36. THEORY OF STELLAR ATMOSPHERES
(THÉORIE DES ATMOSPHÈRES STELLAIRES)

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PREFACE

This report has been prepared by the President in collaboration with the Secretary of the Commission. It is based on (1) material supplied by those members and associates of the Commission who responded to requests made in our circulars, (2) a bibliographical search intended to supplement the above material, (3) discussions with other interested persons, and (4) our own knowledge and impressions of the activity within the province of the Commission over the last three years. The report is divided into three parts. Part A is a scientific review aimed not at a comprehensive summary of all work but at a selective review of that which has, in our opinion, introduced some significant change in our concept of a stellar atmosphere or in the likely direction of future developments. Part B is a bibliography. It is this part of the report that is intended to provide an exhaustive summary of work done in the field over the last three years. To authors of those papers we have inadvertently omitted, we offer our apologies: neither were they sent to us nor did we locate them ourselves. Finally, Part C is an outline of the aims and activities of the Commission.

The decision to write the entire report ourselves, rather than delegate specific sections to other people, was aimed at providing a more coherent approach to the subject as a whole. Clearly, this represents only one of many possible approaches, and the form of the report is highly individual. The choice of what to include without encroaching on the fields of other commisions has become increasingly difficult. No longer can Commission 36 confine itself to theoretical models of stellar atmospheres. Empirical analyses that reveal inconsistencies in our theoretical assumptions must also be included, as must some consideration of solar phenomena, which are now recognized as being relevant to a wide variety of stars. Reference must also be made to those results of physics that are immediately applicable to the theory of stellar atmospheres. Inevitably, the selection has to some extent been arbitrary.

PART A: SCIENTIFIC REVIEW

I. *Introduction*

a. *A picture of a stellar atmosphere*

Our picture of stellar atmospheres is continually evolving. We are now beginning to realize that a stellar atmosphere in general comprises a number of regions, which differ widely in their properties. This has led to attempts to observe these properties and to understand why such regions exist. Is there some overall pattern in which the nature of chromospheres, coronas, expanding shells, cicumstellar dust, etc. may be better understood? Do all atmospheres have essentially the same regions, observed differences arising only from differences in the *values* of the state parameters, or do the number and variety of regions vary from one type of star to another?

Classically, the atmosphere was viewed simply as the outer boundary of the star, which was itself considered to be an isolated object. The atmosphere was assumed to be a single region, described by the same parameters as were used to construct the interior model: density, temperature, and chemical composition. Spectra were analyzed to determine the boundary values of these parameters, together with the range in these values from one type of star to another and from one region of the sky to another. Most studies of stellar atmospheres still fall into this category, progress being made chiefly through the availability of better observational data and the computation of more accurate single-region models.

The evolution away from this single-region model does not end with the construction of a so-called non-LTE region in which radiative processes are comparable to, or more important than, collisional processes in fixing the populations of the energy levels. Nor does it end with the recognition of solar-type chromospheres in solar-type stars, or indeed with the arbitrary inclusion of shells, dust, etc. in no overall pattern.

Rather, our picture seems to be evolving toward an atmosphere that is a transition region between the stellar interior and the interstellar medium. The properties of the interior are fixed, to a first approximation, by the characteristics of the star itself, independent of its environment. The stellar interior can be characterized as a storehouse of mass and energy, with only a small outward leak and a compensating inner replenishment. Its state – the concentrations of particles and the occupation numbers of the microscopic energy levels – can be described wholly in terms of the local concentrations of mass and energy, the fluxes of these quantities being irrelevant. This is a local thermodynamic equilibrium description in the broadest sense, using the methods of linear non-equilibrium thermodynamics. By contrast, the properties of the interstellar medium are fixed statistically by the fluxes of mass and energy from the background stars, and its state must be described in terms of detailed microscopic processes. The departure from local thermodynamic equilibrium is complete and must be described by non-linear, non-equilibrium thermodynamics. Viewed in this way, the stellar atmosphere represents a transition between these two states, which differ both in the set of parameters by which they are described and in the values of those parameters they share in common. In the classical, one-region picture of an atmosphere, this transitional aspect is neglected; the star is viewed as an isolated object, and the atmosphere is described in the same way as the interior. In the current multi-region picture, the star is treated as only quasi-isolated.

This current picture has evolved largely from two advances. One is the recognition that the detailed structure observable in the solar atmosphere is also required for the interpretation of integrated stellar spectra. The other is the recognition that apparently anomalous features observed in particular stars (e.g. P Cygni profiles, Wolf-Rayet spectra, UV, IR, and radio excesses) are simply exaggerated manifestations of physical effects more generally present. Together, they suggest that the 'symbiotic' appearance of stellar spectra is normal and reflects an atmospheric structure composed of several regions, differing in their physical properties.

To summarize, we might say that we are moving from a period in which research on stellar atmospheres focused on radiative loss of energy into a period in which it is recognized that mass flux may also be important in dispersing the energy generated in the stellar interior. Although the mechanical energy, together with the additional radiative energy associated with the mass flux, may indeed by small compared with the total energy produced, its effect on the structure of the atmosphere, and on the relation between the star and the interstellar medium, may well be essential. Just as early investigations underestimated the effect of radiation relative to mass (i.e. collisions) in fixing the state of the atmosphere and determining its spectrum, so they overestimated the role of radiation relative to mass in transporting its energy. If the inclusion of mass transport effects a significant change in the structure of model atmospheres and envelopes, perhaps we should also consider to what extent such changes can propagate downwards.

b. *A preliminary set of atmospheric regions*

An atmospheric region is distinguisted by the set of state parameters that suffices to give the local concentrations of particles and the occupation numbers of the energy states, both microscopic and macroscopic. The region is then described by specifying the range in the values of these parameters. Any attempt to divide the atmosphere into a set of regions is necessarily limited by our knowledge of the physical processes involved. We present here a preliminary set, which extends from the interior of the star to the interstellar medium, and within which each region is characterized by the behavior of one or more physical quantities. It is according to this scheme that we have then grouped the investigations discussed in the remainder of this report.

Subphotosphere: That region in which the radiation field is fixed by its storage properties, and its transfer is by diffusion. Any transfer of mechanical energy is also by a diffusion-type process, characteristic of a storage region. Microscopic distribution functions are in LTE.

Photosphere: That region in which (a) the radiation field changes from quasi-isotropic to strongly anisotropic, (b) the energy transport is by radiation or quasi-static convection, and (c) there is hydrostatic equilibrium. We divide this region into two subregions, the collisionally controlled photosphere, in which collisions suffice to maintain local thermodynamic equilibrium, and the radiatively controlled photosphere, in which radiative processes play a significant role in fixing the occupation numbers of the energy states.

Chromosphere: That region in which the velocity fields change their character from non-dissipative to dissipative. Here it is the gradient of the mechanical energy flux that is important.

Corona: That region in which the mass flux becomes non-negligible in producing an enthalpy term, which must be included in the energy balance. Here it is the value of the mechanical energy flux that is important.

Circumstellar shells and nebulae: Those regions in which the interaction between stellar and interstellar material becomes increasingly important.

c. *Three approaches to determining state parameters*

Attempts to define and determine the values of the state parameters for a given atmospheric region may be divided into three broad categories: empirical, quasi-empirical, and theoretical. In the bibliography for this report, we group the various investigations according to the atmospheric region discussed and the approach taken.

1. *The empirical approach*

A set of observations, identified with a particular atmospheric region, is analyzed to give particle concentrations and occupation numbers, and an attempt is then made to find a set of paramvters by which to represent them. Solar eclipse studies, where the motion of the Moon's limb provides a way of locating a particular region, are the prototype of this approach. Eclipsing variables such as 31 Cygni present the closest stellar analogues. Since no one set of observations can cover all the relevant spectral regions, no atmospheric region can be analyzed wholly empirically, and care must be taken to distinguish those relations implicitly introduced. In the analysis of eclipse data, for example, the degree of ionization cannot be observed directly: any theoretical method introduced to determine it will depend critically on which lines and continua are included.

2. *The quasi-empirical approach*

Here a set of state parameters is adopted a priori, as are the values of some of these parameters throughout the atmosphere. The remaining ones are obtained by observation or theoretical assumption. The model is then used to predict all, or at least some, available observations and the distribution adjusted until an 'adequate' match is obtained. The uncertainty in this approach lies in the adequacy of the assumed set of state parameters and in the uniqueness of the predictions. What, for example, is the physical significance of the 'micro- and macroturbulence' parameters introduced ad hoc in every approach of this kind?

In practice, it is usually the distribution with height of electron temperature that is assumed, together with hydrostatic equilibrium and 'turbulence' parameters of some kind. The extensive work of Avrett, Cuny, and others on the solar atmosphere are examples of this type of approach. The category also includes the wide variety of models that adopt the LTE state parameters and the gray-body or radiative equilibrium temperature distributions. Currently, various approximations to non-spherically symmetric models are being explored by assuming a dependence of density on radius.

The approach provides the flexibility necessary to investigate the conditions for the production of, for example, emission lines in the absence of mechanical heating, fluorescent and laser effects, and various kinds of symbiotic effects. The latter include the appearance of apparently high and low excitation spectra in the same atmospheric region, of apparently incompatible spectra in different atmospheric regions of the same star, and of evidence for both an expanding atmosphere and a static atmosphere in different regions of the same star. The danger in this approach is that an ad hoc model be taken literally, without establishing under what conditions the assumed state parameters, and the ranges of these parameters, are physically consistent.

3. *The theoretical approach*

Here the model is based entirely on some set of theoretical assumptions, which, if it is to include different atmospheric regions, must include assumptions on their physical character. The extensive investigations of Auer and Mihalas probably represent the most systematic attempts to apply this approach to an atmosphere with two regions, one classical, the other in which the assumption of collision-dominated LTE is dropped. Attempts are now being made to represent chromospheres by three-region models based on theories of non-radiative energy dissipation. The extended-atmosphere models based on radiation pressure alone do not, however, include added atmospheric regions in the above sense.

The danger in this approach is that any given model be taken too seriously. Rather, successively less restrictive models should be computed until we have a complete picture of the microscopic processes that determine the state parameters under all conditions and can predict a set of atmospheric regions in accord with *ALL* observations. The biggest difficulty is in knowing all the physical effects and the correct physical picture in which to include them.

II. *Subphotosphere*

In one class of models, mass motions are introduced for the sole purpose of reducing unstable radiative temperature gradients and are forced to vanish outside the unstable regions. With this approach, the emphasis has been on attempts to find a replacement for the mixing length theory of convection, which no one defends but everyone continues to use. With one exception, such attempts have so far been limited to investigations of the laboratory environment. The exception is the collaborative work of groups in New York and Nice (Latour, Spiegel, Toomre, and Zahn) in applying the non-linear theory to A-stars and the solar atmosphere. Preliminary results for A-stars confirm the mixing length result that there is negligible transport of convective energy but differ markedly from mixing length theory in the predicted velocities and the degree of convective penetration between upper and lower convective zones.

In a second class of models, the mass motions arising from the instabilities in the radiative temperature gradient are allowed to couple both with the mechanical energy dissipated elsewhere in the atmosphere and with the mass flux from the star. It is this approach that appears to have been most productive over the past three years.

(a) Studies of helium rich stars, in which one would expect convection zones to extend to stars of higher effective temperatures, indicate very high convective velocities. This is particularly true in white dwarfs, where, because the continuous opacity is low, the atmosphere includes regions of high density. Here the acoustic fluxes associated with such convection, as computed by the standard methods, become outstandingly high (cf. work by Nariai and Böhm's group in Seattle). Indeed the highest acoustic flux yet predicted, some 10^{11} erg cm^{-2} s^{-1}, has been obtained by Böhm's group, treating this problem. Such results raise the interesting possibility of a chromosphere in a collisionally controlled atmospheric region.

(b) A result that apparently depends on magnetic fields leads to the conclusion that the mass flux in a stellar wind must be independent of magnetic fields. That the magnetic field, and hence rotation, decay with age is suggested by (1) the Skumanich-Wilson study of the relation between stellar age and Ca$^+$ emission, together with (2) the correlation, in the Sun, between Ca$^+$ emission and surface magnetic fields, and (3) the idea that surface magnetic fields arise in the coupling between convection and rotation. The detailed results suggest a linear relation between field strength and rotational velocity. Durney has shown that the momentum removed by the solar wind could not give such a linear relation if the mass loss depended on the magnetic field. Thus the magnetic field cannot be responsible for the mechanical energy required for the solar wind.

This result bears on the relation between the existence of a chromosphere and corona following from Praderie's suggestion that mass flux is a necessary condition for a chromosphere and dissipation of mechanical energy a sufficient condition. Durney's result suggests that either (1) the total mechanical energy dissipated in the chromosphere is independent of the magnetic field, or (2) the coronal temperature is independent of such dissipation, or (3) some combination of coronal temperature and density is independent of this dissipation.

(c) While great emphasis has been placed on convective motions as a source of acoustic flux for stellar chromospheres, the convective mode is only one of several unstable modes associated with a steep temperature gradient, and thermal instabilities only some among many possibilities in stellar atmospheres. Independent investigations by Leibacher and Ulrich of waves trapped in the photosphere and subphotosphere provide interesting alternatives. These waves are associated with the so-called opacity and λ destabilizing processes in pulsating stars. In this formulation, the mechanical energy associated with a mass flux first appears in a stored configuration with a small leak corresponding to a combination of (1) the high frequencies not trapped by the solar minimum temperature and (2) the 'tunneling' exit in the upper photosphere. This brings into focus the parallel between the mechanical energy 'stored' in the sub-chromosphere, and the radiative energy 'stored' in the sub-photosphere, each propagating by 'diffusion' mechanisms. A further mechanism, suggested by Hearn for mechanical heating in hot stars, involves the interaction between acoustic waves and radiation pressure and may be of particular interest in Of and Wolf-Rayet Stars.

All these efforts suggest that we need no longer confine our attention to solar type chromospheres dependent on convectively produced acoustic flux for their energy and on magnetic fields for its dissipation.

III. *Collisionally controlled photosphere*

a. *Model atmospheres*

Of the large variety of LTE models in continuous production, perhaps the most interesting are those for cool stars and those in which the assumption of a plane parallel atmosphere has been dropped.

1. *Cool stars and opacity sources*

Here, as in many LTE models along the spectral sequence, the greatest advance lies in the inclusion of more realistic – and in some cases quite unexpected – opacity sources, as for example C_2^- (Johnson, Vardya). In considering the increasing number of line blanketed models, we must however remember that the assumption of LTE tends to overestimate the effects. Solar limb darkening results, for example, imply a strikingly low value for the temperature minimum (less than 3500°), if the spectra of molecules such as CO are assumed to be formed in LTE.

A systematic approach is now underway at the Institut d'Astrophysique in Paris to establish which opacity sources control the electron temperature in each part of a variety of atmospheres, both for LTE and non-LTE models. It is urged that those who compute model atmospheres output this data in a routine auxiliary table.

2. *Extended atmospheres*

An excellent summary of both extended and expanding atmospheres has been prepared by Böhm. Here we emphasize only the highlights and a few additional points.

With one exception, progress in this field has been made exclusively through the use of more accurate transfer solutions, the major advance being the introduction of a variable Eddington factor (Hummer and Rybicki). Gray models in which the opacity is assumed to vary as r^{-n} reemphasize the forward peaking of $I_\nu(\mu)$ and the flatter distribution of $I_\nu(\nu)$.

Cassinelli, on the other hand, treats the nongray case and uses the momentum equation to *compute* an opacity distribution. He obtains the expected result that the total change in T_e between the boundary and $\tau = 1$ is greater in the extended atmosphere, corresponding to the greater range in the dilution factor for the radiation field. He also finds the more surprising result that the boundary temperature is higher, and the boundary-temperature gradient lower, for non-gray than for gray models. Hummer and Mihalas obtain a similar result for a plane parallel model, which they attribute to heating in the Lyman continuum. We suggest, but have not yet demonstrated, that in both cases this result simply reflects the effect of electron scattering.

b. *Abundance determinations*

The vast majority of papers dealing with the collisionally controlled (LTE) photosphere are aimed at the determination of abundances. Previous Commission 36 reports have emphasized the importance of such results for interpreting differences in stellar spectra in terms of differences in stellar composition. That we do not do so here may be strongly criticized: all the papers we could find on the subject are included in the bibliography. Here, however, we elect to draw attention to the few investigations that explore the possibility of internal inconsistencies in analysis, which may signify that the derived abundances are open to question. As examples, we mention two such investigations, both solar. In the corresponding section on radiatively controlled photospheres, the problem is discussed in more detail.

Polarization studies at the Institut d'Astrophysique in Paris (Dumont, Pecker, Debarbat) provide an independent measure of electron density and thus of metal abundance. This work suggests higher values for the metal abundances than are normally accepted.

The increase in the accepted value of the iron abundance has been discussed extensively elsewhere. Suffice it to say that analyses of chromospheric and coronal lines, and of some forbidden transitions in photospheric spectra, appeared to give higher abundances than photospheric analyses of permitted transitions. It is now recognized that many of the photospheric discrepancies can be reduced by the use of more accurate f-values. Recent work on additional Fe I lines (Lites and Athay) suggests, however, that the inclusion of non-LTE processes may also be important in increasing the photospheric value. Similar work in Geneva (Müller, de la Reza) on Li, Be, and K also suggests that non-LTE processes may have a significant effect on abundance determinations. These studies belatedly confirm the heavily criticized non-LTE analyses of metals in the solar spectrum made a decade ago by the Pecker group at Meudon and Nice. Together, these results indicate that the boundary between the collisionally and radiatively controlled photospheres is deeper than had been previously accepted.

IV. *Radiatively controlled photosphere*

a. *Abundance determinations*

The above results on metallic abundances in the Sun indicate that even relatively weak lines may be influenced by the radiation field. Inclusion of radiative processes tends to increase the determined abundances by about half an order of magnitude. This increase arises because the energy levels are photoionization dominated in a region of decreasing electron temperature and hence are underpopulated relative to their LTE values at the local electron temperature. Abundances determined on the basis of LTE will thus be too small.

By contrast, the assumption of LTE for the formation of the Mg II lines in O and B stars leads to abundance determinations that are greater than normal. That the excessive strength of these lines can be accounted for by the inclusion of radiative processes with normal abundances has been shown by calculations of Mihalas.

The kind of differential effects that may occur even for lines of a given ion are illustrated by the work of Auer and Mihalas on the He I problem. They find that in B stars, lines in the blue-violet region of the spectrum may be analyzed as though they were in LTE, while those in the visual and red show very strong non-LTE effects. The direction of these effects depends on temperature and gravity, and far from being confined to strong lines, they are often strongest when the lines are very weak. These results arise in a general way because the lines are photoionization dominated and, as in nebular recombination lines, the size of the non-LTE effect is determined by the ratio of

$[b_L/b_U-1]$ to $[\exp(h\nu/kT_e)-1]$. Thus in the red, where $h\nu/kT_e$ is small, significant non-LTE effects will occur even for relatively small b-ratios.

All these results emphasize the great caution with which LTE abundance determinations must be viewed, and together they illustrate the two competing effects that determine the direction of the non-LTE corrections. Because of the dominance of the scattering term in the expression for the source function, line depths and limb darkening, which depend on population ratios, will in general exceed predictions based on the assumption of LTE. The absolute populations, however, depend on the dominant mechanism – collisional or radiative – by which the levels are coupled with the continuum. Thus the actual abundance corrections may be positive or negative and may even differ for different lines of a given ion.

b. *Line profiles*

Perhaps the single outstanding problem in obtaining satisfactory line profiles is the necessity to introduce the arbitrary parameters of micro- and macro-turbulence. In solar models based on the Ca II lines, for example, the inclusion of micro- and macro-turbulence has a greater effect than that of replacing the three-level by a multi-level atom or of replacing the simplest transfer solutions by the most sophisticated. (This does not, however, imply that LTE line profiles modified by velocity fields give the correct atmospheric model. In fact, they give the wrong sign for $\mathrm{d}T_e/\mathrm{d}h$). Hence the problem lies not in the computation but in our physical understanding of the empirical phenomena. Various attempts have been made, with varying success, to account for these two parameters in terms of the velocity fields associated with chromospheric heating. However, since the same problem exists in predicting the Mg II line profiles in O and B stars, this explanation would imply the existence of chromospheres, or some other explanation of 'turbulence', in hot stars. Indeed Mihalas has suggested that the behavior of He II λ 10124 in emission in Of stars might be explained by the existence of a chromosphere, and many references have been made to the similarities between Of and WR classes. It is also interesting that the question of 'turbulence' arises as the common factor in discussions of (1) the Wilson-Bappu effect, (2) Kraft's use of the width of Hα as a luminosity indicator, and (3) the anomalous widths of line profiles in supergiants.

c. *Model atmospheres*

1 *Plane parallel atmospheres*

Since a model is a representation of a real stellar atmosphere, we must consider two questions: (1) to what extent do we know, and can we include, all the relevant physical processes, and (2) to what sophistication need we compute their effect?

To the extent that a limited number of ions and transitions suffice, the most complete representation of photospheres as defined in this report is probably given by the linearization method of Auer and Mihalas. Here a simultaneous differential correction is applied to all relevant state parameters at each point in the atmosphere, subject to all the photospheric conditions. Application of this method to O, B, and some A-stars demonstrates clearly the significant effect of non-LTE processes on the distribution of electron temperature and distinguishes the effect of lines arising from ions that are a major source of continuous opacity. Impurities, that is lines from ions not associated with continuous opacity, have thus far been treated mainly to infer their behavior in a given model rather than to study their effect on the model itself.

An algebraic approach, aimed only at a numerical accuracy compatible with the limitations of the physical representation, has been initiated by Gebbie and Thomas. Here the processes that affect the values of the states parameters are divided into two classes: those that arise from changes in the populations of the energy states, and those that arise from changes in the transfer quantities such as mass and radiation. The latter include the effects of impurities and mechanical heating. The effect of lines from ions associated with continuous opacity has in some cases been predicted algebraically by this method.

Among the photospheric models that have been computed, both LTE and non-LTE, perhaps the most controversial aspect is the effect of the lines. In the LTE models, this effect depends largely on the kind of statistics adopted for their distribution (cf. these by Peytremann and Querci). Athay's non-LTE approach to the Sun is also in a sense statistical, as are the non-LTE picket-fence calculations of Mihalas and Luebke, which are based on the relative sized of a homogeneous set of lines, all characterized by the same collisional and continuous opacity parameters.

Thomas' original arguments that the effect of impurity cooling would be less in non-LTE than in LTE was based on the behavior of a single line at a *fixed* geometrical depth. Athay's counter-arguments, on the other hand, concern the effect of the lines on the boundary temperature. It is therefore interesting to note that Peytremann's LTE calculations predict a boundary temperature for the Sun of some 4280 K, in essential agreement with Athay's non-LTE calculation of 4330 K. The latest empirical models (Eddy, McQueen, Noyes, Vernazza) do indeed lie near or slightly below these values, and unless molecular results (Lena, Hall) are strongly affected by non-LTE processes, suggested boundary temperatures may drop to 3800–3500 K. The picket-fence calculations of Mihalas and Luebke show, however, that the effect of impurity cooling diminishes as the collision parameter decreases. Thus it should differ for collisionally and radiatively controlled lines, and it should vary with density from one luminosity class to another. At present, one can only say that the situation is uncertain. In discussions of line blanketing, however, care should be taken to distinguish the effect of impurity cooling from the heating and cooling effects of lines associated with ions that are a major source of continuous opacity.

2. *Expanding and extended atmospheres*

The *Proceedings of the Munich Symposium* provide a good overall picture of progress in this topic. Here we refer to them, remarking only as follows.

While the number of investigations of problems associated with moving atmospheres continues to increase, most of them still focus on the approach initiated by Sobolev: for sufficiently large velocity gradients, the value of the net radiative bracket (which, multiplied by the population of the upper level, gives the net rate of radiative transitions) is effectively that of a homogeneous finite slab. The form of the source function then becomes as simple as for a locally opaque configuration: in neither case does the radiation field appear explicitly in the expression for the source function, which is thus determined locally by the ratio of the source to sink term. In the locally opaque case, the sink term is the destruction probability; in the finite slab case, it is the escape probability. Recent generalizations of the Sobolev approach (Castor, Hummer, Kalkofen, Magnan, Rybicki) have attempted to determine the size of the necessary velocity gradient in terms of the gradients of other properties of the medium and the destruction scale (which, if destruction occurs by collisional de-excitation alone, is the same as the thermalization length). The outstanding problem seems to lie in determining the effect of the moving atmosphere on the value of the source function, rather than on the opacities, which then determine which parts of the source function distribution give rise to the observed radiation field. Results to date indicate that the moving atmosphere does not have a very large effect on the source function itself. So far, these methods have been applied mainly to the interpretation of P Cygni type profiles in terms of mass loss.

An extreme approach to determining the effect of a moving atmosphere on the source function has been developed by Lucy. He treats the scattering term alone, neglecting those contributions to the source and sink terms that come from the properties of the atmosphere alone. The value of such an approach for diagnosing the physical properties of the atmosphere remains to be demonstrated.

In a novel and controversial application of the Sobolev approach (Pecker-Gordon), the spectra of supernovae are interpreted in terms of detailed atmospheric processes. This is particularly interesting because of the variety in the treatment of supernovae from other aspects.

The extent to which wholly photospheric models can explain anomalous features in hot stars is still being explored. Following Parker's demonstration that all stars must have stellar winds, Cassinelli and Castor attempt to determine the size of wind that would result from radiative heating alone. Assuming a gray continuous absorptive opacity and LTE, they find that the ratio of the force due to radiation pressure must exceed about nine tenths that due to gravity in order to produce winds that are observationally significant. As an estimate of the rate of mass loss, they use the ratio L/cv_∞ (where L is the luminosity and v_∞ the velocity at infinity), which exceeds by c/v_∞ the limit set by Lucy and Solomon. We note, however, that this should be an upper limit, corresponding to an optically thick wind, rather than to the optically thin case treated. Attempts (Castor, Van Blerkom) to interpret Wolf-Rayet spectra in terms of purely radiative photospheres have succeeded in one case, although it is not clear at the moment that they can reproduce the high ionization level (O VI) observed in some Wolf-Rayet stars. Such work is important in establishing the real anomalies between correct photospheric models and observations.

3. *The temperature minimum*

The question of a temperature minimum, beyond which T_e increases outwards, did not arise in the classical model where T_e decreased monotonically to the boundary temperature. The dissipation of mechanical energy will cause T_e to increase outwards in a chromosphere; non-LTE effects alone may cause T_e to rise even in a radiatively controlled photosphere. This possibility was first discussed by Cayrel for H^- and has since been generalized by calculations of Auer and Mihalas and of Gebbie and Thomas. Whether an outward rise in T_e actually occurs in the absence of mechanical heating will depend on the competing effects of impurity cooling and the heating by additional continua. Because the number of contributors to the continuous opacity differs from one part of the atmosphere to another and from one spectral type to another, the problem remains to be explored in detail. Observationally, it is complicated by the presence of chromospheric heating and inhomogeneities.

d. *Emission lines*

Here the primary problem lies in distinguishing those lines that can be explained by a wholly photospheric model from those that imply the existence of a region with quite different physical characteristics. For example, much attention is being given to the interpretation of observed P Cygni profiles. The question, as yet unresolved, is whether the ratio of emission to absorption components and the high expansion velocities inferred from the blue absorption component can be explained simultaneously in terms of an extended atmosphere with a radiation driven wind. However, attempts to explain individual emission lines without invoking chromospheres or extended atmospheres have been more successful. For example, the appearance of N III λ 4634 has been explained (Nussbaumer, Mihalas, Hummer) by a mechanism for underpopulating the lower level of the transition, as distinct from fluorescent overpopulation of the upper level. The behavior of He II λ 10124 in Of stars, on the other hand, suggests that it is formed in a chromosphere (Lockwood and Mihalas). Apparently there is no general rule by which the presence of an emission line can be interpreted in terms of fluorescent mechanisms, extended atmospheres, chromospheres, etc. Nevertheless, it is to be hoped that some kind of classification scheme may emerge from the detailed investigations now in progress.

e. *Photospheric shells*

We distinguish a shell as being photospheric if its state is controlled by radiative processes rather than by dissipation of mechanical energy. Thus planetary nebulae and H II regions, which are dealt with extensively in the reports of other commissions, are primarily photospheric shells.

The outstanding problem here is the interpretation of the infra-red excesses observed in a variety of stars. For a discussion of the problem, we refer to the summary by Pecker. In spite of its theoretical importance, most of the progress in this field has been observational and therefore lies outside the province of this commission. The important theoretical problems remain to be tackled: Are dust shells formed from stellar material or from interstellar matter? Can the bolometric correction derived from infra-red observations, together with the flux of mass and energy from UV observations, be reconciled with the effective temperature and surface gravity hitherto assigned to a particular star? Indeed do the three parameters, effective temperature, surface gravity, and chemical composition, suffice to specify an atmospheric model?

V. *Chromosphere and corona*

Here progress over the past three years has lain more in defining than in solving the theoretical problems. The outstanding question is the degree to which chromospheric and coronal phenomena are present in the atmosphere of all stars. Almost all theoretical approaches to this problem deal with the convective production of acoustic waves, as in the Sun. The exceptions deal with additional sources of mechanical energy, such as opacity and ionization instabilities and radiation driven acoustic waves, and their necessary consequence for the production of chromospheres and mass flux. Detailed observational work is also restricted almost entirely to the Sun, with the exception of P Cygni profiles and other specific emission features such as the cores of the H and K lines of Ca^+ and Mg^+ in a variety of stars. The observational stellar work does, however, provide increasing evidence for atmospheric heating and mass loss beyond that attributable to radiation alone (cf. summaries by Praderie and by Feast, observations by Morton *et al.*, and calculations by Lucy and Solomon, Cassinelli and Castor, and Nariai on the mass loss from radiative effects alone).

Following Praderie's suggestion that the existences of a chromosphere and a mass flux are intimately linked, perhaps the most likely trend in the next few years will be toward an atmospheric model for which mass flux is a necessary condition, the corona being the region from which mass is actually lost, and the chromosphere the region in which most of the mechanical energy required to produce coronal conditions is dissipated. For this, the Sun should be extremely useful as a guide but myopic as a restriction. The evolution of thinking on Wolf-Rayet and other hot stars, with regard to chromospheres, coronae and mass flux, provides an excellent example.

a. *Chromospheres*

The location and physics of a chromosphere depend to some extent on whether we define it by a positive outward increase in electron temperature, T_e, or by the presence of mechanical heating. They will also depend on whether we consider the corona to begin at the top of the *steep* rise in T_e, or at the point where T_e is maximum, or at the point where the enthalpy term associated with the stellar wind exceeds the radiative losses. These questions are not entirely semantic and are at present being heavily debated as, for example, in the proceedings of the *Goddard Colloquium* on stellar chromospheres.

One approach to locating the base of the chromosphere, as defined by the temperature minimum, would be to treat impurity cooling as a perturbation on the T_e gradient as determined by the continuous opacity alone. Such a temperature distribution would have one minimum where collisional ionization gives way to photoionization and a second minimum where impurity cooling enters – although the second may, according to Athay, swamp the first. The subsequent increase in T_e may then result either from mechanical heating or from the effects of radiatively controlled lines as, with decreasing density, they overcome the effect of collisions. The line blanketing problem is itself sufficiently complex that the coupling between it and the mechanical heating has generally been ignored. However, the onset of dissipation from 'trapped' waves depends critically on the location of an initial outward increase in T_e (Leibacher, Ulrich, Stein), which could result either from radiative processes or from heating by the small fraction of waves never trapped. Thereafter, of course, the mechanical dissipation amplifies. Such problems, which are likely to receive much attention in the next years, tend to blur the distinction between a chromosphere defined by an outward increase in T_e and one defined by mechanical heating.

Many questions arise in attempts to solve these problems observationally. What part of a line profile can be used, i.e., when does the source function go to the Planck function at the local value of T_e? How is the source function affected by coherent scattering versus complete redistribution in the line wings? What is the connection between the scaling factor, Δv_D, and microturbulence, and what is the physical significance of each? What is the effect of molecular lines? To what extent is T_e inhomogeneous near the minimum, and what effect does this have on the diagnostics? What is the physical basis for attempts at scaling from the Sun to other stars?

Another problem equally important as that of the solar temperature minimum is the behavior of T_e between the minimum and the corona. Rocket UV studies (Avrett, Kalkofen, Noyes, Vernazza) have confirmed the visual eclipse results of a decade ago (Thomas, Athay, Pottasch), which indicated that T_e rises rapidly above the temperature minimum, then levels off to a more gradual rise for about the next 1000 km, and finally increases steeply to the corona. The far-UV studies also show an additional small plateau between 10^4 K and 10^6 K in the steep temperature rise. This plateau, predicted by earlier work, establishes radiative cooling as a controlling process in the steep temperature rise. The agreement between the visual and far-UV studies confirms the essential correctness of the diagnostic method, which depends critically on the non-LTE factors, b_1 and b_2, for hydrogen.

These analyses also indicate the very small height of the solar chromosphere – something between 1000 km and 2000 km. This result is of particular interest in relation to studies of Wolf-Rayet stars, in which the entire visual spectrum is now interpreted as being formed in a coronal region, again implying a small height for a chromosphere. The question then arises of whether we should expect *all* chromospheres to be of relatively small extent.

In computations of the distribution of mass accompanying a given temperature distribution, we again encounter the problems associated with the introduction of ad hoc turbulence parameters. These have been discussed in the section on line profiles; here we need stress only that the relation between the 'turbulence' used in the absorption coefficient and that used for the momentum balance is presently obscure.

The effect of any inhomogeneities in the structure of the atmosphere remains uncertain. There is some indication that for sufficiently small elements, the sum of the radiative plus mechanical fluxes is constant (Evans, Catano, Thomas). Observationally, it seems clear that for elements as large as sunspots, this assumption would not be valid. The extent to which such theories of flux conservation are valid is particularly important with regard to the variety of line profiles observed over small regions and plages. Stellar counterparts exist in, for example, the spectra of Am and Ap stars, for which the interpretations concentrate more on the thermodynamic effect of inhomogeneities than on the microscopic response of parameters involved in line formation.

b. *Coronas*

Coronal models in which mechanical energy is balanced against radiative loss have been computed for a variety of stars with solar-type sources of mechanical energy. The results are characteristic of models based on this limited approach.

Reference has already been made in this report to two aspects of coronal structure that have received particular attention over the last three years. The first is the small extent of chromospheres relative to coronas; the second is the realization that the primary characteristic of the corona is its mass flux.

Over the past twenty years, estimates of the height at which the corona begins have decreased steadily from some 50000 km above the visual eclipse limb (Aller's textbook) to some 5000 km (Woolley and Allen), down to the present estimate of some 2000 km. These results indicate that the mechanical energy available to raise T_e above its radiative-equilibrium value is stored for some short distance above the base of the photosphere and then dissipated over a small height range. A small fraction of the original mechanical energy passes through the chromosphere to be dumped in the corona, where it serves to blow off everything above that level.

When it was first recognized that the corona was hot, its basic character was thought to be determined by the balance between mechanical dissipation of energy and radiative loss. Later it was believed that the mechanical energy dissipated was balanced by thermal conduction downward to the chromosphere and outward to the extended corona. Then Parker's work on stellar winds laid the basis for the current belief that the state of the corona is fixed mainly by the wind it produces.

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PART C: AIMS AND ACTIVITIES OF THE COMMISSION

It has been our view that Commission 36 should serve as a center for the exchange of ideas and results on the structure of stellar atmospheres and for collaboration with other commissions in related fields. We believe, moreover, that it should serve this function not only for its formal members and for members of the IAU, but for all interested astrophysicists.

Toward these ends, we have:

(1) Established a class of associate membership, which includes all those who, for official reasons, either cannot or do not wish to become formal members. The list of members and associates is available on request.

(2) Established a center for the exchange of bibliographical material, for those members who wish to use it. The present bibliography is based in part on this material.

(3) Encouraged the organization of colloquia and symposia, of which the following were sponsored in part by the Commission.

'Wolf-Rayet and High Temperature Stars', *IAU Symposium*, No. 49, Buenos Aires, August 9–14, 1971. Chairman: M. K. V. Bappu.

'Stellar Chromospheres', *IAU Colloquium*, No. 19, Greenbelt, Maryland, February 14–18, 1972. Chairman: A. B. Underhill.

'Extended Atmospheres and Circumstellar Matter in Spectroscopic Binary Systems', *IAU Symposium*, No. 51 (Struve Memorial), Victoria, B. C., September 6–12, 1972. Chairman: K. O. Wright.

In addition, the following conferences, although not sponsored by Commission 36, dealt with topics of interest to its members:

'Line Formation in the Presence of Magnetic Fields', Boulder, August 3 – September 2, 1971. Chairman: R. G. Athay, L. House, and G. A. Newkirk.

'Supergiant Stars', Trieste, September 6–8, 1971. Chairman: M. Hack.

'Red Giant Stars', Bloomington, Indiana, October 4–6, 1972. Chairman: H. R. Johnson.

(4) Encouraged the quick and inexpensive publication of proceedings of current symposia, including the following:

'Spectrum Formation in Stars with Steady-State Extended Atmospheres', Proceedings of *IAU Colloquium* No. 2, Eds. H. G. Groth and P. Wellman. NBS Spec. Publ. 332 (Washington, D.C.: U.S. Government Printing Office) 1970. Price $1.75.

'The Menzel Symposium on Solar Physics, Atomic Spectra, and Gaseous Nebulae', Ed. K. B. Gebbie. NBS Spec. Publ. 353 (Washington, D. C.: U.S. Government Printing Office) 1971. Price $1.75.

'Stellar Chromospheres', Proceedings of *IAU Colloquium*, No. 19, Eds. E. H. Avrett and S. D. Jordan. NASA SP-317 (Washington, D. C.: U.S. Government Printing Office) 1973.

'Line Formation in the Presence of Magnetic Fields', Eds. R. G. Athay, L. House, and G. A. Newkirk (Boulder: NCAR-HAO) 1971. Price free.

'Théorie des Atmosphères Stellaires', Eds. D. Mihalas, B. E. J. Pagel, and P. Souffrin (Geneva: Observatoire de Genève) 1972. Price $6.00.

'Mass Loss From Stars', Proceedings of the Second Trieste Colloquium on Astrophysics, Ed. M. Hack (Dordrecht-Holland: D. Reidel Publishing Co.) 1969. Price $22.10

In addition, the proceedings of the two IAU Symposia mentioned above are being published by D. Reidel Publishing Company, Dordrecht, at the standard IAU prices.

R. N. THOMAS
President of the Commission