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

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I. INTRODUCTION, COMMISSION ACTIVITY, SYMPOSIA AND COLLOQUIA

Commission 36 has cosponsored the following colloquia and symposia: (1) IAU Colloquium No. 51, "Convection and Turbulence in Stellar Atmospheres", London, Ontario (27-30 August 1979); (2) IAU Symposium No. 80 "The HR Diagram, the 100th Anniversary of Henry Norris Russell", Washington DC (2-5 November 1977); (3) IAU Symposium No. 83 "Mass-Loss and Evolution of O-Type Stars", Qualicum Beach, Vancouver Island (5-9 June 1978).

In connection with the XVIIth General Assembly in Montreal, the commission participated in the organization of a Joint Discussion with Commissions 10, 12, 29, 35, and 44 on the topic of "Physics of the Chromosphere-Corona-Wind Complex and Mass-Loss in Stellar Atmospheres", and Joint Meetings with Commissions 29 and 45 on the topics "Stellar Abundances" and "Stellar Rotation".

Owing to limitations of space, this report will not give a comprehensive discussion of all aspects of the field, nor an exhaustive bibliography. Rather, it focuses on a few important and active areas in which significant progress has been made recently. The author of each section of the report is indicated explicitly; references are collected at the end of the report, arranged by sections.

II. RECENT PROGRESS IN THE THEORY OF STELLAR ATMOSPHERES

A. Winds from Early-Type Stars (J.P. Cassinelli)

1. Introduction

Mass-loss from O-stars, OB supergiants, Wolf-Rayet stars and central stars of planetary nebulae is revealed by broad P-Cygni lines from light ions in relatively low ion stages such as C^{+3}. These flows are characterized by large mass-loss rates (10^{-8} to 10^{-5} $M_\odot$/yr), and large flow speeds (600 to 3500 km/sec). The observations and the evolutionary consequences of large mass-loss rates are summarized by Conti (1978), and the basic equations of wind theory are presented by Mihalas (1978).

Infrared-continuum and ultraviolet-line surveys have been completed and provide information on the mass-loss rates, terminal velocities, and ionization-structures of the winds, but the temperature structure is still uncertain.

1) Barlow and Cohen (1976) derived mass-loss rates, $\dot{M}$, from their infrared continuum photometry. They found that $\dot{M}$ is nearly proportional to the stellar luminosity ($\dot{M} \propto L^{1.1}$) and is only weakly dependent on the effective temperature of OB supergiants and O*f* stars.

2) The catalogue of <u>Copernicus</u> satellite spectra by Snow and Jenkins (1977) provides a rich source of information on the wind structures. Abbott (1978a) has derived an empirical relation between terminal velocities and photospheric escape speeds: $v_\infty = 3\ v_{esc}$.

3) The Copernicus spectra show strong lines of anomalously high stages of ionization such as O VI in O stars, and Si IV in late B supergiants. Summaries of the anomalies, along with two different explanations, are given by Lamers and Snow (1978) and Cassinelli and Olson (1979). The discovery of these anomalies has revived widespread interest in chromospheric and coronal models for the winds, as had been proposed by Cannon and Thomas (1977) and Hearn (1975).

2. Theoretical Work

The most complete theoretical model for the winds of hot stars is that of Castor, Abbott and Klein (1975, 1976), hereinafter CAK. It is successful in explaining the observed mass-loss rates and terminal velocities. However, CAK did not address

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the problem of mechanical energy deposition and the accompanying production of high stages of ionization such as O VI. In the last three years two especially active areas of theoretical research have emerged: 1) Castor, Abbott and Klein have refined their original model to provide rebuttal to several early criticisms of it. 2) Primarily to explain the observed ionization anomalies, several authors have derived semi-empirical models of winds, with various assumptions concerning the temperature structure.

Line-Driven Wind Theory

In the radiation-pressure model of Lucy and Solomon (1970), as extended by CAK, the envelope is accelerated by transfer of momentum from the radiation field to particular ions by line-absorption in the ultraviolet. The observed high mass-loss rates require a large number of absorbing lines. Abbott (1977, 1978b) compiled extensive lists of lines and found that there are enough strong lines available to account for the observed mass-loss rates. Furthermore, he delimited the region in the HR diagram in which the acceleration due to line opacity in a static atmosphere exceeds gravity at large-enough optical depth to guarantee that the atmosphere must expand. This is a region in which the winds can be "initiated" solely by the radiation mechanism, and it corresponds well to the zone in the HR diagram where outflows are actually observed. While it now seems clear that winds can be produced entirely radiatively, whether they actually are or not is still under debate. Thomas (1978) criticizes the fully radiatively-driven wind models for assuming laminar, steady-state flow, and contends that the mass-loss results from subphotospheric motions in accordance with the thermodynamics of open systems.

Improvements in the predicted velocity-structure have been developed by Castor (1978). Accounting for angular redistribution of multiply-scattered line radiation, and for the velocity dependence of the ionization balance, he derived a slower velocity-rise of the flow. This agrees better with the velocity-law inferred from the infrared continuum and ultraviolet line profiles (Lamers and Morton, 1976). Klein and Castor (1978) defended the assumption that the winds have temperatures not very different from stellar effective temperatures on the basis of theoretical fits to observed Hα and He I emission lines.

The CAK theory can explain the empirical results that $\dot{M} \propto L^{1.1}$, that $v_\infty = 3\, v_{esc}$, and that the winds of supergiants are nearly independent of T_{eff} (Abbott, 1977). These successes suggest that a major part of the mass-loss mechanism has been accounted for. However, the presence of O VI in the observed spectra, and evidence of variability of the stellar winds (York, et al. 1977, Stalio and Upson 1978) indicates that the picture is far from complete.

Semi-Empirical Models

It is now possible to derive rather good estimates of the fractional abundances, and even spatial variations, of ions from the observed P-Cygni lines using the families of theoretical profiles that have been calculated by Olson (1978) and Castor and Lamers (1979). The relative abundance of the ions depends on the assumed electron temperature and the diffuse radiation field within the wind, and on the hard radiation-flux incident on it. From the observational data now available, it is not possible to derive temperatures unambiguously. Casinelli, Castor and Lamers (1978) discuss three quite different models that can explain the anomalous ionization.

a) Lamers and Morton (1976) and Lamers and Rogerson (1978) found that the overall ionization conditions in the winds of ζ Pup (O4*f*) and τ Sco (B0 V) are like that of any optically thin plasma at 2×10^5 K, and proposed a "warm wind" model.

b) Castor (1978) found that the ionization could be explained with a lower temperature, (6×10^4 K) if account is taken of the diffuse field in an optically-thick wind.

c) Cassinelli, Olson and Stalio (1978) and Cassinelli and Olson (1978) proposed a model in which the winds are cool (.8 T_{eff}), but are subjected to radiation from a small hot corona. The high ion stages are produced by the Auger mechanism following K-shell absorption of x-rays. This model explains the anomalous ionization in the O and B supergiants, and predicts that there should be a 2 kev flux that is large enough to be detected by the HEAO-B satellite, scheduled for launch in late 1978.

3. Directions for Future Work

On the observational side, better estimates of mass-loss rates ought to be forthcoming from VLA radio measurements. X-ray observations are crucial for determining the existence of coronae. Thus far only ζ Pup has been studied in great detail at all spectral wavelengths; other stars need this attention so as to avoid a distorted picture. Studies of variability, and of photospheric motions, are needed to elucidate the cause of the mechanical heating.

On the theoretical side, the semi-empirical models will need continual improvement as new data become available. Mechanisms for heating a coronal region, or a broader warm region, need to be investigated. Sufficient data are now available on the optically-thick winds of Wolf-Rayet stars (Hartmann, 1978a,b; Johnson 1978) that significant progress should be possible. A study of the effects of rotation on line-driven winds is needed to understand the flows from Oe and Be stars (Castor 1978). Much work is already underway on the effects of mass-loss on evolution (Conti 1978) and on the effects of winds on the interstellar medium (Weaver; Castor and McCray 1977).

B. Mass-Loss From Late-Type Stars (D. Reimers)

Within the last few years, our knowledge concerning circumstellar envelopes and mass-loss in red giants has increased rapidly, mainly as a result of new and better observations (new technologies) in a variety of wavelength regions. However, reliable mass-loss rates are still difficult to estimate, as the discrepant results obtained by different authors show (Sanner, Bernat, Reimers). In spite of the uncertain rates, various authors have included red-giant massloss in stellar evolution calculations (e.g. Fusi-Pecci and Renzini, Mengel, Wood and Cahn). There is still no convincing theory of mass-loss in red giants. Even the basic underlying mechanisms have not been identified with certainty.

1. Optical Observations

The P-Cygni character of the circumstellar (CS) lines in red giants has been investigated for the first time by means of high-resolution echelle spectrograms (Goldberg et al. 1975; Bernat and Lambert, 1975; Sanner, 1976) and by Fourier transform spectrograms. At high resolution, the profiles of strong lines such as the Na I and K I resonance lines show multiple components or weak satellite lines (Goldberg et al., Sanner). The amount of shell emission seems to be time-variable due to radial velocity variations of the underlying stellar Fraunhofer lines (Goldberg et al.).

Resonance-line re-emission from shells has been detected directly in α Ori and μ Cep (Bernat and Lambert, 1976; Münch et al. 1976), in particular in α Ori out to $\sim$30"=600 stellar radii-(Bernat et al. 1978). Two-dimensional images of the shell of α Ori have been constructed (Bernat et al. 1978; Lynds et al. 1977). There seem to be no gross departures from spherical symmetry on a scale an order of magnitude larger than the stellar radius.

In a study of the incidence of mass-loss in red giants, CS lines have been found in all stars cooler and more luminous than a line in the HR diagram defined by (spectral type K 5, M_v=0), (K 4, -1), (K 2, - 1.8), (G 5, -4), (G 0, -5). A simultaneous study of wind-velocities in the whole red giant region ($\sim$150 stars) revealed a loose correlation of the wind-velocity with the escape velocity at the stellar surface (Reimers 1977). In K giants like α Tau, variations of CS lines on a time-scale of months (minor changes within days) have been detected (Reimers, 1977; Kelch et al. 1978). It is not yet clear whether most of the variations indicate real changes of the flow, or changes in the degree of ionization.

Rates of mass-loss of M supergiants as determined from CS P-Cygni profiles are controversial (by a factor 100!) (Sanner, 1976; Bernat, 1977; Hagen, 1978). The main reason is that it is difficult to determine the location of the shells (inner shell radii). This difficulty can be avoided by use of CS lines visible in the spectra of close visual companions like α^2 Her and α Sco B (Reimers, 1977; Kudritzki and Reimers, 1978; van der Hucht et al. 1979). Mass-loss rates of globular-cluster stars have been derived by Cohen (1976) and Mallia and Pagel (1978).

2. Infrared Observations

Recent advances in detector technology have brought to light many new facts about circumstellar dust around highly-evolved stars (cf. review by Merrill, IAU Coll. 42). In particular systematic studies of objects in the 2-μ Sky Survey and the AFCRL/AGL Infrared Sky Survey have revealed a large number of highly-evolved objects with silicate-, Si C-, and C-dust emission (decreasing abundance-ratio O/C along the sequence M, MS, S, SC to C stars). In the most evolved M-type Miras, the 9.7-μ silicate emission even reverses to strong self-absorption (Merrill et al. 1976; Forrest, et. al. 1977). The most evolved objects are hidden in their own dust envelopes which completely absorb and re-emit the stellar flux. A number of objects have been detected first as Type II OH masers, and subsequently as infrared stars, and Mira stars with periods up to 750 days (Schultz et al. 1976).

Besides the earlier lunar-occulation technique, spatial interferometry has now been used to resolve CS dust envelopes on the sky (McCarthy, Low, Howell, 1977). In particular, the angular diameter of the silicate dust envelope of Mira itself has been detected to vary in phase with the star (McCarthy et al. 1978). The question whether dust condensation begins at the surface of the stars or only at distances of several stellar radii is not yet settled.

It has become clear that the featureless dust emission--except broad bands--does not give unambigious information about the amount of dust, the dust temperature, and the gas-to-dust ratio as long as grain opacities, condensation processes etc. are so poorly known (cf. Schmid-Burgk and Scholz, 1976). Mass-loss rates determined from dust-emission thus remain very uncertain.

3. Radio Observations

The maser lines of OH, H_2O and SiO in Mira stars and supergiants will not be discussed here (cf. review by Winnberg, IAU Coll. 42). In the present status of theory they do not yield reliable mass-loss rates.

Owing to the increased sensitivity of radio receivers at mm-wavelengths, thermal emission in lines of molecules such as CO, HCN, CS, SiO, SiS, HC_3N, C_2H_2 and CH_4 have been detected in infrared stars like IRC + 10216 (Mufson et al. 1975; Lo and Bechis 1976; Kuiper et al. 1976; Zuckerman et al. 1977). The lines are formed in cool expanding envelopes around highly evolved stars ('proto-planetary nebulae' Zuckerman 1978). Most of these are carbon-rich stars and S-type stars. These objects offer unique opportunity to obtain both fairly reliable mass-loss rates and molecular and isotopic abundances of the material ejected to the interstellar medium. The mass-loss rate of IRC + 10216 is about $2\cdot10^{-5}$ $M_\odot$/yr (Goldreich and Scoville 1976; Kwan and Hill 1977). The search for 21-cm HI emission in these stars has thus far been unsuccessful, probably because hydrogen is present mainly as H_2. There is a possible detection of the 21-cm line in α Ori (Zuckerman, 1978).

In the GO Ia supergiant HR 8752, radio emission has been measured between 2.7 and 90 GHz (Smolinski et al. 1977). In terms of a spherically expanding stellar wind, a mass of $0.5\cdot10^{-3}$ $M_\odot$ of ionized hydrogen is required. This is consistent with the [NII]-emission detected earlier, and with recent optical observations of a shell around the star (Lambert and Luck, 1978).

4. Theoretical Aspects

Accurate rates of mass-loss for various types of stars are of vital interest to stellar-evolution theory. Though we may be able to measure mass-loss rates with sufficient accuracy for a few stars by purely empirical means, it appears that the final aim, knowledge of mass-loss rates in all relevant evolutionary phases, cannot be achieved so long as the basic mass-loss mechanism(s) has not been identified and before the theory of stellar winds in late-type stars has been worked out.

For the difficulties of the various theoretical attempts [thermally (acoustically)-driven winds; wave-driven winds; radiatively-driven winds] we refer to the

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review by Weymann (IAU Coll. 42). Semi-theoretical estimates of mass-loss have been made by Renzini (1976) and Mullan (1978). However, the various assumptions made are questionable. One of the principal factors inhibiting progress in the theory of stellar winds for red giants is that the region where the mass-loss mechanism is operating is difficult to observe. In red giants, contrary to conditions in hot stars, the amount of mechanical energy required to produce the slow winds (a fraction of $\sim 10^{-5}$ of the stellar luminosity) is fixed by the potential energy of the escaping matter. This means that energy deposition is needed mainly quite near the star. The CS lines, however, are formed in the cool outer envelope ($r \gtrsim 5$ to 10 stellar radii). It thus appears that we cannot learn much about the mechanism from optical lines (and the same seems to apply to infrared and radio observations).

One may hope that the following observations--combined with appropriate diagnostic techniques--will help us to understand the unknown transition zone between chromospheres and CS envelopes: blue-shifted Hα emission and absorption components; FeII emission-lines and radio emission from stars like α Ori; observations of extended chromospheres and "prominence" features (satellite lines) in eclipsing binaries like ζ Aur and 31 Cyg; UV observations of M giants and supergiants (as indicated by preliminary emission-line data from IUE--cf. Commission 44). Observations of CS lines with high spectral resolution (multiple components), and of the marked time-variations of CS lines in K- and early-M giants, combined with observations of light-variations of the stars may also be helpful for identifying the mechanism.

Much remains to be done, both theoretically and observationally, before we understand mass-loss in late-type stars.

C. Stellar Chromospheres and Coronae (J. Linsky)

1. Introduction

Important advances have been made recently in this field due to the development of spectroscopic diagnostics and the growth of ultraviolet and X-ray data from space. These data lead to estimates of physical properties in chromospheres and coronae of individual stars, and to a first generation of models. In some cases crude estimates of radiative losses have been made; these pose tests of theoretical estimates of nonradiative heating rates.

2. Spectroscopic Diagnostics

The physical properties of astronomical plasmas are inferred from observed line and continuum profiles and intensities. Dupree (1978) has reviewed the status of ultraviolet and X-ray diagnostics for plasmas hotter than 5×10^4 K, and Praderie (1976) and Linsky (1977) have reviewed the literature on chromospheric diagnostics.

Basri et al. (1979) have shown that the incoherence fraction for redistribution in the wings of Lα is frequency dependent, but that it is feasible to derive chromospheric models using wing-intensities. Fluorescent processes that have been investigated recently include pumping of the O I resonance lines by Lβ (Haisch et al. 1977), of the H_2 Lyman bands by Lα (Jordan et al. 1978), of the fourth positive system of CO by C IV resonance lines (Bartoe et al. 1978) and Bowen fluorescence of O III (Raymond 1978; Margon and Cohen 1978). Stencel (1977) and Canfield and Stencel (1976) have discussed formation of emission lines in the wings of the Ca II H and K lines. Lites et al. (1978) analyzed the C II resonance lines, and Tripp et al. (1978) analyzed the Si II and Si III ultraviolet lines.

3. Theoretical Models and Empirical Tests

The goal of computing ab initio theoretical models of the outer atmospheres of stars including shock-wave or other nonradiative heating processes has not yet been attained. Cannon and Thomas (1977) suggest that an "imperfect wind tunnel" analogy, with an imposed outward velocity in the subatmosphere, may provide the proper physical framework for such calculations. Klein et al. (1978) have shown that low-amplitude upward-propagating waves can form shocks in A- and B-type stars, and have computed the observable effects of precusor radiation, accretion shocks, and conversion of mechanical to thermal energy.

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For late-type stars, Renzini et al. (1977) and Ulmschneider et al. (1977) have computed acoustic energy-fluxes and chromospheric heating-rates. One test of this theory is the predicted mass column-density of the temperature-minimum for different stars, as reflected in the Ca II K_1-widths. Ulmschneider et al. (1978a,b) have computed the locations of temperature minima, but Cram and Ulmschneider (1978) point out inconsistencies between predictions and measured K_1 widths. A second test of the theory involves chromospheric radiative loss-rates. Linsky and Ayres (1978) and Linsky et al. (1978) point out the extrapolated total chromospheric loss-rates in lines appear to be independent of stellar gravity, whereas the computed heating-rates of Ulmschneider et al. (1977) show a large increase with decreasing gravity. Estimates by Praderie and Thomas (1976) of the mechanical energy input into the solar chromosphere have been criticized by Ulmschneider and Kalkofen (1978) and Kalkofen and Ulmschneider (1978). Indeed, even the basic hypothesis that solar-type chromospheres are heated by short-period acoustic waves has been questioned by Cram (1978).

Hearn (1975, 1977) has porposed a method for computing coronal and wind properties based on a minimum-energy principle. His equations have been modified by Haisch and Linsky (1976) and applied to dwarfs and giants by Mullan (1976a). This approach has been criticized by Vaiana and Rosner (1978), Antiochos and Underwood (1978), and Endler et al. (1978). Withbroe and Noyes (1977) have reviewed the mass-and energy-flow in the solar corona.

4. Modeling of Stellar Chromospheres

Models for chromospheres and upper photospheres have been constructed for FO-MO dwarfs (Ayres et al. 1976, Kelch 1978, Kelch et al. 1979) and for G-K giants (Kelch et al. 1978). The analysis of the Ca II H and K line-profiles and Mg II h and k line-fluxes, may require revision if redistribution in the line wings has not been properly treated. Further, these are one-component atmospheres, an approximation just barely valid for the Sun and possibly grossly inadequate for stars like Arcturus (Heasley et al. 1978).

Bearing in mind these potential problems, the general trends found for the 18 stars now studied can be summarized as follows: (1) In most cases the temperature in the upper photosphere inferred from the K line-wings is hotter than that computed from radiative-equilibrium models, implying significant nonradiative heating. (2) With increasing nonradiative heating, as measured by the radiative loss-rate in chromospheric emission lines, the temperature minimum moves deeper into the atmosphere. (3) Active-chromosphere dwarf stars, as indicated by bright emission lines, have large chromospheric radiative-loss rates and steep chromospheric temperature-gradients. In particular, Kelch et al. (1979) have shown that Hα emission, which characterizes dMe stars, can be simply explained by the steep chromospheric temperature gradients implied by the bright K-line emission in these stars. (4) The mass column-density at the top of the chromosphere is a simple function of stellar gravity for dwarfs and giants.

Much work remains to be done to model the chromospheres of supergiants, RS CVn-type binaries, and metal-poor stars. Ultraviolet spectra from IUE yield fluxes for the Si II lines, and C I and Si I continuua which test the models based on fluxes of the Ca II, Mg II, Lα, C II-IV, Si II-IV, and N V lines, and help to extend these models into stellar transition regions. Active regions appear to play a major role in explaining the cyclic variability of the K-line in G-K dwarfs studied by Wilson (1976) and variability in dMe stars like BY Dra (Kunkel 1975). Since magnetic field-strength and K-line brightness are correlated in the Sun (Skumanich et al. 1975), strong magnetic fields are likely to be the cause of stellar plages and chromospheric activity. The fundamental question of how magnetic fields enhance nonradiative heating-rates to produce steeper chromospheric temperature-gradients and enhanced emission line-fluxes remains unanswered.

5. Location of Chromospheres and Coronae in the HR Diagram

Ca II K-line emission provides evidence for chromospheres in stars as early as γ Boo (A7 III). This is consistent with mechanical-flux calculations based on the

Lighthill-Proudman theory, but it is disconcerting that the K line ceases to be a useful chromospheric diagnostic at just this class of stars.

The identification of chromospheres and coronae in A-type and hotter stars requires ultraviolet and X-ray observations. Praderie et al. (1975) proposed a chromosphere or temperature inversion in Vega (A0 V) to explain excess emission shortward of Lα, but Snijders (1977) has shown that the observed Copernicus data are explained by non-LTE calculations of the C I continua without invoking a temperature inversion. The detection of soft X-ray emission from Sirius (Mewe et al. 1975) raised the question whether Sirius A (A1 V) or its white-dwarf companion is the emitter. Ultraviolet observations of Cash et al (1978a) and Brune et al (1979) appear to rule out photospheric emission from Sirius B as the source of the X-ray emission, hence the only plausible alternative is emission from a corona surrounding one of the stars (cf. Mullan 1976a; Hearn and Mewe 1976). The apparent detection of X-ray emission from Vega (Topka et al. 1977) provides further evidence for coronae in A-type stars. Cassinelli and Hartmann (1977) and others have proposed that O-type stars have coronae, and Kondo et al. (1976a) have detected Mg II emission in several B-type stars. The HEAO-B satellite should provide more complete information about coronae in hot stars.

New ultraviolet data from IUE provides powerful tools for studying chromosperes and transition regions in F-K stars. Linsky et al. (1978) have shown that: (1) the 1175-2000 Å spectra of cool stars contain emission lines indicative of chromospheres and transition regions (log T=4.3-5.4); (2) the RS CVn stars exhibit larger surface fluxes in transition lines than chromosphere lines, compared to the quiet Sun; and (3) during a large flare HR1099 shows chromospheric and transition-region emission-line fluxes comparable to those in solar flares. Prior to IUE, the outer atmosphere of Capella was studied by Dupree (1975), Vitz et al. (1976), and Haisch and Linsky (1976).

HEAO-1 soft X-ray spectra of the RS CVn stars Capella, HR 1099 and UX Ari (Cash et al. 1978b; Walter et al. 1978a,b) indicate 10^7 K coronal plasma, considerably hotter than the active solar corona. The RS CVn systems are also powerful nonthermal radio emitters (Owen et al. 1976; Owen and Spangler 1977). These systems are binaries in which one or both components are slightly evolved (Popper and Ulrich 1977), and may have a hot disk around the secondary, or dense solar-like chromospheres produced by tidal coupling (cf. Young and Koniges 1977; Naftalan and Drake 1977; Rhombs and Fix 1977).

In their survey of 22 late-type stars with IUE, Linsky and Haisch (1979) noted a sharp division of stars in two groups. The solar-type stars, i.e. F2-K4 dwarfs and G giants, show emission lines indicative of plasma at temperatures of 2.5×10^5 K and hotter. The α Orionis-type stars, i.e., the K giants and G-M supergiants, show emission lines from material no hotter than 10^4 K. It appears that either the α Orionis-type stars do not have transition regions and coronae, perhaps due to the onset of supersonic winds (Mullan 1978; Reimers 1977; Stencel 1978), or that their transition regions and coronae have emission measures far smaller than the Sun's.

Little is known about the outer atmospheres of normal M dwarfs, but dMe flare-stars exhibit bright chromospheric emission lines and both X-ray and radio emission during flares (e.g., Karpen et al. 1977; Haisch et al. 1977, 1978; Spangler and Moffett 1976; Robinson et al. 1976). Models for stellar flares have been proposed by Mullan (1976b, 1976c, 1977).

T Tauri stars exhibit extremely bright chromospheric emission lines, but coronae from these young objects have not yet been detected by X-ray or radio emission. Ulrich (1976, 1978) has reviewed the present status of models for these stars.

6. Width-Luminosity Relations

Correlations between emission-line widths and stellar luminosity exist for the Mg II and H I resonance-lines (Dupree 1976; Kondo et al. 1976b) as well as for Ca II and Hα. Lutz and Pagel (1977) have discussed the empirical dependence of Ca II widths on gravity, effective temperature, and metal abundance. Ayres (1979) has derived scaling relations for the K_1 and K_2 widths, giving their dependence on gravity and on chromospheric nonradiative heating rate; his K_1 scaling relation appears to be consistent with data for a wide range of stars (Kelch *et al*. 1979; Linsky, *et al*. 1979).

D. Model Atmospheres for Late-Type Stars (Bengt Gustafsson)

1. Contemporary models

Recent years have seen an increased interest in problems relating to late phases in stellar evolution, to nucleosynthesis, and to the composition and chemical evolution of galaxies. This has led to a greater demand for accurate methods of interpreting late-type stellar spectra. In this effort model atmospheres are necessary--they form the link between observations of stellar radiation and theories of stellar evolution.

Most recent models of late-type stellar atmospheres (Table 1) are purely "theoretical": they are constructed *ab initio* using the classical assumptions of plane-parallel stratification, hydrostatic equilibrium and LTE. The only non-radiative flux considered is convection, in the framework of the mixing-length "theory". A very important improvement has been the development of methods for handling blanketing by enormous numbers of atomic and molecular lines.

Table 1. Recent grids of blanketed model atmospheres for late-type stars

Author(s)	Ranges of parameters T_{eff}	log g	[A/H]	Method	Notes on sources of line absorption
BEGN[1,2]	3500-6000	0.0- 4.5	-3.0-+0.5	ODF	no TiO or H_2O
Johnson et al.(1978)	2500-4000	0.0- 2.0	0.0	OS	no H_2O
Kurucz (1978)[3]	5500-50000	0.0- 4.5	-2.0- 0.0	ODF	no molecules
Mould (1975,1976)	3000-4250	4.75,5.75	-2.0- 0.0	ODF	
Peytremann (1974)[4]	5000-8500	2.0 4.5	-1.0- 0.0	OS	no molecules
Querci et al. (1974) and Querci and Querci (1975)[5]	2600-4500	-1.0-+1.0	C star models	ODF	
Tsuji (1976,1978)	2200-4200	-2.0-+2.5	0.0	VAEBM	varying CNO

1) Gustafsson et al. (1975), Bell et al. (1976), Eriksson et al. (1978).
2) Colors and fluxes given and discussed by Bell and Gustafsson (1978), Gustafsson and Bell 1978) and Manduca *et al*. (1977).
3) Colors discussed by Relyea and Kurucz (1978) and Buser and Kurucz (1978).
4) Colors discussed by Peytremann (1975).
5) Fluxes discussed by Querci and Querci (1976).

A prerequisite for the computation of realistic blanketed models is an extensive compilation of spectral-line data. Thanks to the efforts of Kurucz and Peytremann (1975) and of Bell (see Bell and Gustafsson 1978) such compilations now exist and are in wide use for calculating both spectra and colors.

There are two different current methods for handling line-blanketing in the calculation of model atmospheres (cf. Table 1). These are the opacity (probability) distribution function (ODF) method, and the opacity-sampling (OS) method. The merits and drawbacks of each have been discussed by Carbon (1974), Gustafsson *et al*. (1975), Sneden *et al*. (1976) and others. An optimal scheme for computing blanketed model atmospheres has not yet been designed, especially for the upper layers where the LTE assumption fails. Methods for distributing the sample wavelength points of the OS method economically should be developed further.

Attempts to design approximate, but more easily manageable, methods to handle line-absorption have been made. One example is the so-called Voigt-analog-Elsasser

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band model (VAEBM) for molecular opacity used by Tsuji (1976, 1978). The merits of such methods must be studied by comparing the resulting models with more accurate ones.

2. Comparisons with Observations

Present-day models have no chromospheres or coronae--they will (at best) be model photospheres. In recent years models including chromospheric-heating mechanisms have reached some level of sophistication (Ulmschneider *et al*. 1977) but uncertainties in them are still considerable (Cram 1977b). The following discussion will therefore be confined to spectral features formed in the photospheres, i.e. continua, relatively weak spectral lines, and the wings of strong lines.

For the Sun, accurate observations and modern semi-empirical models have been compared with theoretical models (Ayres 1977, 1978, Gustafsson and Bell 1978, Kurucz 1978 and others); reasonable agreement is found. However, the theoretical models seem to show a flux excess in the ultraviolet (see below). Discrepancies in the infrared limb-darkening may be caused by the inadequacy of the mixing-length theory (Holweger 1978). Few comparisons with the observations of fine structure and dynamical phenomena in the solar atmosphere are as yet possible owing to the limitations of the standard models. However, the importance of these observations, and attempts at understanding them, for improving the theory of late-type stellar atmospheres can hardly be overestimated.

Comparisons of observed and computed low-resolution scans and colors of late-type stars have been made by several authors (see Gustafsson 1979 for references); these provide new information on the fundamental parameters of stars, and on properties of various photometric systems. Some information about the degree of realism of the models also emerged; in many respects the agreement between the fluxes of stars and models is very satisfactory, but significant discrepancies have been noticed:

Relyea and Kurucz (1978) compare theoretical and observed *uvby* colors and find deviations for late A and F stars. They suggest that these discrepancies may possibly be caused by an inadequate treatment of convection. Böhm-Vitense (1978) also suggests that an increased convective efficiency or an unknown source of continuous opacity may explain why her models for F-dwarfs are brighter in the ultraviolet than stars. For G- and K-giants Gustafsson and Bell (1978) have found a similar but stronger ultraviolet discrepancy which increases systematically with metal abundance. They tentatively ascribe it to very weak metal or molecular lines omitted in the computations; an unknown continuous opacity source, or possible departures from LTE, may also be responsible. Although this effect is pronounced in the ultraviolet flux, the effects on the atmospheric structures are quite small, except for models with T_{eff}>5000 K.

Comparisons at higher resolution of stellar spectra with synthetic ones show a reasonable overall agreement (cf., e.g., Gustafsson and Bell 1978), if a few *ad hoc* parameters describing macro-and microturbulence are introduced. However, some discrepancies for photospheric spectral lines remain:

Ramsey (1977) has observed a greater ionization of calcium than is expected from the Saha equation in late K and M stars, in qualitative agreement with the predictions by Auman and Woodrow (1975). This overionization may be produced by "hot" photoionizing radiation from deeper atmospheric layers. A similar effect for iron was found in solar-type models by Lites and Cowley (1974), and in F-dwarf models by Nissen and Gustafsson (1978). [The overionization of Fe reported by Oinas (1977) for stars later than K2 seems difficult to understand. Cohen (1978) does not find an ionization anomaly for iron in low-gravity Population II giants, although these atmospheres are much more transparent to radiation at short wavelengths.] The structural effects caused by overionization appear to be unimportant with the possible exception of stars with $T_{eff}\lesssim$3500 K and metal-poor F and G stars. Departures from the LTE excitation equilibrium of metals may also affect atmospheres via blanketing effects; this is probably of importance mainly for stars with T_{eff}>5000 K.

Discrepancies also occur in the strengths of molecular bands, and at least for TiO in M stars this is important because the TiO absorption efficiently heats the outer layers in cool models (Krupp *et al*. 1978). The models predict far too strong

TiO bands for dwarfs (Mould 1975), giants and supergiants (Lengyel-Frey 1977 and Johnson et al. 1978). This might be due to uncertainties in the temperature scale or to departures from LTE for TiO and/or Ti, but the situation is not well understood at present.

Kelch et al. (1978 and papers listed therein) and Desikachary and Gray (1978) have compared observed and theoretical Ca II K profiles for more than ten late-type stars. They suggest that the upper photospheres ($\tau_{Ross} \lesssim 0.01$) of current theoretical models are too cool, typically by 100 K at $\tau_{Ross}=0.001$). Although these studies are subject to several uncertainties, this discrepancy seems rather well established. It may be a consequence of the assumption of LTE--the large surface cooling occurs because the spectral lines are assumed to be formed in absorption.

Other strong spectral lines, e.g., the vibration-rotation bands of CO (cf. Heasley et al. 1978), may be of interest for studying the structure of late-type atmospheres. For the CO lines the LTE assumption is valid in most of the photosphere, but the surface-cooling by CO in the outermost layers may be reduced by non-LTE effects (Carbon et al. 1976).

Departures from LTE are known to lead to observable discrepancies between models and spectra of late-type stars in some cases: CN 3883Å band (Mount et al. 1975), sodium lines (Kelch and Milkey 1976), oxygen triplet at 7774Å (Eriksson and Toft 1978), lithium 6708Å line (Luck 1977, de la Reza and Querci 1978). However, these departures do not appreciably affect atmospheric structures. A general study of non-LTE effects on molecular lines is given by Hinkle and Lambert (1976).

3. Models of Tomorrow

Improvements in our understanding of the physics of stellar atmospheres will emerge from the continuing confrontation of models with observations. Improvements in atomic and molecular data--identifications of spectral lines, oscillator strengths, damping parameters, dissociation energies, etc.--are needed. High-precision studies, such as the work on iron by Blackwell and collaborators (Mon. Not. Roy. Soc. 1972-78) are of great value. However, broad surveys of, e.g., weak metal lines and molecular lines, are also very important, as are studies of grain-formation and absorption in cool stellar atmospheres. For investigations where the LTE assumption is relaxed, present uncertainties in collision and other cross-sections are very troublesome.

The simultaneous solution of the statistical-equilibrium and radiative-transfer equations subject to the condition of constant flux is costly of computer time for realistic late-type models. The effort required increases rapidly with the complexity of the model atoms and the number of transitions treated; thus attempts to find general rules of how a given atom may be modeled as simply as possible without loss of physically-important information need to be made.

Departures from plane-parallel geometry can be treated with present-day techniques. Watanabe and Kodaira (1978) found sphericity effects in red supergiants to be greater than expected, owing to the coupling of temperature-sensitive molecule formation to the cooling caused by flux-dilution. Schmid-Burgk and Scholz (1977) showed that sphericity effects for a Population II F-giant might be observable.

Methods for handling radiative transfer in inhomogeneous media are now available (see, e.g., Cram 1977a and Mihalas et al. 1978 and references therein), but the construction of self-consistent model atmospheres also requires an understanding of how the inhomogeneities in late-type stellar atmospheres form and develop. Inhomogeneities and velocity fields may be connected with various phenomena: differential rotation, magnetic fields, radial and non-radial oscillations, granular and super-granular motions, mass flows, etc. However, for many of these phenomena convection is the basic generating factor, and to understand them we shall need a well-founded theory of convection in stellar atmospheres (also needed for an understanding of the energy balance). Recently, numerical simulations (Graham 1977, Nordlund 1976, 1978, Weiss 1977, Peckover and Weiss 1978) have initiated promising developments which may eventually lead to realistic predictions of convective fluxes, velocity fields and mass-flows in photospheres. Very accurate observations of line profiles (wavelength shifts and widths) in stellar spectra should be of great value in this work as will be research on the (magneto)hydrodynamics of the solar atmosphere. This work offers hope that quantitative predictions of inhomogeneities, non-thermal Doppler-shifts, departures from hydrostatic equilibrium, and non-radiative heating in stellar atmosphere might become possible within the foreseeable future. It seems likely that the model atmospheres of tomorrow will differ significantly from those of today, particularly as a result of treating phenomena not considered in classical models (cf. Cram 1978).

E. Radiative Transfer in Extended, Expanding, and Multidimensional Atmospheres (D. Mihalas)

In contrast to the previous sections of this report, the discussion in this section will concentrate primarily on developments of methodology and technique.

1. Extended Atmospheres

A number of different methods for solving the transfer equation in static spherical media exist, and this problem can now be considered to be solved. The two main approaches are: (a) ray-by-ray solutions along the tangents to a set of spherical shells within the medium, and (b) solutions of moment equations. For a broad discussion cf. Mihalas (1978, §7-6 and §11-14).

In the case that the source function is frequency-independent, a ray-by-ray solution can be used to solve directly for its depth-variation. The formulation can be made in terms of either integral-operator (Schmid-Burgk 1975) or difference-equation techniques (Mihalas and Hummer 1974); in the latter case the integration scheme devised by Auer (1976) is advantageous.

To solve the moment equations one requires closure relations among the moments, and hence information about the angular distribution of the radiation field as a function of depth. Given these closures, the moment equations may be solved stably by using a "sphericality factor" (Auer 1971). The solution may be effected by standard difference-equation techniques, both for complete and partial redistribution in the scattering process. To obtain the angle-dependent information required to determine the closure relations, a general approach is to perform a ray-by-ray formal solution assuming a given source function, and then to iterate between the formal solution and moment equations until consistency is obtained (see, e.g. Mihalas 1978 §7-6). Alternatively, one can develop approximate closure relations by a suitable generalization of the Eddington approximation to allow for the strong forward-peaking of the radiation field in the outermost layers. Such approaches have been studied by Simonneau (1976, 1978a, 1978b), Unno and Kondo (1976, 1977); and Masaki and Unno (1978); these methods appear to offer simple and accurate results in many cases.

Analyses of stellar spectra allowing for atmospheric-extension effects have been performed by Schmid-Burgk and Scholz (1976, 1977) and Watanabe and Kodaira (1978). Temperature-correction procedures for extended stellar atmospheres have been studied by Grinkevich (1976), Mihalas and Hummer (1974), Schmid-Burgk (1975) and Stebnev (1976).

2. Expanding Atmospheres

Considerable progress has recently been made in solving line-formation problems in moving media. A superb review of the physics of the problem has been given by Hummer (1976) who points out in particular the severe diagnostic difficulties implied by the breakdown of the Eddington-Barbier relation in moving atmospheres. Mathematical schemes for solving moving-medium transfer problems fall into three basic categories: (a) observer-frame, (b) comoving-frame, and (c) escape-probability (Sobolev) methods. Each approach has advantages and disadvantages, and no one scheme is well-adapted to all problems; see Mihalas (1978, Chap. 14) for a broad discussion.

Observer-frame methods are well-suited for complex velocity-fields and geometrical structures in the low-velocity regime; effective mathematical techniques are easy to formulate for both planar and spherical atmospheres; see e.g. Mihalas (1978, §14-1). A perturbation method that offers computational economies has been developed by Cram and Lopert (1976). Solutions of the transfer equation for important resonance lines (e.g. Lα, CaII H and K) have been obtained by Cannon (1976a) for multidimensional structures and velocity fields, allowing for angle-and frequency-dependent redistribution.

Comoving-frame methods can treat high-velocity flows and are well posed for studying redistribution effects, but thus far have been formulated only for monotone expansion of the atmosphere. Haisch (1976) has derived the comoving-frame equations using a tensor formalism. Methods for treating multilevel atomic models in the comoving frame have been developed by Mihalas and Kunasz (1978). Redistribution effects by atomic and electron scattering in expanding spherical media have been studied by Mihalás et al (1976b), Peraiah (1978b), and Wehrse and Peraiah (1978). Studies by Vardavas (1976), Mihalas et al (1976a), and Hamann and Kudritzki (1977) have shown that in moving media it is essential to angle-average redistribution functions in the comoving fluid frame and that redistribution functions angle-averaged in the laboratory rest frame introduce spurious effects on line-formation. The differences between results obtained from redistribution functions angle-averaged in the fluid frame and from full angle-frequency dependent redistribution fundtions are minor (Vardavas 1976). Partial redistribution effects with dipole scattering in expanding media have been treated by Peraiah (1978a).

The escape-probability (Sobolev) method has often been applied with good success to expanding flows; recent formal developments have been made by Grachov (1976, 1977, 1978). For flows in which the line-of-sight velocity is nonmonotonic (e.g. decelerating expansion or accretion) the purely local nature of the approximation is lost, and two or more separated regions of the atmosphere can be radiatively coupled. Generalizations of the method to treat this complication have been developed by Grinin (1977), Marti and Noerdlinger (1977), Rybicki and Hummer (1978), and Surdej (1977, 1978), and have been used by those authors to perform exploratory calculations in a variety of cases. Expanding and differentially-rotating atmospheres have been studied by Grinin (1976). Detailed numerical modeling of H and He II line-profiles in Of stars has been done by Klein and Castor (1978) using the Sobolev method. Karp et al. (1977) have applied escape-probability techniques to estimate the effects of spectrum lines on radiative opacities in expanding media. Karp (1978) has used Sobolev methods to assess the accuracy of observational methods of estimating velocity gradients from doppler shifts, and Duval and Karp (1978) have examined the combined effects of expansion and rotation on spectral line shapes.

3. Multidimensional Atmospheres

Relatively little work has yet been done on the difficult problem of radiative transfer in multidimensional media, and both the physical foundations and mathematical methodology relating to this problem are in a state of rapid development. A comprehensive and critical survey of the literature through 1976 has been given by Cram et al. (1976). A number of important review papers presented at the 1976 IAU General Assembly in Grenoble have been published separately (Cannon 1976a).

Radiative transfer in cylindrical media has been treated by Stenholm (1977) using Rybicki's core-saturation, wing-diffusion technique and by Heasley (1977) using moment methods with an integrating factor reminiscent of that used for spherically symmetric media (see also Schmid-Burgk 1974). Mihalas, et al. (1978) have developed an efficient method for treating radiative transport in two-dimensional moving media; the computing effort in this method scales linearly with the number of angles and frequencies, and hence it is well suited for problems in cylindrical geometry, both static (Mihalas 1979) and moving (Mihalas and Auer 1979).

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D. MIHALAS, President of the Commission

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