al (1976) are able to account for the increased absorption below 1700A completely by line blanketing and Al I photoionization.

The model of the chromosphere-corona transition region has been constructed by Dupree (1972). The heights in her model were somewhat arbitrary; they have therefore been adjusted to the heights of the VAL-model by Noyes and Withbroe (1972)—see Figure 2. The principle characteristic of this region is the constancy of electon pressure and the quantity $T_e^5 \, (dT_e/dh)$ which corresponds to a conductive energy flux of 1.25×10^6 ergs from the corona to the chromosphere. It is this flux which is responsible for heating the chromosphere. The origin of the coronal energy is known to be the mechanical energy transmitted to it from the granules and spicules through shock waves or Alfven type waves. Most of the emission lines arise in this transition region in which temperature rises from 10^4 to 10^6 degrees.

CONCLUSION :

We have reviewed the development of our ideas about the solar atmospheric model from the beginning to the present time. The models discussed here refer to the mean conditions in each horizontal layer. It is well known that all solar phenomena such as granulation, spots, faculae, prominences, spicules and flares are manifestations of horizontal inhomogeneities. The mean model is expected to help us in understanding them as perturbations superposed on the average conditions by the magnetic fields and other forces. For example Koop and Kuperus (1968) have suggested a model relating spicules and supergranulation in which the spicules are chracterised by the compression of isotherms in their viscinity. Research in this direction is continuing at the present time. The five minute and other periodic oscillations of the sun represent another kind of perturbation which is receiving increased attention of the solar physicists in the last couple of years.

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