COMMISSION 36: THEORY OF STELLAR ATMOSPHERES (THÈORIE DES ATMOSPHÈRES STELLAIRES)

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I. INTRODUCTION, COMMISSION ACTIVITY, SYMPOSIA

Commission 36 acts as a cosponsor of the following Symposia: (1) IAU Symposium No. 102 "Solar and Stellar Magnetic Fields: Origin and Coronal Effects" Zürich, Switzerland (2-6 August 1982) and (2) IAU Symposium No. 103 "Planetary Nebulae" London, UK (10-14 August 1982). The commission participates jointly with Commissions 29, 35, and 45 in the organization of a Joint Discussion at the IXth General Assembly on the topic "Mass-Loss-Phenomena".

II. RECENT PROGRESS IN THE THEORY OF STELLAR ATMOSPHERES

In accordance with decisions taken earlier this report is not intended as a comprehensive review of all work done in the field covered by our Commission. Rather, it focuses on a few areas in which significant progress has been made. In view of the fact that our understanding of the physical structure of stellar atmospheres is strongly influenced by new observations and their results, the individual contributions will all concentrate on the general topic

The Impact of New Observational Data on the Theory of Atmospheres.

A. The Impact of Ultraviolet Observations of Early-Type Stars on the Theory of Stellar Atmospheres (Anne B. Underhill)

Introduction. An important goal of the theory of stellar atmospheres is to provide an interpretation of stellar spectra in terms of a model of the outer layers of the star, and of the physical processes which occur in the atmosphere. The impact of ultraviolet observations on the theoretical concepts used for this purpose has been to bring about a reassessment of the forms which are appropriate for the equations describing a model stellar atmosphere, and of the boundary conditions which are to be applied when seeking solutions. Some studies, noted below, have been made to find how outflow will change a stellar spectrum from what it is in the case that hydrostatic equilibrium exists, and how the deposition of heat in a stellar atmosphere will change the temperature structure and state of motion of the atmosphere from what it is when the only source of energy in the atmosphere is the radiation field from the core of the star.

Observations of the spectra of early-type stars over the wavelength range from about 1000 Å to 7000 Å at high and low resolution have clearly demonstrated that the atmospheres of hot stars consist of two parts: (1) an inner stationary part whose spectrum may be predicted rather successfully by the traditional methods for making model atmospheres and calculating spectra, using LTE or NLTE physics as appropriate, and (2) an outer part which contains at least some gas at a high temperature, which shows evidence for outflow at velocities greater than the velocity of escape from the star, and which sometimes produces relatively short-lived, discrete absorption lines which are shortward displaced. The latter observations indicate that the outer atmosphere is inhomogeneous and that its physical state is variable.

Underhill (1980, 1981a) has suggested that the term "photosphere" should be reserved for the inner part of the atmosphere where the traditional methods of predicting synthetic spectra are adequate, and that a new term "mantle" should be used to describe the outer part of the atmosphere where one is seeing the effects of the deposition of energy and momentum from non-radiative sources. She has made this suggestion because different forms of the conservation equations are required for modelling the two parts of the atmosphere, and different constraints on the behavior of the sources of energy and momentum apply in each of the two regions. It is undesirable to use the terms "chromosphere" and "corona" when referring to parts of the outer atmosphere of an early-type star, because these terms bring with them specific ideas about the temperatures, densities, and velocities of outflow, ideas which are true for the Sun. Our present observational knowledge suggests that the temperature, density, and velocity ranges which occur in the mantles of early-type stars are rather different from those which occur in the mantle of the Sun. Although two early-type stars may have similar photospheres, they may have quite different mantles. This is an observed fact.

This review is concerned with summarizing the results which have been obtained on modelling the mantles of early-type stars and determining the physical state of these mantles.

Model Constraints for Photospheres. The photospheres of early-type stars may be modelled fairly successfully using the traditional constraints of plane parallel layers of gas in hydrostatic and radiative equilibrium. The constraint of statistical equilibrium must be used to determine the distribution of the atoms and ions over their several energy states if the strong lines formed in the photospheres of early-type stars are to be predicted accurately. Most of the continuous spectrum may be predicted with satisfactory precision using the simple hypothesis of LTE.

Model Constraints for Mantles. Although some observations suggesting that the mantles of early-type stars are inhomogeneous exist, the property of inhomogeneity has to be ignored at present when making models for mantles. It is assumed that the mantle consists of spherical layers of gas lying above a photosphere which may be modelled by traditional procedures. In the mantle, there is flow which is assumed to be a function of the radius only. Matter is conserved in spherical shells. Use of the principles of conservation of mass and conservation of momentum, and assumption of a steady state, lead to the following equation:

$$v(r)\,\frac{dv}{dr}\left[\left(\frac{a(r)}{v(r)}\right)^2 - 1\right] = \underline{F}(r) - \frac{2a^2}{r}\left(1 - \frac{d\ln T}{d\ln r^2}\right). \qquad (1)$$

Any acceptable functional form for v(r) must be a mathematically well behaved function, and it must satisfy equation (1). This means that the right side of equation (1) must vanish at the critical radius where $v(r) \equiv a(r)$.

The temperature law in a model mantle may be found from

$$v(r)\, E_g(r) + \rho a^2 v(r) \nabla (\frac{1}{\rho}) = G - L. \qquad (2)$$

The function T(r) should be well behaved mathematically. In equations (1) and (2), a(r) is the isothermal speed of sound in the medium, $a^2 = kT/\mu m_H$. Here $\underline{F}(r)$ is the net force acting on each element in the medium, directed along a radius, E_g is the internal energy of each element of volume, G is the rate at which energy is gained by each element of volume, and L is the rate at which energy is lost by each element of volume. The functional forms for ρ(r), v(r), and T(r) resulting from the solution of equations (1) and (2) must match with conditions in the photosphere, where v(r) is negligibly small, and with conditions in the interstellar medium, where r is very large.

Energy may be transferred in the model mantle by means of radiation, conduction, and convection. Non-radiative energy and momentum may be deposited in an element of volume as the result of hydrodynamic processes, perhaps in the presence of magnetic fields. If it is supposed that energy is transferred only by means of radiation, and that the only source of energy in the atmosphere is the radiation field, then equation (2) leads to the constraint of radiative equilibrium for determining the temperature law in the atmosphere. The forces which may be included in $\underline{F}(r)$ are the force of gravity, the force due to radiation, and the force resulting from the deposition of momentum from the interactions between any magnetic field that may be present and whatever field of local motion is present.

Studies of equation (1) by Castor and Cassinelli (1973) and by Thomas (1973) have shown for the case that only the forces of gravity and radiation are considered and the absorption coefficients have values valid for a static atmosphere, that an acceptable solution for v(r) can be found only if heat is added to the gas in the neighborhood of the critical radius. Several authors (Cassinelli and Hartmann 1975, Castor et al. 1975, Weber 1981) have made model mantles assuming the constraint of radiative equlibrium. In order to obtain flowing models, each had to introduce a somewhat fictitious form for the absorption coefficient in the region of the model where the flow is subsonic. (It is beyond the scope of this review to describe the arbitrary factors which are introduced.) Other authors (Mihalas and Kunasz 1978, Olson 1978, Castor and Lamers 1979, Surdej 1979, Kunasz 1980, Hamann 1981, Olson 1981) have assumed forms for the velocity, density, and temperature laws, and have predicted the shapes of the absorption lines which will result. In these studies, no attempt is made to ensure that v(r), ρ(r), and T(r) satisfy equations (1) and (2). The spectrum of the amount of the continuous flux in the infrared and radio ranges has been predicted by Wright and Barlow (1975), by Panagia and Felli (1975), and by Cassinelli and Hartmann (1977). The predictions are based on assumed functional forms for v(r), ρ(r), and T(r).

Hearn and Vardavas (1981a,b) and Vardavas and Hearn (1981) have investigated what type of mantle will result when non-radiative energy is deposited in the photosphere of a model star, but no radiative force is active. They find that a high-temperature corona will be formed around an early-type star, but that the rate of mass loss will be negligibly small.

One may conclude from these studies that the formation of model mantles with properties like those observed for early-type stars requires the deposition of both non-radiative energy and non-radiative momentum at appropriate rates near the critical radius.

It should be noted that the studies which assume that the acquisition of momentum from the radiation field is sufficient to generate a wind, also assume that the acquired outward momentum, (which is acquired only by ions of species with absorption lines in the wavelength range of interest), is transferred efficiently to all species in the stellar atmosphere including the abundant H^+ and He^{++} ions. Presumably, this transfer of momentum takes place as a result of collisions resulting from the thermal motions of the atoms and ions.

On the other hand, studies which use diffusion as a means of obtaining abnormal concentrations of certain species in the atmospheres of Ap and Bp stars (see, for instance, Montmerle and Michaud 1976, Michaud et al. 1976) use the action of the force of radiation to create small drift motions of one species relative to another, and thus cause a separation of the species after a long time. In this work, it is concluded that, although the densities are greater in the important layers of Bp stars than in winds and the temperatures are comparable, the redistribution of momentum to all components proceeds sufficiently inefficiently that one particular species will drift slowly away from the rest of the species.

The rate at which acquired momentum is redistributed in a stellar atmosphere is a function of the rate of collisions in the atmosphere. This rate will depend on the density and on the size of the thermal (and other) motions. The question of the efficiency of the redistribution of momentum in a wind and in a Bp star requires further study. If the redistribution of momentum at low densities in a wind is not complete, then all of the fluid, in particular the abundant H^+ and He^{++} ions which do not absorb radiation, may not be accelerated and flow from the star. This would have the result that the inferred rates of mass loss estimated from assuming the complete and efficient redistribution of momentum would be upper limits. The action of Coulomb forces between the ions and electrons would affect the rate of redistribution of momentum. Such forces would be active in the atmospheres of Bp stars as well as in winds. What is in question here is not the relative sizes of drift and flow velocities for particular species, but the efficiency with which momentum, which has been acquired by one particular species as a result of absorbing radiation, is distributed to all components of the stellar atmosphere in the envisaged environment.

It should be noted, also, that the rates of mass loss from early-type stars, derived from measured radio and infrared excess fluxes by means of the theories noted above, give an upper limit to $\dot{M}$ because the theories assume that the gas reaches its distribution in an extended plasma radiating infrared and radio energy, as a result of uniform, spherical outflow. If, on the other hand, much of the emitting gas were suspended in magnetic structures (as in the Sun), the measured radio flux would imply a density of particles that is far greater than the actual density of matter streaming from the star in a wind.

The ultraviolet spectra of B stars show two lines of Si II which are excessively broad because they have an unusually large damping constant (Underhill 1981b). This observation demonstrates that autoionization and dielectronic recombination along specific channels in Si II are a normal phenomenon in the atmospheres of normal main-sequence B stars. Consequently, the ionization balance in Si is certainly not equal to that calculated in LTE, nor to that calculated in NLTE by Kamp (1976). Many other ions visible in the spectra of O and B stars have an energy-level structure like that of Si II in the sense of possessing levels which may participate in autoionization and dielectronic recombination. Consequently, attention should be paid to evaluating the effects of autoionization on the ionization balance for complex atoms and ions before deducing that anomalous abundances are present. The inferred ionization balance may be anomalous because of neglect of certain specific channels for ionization and recombination. Unfortunately, experimental knowledge of doubly-excited states of ions is sparse and unlikely to grow in quantity quickly. Consequently, more theoretical studies of autoionization, like that of Si II by Artru et al. (1981) should be encouraged.

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B. UV-Observations of Late-Type Stars (D. Reimers)

The launch of the International Ultraviolet Explorer (IUE) has had a major impact on our knowledge of UV spectra of a wide variety of cool stars. For the first time it has become possible to study chromospheres and coronae of normal cool stars other than the Sun and thus to place the structure of the outer layers of the Sun, solar activity, and the solar wind in the context of these phenomena in other late-type stars. Vice versa, the detailed knowledge of solar phenomena will be helpful in understanding the UV spectra of spatially unresolvable late-type stars and thereby the structure of their outer layers.

Extensive reviews have been given by Dupree and Hartmann (1979), Hartmann (1980), Dupree (1981), Linsky (1981), and at the ESA and NASA symposia on the first two years of IUE where more detailed results and literature can be found.

Details about the identification of UV emission lines, particularly difficult if observed with low resolution, can be found in Brown et al. (1979); Ayres, Moos and Linsky (1981) and Hartmann et al. (1981).

Single dwarf stars. The typical chromospheric lines of O I, Si II, Mg II and transition-region (TR) lines of C II, He II, C IV, Si IV and NV have been detected by Böhm-Vitense and Dettmann (1980) in spectral types F2 and later on the main-sequence, in apparent accordance with the theoretical expectation that the onset of convection determines the presence of chromospheres. However, the IUE cannot detect TR lines against the bright photospheric spectra of earlier type stars (cf. Linsky and Marstad, 1980).

G and K type dwarfs typically show TR emission lines indicating plasma at $T \approx 2\cdot10^5$ K with surface fluxes comparable to the quiet Sun (e.g., α Cen A and B, Ayres and Linsky, 1980) or comparable to bright solar active regions (ε Eri, ξ Boo A; Hartmann et al., 1979). Active dwarf stars like ξ Boo A (G 8 V) and E Q Peg (d M4) show remarkably similar UV spectra, independent of their effective temperatures (Hartmann et al., 1979). Compared with quiet dwarfs there is probably more material at high temperatures: the C IV/C II ratio is ≈ 2 in active dwarfs and 1 in quiet dwarfs (Brown et al., 1979).

Linsky et al. (1980) find that d M e stars exhibit prominent TR emission lines with surface fluxes up to 50 times the quiet Sun in C IV as late as d M 6 e, while the d M stars show much weaker lines or none at all. For the d M e flare star Proxima Centauri, Haisch and Linsky (1980) found evidence for a TR and a quiescent corona with $T\ \ 3.5\cdot10^6$ K outside of flares.

Ayres, Marstad and Linsky (1981) find that in G-K dwarfs and G giants TR line surface fluxes scale as the surface fluxes of the chromospheric Mg II λ 2800 lines to the 1.5 power. So coronae and chromospheres are physically associated. The large range of chromospheric activity (= surface fluxes of chromospheric lines) at a given location in the HR diagramme was demonstrated earlier by Basri and Linsky (1979).

In a detailed study of high-resolution IUE spectra of Procyon (F 5 IV-V), Brown and Jordan (1981) find a maximum coronal temperature of $3\cdot10^5$ K if the UV emission lines do not come from limited areas of the stellar disk. Pure acoustic waves cannot account for the required energy flux. According to Ayres et al. (1981) F type dwarfs and giants have brighter TR lines relative to chromospheric lines if compared with G and K types. Periodic variations in the UV fluxes of chromospheric Si II, Mg II and H I lines have been found in six main-sequence F,G, and K stars (Hallam and Wolf, 1981). These variations are probably caused by rotational modulation and offer a new method to determine rotational periods in slowly rotating stars. The derived periods agree with those found recently from Ca II H+K modulation (Vaughan et al. 1981).

Giants and supergiants. In their study of A,F, and G stars, Böhm-Vitense and Dettmann (1980) found that among supergiants, classical chromospheric and TR emission is seen only on the red side of the Cepheid instability strip. The spectra of stars of LC III are dominated by Si II 1808 Å and O I 1302 Å which increase systematically relative to C II 1335 as one goes up the giant branch from late G giants to middle K giants (Brown et al., 1979). Among supergiants, O I dominates in earlier stars like α Aqr and is weaker relative to Si II in M supergiants like α Ori.

In their initial study with the IUE, Linsky and Haisch (1979) and subsequently Ayres et al. (1981) found no transition-region line emission in giants cooler than about V-R = 0.80 and in supergiants. They proposed that a sharp dividing line exists in the HR diagramme between stars with and without TR emission lines and that this line nearly coincides with the onset of cool stellar winds in the HR diagram as found from Ca II H+K lines (Reimers, 1977).

Subsequent work has shown that the suggested division is not sharp: there are early G supergiants like α and β Aqr and δ TrA and middle K giants of LC II like α TrA, θ Her, ι Aur (Hartmann et al. 1980, 1981; Reimers, 1981a, 1981b) which possess both cool winds and hot transition regions ("hybrid" stars). The more gradual transition between corona- and wind-dominated outer layers is also indicated by the systematic variation of the C II/O I ratio of giants (Brown et al. 1979) and of the systematic variations of Ca II and Mg II emission asymmetry as well as the appearance of circumstellar absorption lines (cf. Dupree and Hartmann, 1980).

Important progress in our understanding of the connection between coronae and winds in red giants comes from high-resolution IUE observations of the hybrid star α TrA (Hartmann et al. 1981): line profiles of low ionization species (chromospheric) are narrow compared to profiles of C III and C IV lines. The widths of the latter correspond roughly to the wind terminal velocity as seen in the Mg II and Ca II lines. This may indicate that the TR lines are formed in an extended "warm" wind. In addition, the six known hybrid stars have double circumstellar Mg II and Ca II lines, one low-velocity component (chromospheric ?) at -5 to -20 km/s one high-velocity component (distant shell ?) at -60 to -100 km/s (Reimers, 1981b). The "warm" (10^5 K), extended wind acceleration region then seems to separate the cool wind region geometrically in height above the stellar surface and in wavelengths of CS lines into two parts.

Alfven-wave driven wind models are able to reproduce the basic observations (Hartmann and McGregor, 1980). However, magnetic fields are not known in red giants, and the observed complex time variability of winds in hybrid (and related) stars shows that more sophisticated models are required. In hybrid stars, TR lines follow the same correlations with chromospheric lines as found in stars without observed winds (Reimers, 1981b). So there seems to be no large influence of the winds on the atmospheric structure of TR line emitting regions as might be expected in case a massive cool wind efficiently cools the outer layers. Also, in hybrid stars the range of stellar activity is similar (~ factor 10) as in other single giants. In the UV line (and X-ray) study of the 4 Hyades giants with very similar spectral types (photospheres), it has turned out that two of them have fairly strong C IV and N V lines (and X-rays), two of them not. It was already known from the study of radiative losses through the Mg II lines in a large variety of cool stars (Basri and Linsky, 1979) that stellar activity covers a range of more than a factor of ten at a given location in the HR diagramme. The additional parameter - besides gravity and temperature - which controles stellar activity and thus strongly influences the structure of the chromospheres, coronae, and winds in red giants is probably rotation via dynamo-induced magnetic fields (see below).

In the mean, TR surface fluxes seem to decrease sharply towards cooler supergiants like α Ori where the upper limit for CIV emission is only $2 \cdot 10^{-3}$ times the quiet solar C IV surface flux (Linsky, 1981; Basri et al. 1981).

Red giants with hot companions. With the IUE, it has become possible to observe at high resolution the UV spectra of the B star companions of K and M supergiants uncontaminated by the photospheric spectra of the red giants. The B star is then an astrophysical light source which probes the structure of the extended atmosphere and inner stellar wind region of the red supergiant which is otherwise barely accessible. Particularly valuable have been observations during and near to the total eclipses of the B stars in VV Cep (Hagen et al. 1980), ζ Aur (Chapman, 1981), and 32 Cyg (Reimers et al. 1981).

Three different types of lines have been seen:

i) P Cyg type lines formed by scattering of B star photons in the extended chromosphere and wind of the red giant. During secondary eclipse, these lines dominate the pure emission line spectra in the UV. These lines can be used to determine mass-loss rates of the red supergiants.

ii) Lines absorbed in the higher density parts of the extended chromospheres when B star light passes the red giant near secondary eclipse: together with the time sequence of the eclipse in the UV, such lines can be used to infer the structure of the extended chromospheres.

iii) Near the B stars, lines from highly ionized species (C IV, Si IV, Fe III) are emitted, probably in a shock front formed when the B star moves through the wind of the red giant. Other broad emission lines superimposed upon the B star continua may come from rotating disks around the B stars formed by mass-accretion from the winds (δ Sge, Reimers and Kudritzki, 1980).

In VV Cep, egress from eclipse in the UV lagged behind the visible egress by 2 to 3 months due to the higher opacity of the M star chromosphere in the UV (Hagen et al. 1980). Accordingly, the visible radius is smaller by ~ 25% than the UV radius. At high resolution, the B star continuum is chopped by a complex absorption spectrum due to low excitation lines of neutral and singly ionized metals. Neutral Fe lines weaken more rapidly during egress from eclipse than Fe III lines.

In ζ Aur, Chapman (1980, 1981) and Stencel and Chapman (1981) observed ingress, total eclipse, and egress from eclipse at high resolution. Mg II absorption lines formed in the plasma near the K giant allowed to determine the electron density (10^7 - 10^6 cm^{-3}) in the range 4 to 8 K star radii. A mass-loss rate of $2 \cdot 10^{-8}$ $M_\odot$/yr was obtained. The spectacular emission line spectrum seen during eclipse has not yet been fully exploited. There is evidence for an accretion shock around the B star and a terminator shock around the K star. Hack (1981) identified multiple absorption components at phase 0.91 and 0.27 which indicate the cloudy structure of the K star wind.

32 Cyg shows near phase 0.2 numerous P Cyg lines formed in the wind of the primary, often with multiple absorption components with velocities up to -400 km/s. A rough estimate of mass-loss yielded $4 \cdot 10^{-7}$ $M_\odot$/yr (Stencel et al. 1980). The system was observed by Reimers et al. (1981) during eclipse and shortly after eclipse. An emission line spectrum similar to that of ζ Aur during eclipse was observed. Emission lines due to line scattering in the wind, due to line fluorescence (optical pumping)(Hempe and Reimers, 1981), as well as lines from a shock front associated with the B star and from an accretion disk have been identified.

Hempe (1981) has developed a computer code for spectral line radiative transfer in a medium where the light source is outside the density and velocity field symmetry center applicable to the observed phase-dependent P Cyg profiles in ζ Aur systems.

Following the earlier studies of CS lines in the spectrum of α Sco B by Kudritzki and Reimers and v.d. Hucht et al., Bernat (1981) tried to improve the accuracy of the mass-loss rate of α Sco from a study of high-resolution IUE spectra of α Sco B. He reached the disturbing conclusion that different ions yield mass-loss rates different by nearly a factor of 100.

Further systems observed at high resolution with IUE are Boss 1985, AC Cas, 31 Cyg, ε Car, 47 Cyg and Boss 5481.

RS CVn and W UMa stars. RS CVn systems - close, detached late type giant and subgiant binaries - are strong sources of UV emission. Well observed members of this class are λ And (Baliunas and Dupree, 1979), HR 1099 (Linsky et al., 1979), HR 4665 (Dupree et al. 1979) and ζ And (Reimers, 1980). The line surface fluxes - typically an order of magnitude higher than in the quiet Sun - show a progression of increasing enhancement with increasing temperature like in a solar active region. TR pressures are similar to solar active region values. A dependence of surface flux upon orbital period (and rotational velocity) has been found which can be considered as an extension of the increase of chromospheric flux (activity) with increasing rotational velocity known from late- type dwarf stars.

In case of Capella (α Aur) it has been shown that virtually all of the bright TR line emission is from the secondary which is a fast rotator, contrary to the primary (Ayres, 1980). Probably, dynamo action is responsible for the rotation-activity connection in late-type stars. RS CVn stars follow the same relations between chromospheric and TR emission line fluxes as other late-type giants (Ayres, Marstad and Linsky, 1981).

Chromospheric models have been constructed for HR 1099 and UX Ari with typical TR pressures of the order of 0.5 dyn cm^{-2} (Simon and Linsky, 1980).

In UX Ari, one of the brightest RS CVn stars, a flare was observed with IUE (Simon et al. 1980). TR line surface fluxes are $\approx 10^3$ times the quiet solar value.

W UMa stars - short-period, late-type dwarf binaries which are so close that they may have a common convective envelope - are on the extreme extension of the rotation-activity relation. TR line surface fluxes are typically 2 orders of magnitude brighter than in the quiet Sun (Dupree, 1980).

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C. Model Atmospheres and Observations from the Visual to the Infrared (D.L. Lambert)

In recent years, the groundwork has been laid for a tremendous explosion in observational stellar astrophysics which will surely impact upon those theoreticians interested primarily in model stellar atmospheres. Factors of note fuelling the explosion include an increase in observing time on large telescopes, the development and installation of highly efficient detectors in a variety of spectroscopic, photometric and other auxiliary instrumentation, the extension of spectroscopy (and other pursuits) out of the narrow spectrum interval readily accessible through photography. The explosion combined with vigorous activity in theoretical and experimental atomic and molecular physics and the continued growth in computers promise to make the coming decade a testing time for model atmospheres.

For this necessarily brief report, I elected to sketch a handful of the observational opportunities which should encourge and enable theoreticians to explore territory beyond the current frontiers of model atmosphere construction as they are defined by the set of standard assumptions. Key questions include: what is the nature and origin of photospheric inhomogeneities (granulation)? What is "turbulence"? Is it possible to construct a self-consistent theoretical model of a stellar chromosphere/corona including the sources of heating? What induces mass loss?

Although the advantages of gains in telescope time, detector efficiency and spectral bandpass are often combined in an observational program, I shall stress a few examples where one of these factors is often preeminent. Since I defer the provision of references to a detailed report, I apologize to authors whose ideas I may have appear to have usurped.

1. Observing time on large telescopes. Although trite, the observer's cry "the most interesting stars are at or below the effective limiting magnitude" summarizes one way in which large telescopes are exploited. For example, high dispersion spectroscopy previously restricted to bright field stars is now applied to the giant branches of globular clusters. This development calls for a model atmosphere grid spanning a large metal abundance range. Photometry and low dispersion spectroscopy of the brightest stars - giants and supergiants - in the nearest external galaxies further stimulate expansion of atmosphere grids. Construction of composite HR diagrams for the O-rich and C-rich evolved stars, especially those on the asymptotic giant branch, has provoked considerable interest among theoreticians concerned with the stellar interior and the stellar atmosphere. While model atmospheres are sought for the interpretation of observational data (e.g. the calibration of photometric indices, the reconstruction of low resolution spectra), the problems raised by the HR diagrams go beyond the current frontiers and into questions of mass loss, circumstellar dust/gas shell, atmospheric instabilities, spherical geometry and NLTE in extended cool atmospheres.

2. Beyond the photographic plate. With the exception of direct imaging, the observer can now pursue almost all standard investigations from the visible to the infrared. (Opportunities afforded by the ultraviolet are discussed elsewhere in this report.) This expansion of the spectral interval has numerous implications. Brief statements must suffice.

The Chromosphere. Although the ultraviolet spectrum is now the major source of information about a chromosphere, the red and infrared provide useful supplementary data. The He I 10830 Å triplet, which betrays the presence of hot ($T \sim 30{,}000$ K) chromospheric gas, may be monitored. In the late K and early M giants, the He I line appears to result from one or two large active regions. Ultraviolet spectra taken at lines of He I maximum absorption/emission strength should be helpful to the construction of chromospheric models.

Models predict that the CO 5μm V-R line cores are optically thick in the top of the classical boundary layer of giants and supergiants. Since the CO rovibronic levels may approach LTE, an emission reversal in the deep line core would betray the homogenous chromosphere now constructed from a variety of visual and ultraviolet data. Todate, the emission has not been seen.

The H^- Opacity Minimum. One crucial advantage resulting from access to a broad spectrum interval is the continuous change in sampling of the atmosphere as the continuous opacity changes. In the infrared, the opacity in cool stars reaches a minimum near 1.6 μm and then increases as about the square of the wavelength further into the infrared. Flux near 1.6 μm emerges from the deep photosphere. Line profile widths and asymmetries should provide information on the deep convection zone predicted for certain models. Detailed comparisons of spectra at 1.6 μm and in regions where opacity is greater (say, near 8000 Å where H^- opacity is a maximum) should reveal much structural information. Spectrophotometry from airplanes providing essentially uninterrupted coverage of the infrared provides another test of models (note too the infrared flux-method for deriving T_{eff}).

Molecules and the Infrared. Happily, key heteronuclear molecules have V-R transitions in the infrared where cool stars are bright. A few molecules including the homonuclear C_2 also provide infrared electronic transitions. Certain molecules (e.g. CO) are detectable only in the infrared. Not only do these molecules permit an abundance analysis, whose completion would be at best uncertain without access to the infrared, the molecules also contribute structural data. The molecule-atom equilibrium may serve as a surface gravity indicator. Relative intensities of rotational lines provide an excitation temperature which should be a mean kinetic temperature thanks to near LTE equilibrium in the rovibronic structure. Polyatomic molecules (e.g. H_2 , HCN, C_2H_2) monitor the really cool gas. Perhaps, the most dramatic illustration of the impact of infrared observations on understanding of atmospheric structure is provided by high resolution spectroscopy of Mira variables.

Since the amplitudes of infrared light curves are quite small, high resolution spectra of near-uniform quality are obtainable across the light cycle. At certain phases, the CO and OH V-R lines (and other lines) are doubled. One component is assigned to the warm photosphere and the second component to a cool overlying shell. The photosphere clearly pulsates with the near photospheric velocity in excellent agreement with the velocity derived from the circumstellar Si O radio emission. For about a month prior to maximum, the CO and OH lines reveal two warm layers. One layer is gas from the previous pulsation now falling back toward the star. The other layer forming the new pulsation is moving outwards. Here is a challenging problem for the theoretician who can count on a rapid expansion of the supporting observations.

Circumstellar shells and winds. With the free-free λ^2 opacity, optical depth of unity must first occur above the photosphere for wavelengths in the infrared or radio. Currently, this opacity increase is exploited most extensively for the early-type stars with strong winds. Wind profiles and mass-loss rates are obtainable. In cool stars, circumstellar (silicate and graphite) dust shells emit best at about 10 µm when optically thin.

The cool gas is a dusty circumstellar shell may be detected through the CO 5 µm V-R fundamental transitions. This gas produces an absorption line, perhaps, with a P Cygni emission component. For the nearest stars, it may be possible in the near future to obtain spectra off the star to show the circumstellar CO emission. For heavily embedded stars, the stellar wind impacting on interstellar gas may produce CO emission lines - a useful diagnostic of the transition zone between the stellar wind and the ambient gas.

3. High spectral resolution. High spectral resolution allied with high S/N enables precise measurements of line position and profile from which deductions may be made about atmospheric dynamics including waves, pulsations and turbulence. The nature of the pulsations in the β Cep and related stars are currently the subject of intensive study and providing stiff new challenges to the theorists. Solar lines in "integrated" light show light asymmetries which can be reproduced successfully by numerical simulations of solar granules. Observations of stellar line asymmetries are now appearing in the literature. Note that the infrared Fourier transform spectrometers are ideal tools for studying molecular line asymmetries. The asymetries should assist the theorist interested in atmospheric inhomogeneities. Accurate line profiles also lead to clearer decomposition into the rotational, micro- and macroturbulent components. As this more detailed information is provided, it will be possible to refine turbulence models and to approach a self-consistent model atmosphere including the hydrodynamics.

4. High temporal resolution. The detection of low amplitude, short period pulsations via spectral line profile changes is one example of new results realized through gains in instrumentation. Perhaps, the next decade will see this spectroscopic search extended to the ultra short-period ZZ Ceti white dwarfs. A more exotic example at the far border of model atmosphere studies would be time resolved spectroscopy of flare stars. The search, as yet unsuccessful, for stellar analogues of the solar 5-minute oscillations promises to extend "solar seismology" to the stars.

5. High spatial resolution. Speckle interferometry has provided a substantial number of angular diameter measurements. At present, information on the intensity profile across a stellar disk is very slight. Initial reports of large-scale inhomogeneities across the surface of Betelgeuse(angular diameter $\phi \sim 0''05$) were apparently premature. The angular diameters of Mira variables have been shown to approximately double in the light of strong TiO bands. Such reports provide an indication of the wealth of model atmosphere related data to come from speckle interferometry conducted with a very large ($\gtrsim$ 10 m) telescope.

Circumstellar shells around numerous stars - principally, cool mass-losing giants and supergiants - are resolvable. Speckle interferometry in the visible has resolved the P cygni shell but not the shells or disks around Be stars. Infrared interferometry has resolved several circumstellar dust shells. Measurements at several wavelengths where the dust opacity is different should lead to simple shell models. "Long" baseline infrared interferometry should soon provide welcome information on the structure of dust shells.

With the advent of high quantum efficiency array detectors, the gaseous component of circumstellar shells can be traced via fluorescent line emission. Currently, the shell around Betelgeuse has been detected in the light of the K I 7699 Å resonance line out to about 1' (or 9500 AU) from the star. Similar observations of numerous bright highly evolved stars are possible. Intensity and velocity information should lead to maps of the gas flow around the mass-losing star. Early-type stars with hot winds may be examined in the light of H recombination lines. (Of course, VLBI studies of radio masing molecular lines also contribute information on the structure of circumstellar shells).

Lunar occultation studies should not be discontinued nor forgotten. Angular diameters from occultation programs provide most welcome data on the T_{eff}-scale.

6. Atomic and molecular Physics. In the strict sense, this discipline is not part of observational astronomy. Since a considerable body of atomic and molecular data is needed both in the construction of model atmospheres and in the interpretation of spectra, I consider it appropriate to emphasize that both experimental and theoretical atomic and molecular physics is experiencing a vigorous renaissance. New experimental techniques - the tunable laser, the Fourier transform spectrometer, for example - are providing more complete catalogs of lines, f-values and continuous absorption cross-section. Ab initio calculations of atomic and molecular properties are being pushed to larger species and to higher precision. On the near horizon lies the possibility that the uncertainties in the basic atomic and molecular data will have a negligible influence on standard LTE model atmosphere constructions. Not too distant may be the time when information on collisional processes may have progressed to the point when accurate NLTE model atmospheres built on the standard assumptions are widely available. Then, when model predictions disagree with observations, it can be confidently claimed that the problem lies not in the basic radiative and collisional data but rather in a breakdown of the standard assumptions: atmospheric inhomogeneities, mechanical heating, etc. Cross-fertilazation between astrophysics and atomic-molecular physics is to be encouraged. Of course, similar injunctions apply to other fields: e.g. numerical mathematics and cumputer science; hydrodynamics.

D. X-RAY OBSERVATIONS

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Detection of X-rays from a star gives unambiguous evidence of the presence of hot ($\sim 10^6 - 10^7$ K) plasma. Since photospheric temperatures of stars do not reach these values, X-rays must be the signatures of more energetic non-radiative processes that occur in stellar atmospheres.

Prior to 1978, there were measurements of X-rays from special kinds of stellar configurations - most prominently binary systems in which X-rays were produced as a result of accretion of material upon a compact object (Forman *et al*. 1978). Additionally there were a handful of direct measurements of active binary systems (Walter *et al*. 1980) - and a few stars measured by rocket instruments. Copious ultraviolet measurements of strong resonance lines from *Copernicus* (OAO-2) and the International Ultraviolet Explorer (IUE) had shown that massive single stars possessed hot plasma at $T \lesssim 3 \times 10^5$ K, which suggested to some researchers that even hotter material - a corona - must exist and indicated the importance of mechanical heating in the outer atmospheres (Lamers and Morton 1976; Lamers and Snow 1978; Cassinelli, Castor, and Lamers 1978). Ultraviolet spectra also showed that many cool stars had extended hot atmospheres whose structures were similar to those of solar active regions (Dupree 1980; Linsky 1981 and references therein). By analogy, one would expect to find hotter material from such systems as well.

However it was only with the launch of the HEAO-2 (*Einstein*) Observatory in the fall of 1978 that a vast amount of new measurements of X-rays from diverse objects became available. Most of the objects detected were stars of F, G, and K spectral types (Vaiana *et al*. 1981; Helfand and Caillault 1982). It is important to evaluate these observations with respect to physical parameters such as stellar temperature, gravity, age, and rotation in order to constrain physical models and to accomodate the presence and structure of a corona in the context of stellar atmospheric structure and evolution.

From the first studies and surveys, it is apparent that main sequence stars of every spectral type - from O to M - exhibit X-rays. The median X-ray surface flux ranges from ~ 10^{7} erg cm^{-2} s^{-1} among the spectral type O main sequence stars and is lower, ranging from 10^{6} - 10^{5} erg cm^{-2} s^{-1} through the F, G, and K stars with indication of an increase by a factor of 4 in the M dwarfs (Harnden et al. 1979; Seward et al. 1979; Vaiana et al. 1981. At every spectral type, however, there is at least an order of magnitude spread in the X-ray flux (Vaiana et al. 1981). X-rays are found from a few white dwarfs, giant and supergiant stars of early spectral type and but a handful of G and K giants. There is a distinct absence of detections of the coolest giant and supergiant stars in the upper right quadrant of the H-R diagram.

In the case of the coolest giants and supergiant stars, upper limits to the X-ray surface fluxes are in the best cases substantially lower than the quiet Sun and comparable to the flux in coronal holes or less. In some, there may be a true absence of hot material or it may be present but very weak.

If we assume that these X-rays arise from stellar coronae, then the first of conventional ideas - that coronae are caused by acoustic waves generated by subphotospheric convective zones is severely challenged. Coronae are ubiquitous in main sequence stars, and in conventional theory deep convection zones are generally thought to occur in stars of spectral type F and later. Moreover at any position on the main sequence there is a variation of at least an order of magnitude in the X-ray luminosity suggesting that a third dimension needs to be added to the temperature-luminosity classification to explain coronal activity. Such a conclusion supports earlier results inferred from the chromospheric emissions (Wilson 1966) that a simple acoustic heating theory cannot explain the observations (Vaiana et al. 1981).

Two facts suggest that magnetic fields may be associated with the X-ray emission. First, in many cases plasma with temperatures indicated by X-ray emission cannot be contained by a stellar gravitational field alone. Secondly, our knowledge of the Sun's atmosphere gives evidence for the presence of magnetic loop structures configuring and constraining X-ray emitting gas. It seems likely that similar magnetically confined structures are present in the atmospheres of cool stars at least, although direct measurements of the magnetic field have been successful for only a few objects (cf. Robinson, Worden, and Harvey 1980). The mechanism of producing hot gas in stars is not known but acceptance of the influential role of magnetic fields allows a variety of local and global heating mechanisms to be considered.

In the OB giants and Of stars, there is not a firm theoretical understanding of either the origin of hot plasma or its configuration. If the coronal zone were confined to a slab at the base of the wind (Hearn 1975), it must be thin ($< 0.1R_*$) to satisfy H and IR constraints but with large emission measure ($\sim 10^{58}$ cm^{-3}) to excite the wind by Auger ionization (Cassinelli 1979). However, this thin slab model does not produce enough soft X-rays to match the Einstein observations (Long and White 1980; Cassinelli *et al.* 1982; Cassinelli and Swank 1982). An alternate model (Lucy and White 1980; Lucy 1981) suggests that the X-rays are produced by shocks resulting from instabilities in line driven winds (MacGregor, Hartmann, and Raymond 1979; Carlberg 1979). This model also predicts an X-ray flux that is lower than the observations, and in addition cannot produce the high temperature (10^7 K) plasma whose presence is inferred from X-ray spectroscopic measurements (Seward 1981; Cassinelli and Swank 1982). A stationary shock far out in the wind (Cassinelli *et al.* 1982) which is similar to that existing in the solar wind (Hundhausen 1973) might provide the requisite high energy X-ray fluxes with little absorption, but further investigation is needed.

Cool stars (spectral types F, G, K, and M) on the main sequence exhibit X-ray surface fluxes which not surprisingly show very poor agreement with predictions (Hearn 1972, 1973; Renzini *et al.* 1977) of the available energy provided by acoustic flux theory (Vaiana *et al.* 1981). Our knowledge of the Sun suggests that the X-ray emission from cool stars may be dominated by loop structures controlled by the magnetic field in such a way that atmospheric heating is only weakly related to properties of the stellar convection zone. The predictions of a standard conductively dominated loop structure conform to the observed relation between ultraviolet (N V) and soft X-ray emission in a number of active stars (Walter *et al.* 1980; Hartmann *et al.* 1982). Spectroscopic studies of active RS CVn binaries suggest that plasma may occur in two temperature regimes, which require differing scales of loop structures dependent on the atmospheric pressure (Swank *et al.* 1981).

The dearth of X-ray emitters among the cool giant and supergiant stars defines an anticorrelation between the strength (or presence) of X-ray emission and the presence of a strong stellar wind inferred from optical and ultraviolet measurements (Ayres *et al.* 1981; Dupree 1981; Hartmann *et al.* 1981). The total energy demands of the atmosphere and accompanying massive cool wind of a luminous star may in fact be the same order of magnitude as for the dwarf stars, except the energy is used to drive the wind, the high densities lead to efficient cooling, and the X-ray radiative losses are weak (or absent). Energy and momentum deposition by Alfven waves (Hartmann and Macgregor 1980) appears to be successful in explaining the observed temperature and velocity structure of the cool extended atmosphere.

Much effort is now directed towards establishing the physical parameters of the stars and their relation to X-ray emission. Increased rotational velocities are correlated with enhanced emission. The precise analytic dependence of L_x or L_x/L_{bol} on V or V sin i is under study. It is obvious that coronae are not thought to be powered directly by rotational energy but that the dynamo mechanism is enhanced by a faster rotation.

X-ray emission as measured by the X-ray to bolometric flux ratio is directly correlated with angular velocity of the star. Close binary systems such as RS CVn types (Walter and Bowyer 1981; Ayres and Linsky 1981), W UMa types (Cruddace and Dupree 1982) or BY Dra types (Caillault 1982), and single stars (Pallavicini *et al.* 1981; Walter 1981) show such a correlation, a fact that lends support to the overriding importance of magnetic fields in determining the level of X-ray radiative losses. Increasing the angular velocity of a star must naturally increase the efficiency of dynamo action and lead to stronger magnetic fields and more vigorous activity, although a quantitative theory is lacking to predict the correlation (Weiss 1981).

Rotation will cause modulation of X-rays if there is an inhomogeneous distribution of emitting regions. There are a few indications of X-ray variability in O stars on a 5 day (15 Mon) to a year time scale (ι Ori and δ Ori) (Snow, Cash and Grady 1981), and in a B star (κ Ori) (Cassinelli *et al.* 1982). However, outside of flaring events, there is not enough observational material to evaluate rotational modulation.

There is some evidence for the evolutionary decay of X-ray activity with age. Surveys of stars or stellar groups suggest that among the F and G dwarf stars, there is a systematic decrease of 3 orders of magnitude in X-ray luminosity ranging from the Orion stars (Chanan 1981) to the Pleiades (Helfand 1981), Hyades (Stern *et al.* 1981) and field stars (Helfand and Caillault 1982). How this decay is related to the decreased stellar rotation rate, which is also associated with increasing age (Skumanich 1972), remains to be determined.

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