36. COMMISSION DE LA THEORIE DES ATMOSPHERES STELLAIRES

PRÉSIDENT: Professor Dr K. H. Böhm, Lehrstuhl für Theoretische Astrophysik, Universität Heidelberg, Mönchhofstrasse 12–14, 69 Heidelberg, Germany.

VICE-PRÉSIDENT: Professor Dr A. B. Underhill, Astronomical Observatory 'Sonnenborgh', Zonnenburg 2, Utrecht, The Netherlands.

COMITÉ D'ORGANISATION: C. de Jager, V. V. Sobolev, R. N. Thomas, H. Van Regemorter, M. H. Wrubel.

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I. INTRODUCTION

Commission activity between the assemblies

A conference on the theory of line formation ('Second Harvard-Smithsonian Conference on Stellar Atmospheres') was held in Cambridge, Mass., on 20–22 January 1965. The meeting was organized by the Smithsonian Astrophysical Observatory and the Harvard College Observatory. A fairly large number of papers were presented. There was a strong emphasis on non-LTE line formation problems for 'few level' atoms.

An IAU Colloquium on the 'Blanketing Effect' (organized by this Commission) was held at the Heidelberg University on 17–19 March 1966. Four review papers and 12 shorter communications were presented. The main emphasis of the talks and discussion centered around:

(1) The applicability of the present form of the line broadening theory to stellar atmospheres, especially to low density regions. (There was no doubt about the applicability under usual laboratory conditions.)

(2) The possibilities of developing a non-LTE line blanketing theory.

(3) Statistical methods of treating a very large number of lines in LTE blanketing effect computations.

Other symposia related to the theory of stellar atmospheres

They included:

An IAU Symposium (no. 26) on 'Abundance Determinations in Stellar Spectra', held in Utrecht, 10–14 August 1964. This meeting was sponsored by the IAU Commissions 29 and 36. There were sessions on methods of abundance analysis, in which problems of the theory of stellar atmospheres were discussed.

The 5th Symposium on Cosmical Gas Dynamics, held in Nice, September 1965 (IAU Symposium no. 28, sponsored in part by IUTAM) included a very detailed discussion of the hydrodynamics of the solar atmosphere (including convection, convective overshoot, and oscillatory motion) and of atmospheres of pulsating stars.

It has been attempted to list the books and the proceedings of symposia which have appeared during the last three years and which are related to the work of this Commission, in section I of the bibliography.

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II. BASIC THEORY OF STELLAR ATMOSPHERES

(a) *Theory of Radiative Equilibrium*

Reviews of radiative transfer problems have been given by D. G. Hummer (**37**), in Sampson's book (**1**), and in a very comprehensive way by J. C. Pecker (**62, 61**).

The problem of constructing good non-grey radiative equilibrium model atmospheres (eventually including non-LTE effects) still plays a fundamental role. The Avrett-Krook method has continued to be used successfully in many applications. A new and very elegant temperature correction procedure has been suggested by L. B. Lucy (**48**). The most attractive feature of this method is its theoretical simplicity. K. H. Böhm and W. Deinzer (**16**) have worked out a Fortran programme of this method and have made the first numerical applications. They found that Lucy's method is a very effective temperature correction procedure, unless the scattering contribution to the source function becomes very strong in most parts of the atmosphere. In the meantime L. G. Henyey (**32**) has developed a new temperature correction method, which looks very promising, but which has not yet been tested numerically (K. H. Böhm is preparing such a test). Henyey's method is based on the exact conversion of the monochromatic error ΔF_ν into the monochromatic Planck function correction ΔB_ν.

Another temperature correction procedure based on a certain type of linearization of the equation of transfer has been suggested by P. Feautrier (**28**). A simple modification of the Avrett-Krook method has been suggested by T. L. Swihart (**70**).

A combination of an improved flux iteration method and a revised Λ-iteration scheme has been worked out by T. Tsuji (**74**). It has been successfully tested in the case of a picket-fence model. S. Matsushima and Y. Terashita (**84**) have studied the influence of errors in the absorption coefficient on non-grey models. A useful numerical comparison of non-grey models found by slightly different methods has been given by Gingerich, Mihalas, Matsushima and Strom (**31**).

K. H. Böhm (**15**) found that under certain conditions a temperature inversion can occur in the uppermost layers (where the electron scattering contribution varies rapidly) of very hot non-grey model atmospheres.

Since E. Hopf's early work it has been clear that it must be possible to find an exact solution for at least one standard non-grey problem, namely the LTE picket-fence model. This aim has been achieved recently by C. E. Siewert and P. F. Zweifel (**65**) and by J. C. Stewart (**67**). See also J. C. Stewart (**68**).

A considerable amount of research effort is going into the field of non-LTE radiative transfer. R. Wildt (**77, 78**) is continuing his basic studies of grey non-LTE atmospheres. His approach is based completely on the thermodynamics of the radiation field. He showed that the unattainability of detailed balancing follows from thermodynamics.

An interesting approach to the computation of non-LTE atmospheric structure has been suggested by W. Kalkofen (cf. **44**). The method permits the numerical computation of the temperature stratification and the radiation field in not too high layers in stellar atmospheres. It is based on the (reasonable) assumption that in deeper layers, in which the important continua are formed, the conditions in the strong lines are already very close to detailed balancing. If that is true the line transfer problem is decoupled from the continuum transfer. A very useful discussion of this approach has been given by D. Mihalas (**50**). Numerical applications have been made (see Mihalas and Stone (**49**) and other sections of this report).

A general survey of the present state of the non-LTE approach has been given in R. N. Thomas' book (**72**). He naturally emphasizes line transfer problems (see section II. *f* of this report), but he also includes the interaction between lines and continua. See also Warner (**76**).

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A very useful report on the general theory of the emission coefficient has been given by D. G. Hummer (**36**).

A coupled line-continuum transfer problem for a three-level atom has been treated by W. Kalkofen and Avrett (**3**), Y. Cuny (**20**), and by Johnson and Klinglesmith (**6**). A seven-level problem has been solved by T. Kogure (**46**) in connection with the problem of the Balmer decrement in Be stars. A possible interpretation of the oscillatory phase in novae based on non-LTE effects has been suggested by J.-C. Pecker (**63**). The non-LTE formation of the Lyman-continuum in an isothermal atmosphere has been studied by R. D. Dietz and L. L. House (**86**). Non-LTE problems in Wolf-Rayet stars have been considered by Rublev (**64**).

I. Kolesnik and D. A. Frank-Kamenetsky (**47**) have studied the non-LTE formation of recombination continua in non-stable stars. A related problem has been treated by L. M. Biberman, V. S. Vorobyev and A. N. Lagar'kov (**14**). Deviations from LTE in a pure hydrogen plasma are treated in (**34**).

The problem of finding the temperature stratification of an atmosphere in the presence of line blanketing has found renewed and strong interest during the last years. Computational programmes incorporating LTE blanketing by many lines have achieved a rather high degree of perfection, largely due to the work of S. E. Strom and his collaborators (cf. S. E. Strom and R. L. Kurucz (**85**)). O. Gingerich (**89**) has studied, under which conditions a schematic treatment is sufficient. There is general agreement that the LTE treatment overestimates the blanketing effect. The question is: How much? R. N. Thomas (**73**), R. Cayrel (**2**) and H. Frisch (**88**) argue that the error is probably very large. The problem could be definitely settled only, if we would understand better the formation of subordinate lines in a stellar atmosphere. A blanketing problem has also been treated by T. L. Swihart (**69**).

Considerable progress has been made in the mathematical theory of radiative transfer. V. A. Ambarzumian has developed a method for applying principles of invariance to non-linear transfer problems (**4, 5**). His ideas have been also applied by Nikoghossian to a multi-level line transfer problem (**56**) and by N. B. Yengibarian (**82**). Bellman, Kalaba, Kagiwada and Ueno (**7, 8, 9, 10, 11**) have continued to develop the invariant imbedding technique and applied it to a number of problems (e.g. finite slab, one-dimensional medium with a moving boundary). A different procedure of solving transfer problems in a slab geometry has been applied by R. Bellman, H. Kagiwada and R. Kalaba (**12**). They have (together with S. Ueno) computed graphs of the X- and Y-functions for a wide range of slab thicknesses and albedos (**13**). Extensive tables of Chandrasekhar's X- and Y-functions have also been computed by J. L. Carlstedt and T. W. Mullikin (**17**). Finite atmospheres with coherent isotropic scattering have been studied by V. V. Sobolev (**66**) for the limiting case of large optical thickness. He finds that the resolvent of the integral equation determining $S(\tau)$ can be expressed in terms of quantities characteristic of the semi-infinite atmosphere.

J. I. F. King, R. V. Sillars and R. H. Harrison (**45**) have published tables of Hopf's q-function with 8-digit accuracy.

The problem of light scattering in a finite atmosphere has been investigated by V. V. Ivanov (**40, 41, 42**) and by Ivanov and Leonov (**43**). He finds an exact solution for the resolvent of the integral equation for the source function in a finite atmosphere. Tables of Ambarzumian's functions for anisotropic scattering have been computed by I. N. Minin, A. G. Piliposian and N. A. Shidlovskaja (**52**). A small-angle approximation for the source function in certain scattering problems has been discussed by S. Ueno (**75**).

A detailed study of the grey transfer problem with spherical symmetry is due to R. J. Chapman (**18**).

Other problems in the mathematical theory of transfer have been treated by Collins and Code (**19**), Dave and Walker (**21, 22**), P. Feautrier (**27, 29**), Horak and Janousek (**35**), Hummer

(38), Irvine (39), Mullikin (87), Nagirner (53, 54, 55), Obridko (57), Pahor and Kuscer (58), Pavlov (59, 60), Wilson and Sen (79, 80) and by Yanovitsky (81).

The problem of the conversion of the observed centre-to-limb variation into $S(\tau)$ has been rediscussed (using new mathematical methods) by Delache (23, 24, 25) and by David (83).

Delache has also given a qualitative discussion of radiative transfer in an atmosphere with a stellar wind (26).

Time-dependent radiative transfer has been investigated by I. N. Minin (51) (in connection with the close binary problem) and by T. L. Swihart (71). A study of wave propagation in a random medium by U. Frisch (30) may permit application to radiative transfer problems.

(b) *Continuous absorption coefficients and some other basic data*

There have been further improvements of the theory of the H^--absorption, especially for the free-free transitions. We mention the work by T. L. John (10, 11, 12), by T. Ohmura (32) and by N. A. Doughty and P. A. Fraser (8). The bound-free transitions of H^- have been reinvestigated by Doughty, Fraser and McEachran (7). M. Weinberg and R. S. Berry (36) have drawn attention to the possible importance of a forbidden bound-free continuum of H^- included by perturbing neighbouring particles in a gas of fairly high density. V. Myerscough's, (34) preliminary results indicate that this forbidden continuum will be of importance in the deeper atmospheric layers of a white dwarf like van Maanen 2 and probably also in the upper transition layer of the solar hydrogen convection zone.

There has been a very fast growing interest in the opacity sources in late-type stellar atmospheres. J. R. Auman (1) has succeeded in deriving absorption coefficients due to H_2O for the application to cool stellar atmospheres. A method for estimating the H_2O absorption has been given by M. S. Vardya (23). The problem of the possible importance of negative ions other than H^- and H_2 in late-type stars is of considerable interest. It has been studied by Vardya in (26) and in combination with the general problem of molecular abundances in late-type stars in (27, 28). The Cl^--ion shows a rather large abundance in very cool atmospheres (27, 24). The absorption coefficient of Cl^- has been computed by R. Kandel (13). V. G. Buslavsky (5) has studied opacity sources in late-type stars in general. The presence of a transmission window at $1{\cdot}65\mu$ in late-type stars has been discussed by Vardya (20).

In a semi-emperical investigation M. S. Vardya and K. H. Böhm (22) have looked for undiscovered sources of opacity in an M2 main sequence atmosphere. They find that the question could be answered only in a conclusive way, if we could determine the effective temperature with an error not essentially larger than $\pm$ 100°K.

K. Kodaira (29) finds that the depression at λ 2085 in the solar spectrum can be attributed to the ionization edge of Al I $3p^2P^0$.

It has been found that free-free absorption of He^- can be very important in hydrogen deficient stellar atmospheres. The He^--absorption coefficient has been computed by M. McDowell, M. Williamson and V. Myerscough (15) and by W. B. Sommerville (19).

Work on the calculation of absorption coefficients using the quantum defect method has progressed considerably. The papers of G. Peach (16, 33) seem to be especially useful for astrophysical applications. O. Bély (2) has developed a generalized quantum defect method for hydrogen-like ions. F. Praderie (17) has studied the absorption cross-section for neutral carbon. D. Schlüter (35) has developed a somewhat different method and applied it to Ne I, Ar I, Kr I and Xe I.

New tables of atmospheric opacities have been given by M. S. Vardya (21), A. Cox and J. Stewart (6) and by G. Bode (3).

Monochromatic atmospheric absorption coefficients have been computed by G. Bode (**3**) and by J. Baerentzen and E. Mikkelsen (**31**).

O. Gingerich (**30**) has given a summary of very useful interpolation formulae for absorption coefficient computations. A description of the simplified treatment of line absorption in blanketing computations is due to Vardya (**25**).

The problem of autoionization and dielectronic recombination in the outer layers of a star has continued to receive considerable attention. We mention the work of A. Burgess (cf. **4**), L. Goldberg, A. K. Dupree and J. W. Allen (**9**) and W. van Rensbergen (**18**).

The excitation of H-atoms by protons has been studied by McCarrol and Salin (**14**).

(*c*) *Hydrodynamic Phenomena in Stellar Atmospheres*

The proceedings of the Joint Discussion on this subject have been published in *Transactions IAU*, **12B**, 531. Hydrodynamic problems of stellar atmospheres have been also discussed at the Nice symposium (see section I of this report).

Convection, Turbulence:

E. A. Spiegel (**43, 44**) summarized the present possibilities for a physical theory of turbulent convection in the Boussinesq approximation.

A general survey of the available data on models of the solar hydrogen convection zone has been given by K. H. Böhm (**4**). He has also discussed convection overshoot at the upper (**4**) and lower (**4, 6**) boundaries of the convection zone. The latter problem has been recently investigated by K. Kohl (**55**). The physical mechanism of convective penetration has been discussed by D. W. Moore (**31**). The possible importance of convective overshoot for the atmospheric Lithium depletion has been studied by R. Weymann and R. L. Sears (**50**) and by Böhm (**6**). The general problem of convective dilution of elements has been studied by E. Schatzman (**39**). Problems of the outer convection zone in connection with the specification of the outer boundary conditions for internal structure calculations have been discussed by L. H. Henyey, M. S. Vardya and P. Bodenheimer (**13**) and by J. Faulkner, K. Griffiths and F. Hoyle (**10**). A semiempirical discussion of stellar convection zones has been given by O. C. Wilson (**51**).

D. Mihalas (**29**) has treated the transition region between a *nongrey* radiative equilibrium atmosphere and a convection zone described by the mixing length theory. A related problem has been studied by N. Sack (**37**). K. Böhm (**5**) has suggested that M-dwarf atmospheres may show an observable deviation from a radiative equilibrium stratification due to the fairly large convective energy transport in these atmospheres. Swihart and Margrave (**45**) are studying inhomogeneities in the solar atmosphere.

Very interesting work on the deformation of magnetic fields by convection has been done by N. O. Weiss (**48, 49**).

K. Walter (**47**) has proposed a very unconventional theory of the outer solar convection zone.

Polytropic atmospheres are still a very useful tool for studies of convection in compressible atmospheres: E. A. Spiegel (**42**) has investigated convective instability in such atmospheres using a perturbation treatment with respect to layer thickness. As an alternative he has explored a variational approach and the WKB approximation. The onset of convection in a polytropic atmosphere with a uniform magnetic field has been studied by S. A. Kaplan and N. S. Petrukhin (**17**). They have derived a simple instability criterion for this case. A generalization of the Schwarzschild criterion for an atmosphere with a magnetic field has been discussed by D. O. Gough and R. J. Taylor (**12**). A. Baglin (**1**) has generalized the Schwarzschild criterion for the case in which a separation of elements occurs in a strong gravitational field. S. Yamaguchi (**52**) used a variational technique to study the convective instability in a layer with depth

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dependent superadiabatic gradient. Limitations of the applicability of the Schwarzschild criterion have been discussed by G. F. Sitnik (40).

W. Deinzer (7) has used the suppression of convection by a magnet field in a heuristic way to construct a magnetohydrostatic model of a sunspot.

Convective overstability in a geometrically thin medium with a superadiabatic gradient has been investigated by S. Kato (18).

A simple model permitting a physical explanation of overstability has been developed by D. W. Moore and E. A. Spiegel (32).

J. Baerentzen (2) has given new formulae for the computation of the adiabatic gradient and the specific heat.

Turbulence in stellar atmosphere has been discussed by Hollandsky (15), Hollandsky and Chub (16), I. M. Kopylov (22), P. E. Nissen (33) and E. C. Olson (34, 35). O. P. Hollandsky (14) has discussed the possible influence of the radiation pressure on the sound velocities in the atmospheres of hot supergiants.

Oscillations

Considerable attention has been paid to the problem of the generation of the photospheric oscillation or waves by the granulation. M. J. Lighthill (25) has given a very comprehensive and illuminating survey of this problem. S. Kato (19) has investigated atmospheric oscillations excited by turbulence near the critical frequency.

He has also studied (20, 21) the response of an unbounded atmosphere to a point disturbance. F. Meyer and H. U. Schmidt (28) have made extensive computations of the response of the solar atmosphere to a granular disturbance. P. Souffrin (41) has studied the variation of hydrodynamic waves with distance from the hydrogen convection zone. He has generalized diagnostic diagrams for an isothermal atmosphere to include radiative dissipation. He finds that gravity waves should be unimportant in the photosphere because of their strong radiative damping. A standing-mode gravity wave in the chromosphere has been studied by Y. Uchida (46).

Empirical data on photospheric oscillations have been gathered, reduced and interpreted in a very careful way by F. N. Edmonds (8, 9), by P. Mein (27) and by J. B. Zirker (53). A very interesting new observational study of the velocity fields in the photosphere has been made by E. Frazier (56). He finds a definite splitting of the maximum of the oscillation power spectrum into two peaks. He was also able to detect convective overshoot into the uppermost layers of the photosphere.

Other problems

Heating of an atmosphere by shock waves has been investigated by G. A. Bird (3), by M. Kuperus (57) and by M. Saito (38). The propagation and coupling between the three magnetohydrodynamic modes in a stratified medium has been studied by U. Frisch (11).

S. V. Rublev (36) has investigated the dynamics of Wolf-Rayet atmospheres. An important empirical study of the mass loss of T-Tauri stars is due to L. Kuhi (23).

Other hydrodynamic problems have been treated by Lemaire (24), McLean (26), and Grover and Hardy (54).

(*d*) *Thermodynamic Problems of Stellar Atmospheres*

In this section we shall discuss very briefly only those papers which have not yet been considered in connection with either the computation of absorption coefficients or with the convection problem.

B. Schlender and G. Traving (3) have shown that the approximate computation of partition functions can be greatly simplified if one uses a Chebyshev approximation. Applications of this method can be found in the paper by G. Traving, B. Baschek and H. Holweger (**5**). The problem of pressure dissociation and its influence on molecular partition functions has been investigated by M. S. Vardya (**7, 9**). He has also (**8**) computed some basic thermodynamic quantities for a mixture of H, He and 16 other elements (with solar photospheric abundance ratios) allowing for different stages of ionization and the formation of H_2, H_2^+ and H^-.

Molecular abundances in stellar atmospheres have been calculated by Tsuji (**6**), by Wyller and Morris (**10**) and by J. F. Dolan (**1**). Wyller and Morris have studied 15 diatomic and 16 triatomic types of molecules in the atmospheres of carbon stars. Dolan and Vardya (Ref. **27**, Section (*b*)) has also paid special attention to polyatomic molecules.

Nonequilibrium ionization in an atmosphere due to the ejection of 'plasma bunches' has been considered by I. G. Kolesnik (**2**). Studying the importance of inelastic collisions, S. Souffrin (**4**) has reached the conclusion that in normal stellar chromospheres there will be no observable deviation from the Maxwellian distribution of particles.

(*e*) *Extended Envelopes*

Most of the work done in this field belongs either to the subject of other commissions or ıas been treated in other sections of this report. In this section we have just listed a few refer- :nces, which otherwise could not be easily fitted into our classification scheme. These papers :ontain discussions of (*a*) the influence of the solar wind on abundance determinations in the olar corona (J. C. Brandt, **1**), (*b*) problems of expanding stellar envelopes (Gorbatzky, **2**) (*c*) ı study of shells of Be stars (Lacoarret, **4**, (*d*) the extended chromosphere of 31 Cygni (Magnan, ') and (*e*) a few problems of solar and stellar chromospheres and coronas (Hughes, **3**; Livshitz, ;; Livshitz and Nikolsky, **6**; and Athay, **8**).

(*f*) *General Theory of Line Profiles and Line Formation*

Problems of the physical theory of the line absorptions coefficient mostly belong to the field ıf Commission **14**. I shall mention only a few references to work being done by Commission nembers or to papers related to this work.

A very useful survey of the theory of line broadening and its astronomical applications has ɪeen given by H. van Regemorter (**47**). The same author (together with S. Bréchot, **46**) has lerived a generalization of the impact broadening theories of Lindholm and of Baranger, taking nto account (among other effects) inelastic collisions. H. Pfennig (**38**) and H. Pfennig, ᴇ. Trefftz and C. R. Vidal (**39**) have drawn attention to the fact that until recently the Kolb- Griem Stark broadening theory had not been tested in the laboratory in the density range which s of interest in the theory of most stellar atmospheres. Recent experiments of Ferguson, Schlüter and Vidal in the range $N_e \approx 10^{13}\,\mathrm{cm}^{-3}$ give (according to Pfennig, Trefftz and Vidal, **39**) results which are much closer to the quasistatic theory than to the Kolb-Griem heory. The theoretical reason for this result is not yet understood. The Stark broadening unctions for the hydrogen lines have been recomputed by F. N. Edmonds, H. Schlüter and D. C. Wells (**16**). They take into account the effects of correlation and shielding. The results are epresented graphically for the Lyman-Balmer-Paschen- and Brackett-lines up to $n = 18$. The problem of determining the electron density from line merging due to Stark effect has ɪeen reinvestigated by L. N. Kurochka (**29**) and C. R. Vidal (**49**). Kurochka (**30**) has also onsidered the possible influence of the Doppler effect on line merging. The Influence of Stark ɪroadening on abundance determinations has been studied by D. Mugglestone and B. J. O'Mara (**32**). New Computations of Voigt functions are due to C. Chiarella and A. Reichel (**12**).

A general survey of stellar atmospheres and their line spectra has been given by K. O. Wright (**51**). A series of papers on the measurements of lifetimes of excited levels has been introduced by E. Schatzman (**41**).

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The following work has been done on LTE line formation (mainly in connection with the problem of atmospheric abundance analysis): Baschek, Holweger and Traving (9) have published their Algol programme for the quantitative analysis of stellar spectra. This programme has been translated into Fortran by Peytremann (55). 'Differential curves of growth' have been discussed by Baschek and Traving (10). They have published tables and graphs of the derivatives of Unsöld's curve of growth. Pagel has applied the differential curve of growth method (37). F. N. Edmonds (17) has compared curves of growth and contribution curves for the same line, but for different fine analysis methods. Mugglestone and O'Mara (31) have considered the influence of saturation effects on the abundances derived from faint and medium-strong lines. They especially discuss the determination of the oxygen and notrogen abundance in the solar photosphere.

A very useful and interesting theoretical study of the broadening of lines by the presence of a turbulent velocity field has been made by G. Traving (44). He has investigated in quantitative detail the influence of the scale of the hydrodynamic motion on the curve of growth. 'Microturbulence' and 'macroturbulence' in the usual sense appear as limiting cases in his theory. Y. Yamashita (52) has studied the curve of growth for lines formed by pure absorption in an atmosphere where $S(\tau)$ has a linear + exponential depth dependence and where (κ_ν/κ) can be described by a step function. Unno and Yamashita (45) have studied curves of growth for line profiles, which have been truncated at an artificial continuous level. Tables for the calculation of the formation depth are given by Balli, Kiral and J. C. Pecker (8).

A considerable amount of work has been done on noncoherent scattering in resonance lines: D. I. Nagirner and V. V. Ivanov (34) have considered the non LTE line formation with complete redistribution for a two-level atom in an infinite medium. D. I. Nagirner (33) has found an explicit expression for the resolvent of the integral equation for the source function for coherent and for completely noncoherent scattering. Ivanov and Nagirner (24) have shown that the radiation emerging from an atmosphere in a resonance line can be expressed in terms of a generalized H-function. A large number of solutions of the two-level line transfer problem with complete redistribution has been given by Avrett and Hummer (7) and by Avrett (6). Hummer and Rybicki (21) have studied the non-LTE line formation for a two-level atom with spatial variation of the Doppler width (see also Hummer, 53). The problem of *general* noncoherent scattering (i.e. without *complete* redistribution in frequency) has been reviewed by D. G. Hummer (20).

S. Dumont (14) has developed the discrete ordinate method for computing the integrals in the source function for complete non-coherent scattering.

K. D. Abhyankar (2, 3) has studied thoroughly the Schuster problem for an expanding atmosphere.

The general problem of non-LTE line formation has been extensively discussed in R. N. Thomas' book (42) and in his article (43). J. T. Jefferies (25) has surveyed the multi-level problem in the theory of line formation. A review of the computational problems in the theory of non-LTE line formation has been given by Hummer and Rybicki (22). The problem of the thermalization length has been studied by D. G. Hummer and J. C. Stewart (23). A new method for solving the transfer problem in the non-LTE case has been suggested by E. Böhm-Vitense (11).

Under which conditions are the source functions for the lines of a given multiplet equal at a given depth? This important question has been discussed by J. Waddell (50), R. G. Athay (3 and most recently by E. H. Avrett (54). In a series of papers R. G. Athay (4, 5) has develope a new and simplified theory for calculating the equivalent width of lines formed under non LTE conditions. The method seems to be especially suitable for lines formed in a chromosphere The possibility that doubly excited levels may play an important role in the formation of the H- and K-emission cores has been discussed by L. Goldberg (19).

H. R. Johnson (**26, 27**) has studied the non-LTE formation of the NaD lines in the solar photosphere. S. Dumont (**15**) has considered two- and three-level approximations for Ca II and Mg II. Y. Cuny (**13**) finds in a study of the non-LTE formation of the Balmer lines in the Sun that the residual intensities are almost independent of the chromospheric temperature. In an empirical investigation, Gökdoğan and J.-C. Pecker (**18**) find systematic differences between the curves of growth for different multiplets, even if these multiplets have the same excitation potential.

The important problem of radiative transfer in lines in the presence of a magnetic field has been studied by V. N. Obridko (**36, 35**) and D. N. Rachkowski (**40**).

III. MODEL ATMOSPHERES AND THEORY OF SPECTRA FOR INDIVIDUAL STARS OR GROUPS OF STARS, METHODS OF ABUNDANCE DETERMINATIONS

(a) 'Normal' Stars (except Sun) and General Literature on Methods of Abundance Determination

A general survey of methods and results of abundance determinations has been given by A. Unsöld (**72**). The method of model atmospheres has been discussed by Baschek, Kegel, Bode, Kodaira, Kohl and Traving (**7**). A critical summary of abundance determinations for early-type stars has been given by G. Traving (**78**), the corresponding discussion for stars of type F0-G5 is due to G. Wallerstein (79). B. E. J. Pagel (**57**) gave a critical summary of abundance determination for spectral type G8 and later. The problem of determining basic atmospheric parameters for a chemical analysis has been discussed by C. R. and A. P. Cowley (**49**). A critical investigation of the theoretical considerations influencing the determination of a model atmosphere and the prediction of line profiles has been given by A. B. Underhill in (**69**) and to a certain extent in (**70**). The possibilities of a spectral analysis using hydrogen lines only have been studied by E. Böhm-Vitense (**14**). D. Fischel (**21**) has investigated the influence of the chemical composition on the structure and the metal index of a stellar atmosphere. Tables for the limb darkening for a grid of stellar atmospheres have been published by O. Gingerich (**29**).

Rotating atmospheres and their radiation have been discussed by G. W. Collins (**18**), Y. Osaki (**56**) and J. Hardorp and P. Strittmatter (**32**). A thorough discussion of the comparison of computed fluxes of blanketing models with observations is due to A. Underhill (**70**). E. Peytremann (**58**) is trying to interpret the Geneva seven-colour photometry. He uses model atmospheres and takes the blanketing effect into account. The possible importance of the blanketing effect for the UV spectrum of γ Pegasi has been discussed by Böhm-Vitense, Pyper and Wallerstein (**13**).

Problems of the empirical determination of stellar atmospheres have been studied in great detail by F. van't Veer (3) and has been applied by him to the derivation of sunspot models.

Very hot stellar atmospheres

Model atmospheres for neutron stars ($T_{eff} \sim 5 \times 10^6$ °K) have been investigated by Orszag (55) and D. C. Morton (**52**). Mrs K. B. Gebbie (**80**) and K. Böhm and W. Deinzer (**11, 12** and unpublished results) have computed model atmospheres for central stars of planetary nebulae. Böhm's and Deinzer's non-grey model atmospheres cover the O'Dell- and the Harman-Seaton sequence. The effective temperature ranges from 38 000°K to $1{\cdot}8 \times 10^5$ °K. A study of hot stars of low luminosity is due to V. V. Sobolev (**60**).

Normal early type stellar atmospheres:

A new fine analysis of τ Scorpii has been made by M. Scholz (**59**). He has determined a new non-grey model atmosphere ($T_{eff} = 32\,800$°K, $\log g = 4{\cdot}2$) using Lucy's method. (See section II.*a* of this report.) D. Mihalas and his collaborators have made very extensive studies of early type stars. They have computed a set of model atmospheres, hydrogen line profiles and helium line strengths (Mihalas, **45**), determined the temperature stratification for a B1 star taking into account line blanketing (Mihalas and Morton, **50**), determined abundances of He (Mihalas, **46**) and of Mg (Henry and Mihalas, **33**). Furthermore Mihalas (**48, 51**) has applied W. Kalkofen's (see section II.*a*) method in order to study the non-LTE formation of the hydrogen continua in early-type stars. Adams and Morton (**1**) have computed the temperature stratification for a B4 star including the effects of line blanketing. Morton (**53, 54**) has also investigated the theoretical line profiles in the ultraviolet spectra of early-type stars.

A. B. Underhill (**71**) and Guillaume, van Rensbergen and Underhill (**31**) have determined the theoretical near ultraviolet spectra of early B stars. They find that broadening effects due to microturbulence are more important in determining the line spectrum than changes in the $p - T$ relation of the model.

A theoretical model of a B 1·5 star with line blanketing has been computed by C. Guillaume (**81**).

Strom and Avrett (**62, 64**) have studied the temperature stratification for a number of early-type stars. Kalkofen and Strom (**38, 63**) used Kalkofen's theory (see above) to compute the influence of non-LTE effects on the stellar continuum fluxes for spectral types B5–A5. They find Balmer discontinuities which are smaller than in the LTE case.

I. M. Kopylov (**42**) has worked out an improved version of Unsöld's method of determining electron densities in hot stars. He finds corrections to Unsöld's values ranging from $-0{\cdot}45$ (O stars) to $-1{\cdot}5$ (F–stars) in $\log n_e$.

M.-O. Baylac (**9**) has investigated the continuous spectrum of B0–F0 stars in the photographic infrared. She finds that the measured Pachen discontinuities are always larger than the calculated ones.

A and F Stars

K. O. Wright (**76**) has studied the excitation temperatures of A– and F–stars. The temperature stratification for A stars, including effects of line blanketing, has been calculated by D. Mihalas (**47**).

Conti, Wallerstein and Wing (**20**) have derived abundances for the main-sequence stars of type A to K in the Hyades. Baschek and Oke (**8**) have determined effective temperatures and surface gravities for normal A, for Ap and Am stars. K. Kohl (**40**) made a fine analysis of Sirius and essentially confirmed the fact that his star has peculiar abundances. These are the subjec of a new study by Cl. Chevalier (**17**). L. Houziaux (**35, 36**) has carried out a theoretical investigation of the Lyman lines in A (and B) stars. He has also studied the profiles of the infrarec oxygen triplet at λ 7772 in spectrum of Vega (**37**). F. Edmonds (**22, 23**) and Edmonds anc Talbert (**24**) have made a very thorough study of Procyon. Edmonds computed a set of eigh non-grey models for this purpose. He finds an effective temperature of 6780 °K. Baschek Holweger, Namba and Traving (**6**) have made a detailed analysis of the spectrum and th atmosphere of β Virginis. They find an overabundance of a factor of about two (with respec to the Sun) for all elements from C to La.

Spectral Type G and later

The influence of the surface gravity on the UBV colours of G stars has been discussed b Baschek (**5**); Matsushima and Terashita (**43, 44**) have computed non-grey model atmosphere for solar type stars. The formation of the forbidden [O I] lines in late-type stellar atmosphere has been discussed by R. E. M. Gasson and B. E. J. Pagel (**28**) and by P. S. Conti *et al.* (**61**). Gasson (**27**) in her thesis has made a detailed analysis of the spectrum of Arcturus.

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G. Cayrel (**16**) has studied differentially the physical parameters and chemical composition of seven early-type K stars (five of these are giants) and the comparison star ϵ Virginis. Model atmospheres for M stars have been derived by J. R. Auman (**4**), T. Tsuji (**68,** see also **67**), by M. S. Vardya and R. Kandel (**73**), and by V. G. Buslavsky (**15**). K. S. K. Swamy (**65**) has computed and discussed the profiles of strong lines in K dwarfs. Problems of the curve of growth analysis in cool stars have been studied by Fujita and Tsuji (**26**) and by Yamashita (**77**). L. W. Fredrich, H. R. Johnson and T. Fay (**25**) discussed the infrared spectrum of cool stars. They find that most observed features in the region 8500–12 000 Å can be attributed to CN.

White Dwarfs

Model atmospheres for white dwarfs of type DA have been calculated by Terashita and Matsushima (**66**). Model atmospheres consisting either only of helium or of hydrogen have been derived by A. K. Kolesov (**41**) for the temperature range 12 000–20 000°K. He finds that convection is very important for helium white dwarfs. A detailed study of the blanketing in white dwarfs has been made by V. Weidemann (**75**).

Other problems

Studies of atmospheric Li abundances have been of very great interest during the last three years. We mention only the two fundamental papers by Herbig (**34**) and by Wallerstein, Herbig and Conti (**74**). The production of Li, Be, B by spallation processes in stellar atmospheres has been discussed by Bernas, Gradstajn, Reeves and Schatzman (**10**). In this connection we should also mention the work by J. Audouze (**2**).

(*b*) *Sun*

In this section we quote only some papers which have some relation to the general theory of stellar atmospheres. Other investigations on the solar atmosphere are the subject of the report of Commission 12.

A new and very elaborate semiempirical investigation of the stratification of the solar atmosphere has been made by H. Holweger (**10**). He concludes that the local temperature at $\bar{\tau} \sim 10^{-6}$ is about 3900°K. According to Holweger all non-LTE effects in the solar atmosphere are too small to influence abundance determinations in a perceptible way. The latter question has also been studied in detail by Müller and Mutschlecner (**19**). B. E. J. Pagel (**21**) has discussed the maximal values of departures from LTE compatible with the empirical data on excitation temperatures. A new study of the solar spectrum for the purpose of new abundance determinations has been started by L. H. Aller (**1, 17, 31**) and his collaborators. He is paying special attention to the less abundant elements lke Sb, Ba, Be, Cd, Nb and recently yttrium (see **31**). He considers (1) an extrapolation of the Pierce-Waddell model to higher layers and (2) Pagel's model joined to the one determined from centre-to-limb variation at 9000 Å and 16 000 Å by Pierce and Waddell. C. R. Cowley (**5**), and Müller and Mutschlecner (**19a**) has studied the nickel abundance; King, Lawrence and Link (**15**) have determined the gallium, silver and indium abundances in the solar atmosphere. E. A. Müller (**20**) has made new abundance determinations for a few elements. She finds a new value for Li: $\log(N_{\mathrm{Li}}/N_{\mathrm{H}}) = 11{\cdot}2$. Schmahl and Schröter (**25**) derive $-11{\cdot}4$ for the same ratio from sunspot spectra. Goldberg, Kopp and Dupree (**9**) have rediscussed the important problem of the Fe abundance determination in the photosphere. Excitation temperatures have been determined by Teplitskaya (**26**).

Baschek, Holweger and Müller (**2**) are studying the centre-to-limb variation of weak and medium-strong O I and a few C I lines. C. de Jager and L. Neven (**12**) have made centre-to-limb observations of 50 infrared lines and have discussed (**13**) the centre-to-limb variation of the infrared carbon multiplet. The second paper is the first application of a new method for the systematic analysis of Fraunhofer lines belonging to one multiplet. A theoretical study of

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blends of metallic lines has been undertaken by Fujita (6). An investigation of the limb intensity of $H\alpha$ is due to P. R. Wilson (29). The averaging process for photospheric lines which show fluctuations has been discussed by the same author (28). Simplified blanketing models of the photosphere have been computed by Gingerich (8).

J. Houtgast (11) has derived absolute intensities in the range 3000–4000 Å of the solar spectrum at about 200 wavelengths.

Non-LTE line formation processes in the solar atmosphere have been studied by several authors:

P. Chamaraux (3) and H. R. Johnson (14) have made a non-LTE computation of the NaD lines. They find large departures from LTE outside the temperature minimum. According to these investigations the NaD lines are collisionally dominated. A related study is due to B. J. O'Mara (17), who has also computed Ca line profiles. A theoretical study of the Ca II and Mg II lines has been made by S. Dumont (4).

R. E. M. Gasson (7) has confirmed the multiple character of the damping branches of the solar curve of growth.

W. Unno (27) has worked out a generalization of Goldberg's method (for the determination of the depth dependence of turbulence) which includes the effects of macroturbulence. A critical discussion of the inference of velocity fields from line asymmetries is due to Kulander and Jefferies (16).

Zwaan (30) has made a very detailed semi-empirical study of sunspot models. Miyamoto (18) has studied the thermal instability of chromospheric material.

Basic problems of line formation in the solar corona have been investigated by Pottasch (22, 23) and by C. Pecker-Wimel and R. N. Thomas (24).

(c) *Atmospheres of Typical Population II Objects and of Peculiar Stars*

Baschek (3) has studied the atmospheric structure and the abundances of the high velocity star Wilson 10 367. Kodaira (16) has investigated the atmosphere of HD 161 817. Kodaira finds a logarithm of the underabundance of metals of $-1{\cdot}11$ (with respect to the Sun). For Wilson 10 367, Baschek gets a corresponding value of $-1{\cdot}6$. Pagel and Powell (19) find that the cool subdwarf HD 25 329 is metal deficient by a factor 20. They make allowance for the complex character of the curve of growth. R. Cayrel (9) is in the process of re-examining the location of Subdwarfs in the ($M_{bol} - \log T_{eff}$)-plane. A detailed analysis of the metal deficient star χ Dra has been made by M. Spite (22). She finds metal deficiencies of about a factor 2. Two population II K giants, HD 6497 and HD 6833 have been studied by G. Cayrel (unpublished).

A considerable amount of work is being done on peculiar A stars: Auer, Mihalas, Aller and Ross (2) have made a fine analysis of the manganese star 53 Tauri. Mihalas and Henshaw (17) have made an abundance analysis of C II, Mg II, O I, Si II and Si III in Ap stars. L. H. Aller (1) is carrying out an extensive programme of abundance determinations in magnetic stars using model atmosphers. Searle, Lungershausen and Sargent (21) have determined abundances of iron-peak elements in peculiar A stars.

E. Böhm-Vitense (using the oblique rotator hypothesis) has constructed magnetic fields for peculiar A stars which permit an explanation of the observed field variations (5) and also of the velocity and intensity variation of lines (4, 5). She also gives an explanation of the crossover effect, using the same form of the magnetic field (7).

Atmospheres and chemical abundances for metallic line stars have been investigated by P. S. Conti (11) and F. Praderie (20). A theoretical study, in which he tries to explain seven-colour photometric results (Golay system) on metalic line stars, has been done by B. Hauck (14). An analysis of two Ba II stars has been carried out by I. J. Danziger (12). A fine analysis of

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three Centauri A has been made by J. Hardorp (13). He confirms the large He^3 abundance determined earlier by Sargent and Jugaku and finds $T_{eff} = 19\,400°K$, $\log g = 3{\cdot}87$.

Model atmospheres for helium stars have been computed by D. Klinglesmith (18), E. Böhm-Vitense (8), K. Hunger and D. van Blerkom (15). Klinglesmith's computations cover the range $16\,000°K < T_{eff} < 30\,000°K$; $2{\cdot}5 < \log g < 4{\cdot}0$. Böhm-Vitense has studied the range $7300°K < T_{eff} < 12\,900°K$; $2{\cdot}0 < \log g < 4{\cdot}5$. Hunger and von Blerkom have computed a non-grey model for $T_{eff} = 18\,000°K$; $\log g = 3{\cdot}5$ (corresponding roughly to Klemola's star).

Climenhaga (10) and Wyller (23) have studied carbon isotopic abundances in carbon stars. A. Wyller (24) finds that the lithium and calcium lines used in the differential abundance analysis are possibly strongly contaminated by $C^{13}N^{14}$ lines in carbon stars.

K.-H. BÖHM
President of the Commission

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(*a*) *Theory of radiative equilibrium (including blanketing effect, but generally excluding other problems of line formation).*

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III. *Model Atmospheres and Theory of Spectra for Individual Stars or Groups of Stars, Method of Abundance Determination*

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