36. THEORY OF STELLAR ATMOSPHERES (THEORIE DES ATMOSPHERES STELLAIRES

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Consistently with a trend observed in recent past triennial reports, progress in the theory of stellar atmospheres continues to be made in two different directions: (i) the traditional areas of continuum and line radiation transfer, line blanketing, atomic physics and atmospheric structures controlled by the joint conditions of radiative and hydrostatic equilibrium, and (ii) in areas of emerging interest such as oscillations, winds and mass loss, chromospheres, coronae and magnetic phenomena.

The interplay between phenomena that take place in the atmosphere *per se* and the 'causative' phenomena that often lie beneath the stellar surface implies that the work of the Commission often extends into some areas of interest to other IAU Commissions whose work is related to stars. This extension is also apparent in connections to the solar Commissions, for it is increasingly the case that large areas of interest in solar physics converge with corresponding areas of interest in stellar astrophysics. Interestingly, there is a growing awareness of the contribution that work in the areas covered by the Commission will contribute to progress in extragalactic investigations (such as the growing field of galaxy spectral synthesis, the use of analogies to connect theories of stellar mass loss and atmospheric heating to apparently similar processes that take place on the scales of galaxies and even clusters of galaxies, and the application of radiative transfer theory to problems in the early universe).

The volume of work that might be reviewed in this contribution is very large. A search of the ADS data base at

`(http://adswww.harvard.edu/abs_doc/abstract_service.html)`

with obvious key words covering the work of the Commission elicited over 6000 abstracts to work published over the past 3 years. A deeper investigation of a large subsample of these revealed that most were indeed related to the work of the Commission. For this reason, it is no longer feasible to attempt to provide in the report a comprehensive survey. Indeed, the growth of the WWW and effective search engines implies that the effort of doing this might not be repaid by the use of the report as a tool for astronomical research.

Arguably, the report will be of greater value to astronomers working *outside* the area covered by the Commission. If this is so, then the thrust of the report should be more towards providing an overview of progress in a few areas where (i) progress has been swift and (ii) the results appear to bear rather directly on research questions having a significance in other areas of astrophysics.

In addition to items mentioned in the reports below, the following partial list of recently published monographs and proceedings in areas of interest to Commission 36 may prove to be a useful entry into the field:

- Battaner, E., (1996) *Astrophysical Fluid Dynamics*, Cambridge University Press.
- Benz, A.O., (1993) *Plasma Astrophysics*, Kluwer, Astrop. and Space Sci Vol 184.
- Bludman, S.A., Mochkovitch, R., Zinn-Juste, J., (1994) *Supernovae*, North-Holland.
- Caillaut, J.-P., (1994) *Cools stars, Stellar systems and the Sun: 8th Cambridge Workshop*, Astron. Soc Pacific Conf Series Nr 64.
- Corbally, C.J., Gray, R.O., Garrison, R.F., (1994) *The MK Process at 50 Years*, Astron. Soc Pacific Conf Series Nr 60.

I. Appenzeller (ed.), Reports on Astronomy, Vol. XXIIIA, 303–309.

- Greiner, J., Duerbach, H.W., Gershberg, R.E., (1995) *Flares and Flashes*, Springer Lecture notes in physics, Vol 454.
- Hernquist, T.W., Williams, D.A., (1995) *The Chemically Controlled Cosmos*, Cambridge University Press.
- Jasckek, C., Jaschek, M., (1995) *The Behaviour of Chemical Elements in Stars*, Cambridge University Press.
- Linsky, J.F., Serio, S., (1993) *Physics of Solar and Stellar Coronae*, Kluwer, Astrop & Space Sci Vol 183.
- McCray, R., (1994) *Supernovae*, Cambridge University Press.
- Pap, J.M., Froelich, Ch., Hudson, H., Solanki, S., (1994) *The Sun as a Variable Star*, Cambridge University Press.
- Rutten, R.J., Schrijver, C.J., (1994) *Solar Surface Magnetism*, NATO ASI Series C Vol 433.
- Sauval, A.J., Blomme, R., Grevesse, N., (1995) *Laboratory and Astronomical High Resolution Spectroscopy*, Astron. Soc Pacific Conf Series Nr 81.
- Stobbie, R.S., Whitelock, P.A., (1995) *Astrophysical Applications of Stellar Pulsations*, Astron. Soc Pacific Conf Series Nr 83.
- Tayler, A.R., Peredes, J.M. (1996) *Radio Emission from the Stars and the Sun*, Astron. Soc Pacific Conf Series Nr 93.
- Tayler, R.J., (1994) *The Stars: their Structure and Evolution*, Cambridge University Press.
- Ulrich, R.K., Rhodes, E.J., Daeppen, W., (1995) *GONG '94: Helio- and Astero-seismology from the Earth and Space*, Astron. Soc Pacific Conf Series Nr 76.
- Wallerstein, G., Noreiga-Crespo, A., (1994) *Stellar and Circumstellar Astrophysics*, Astron. Soc Pacific Conf Series Nr 57.
- Wilson, P.R., (1994) *Solar and Stellar Activity Cycles*, Cambridge University Press.
- Yuan, Chi, You, Junhan, (1995) *Molecular Clouds and Star Formation*, World Scientific.

1. Progress in basic numerical methods and construction of model stellar atmospheres [I. Hubeny]

We cover here only studies that develop new stellar atmosphere modelling techniques, present new state-of-the-art model atmospheres, or apply newly calculated model atmospheres to analyse individual objects. This report does not cover studies which are primarily applications of existing methods: those which merely use existing grids of models, or compute more or less routine models for analyzing observations.

During the covered period, there were no specialized conferences on the stellar atmospheres theory (with the exception of the workshop *Model Atmospheres and Spectrum Synthesis* held in 1995 see Adelman et al 1996: this was however devoted mostly to standard LTE model atmospheres). There were, however, several conferences on specialized topics which contained several review papers discussing progress in the stellar atmospheres theory and existing discrepancies between theory and observations. Those having published proceedings are:

- White Dwarfs (Koester and Werner 1995)
- Astrophysics in the Extreme Ultraviolet (Bowyer and Malina 1996)
- Hydrogen-Deficient Stars (Jeffery and Heber 1996)

Progress in the past three years may be characterized by two major areas, namely

1. a concentrated effort to solve what may be considered at the 'last problem of the classical models', namely computing fully line-blanketed non-LTE model stellar atmospheres; and
2. efforts to construct so-called unified model atmospheres, which describe the whole atmosphere ranging from an essentially hydrostatic photosphere, to a highly dynamic wind, treated on the same footing.

1.1. NON-LTE LINE BLANKETING

Two research groups were most active in this endeavor. One is centred on Kiel, Potsdam, Hamberg and Tuebingen, the other is centred at NASA-Goddard.

Investigations in the Potsdam/Kiel/Bamberg group have concentrated on two aspects, further development of full metal line blanketed model atmospheres and the application of these models to hot evolved stars.

The approach of Dreizler Werner (1993, A&A 278, 199) to include all lines transitions from iron group elements was improved and tested by Hass et al. (1996, A&A 311, 669). Werner (1996, ApJ 457, L39) demonstrated the importance of CNO lines on the analysis of hydrogen Balmer lines in hydrogen rich atmospheres. A consistent fit to the optical spectrum is only possible if CNO lines are taken into account into the model atmosphere calculations in full detail, including correct Stark profiles. A long-standing problem that the effective temperature derived from fitting different Balmer lines, Hα to Hδ gave dramatically different results (sometimes referred to as the 'Napiwotzki problem'), has thus been solved.

The majority of the applications have concentrated on hot helium rich white dwarfs (spectral type DO) and their immediate progenitors, the PG 1159 stars. Optical spectra of nearly all accessible DO white dwarfs have now been analysed with non-LTE models resulting in reliable stellar parameters for those stars for the first time (Dreizler & Werner 1996, A&A 1996, 314, 217). Spectra of two unusual PG 1159 stars were also analysed (Dreizler et al. 1994, A&A 286, 463, Dreizler et al. 1994, A&A 309, 820). In addition, high resolution optical spectra (ESO-CASPEC and Keck-HIGHRES) as well as HST, ORFEUS and EUVE spectra of DOs and PG 1159 stars have been analyses (Napiwotzki et al. 1995, A&A 300, L5, Werner et al. 1995, A&A 298, 567, Werner et al. 1996, A&A 307, 860). These analyses enable a more detailed insight in the evolutionary past and history of the DO white dwarfs. Finally, a new class of hot white dwarfs has turned out to show signatures of an extremely hot and fast wind (Werner et al. 1995, A&A 293, L75, Dreizler et al. 1996, 303, L53).

The Goddard group have developed a robust numerical scheme, called hybrid complete linearization/accelerated lambda iteration (CL/ALI) method (Hubeny & Lanz 1995, ApJ 439, 875) that combines advantages of the standard complete linearization (low number of iterations), and the ALI scheme (a low computer time per iteration). An upgraded version of computer program TLUSTY (described originally by Hubeny 1988, Comp. Phys. Comm. 52, 103) was subsequently used for studies of various objects.

The first application was to provide a considerably improved analysis of observed EUV, UV, and optical spectra of hot white dwarfs (Lanz & Hubeny 1995 ApJ 439, 905; Barstow et al. 1996, MNRAS 279, 1120) In particular, the group have constructed a self-consistent non-LTE fully line-blanketed model atmosphere for a well-known hot DA metal-rich white dwarf, G191-B2B (Lanz et al. 1996, ApJ 473) which allowed, for the first time, to find an effective temperature and chemical composition that can consistently match the optical, far UV, and EUV data.

They have undertaken a comprehensive study of model atmospheres of O-type stars, and found that metal line blanketing contributes significantly to the solution of the long-standing discrepancy between spectroscopic and evolutionary masses for O-type stars (Lanz et al 1996, ApJ 465, 359).

On the other hand, neither non-LTE metal line blanketed models (computed however with approximate line blanketing), nor LTE line-blanketed Kurucz models were able to explain the high level of flux in the Lyman continuum for two giant early B-stars, ϵ and β CMa, observed with the EUVE satellite (Cassinelli et al. 1995 Apj 438, 932; and 1996, ApJ 460, 949). Since these are the only two hot, non-white dwarf stars for which the Lyman continuum flux is observable, the failure of the present-day models serves as a sobering reminder that the stellar atmospheres theory has still a long way to go.

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1.2. STELLAR WIND MODELS AND UNIFIED MODEL ATMOSPHERES

By definition, unified model atmospheres are those which relax the *a priori* assumption of hydrostatic equilibrium, and which thus treat the whole atmosphere ranging from an essentially static photosphere to a highly dynamical wind on the same footing. This approach was pioneered by the Munich group (Gabler et al. 1989), who also coined the term 'unified models'. The name stresses the unification of the photosphere and the wind: prior to this approach separate models were developed for photospheres and for winds.

– Munich models The Munich group has continued in their systematic study of O-star winds. They constructed improved radiation driven wind models, calculated detailed UV spectra, and used them to re-analyze HST/GHRS observations of the LMC O-star Melnik 42 (Pauldrach et al. 1994), which is claimed to be the most massive star currently known. The previous numerical techniques for calculating unified models were upgraded by Sellmeier et al (1993). Using the new methodology, it was demonstrated that the predicted EUV flux for new unified models of O stars are able to explain a prominent problem of photoionization models of H II regions, known as the "[Ne III]" problem (Sellmeier et al. 1995). Also, unified models for an early B-star were constructed (Najarro et al. 1995) in an attempt to explain the Lyman-continuum flux discrepancy discovered by Cassinelli et al. (1995) by the EUVE satellite (the observed flux in the Lyman continuum is much larger than that predicted by LTE and non-LTE line blanketed model atmospheres - see also review papers by Cassinelli, and Hubeny and Lanz in Bowyer and Malina 1996). Nevertheless, the unified photosphere-wind models explain only a part of the Lyman continuum flux discrepancy, while a large part of the discrepancy remains still unexplained.
  Recently, the Munich group developed a new, very fast approximate method to calculate theoretical H-alpha profiles, and thus to determine stellar mass-loss rates (Puls et al. 1996). A comparison with the improved theory of radiation driven winds (Pauldrach et al. 1994) shows that the observed wind momentum versus luminosity relation is qualitatively reproduced, but some significant discrepancies remain.
– CoStar models The Swiss group presented first so-call CoStar – combined stellar structure and atmosphere models (Schaerer et al. 1996a,b), based on Monte Carlo line-blanketing treatment described

in detail by Scharer and Schmutz (1994), and on the ISO-WIND non-LTE code of de Koter et al. (1993).

- Phoenix group The group continued in their systematic study of important effects that influence emitted spectra of novae and supernovae atmospheres – Hauschildt et al (1994, 1995); Baron et al. (1994, 1995). The most sophisticated non-LTE line blanketed model atmospheres for novae, including detailed line formation for Fe II, were constructed by Hauschildt et al (1996). They showed that Fe II line formation in novae is strongly influenced by non-LTE effects.
- Other studies Studies of extreme stellar winds of Wolf-Rayet continued in Potsdam (group of W.R. Hamann – recent review of their work is presented in Hamann 1996) and Pittsburg (group of D.J. Hillier – recent review of their work is presented in Hillier 1996). The latter group has presented first non-LTE metal line-blanketed model atmospheres for Wolf-Rayet stars. The Goddard group analysed GHRS/HST observation of massive stars in the R136 region of the 30 Doradus cluster in LMC (de Koter et al. 1994), using the ISA-WIND code of de Koter et al (1993).

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2. Theory of stellar mass loss[S. Owocki]

Over the past few years, there has been significant progress in extending the standard CAK theory for radiatively driven mass loss from hot, luminous stars to include many additional processes, e.g.: instability and variability; large and small scale structure; rotational distortion and modulation; photospheric shadowing and ion separation (e.g. in thin B-star winds); and non-LTE optically thick transfer and multiline scattering (particularly in dense WR-star winds).

Regarding wind variability there has emerged a consensus that the associated flow structure must generally exist on both large and small spatial scales. Small-scale, stochastic structure can arise intrinsically from the inherent instability of the radiative driving. There has been progress in calculating the energy transfer in instability-generated shocks, and in estimating the associated X-ray emission. But the reverse shocks that arise directly from the instability yield only a quite small X-ray fillng factor, and so achieving the observed X-ray luminosity, particularly from low-density winds, requires additional, stochastic collision between dense clumps within the wind. Synthesis of UV wind lines from time-dependent instability simulation models have recently proven quite successful in reproducing key profile features, like the extended black absorption troughs of saturated P-Cygni lines. Such relatively small-scale stochastic structure might also explain the multiple "moving bumps" seen in relatively high signal-to-noise spectra of optical emission lines formed in Wolf-Rayet winds, which recent wavelet transform analyses suggest may even be represented by a characteristic scaling law analogous to that found in turbulent flows.

On the other hand, for the most common form of explicit wind variability – namely the recurring "Discrete Absorption Components" (DACs) often seen in unsaturated UV wind lines detected with low

S/N IUE spectra – recent modelling has centered on multi-dimensional dynamical simulations of Co-rotating Interaction Regions (CIRs), in which *large-scale*, spiral wind structure is explicitly induced at the wind base by some disturbance from the underlying rotating star. The apparent slow evolution of DACs can arise in such models from either the relatively slow acceleration of the denser, compressed wind structures, or from velocity-gradient "kinks" that propagate upstream at the relatively fast speed of radiatively modified acoustic waves. Spiral streams of enhanced density also provide a possible explanation for the sometimes upwardly, bowed "banana" shape contours of periodic absorption modulations detected in the recent IUE 'Mega' campaign for long-term monitoring of UV wind line variability.

Much recent work has also examined the role of rapid stellar rotation in focussing wind material into an equatorial "Wind Compressed Disk" (WCD). Dynamical simulations that assume strictly radial line-forces have generally confirmed this wind compression process, but have shown the disk density buildup is limited by leakage of material through both inner-disk infall and outer-disk outflow. Application of this WCD paradigm to Be stars has thus required quite high mass loss rates in order to achieve sufficient disk density to produce, e.g., the observed level of H-alpha emission or continuum polarization (although recent Monte Carlo simulations show that multiple scattering can have the somewhat surprising effect of *enhancing* the polarization over that predicted from a simple, optically-thin analysis). Subsequent work has analyzed the potential role that such wind compression effects could play in wide range of mass outflows, e.g. from Wolf-Rayet stars, Asymptotic Giant Branch stars, B[e] stars, and novae. For outflows with a sufficiently slow initial acceleration, a milder equatorial density enhancement (a "wind compressed zone', or WCZ) can occur even in relatively slow stellar rotators, with rotation speeds well below either the critical "breakup" speed or the outflow terminal speed. For line-driven outflows, however, recent dynamical simulations have indicated that *nonradial* components of the line-force can play a surprisingly strong role, effectively reversing the equatorward flow and thus completely inhibiting formation of a WCD or WCZ. Paradoxically, these simulations have even suggested that, if gravity darkening is taken into account, then the flow from the equator could actually have a *lower* mass loss rate and density than that from the poles!

Apart from such effects of variability and rotation, there has also been considerable effort toward extending spherically symmetric, steady-state wind models. In relatively thin B-star winds, this has focussed on the dual effects of the ion separation and photospheric shadowing. Analysis has shown that the low collision rate from Coulomb friction can lead to ion runaway and thus a multicomponent nature to low density winds. In addition, photospheric shadowing by the Stark-broadened photospheric profile can significantly affect the force from the few strong lines that dominate the driving of such winds. Taking this into account, the predicted domains delineating the progressive transition from single-fluid to multicomponent to negligible wind seems in good general agreement with the occurrence of photospheric abundance anomalies.

For the opposite extreme of the very dense, optically thick winds from Wolf-Rayet stars, there has been considerable progress in understanding the multiline scattering processes necessary to drive the flow. Within an idealized model in which the spectral distribution of lines is assumed to be "effectively gray", both Monte Carlo and nonisotropic diffusion treatments have shown that the standard CAK approach can be extended straightforwardly to the multiline scattering case in which the radial momentum of the wind significantly exceeds that of the photons. This emphasized that the usual WR wind "momentum problem" could be better characterized as an "opacity problem" of identifying enough strong lines with sufficiently broad frequency spacing to avoid large gaps in the spectral distributions. More realistic models based on actual atomic line-lists have indicated that the radial stratification of ionization stages could a key role in filling such spectral gaps. General efforts have focussed on how this ionization stratification is controlled by line-blanketing effects, with particular emphasis on the possible role of effective photon destruction in the He II Ly-alpha transition in fostering recombination in helium, and thus also in a host of elements whose ionization is controlled by the He I continuum.

For O-star winds recent efforts have been toward extending unified wind-atmosphere models and testing these against observations, with emphasis on calibrating a wind-luminosity relation that could provide a standard candle for extragalactic distance determination. Through interactive application of fast non-LTE codes to match observed line diagnostics of wind mass loss rates, particularly H-alpha, in large sample of O-stars, the wind momentum numbers from theoretical models have been found to have significantly weaker luminosity dependence than inferred from observations. Recent efforts have focussed on examining the role of rotationally induced wind compression effects on the use of H-alpha emission as mass-loss-rate diagnostic.

Finally, there have been continuing efforts toward understanding the consequences of mass loss for the overall structure and evolution of massive stars. This has included initial efforts to develop unified models of interior-atmosphere-wind that take account of the effect of the systematic wind depletion of the stellar mass. There have also been dynamical models of the effect of various phases of evolution on the successive layers of wind-blown nebulae, in some cases also including the effects of rotationally induced wind compression in producing the observed nonspherical shapes. Other studies have focussed on the role of such wind blown nebulae and bubbles in triggering further star formation, including the starburst epochs apparent in many galaxies.

3. Magnetic Fields[C. Schrijver]

Whereas relatively little headway has been made concerning the generation of magnetic fields by a dynamo process in the past few years, our understanding of field emergence through the convective interiors, field behaviour in stellar photospheres, and the field extension into outer atmospheres has deepened both by numerical experiments and by solar and stellar observations. Numerical simulations of rising flux bundles in rotating, convectively unstable environments that include, e.g., drag forces acting on rising fields that are anchored at the bottom of the envelope, now successfully reproduce the preferential latitudes and orientations of bipolar magnetic regions. This, together with the large observational datasets now available on solar active regions, and the now very successful models for the large–scale dispersal of magnetic field over the entire solar surface, provides us with the photospheric boundary conditions of magnetic fields in stellar atmospheres. Given these boundary conditions, the curved planes have been computed that separate domains of connectivity: field lines on either side of such a separator connect to very different footpoint locations. These separator lines have been demonstrated to be related to flare sites; this holds promise for the study of outer atmospheric heating.

The spatial resolution of YOHKOH and the stellar spectroscopic results from EUVE have still not resulted in a reconciled picture of the geometry of individual coronal loops: divergence of the loop with height is required from stellar models, but not observed - or perhaps not observable - by YOHKOH. Early SOHO results are showing a very much more dynamic field from photosphere to outer corona than anticipated. The successful detection of a limited set of cool stars at radiowavelengths opens up new diagnostics for the theory of fields in stellar coronae.