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Vistas on Stellar–Solar Atmospheres*

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Abstract

The evolution of the modelling of the stellar atmosphere towards greater physical consistency is described briefly. The progressive relaxation of stringent hypotheses (such as RE, LTE, HE, plane-parallel geometry) in all layers characterizes this evolution. We discuss roughness (i.e. departures from spherical geometry), the origin of the concept, and how its recent application to Skylab and OSO-8 UV data shows its importance, difficult to take into account accurately, but not to be overlooked. In the last part of the paper we argue for a general overall coupling between mechanisms which characterize the stellar–solar machinery described.

1. Introduction

The Universe is known only through radiation from astronomical objects and, more specifically, through its spectrum. Roughly, we get 10^7 times more information from the Sun than from the rest of the Universe; hence the Sun provides a good assessment of our limitations, and it is from the study of the solar spectrum that the theory of astronomical spectra stemmed about a century ago. For historical reasons, these diagnostics and their understanding have been grouped under the general name of 'theory of stellar atmospheres'. In the early days, this theory was concerned almost exclusively with the solar atmosphere, and in fact only with the solar photosphere. At present, we might include in this subject the diagnosis and theory of all sources of radiation, say of all media from which photons observed on Earth originate directly. This includes stellar atmospheres in the ordinary sense, HII regions, interstellar matter at large, and it also includes quasar broad line emission regions, for example, as well as the distant Universe, in spite of their lack of resolution and weak radiation intensity.

2. From Phenomenological to Physical Models

The evolution of the theory of stellar atmospheres not only affected its scope; it has indeed affected its very nature. To briefly summarize this evolution, well known by astrophysicists, it can be characterized as a move from when one had

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essentially to identify and recognize objects and features—stars, nebulae, filaments, fibrils, prominences etc.—considering them, more or less, as isolated individuals, to a time where what counted more were the *interactions* between the various media under consideration; that is, from a 'phenomenological' description to a 'physically coupled' description.

Hence, the concept of 'modelling' has completely changed its meaning; there is little in common between the physical representation of spherical gaseous masses—as studied in earlier days by Emden, Lane or Ritter—and the very complex description we presently tackle.

It is useful perhaps to define the word 'model': for the specialist, it is just a *numerical table*. The better the knowledge we assume to have of an object under study, the larger the number of locations within the medium where this table provides all that we can extract from the observed data—temperature, density, non-thermal velocities, magnetic fields etc.—using them *completely*, and supplementing them by a *minimum of physical equations* linking these parameters with each other. This table which groups all state parameters of the object under study enables new computations. Together with the full physical laws and without any limitation to a 'minimum', one can use the set of tables to compute with some accuracy not only what has been actually observed and used, but also what might be observed at a later stage and therefore serve as a test of the theory.

Although the number of state parameters generally increases with time, marking the progress of observations, this tendency is not always present, and it can happen that there is a trend towards simplification, a more unified description. Let us assume, for example, that with the aid of physical laws a single physical parameter determines the state parameters, which comprise the provisional empirical model; therefore, the choice of this *single* parameter is sufficient to predict *all* observed data. In this case, the complete model is described by *one* number only, and with the physical laws appropriate to the object under study. This reductionist move in the progress of modelling is typical of certain developments in the theory of stellar atmospheres.

In any case, models must always be considered provisional and of temporary validity. The mass of available data on any astronomical object is usually so quickly enlarged that contradictions between new observations and what can be predicted by old models are often obvious; new models thus become necessary. We can therefore define the word 'model' (Pecker 1982) in a rather imprecise way as an approximate schematical representation, but complete enough to allow a reasonable extrapolation of available data.

3. Multiple Evolution of Solar Modelling

The study of the evolution of models from a phenomenological stage to a physically coupled stage is well exemplified by the Sun. We describe the solar case, and then generalize our conclusions later.

It is now well understood (see e.g. Pecker *et al.* 1973; Pecker and Thomas 1976) how progress in solar modelling has been linked with the introduction to the arsenal of physical laws of the blackbody thermal radiation theory, the statistical equilibrium of energy levels, radiation damping, and the aerodynamic and magnetohydrodynamic (MHD) equations. Beginning this progressive development, the first reasonable model of the Sun derived from the spectral distribution of the continuum intensity was a blackbody at $T = 5800$ K. Of course, one knew by then of the existence of Fraunhofer lines, of active features and of granulation, but they were not thought to affect the general structure of what was then called the photosphere, in the most restricted meaning of the word. Thus, model number 1 of the Sun is characterized as a blackbody, even though strictly the Sun is not a blackbody. The temperature T of a blackbody is that of the whole medium, inside its wall, but the spectrum of the Sun comes only from the outer layers, the mean free path of photons being short at solar densities. Thus, model number 1 characterizes only the last media crossed by light, namely the atmosphere, of optical depth near or smaller than unity. It is undoubtedly a 'complete' model, in the sense that it allows the prediction of all the characteristics of the solar radiation; however, it does so very poorly. A blackbody has no absorption lines, whereas the solar spectrum contains more than 100 000 lines, and secondly, a blackbody radiates isotropically when observed through a small hole, whereas the Sun is affected by an obvious limb darkening when observed in visible light.

Hence, the need arose for model number 2 where the temperature gradient $\mathrm{d}T/\mathrm{d}\tau$ is an essential parameter, in addition to T, as some 'average' photospheric temperature. Can we then predict the Fraunhofer lines? Their existence, as absorption features, can indeed be predicted, provided local thermal equilibrium (LTE) is admitted, but line profiles, even in the simplest possible theory, are a function of the gas density ρ, and this cannot be derived unless one knows the relation between ρ and τ. An additional parameter is thus necessary, namely the gravity g, and an additional hypothesis, that of hydrostatic equilibrium (HE). Our model number 2 immediately becomes very elaborate. To specify it fully, and to compute its observable characteristics, one needs also to invoke LTE and radiation equilibrium (RE), assuming that energy is transferred only through radiation. This model gives an elaborate picture of the photosphere, but one which is also quite provisional. For example, it takes no account of granulation, known for about a century, or of the existence of the outer layers, the chromosphere and corona, and the fact that the transition between the RE–HE–LTE photosphere, and the obviously 'non plane-parallel' outer layers, has to be essentially progressive. The definition of this transition is purely observational, and linked with the definition of the Sun's limb, which corresponds to a 'surface', but which implies that the tangential optical depth of all layers above it is of order unity, at the visible wavelengths. (We do not discuss here the idea that the 'surface' is, in principle, a function of wavelength but that, due to the approximately exponential decrease of density in the atmosphere, it is not very sensitive to it in the continuous spectrum.) Hence, our model number 2 cannot be considered 'good', although it is 'complete'.

Clearly, a third model will have to relinquish some of the classical hypotheses, and increase the number of state parameters. This will lead to a more complicated model, where the necessary number of state parameters increases outwards, in a kind of progressive non-degeneracy (see Section 6). In the centre, we have both TE and HE valid and, of course, spherical symmetry. In the bulk of the solar volume, including the convective zone, one can (for practical purposes) accept RE, as far as the low photosphere. In the chromosphere, departures from LTE are already very large, and become major in the corona. Departures from RE are very strong in the chromosphere, and even more so in the corona. Departures from HE start to be striking in the chromospheric spicules, and the solar wind forces a decrease of density outwards much slower than the exponential decrease seen in the low photosphere.

Whereas magnetic energy seemed a peripheral consideration in the study of internal structure, it becomes indispensable in understanding the shapes and appearances of the corona. Spherical symmetry no longer holds in the upper photosphere and chromosphere (what we call the 'roughening effect'), and much less still in the corona.

However, as these well-known departures were introduced one by one to describe the physics of the various layers of the Sun, it became clearer that the behaviour of physical approximations was progressive and continuous. Hence, in addition to the progress described above which sought to encompass in the models, through a proper theory, layers which were not previously covered, another avenue of progress was to examine the validity of the various equilibrium equations, and then to introduce departures from equilibrium, down to progressively deeper layers. For example, it had been realized [see Jefferies (1968) for a bibliography] that Fraunhofer lines formed in the photosphere were not in LTE; although this affected profiles and centre-to-limb analysis only marginally, it led to errors in the abundance determinations which in some cases amounted to an order of magnitude. It then became obvious that departures from LTE had to be introduced in photospheric studies. Similarly, departures from RE were already known 'under' the so-called surface, as well as in the chromosphere and corona. Strictly speaking, HE is nowhere valid; the departures do not only affect the solar wind and, in fact, use of continuity equations suggests (see Cannon and Thomas 1977) that the solar wind has its roots in the subphotospheric layers.

The departures from LTE in photospheric layers and upwards have been extensively discussed, and a pioneer in the field was undoubtedly Giovanelli (1948, 1949). The non-radiative heating of atmospheric layers above $\tau_{5000} \sim 0{\cdot}01$ is still not perfectly understood, although the subject of a great number of studies. The solar wind and the departures from HE have also been studied very extensively.

4. Effects of Roughness: Review of Ancient and Recent Work

Here we discuss the inhomogeneity of the solar surface and report some recent calculations made together with S. Dumont and Z. Mouradian (to be published in detail later). The 'roughening effect', introduced by Redman (1943), is based on the fact that at the extreme solar limb the equivalent widths of Fraunhofer lines, as observed during an eclipse (just after totality), have about the same value as at the Sun's centre. Incidentally, similar reasoning led Hagen (1954) to infer from centre-to-limb radio studies of the Sun (during eclipses) the need for a spicular geometry of the radio continuum emitting chromospheric layers. More recently, Skylab and OSO-8 studies have led many authors to show that all parts of active and quiet regions can display structures that have no spherical symmetry, even on a scale smaller than the revolving power, and that centre-to-limb studies of UV lines make necessary the use of corrections to take them into account. In recent years, we have used this fact to determine the optical thickness of the regions of line formation (C IV, Si IV, O VI), in order to understand the different values obtained by different methods (Dumont *et al.* 1983). It is not straightforward to conduct a proper study of this problem, as it has many aspects and the results are to a degree a function of the structures themselves.

The first idea (Redman 1943) was essentially that *isobaric* surfaces are not flat (see Fig. 1). These early studies aided (Pecker 1949) in a derivation, from centre-to-limb continuum studies (see Fig. 2) using Redman's estimation of the roughness

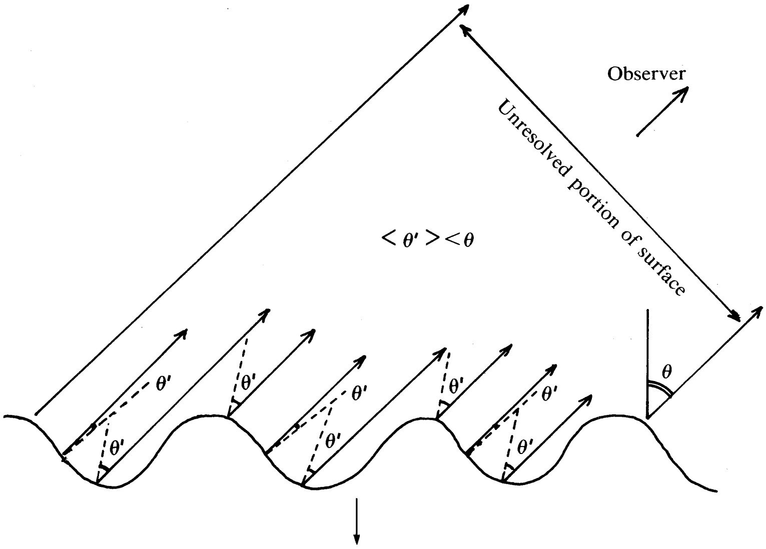

Fig. 1. Geometrical roughness showing the angle θ' between the normal to layers and the observed direction. The average value of θ' is smaller than θ as derived from the apparent location on the solar disc.

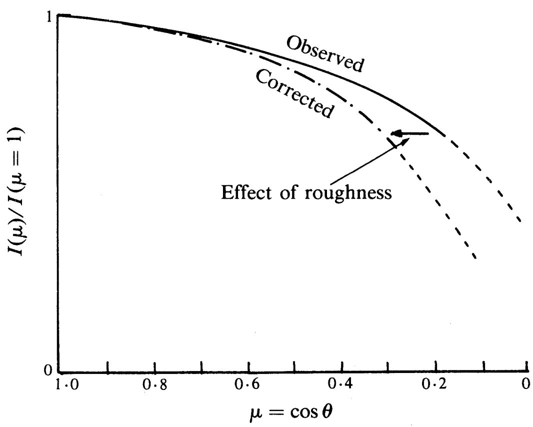

Fig. 2. Observations made near the limb, when corrected for geometrical roughness, correspond to a point where the rays are slightly inclined with respect to the solar radius, in an 'equivalent' plane-parallel description.

effect, of a solar 'surface' temperature of 4200 K, surprisingly close to the known minimum temperature of the solar atmosphere. Around 1950 A. Unsöld, in personal correspondence, expressed serious doubts about these ideas, at least as far as the photosphere was concerned, as any rugosity of the type proposed by Redman would be unstable and lead to supersonic motions, which had not been observed. Unsöld's argument was indeed correct in the case of isobaric rugosity. Evans (1947) and

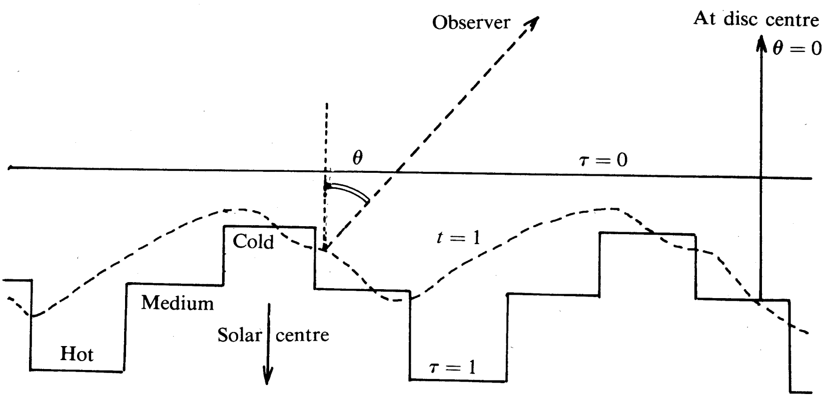

Fig. 3. For optical roughness three columns (cold, medium, hot) are assumed; the full line is the $\tau = 1$ layer, as observed at the disc centre; the dotted curve is the $t = \tau/\mu = 1$ layer, as observed at a point on the disc where the angle between a ray and the solar radius is θ ($\mu = \cos\theta$).

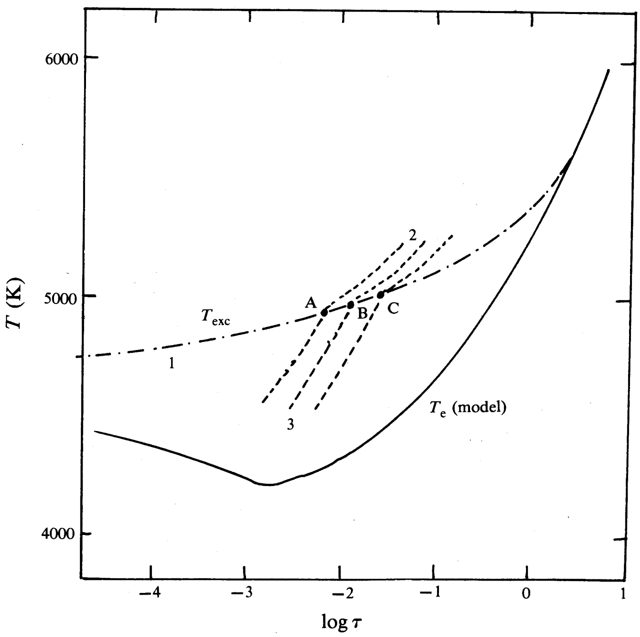

Fig. 4. Effect of optical roughness where the full curve represents the electron temperature (or model) used by Lefèvre and Pecker (1961). Other curves represent excitation temperatures deduced from line observations (Ti I, low multiplets). For the three curves A, B, C—and all other curves of the same multiplet—curve 1 is deduced from the variation of the central line intensity at disc centre from line to line. The curves 2 are deduced, for each line, from the variation at the centre of the disc of the intensity from line centre to line wings. The curves 3 ('fishbone' effect) are deduced from each line, at the centre of the line, of centre-to-limb variation. Differences between the curve 1 and the model measure the effects of non-LTE. Differences between curves 1 and 2 measure non-thermal broadening, while differences between curves 1 and 3 measure the effect of optical roughness.

Lefèvre and Pecker (1961) realized that the roughness is an optical effect, and that the non-flatness or non-sphericity that needed to be introduced was in fact that of *iso*-t *surfaces*, which was then constructed for a model of hot and cold columns (see Fig. 3). The effect is qualitatively the same as isobaric roughness, except that it depends strongly upon the temperature dependence of opacity and varies, accordingly, from line to line and completely from line to continuum. Using Böhm's inhomogeneous model, appropriately modified, it was then possible to interpret the centre-to-limb variation of the central intensities of Ti I low multiplets, which had anomalous behaviour, named by Lefèvre as the 'fishbone' effect (see Fig. 4). Similar considerations have to be applied to understand the centre-to-limb variation of line profiles and velocity shifts.

These problems were essentially those of the *semi-infinite* atmosphere, where the intensity is expressed as an integral over optical depth, with zero and infinity as its limits, the values of the integrand being far from negligible for large optical depths.

With the aim of interpreting data pertaining to layers of small optical thickness, we have recently revisited this problem, in both the case of resolved and unresolved features:

Resolved features. These features, when linked with roughening, give rise to the apparent deformation (different from simple foreshortening) of the intensity distribution obtained by scanning the chromospheric network, and to the variation of the ratio $I_{\max}/I_{\min}$ measured on the disc (from Skylab data, for example). The first group of results thus concerns corrugated layers of non-constant optical depth, such as possibly the transition regions around spicules. Preliminary results are encouraging. The parameters are the shape parameter (semi-angle of the V-shaped curves schematizing the surface) and the optical depths at the top and bottom of the 'hills'; the difficulty in the computation comes from the fact that a single light ray can cross the same layer several times (see Fig. 5).

Unresolved features. Some typical results are shown in Fig. 6. A few conclusions can be made:

(i) For thin layers, the shape of the roughness or its measure does not affect the intensity at all; only the total mass of matter determines the intensities in any given line.

(ii) For thick layers, the case is quite different. Average values of $\cos\theta'$ (or μ'), $\sin\theta'$ (useful in computing the effects of velocity fields) and θ' are different from the values of θ indicated by the location of the observations of the solar disc. Note that this effect concerns not only the limb but the centre of the disc, contrary to what we thought in 1949.

(iii) For layers of intermediate thickness, the calculations lead to various results. First, the relation between, for example, the effective μ' and μ is a function of τ and of the shape parameter. However, deriving τ from centre-to-limb variations of line intensity is also an α-dependent analysis; contradictions within various τ determinations might lead to a reasonable guess with respect to α.

The case of inhomogeneous layers (where geometrical thickness varies from 'hill-top' to 'valley', even when their optical thickness is small) is of course much more difficult; so far, it has been treated only in the case of resolved features. Although the roughness is undoubtedly present and significantly influences the data, we cannot

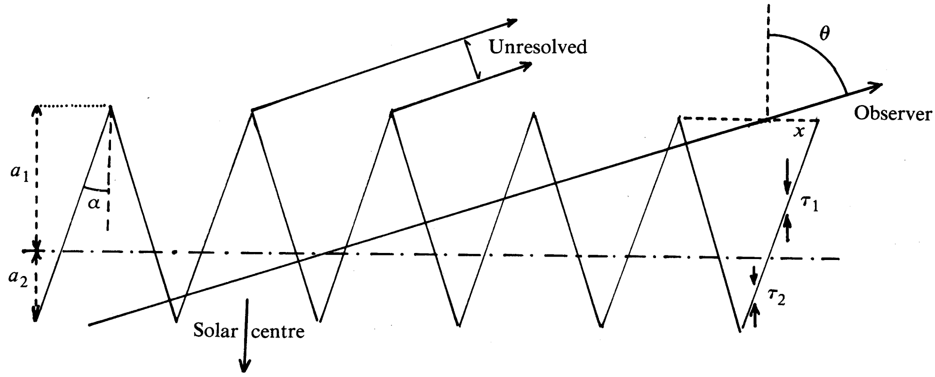

Fig. 5. Shown are the parameters of the roughness effect in layers of intermediate optical depths. The shape is arbitrary and given here by the zig–zag curve, which is characterized by the angle α. The inhomogeneity is characterized by a_2 (bottom) and a_1 (top), measuring the importance of deep (τ_2) or thin (τ_1) regions. The parameters a_1/a_2, τ_1/τ_2, τ_1 and α can be varied. The 'resolved' case may be treated at a given value of x, for a given value of θ; here four 'spicules' are crossed by the light ray. The 'unresolved' case results from an integration over x.

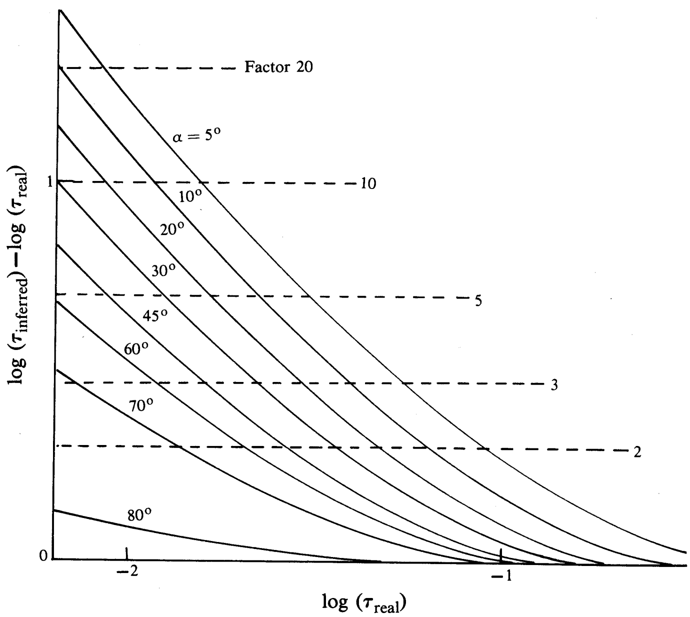

Fig. 6. Shown is the effect of roughness in the case of intermediate optical thickness. From centre-to-limb data, the optical depth of the layer responsible for a given ion line (see Dumont *et al.* 1985) can be derived. The assumption of spicular roughness and of a different α value (where the media 1 and 2 are assumed identical, the homogeneous case, and where the unresolved case has been treated) shows that, for small values of α, the error made in the inferred τ may be as large as a factor of 20 or more, and that the real value of τ is larger than the inferred value of τ.

be sure that it is possible in any straightforward way to introduce it into the actual data analysis.

To what extent should we take these schematic computations into account? Certainly it is useful to analyse centre-to-limb data with great care, possibly by successive iterations and a simultaneous determination of the shape parameter (amplitude α of the roughness), the optical depths, or other astrophysical quantities. We are presently attempting such a study in the case of UV lines of the transition region measured from OSO-8, namely Si II, C IV, Si IV and O VI, but success cannot be guaranteed.

Departures from spherical symmetry, as well as from homogeneity, obviously affect all kinds of radiative transfer calculations. Wilson (1968, 1969*a*, 1969*b*) in particular has extended the treatment of transfer in inhomogeneous media. The ideas behind the roughness effect are essentially those of the late 1960s, but are possibly easier to apply to a practical diagnosis. However, let us now turn briefly to another line of progress.

5. Solar Machinery

The coupling between different layers extends of course well beyond the theory of the solar atmosphere, and the non-equilibrium structural progression. This implies that parameters characterizing the Sun as a whole control some aspects of the atmosphere itself. In fact, the modelling evolution we have described links quite naturally the atmospheric structure and equilibrium to an increasing number of reasonably well-defined parameters, derived from global observations. The first is the 'effective temperature', deduced from the solar constant (i.e. $f = 2$ cal min^{-2} per cm^2 of terrestrial surface):

$$T_{\text{eff}} = \left(\frac{1}{\sigma}\mathscr{L}_\odot \frac{1}{4\pi R_\odot^2}\right)^{1/4},$$

where

$$\mathscr{L}_\odot = f(4\pi d^2) = 1{\cdot}4\times 10^6 \text{ erg cm}^{-2}\,\text{s}^{-1}$$

(at a distance d of 1 AU). Then it was necessary to take into account the gravity in the atmosphere, $g = GM_\odot/R_\odot$. To describe fully the layers of the deep and outer atmospheres, a knowledge of the wind characteristics, details of the chemical composition, the velocity fields, differential rotation, sunspot (and general) magnetic fields etc. must be used as a basis for the computation (involving many essentially independent parameters). The contemporary theory of stellar internal structure couples convection and rotation, links differential rotation with the theory, and links the poloidal field and its evolution with differential rotation, which in turn forces the field towards a toroidal structure; the characteristics of the convective zone control the oscillations which affect the photospheric features, and the chromosphere, if not the wind.

When investigating the Sun from the point of view of solar evolution, one can see, in what may seem a generalization of the Vogt–Russell theorem, that it does not depend on many arbitrary parameters. Strictly, the mass, the angular momentum, the residual interstellar frozen-in magnetic field and the chemical composition are (in principle!) sufficient to 'determine' all that can now be observed. The stochastic aspect of most of observations, when made with very high time or angular resolution, has to result from this simple initial situation; in many parts of the logical chain, it is likely that 'strange attractors' force smooth structures into this stochastical appearance. Hence, *in practice*, we require many non-physically independent parameters, which must be treated as independent.

The remarkable prediction made from gross internal structure considerations of many features of the activity cycle (from the Spörer butterfly diagram to the latitudinal behaviour of coronal holes) shows that the solar machine is, after all, basically simpler than we may often be led to think, in the sense that physically a relatively small number of parameters determines it fully.

6. Concluding Comments

The theory of stellar atmospheres has, at all stages, been much like a 'procrustian bed': One has forced the models to follow the progress of observations, cutting here and there the feet of the provisional theories. At times we have had to face the failings of the provisional theory, to examine its underlying basis, and finally to couple it to some apparently independent branch of astrophysical theory, for example MHD. By closely fitting models to observations of various solar phenomena, of various stellar sequences, one has learnt not only how the basic parameters (the mass notably) vary along the Hertzsprung–Russell (HR) sequences, but also how additional parameters (for example the angular velocity) may be linked both with stellar evolution and with 'initial' values, and how others (magnetic characteristics) introduce dispersion in the HR diagram and in aspects of the active features. The theory of stellar atmospheres initially allowed us to understand the two-dimensional character of the HR diagram, and then helped to determine that the dispersion around the HR sequences is linked to the demand for more physical parameters, local in character, and that the sequences themselves can be understood through the theory of stellar interiors and their evolution. Presently a third period leads us to the point where the two groups of theories will help (eventually) to link the dispersion around the sequences, or the stellar activity, with parameters that are no longer independent but closely linked with each other, and to stellar evolution. The overall picture is becoming a very coherent part of the physics of gaseous masses.

It should also be remembered that, along this same line, and aside from this physical coherence, the theory of stellar atmospheres has given the means of determining basic parameters, such as chemical composition, which link the atmosphere not only to internal evolution, but also to the evolution of the Galaxy and the Universe itself. The theory certainly helps us to rewind the universal clock back to what existed before the time when the stars under study first appeared in the Galaxy. Although begun as an isolated, self-coherent and self-sufficient branch of astrophysical theory, the theory of stellar atmospheres appears now only as a single connected piece in the coherent physical theory of the Universe at large.

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