36. THEORY OF STELLAR ATMOSPHERES (THEORIE DES ATMOSPHERES STELLAIRES)

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I. COMMISSION ACTIVITIES

Commission 36 acted or acts as a sponsor or a cosponsor of the following Symposia and Colloquia.

(1)Symposium No. 122: "Circumstellar Matter", Heidelberg, FRG (June 1986), (2)Symposium No. 132: "The Impact of Very High S/N Spectroscopy on Stellar Physics", Paris, France (June 1987), (3)Colloquium No. 95: "Second Conference on Faint Blue Stars", Tucson, AZ, USA (May 1987), (4)Colloquium No. 102: "UV and X-ray Spectroscopy of Astrophysical and Laboratory Plasmas", Beaulieu-sur-Mer, France (September 1987), (5)Colloquium No. 106: "Evolution of Peculiar Red Giant Stars", Bloomington, IN, USA (July 1988), (6)Colloquium No. 108: "Atmospheric Diagnostics of Stellar Evolution: Chemical Peculiarity, Mass Loss and Explosion", Tokyo, Japan (September 1987).

II. RECENT PROGRESS IN THE THEORY OF STELLAR ATMOSPHERES

The theoreticians on stellar atmospheres have been continuously being challenged by new observational results obtained with ever increasing signal to noise ratio and over a wide range of wavelength. The high S/N ratio spectroscopy demands us to take subordinate physical processes into account such as realistic velocity fields and the gravity-settling effects in the quasi-hydrostatic stellar atmospheres (cf. Review A). The observations in UV and X brought up the theory of hot stellar wind, and those in IR and mm wavelength now stimulate the development of the theory of cool stellar wind (cf. Review B). The theory of expanding atmospheres have been elaborated for stationary cases as well as for dynamical cases (cf. Review C, E), and the community requires more comprehensive treatments in radiative transfer than before (cf. Review D, E). The LMC supernova 1987A allowed us for the first time to investigate the details of the dynamical structure and the development of the expanding SN atmosphere (cf. Review C, E).

As the previous reports of Commission 36, this report presents a few reviews focused on the selected topics which shall characterize the recent progress in the theory of stellar atmospheres.

A. Velocity Fields in Stellar Atmospheres (D. F. Gray)

This portion of the report draws attention to only certain selected topics of current interest regarding velocity fields in stellar atmospheres. It is not intended to be a comprehensive review. Items limited to the solar atmosphere appear in the reports of Commissions 10 and 12.

1. Convection and Granulation.

Convective motions below the photosheres of F, G, and K stars interact with the stars' rotation to generate dynamo activity and they push upward into the

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visible layers producing granulation and turbulence, and setting off various oscillatory motions. Rotation of main sequence stars, its decline with time, and its relation to chromospheric emission is summarized by Soderblom (1985). Futher evidence for dynamos and rotational braking is accumulating (Gray and Nagar 1985; Gilliland 1985). Rotational decline may be regulated by convection (the Rotostat Hypothesis, Gray 1986a, 1986b, Gondoin *et al.* 1987).

Granulation in M giants have been detected by Nadeau and Maillard (1987) using the well-known technique of differential radial velocity shifts with excitation potential. Higher spectral resolution data, which allows the line asymmetries to be measured (Dravins 1987a, 1987b; Gray 1988) have been used to show that G and K dwarfs do have C-shaped bisectors, in agreement with the solar case and in contrast to higher luminosity stars and F dwarfs which show only the upper half of the C. These results, taken with earlier studies (Gray 1982) effective temperature and decreasing luminosity. Macroturbulence dispersion follows this same pattern and suggests that classical stellar macroturbulence is largely the motion of granulation.

Physical modeling of granulation (Nordlund and Dravins in prep.; Nordlund 1985; Steffen 1987) has shown that observed bisectors, with typically ~200 m/s excursions, reflect only about one tenth of the actual velocity displacements going on in the photosphere. While there is little hope for the spatial resolution of stellar granules, and disk-average values for line asymmetries make it hard to separate the real factor from the specific-intensity factor, the situation is made even worse by complications from large-scale non-uniformities on stellar surfaces that cause distortions of the line bisectors which vary as the star rotates (Gray and Toner 1988 in prep.). Secular variations of granulation associated, for example, with cycles needs to be studied (Wallace *et al.* 1987).

Dramatic differences in granulation patterns of Ib supergiants are seen in stars hotter than G0-2 Ib (Gray and Toner 1986). Studies of even higher luminosity stars show further evidence for vertical motions (Boer and deJager 1988 in prep.). Supersonic and near-supersonic macroturbulence velocities are indicated in high-luminosity supergiants (de Jager *et al.* 1988, in prep.).

2. Oscillation, Rotation and Outflow.

Non-radial oscillations have been identified in twelve A stars (Kurtz and Martinez 1987; Shibahashi 1987). Mode identification is progressing mainly using photometry, but phase-averaged spectroscopy has been done on HR 1217 (Matthews *et al.* 1987).

The observational techniques for detecting non-radial ossilations in cooler stars are reviewed by Harvey (1987), and spectroscopic methods have a 40-fold predicted advantage over photometric ones. Radial velocity variations have been detected in Arcturus (~2 days; 160 m/s) and in Pollux (~3 hr; 10 m/s) by P. H. Smith *et al.* (1987).

Velocity fields in the outer regions of stellar atmospheres also show complex behavior. Interesting (radial) differential rotation has been detected in AB Aur (A0ep) by Catala *et al.* (1986) in which Ca II shows a 32 hour period while Mg II show a 45 hour period. Modeling of stellar co-rotating interacting regions (Mullan 1984a, 1984b, 1986) has shed light on the UV emission anomalies of hybrid stars.

Modeling of outflows from bright giants have been successful in reproducing observed line widths as well as satisfying radio data and density-sensitive line ratios (Brosius and Mullan 1986). Mass loss and dust formation for long period variables are greatly enhanced by shock waves, according to recent calculations of Bowen (1988).

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B. Impact of IR and mm-Wave Observations on the Theory of Stellar Envelopes of Red Giants(T. Tsuji)

The infrared and mm-wave observations, after the pioneering attempts in 1960's and 1970's, respectively, are now being matured to be used as standard tools in stellar astrophysics. In this report, we focus our attention to observations (mostly published in 1984-1987) of stellar envelopes that may be related to our understanding on stellar mass-loss, which is one of the major unresolved problems in stellar astronomy today.

1. *Infrared Observations.*

The completion of IRAS survey undoubtedly gave great impact on our subject as on other fields. The unbiased survey is especially useful in providing some statistics on dust formation in evolved stars (Hacking *et al.*, 1985; Habing, 1987). IRAS photometric data provided important constraints on the physical structure of the dust envelope. For example, it was shown that the opacity of dust grains is nearly proportional to λ^{-1} and hence dust grains should be highly amorphus, both in oxygen-rich and carbon-rich envelopes (Rowan-Robinson *et al.*, 1986; Jura, 1986; Zuckerman, Dyck, 1986b). This confirmed the conclusion based on submillimeter observations of limited sample of evolved stars by Spoka *et al.* (1985). The database of low resolution spectra (LRS) by IRAS is a rich source of new materials to study the chemistry of dust envelopes. For example, some carbon stars by optical spectral classification appeared to have silicate emission features in IRAS RLS: Such carbon stars may be binaries with M-giant stars (Little-Marenin, 1987) or may be just evolved from M-giant stars with remnant of oxygen-rich envelopes (Willems, De Jong, 1987). The later idea has further been detailed (Willems, 1987). Also, formation of dust in Mira variables was found to be correlated with the asymmetry of light curve that may depend on the shock strength (Vardya, De Jong, Willems, 1986).

Another important information in understanding the nature of dust around red giants is the spatial structure of dust envelopes and the speckle interferometry in the near infrared has successfully been applied to the envelopes of red giant stars: Dyck *et al.* (1984) have shown that the dust shell of many evolved stars are pretty large and this fact suggests the presence of dust free zone extending out to a few stellar radii around the central stars. Ridgway *et al.* (1986) have shown that the infrared interferometry, combined with photometric data, could provide further details of the dust shell (extinction law, optical depth, dust temperature *etc*). Dyck *et al.* (1987) indicated a possibility of highly asymmetric structure of dust envelope of IRC+10216 and suggested it to have a bipolar structure.

High resolution infrared spectra by Fourier transform spectroscopy (FTS) provided unique information on the inner circumstellar envelope: An interesting attempt is to isolate the contribution of the gas in the envelope from that of the central infrared continuum source with the use of annular entrance apertures by Sahai and Wannier (1985), who showed that resonantly scattered lines of the CO fundamental bands could be well separated and be used as probes of the physical structure of the inner part of the expanding envelope of IRC+10216. The separation of different layers by spectroscopic observations is generally difficult when velocity structures of the layers are not very different. From the detailed analysis of CO overtone bands, however, a possible presence of the quasi-static molecular dissociation zone in the transition region between the warm chromosphere and the cool wind in several normal red giants has been suggested (Tsuji, 1987). This new component is characterized by high turbulent velocity but shows little relative motion to the photosphere. For this reason, such a layer has been difficult to be recognized in normal red giant stars, but has been recognized more clearly in Mira variable stars because of the Doppler-shift of the photospheric lines due to photosheric pulsation (Hinkle,

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Hall, Ridgway, 1982). Thus, the presence of such a quasi-static layer may be a basic characteristics of cool luminous stars in general. The dynamics of the envelope of Mira variables is best explored by infrared spectroscopy and it has clearly been shown that the shock is developed by the outwardly propagating waves generated by stellar oscillation (Hinkle, Scharlach, Hall, 1984; and references cited therein). It is, however, not likely that the shock wave is the direct driving force of mass-outflow, in view of the presence of the static layer noted above. These works also showed that SiO masers may be not originating from the pulsating envelope but rather they may be connected with the quasi-static turbulent layer noted above.

2. Millimeter-wave Observations.

In recent years, molecular spectroscopy in the millimeter wavelength region has made important progress: For example, CO pure rotational transitions have been observed not only in very cool stars with massive winds but also in many ordinary red giant stars (*e.g.*, Wannier, Sahai, 1986; Olofsson, Eriksson, Gustafsson, 1987). From these observations, stellar mass loss rate has been determined with better accuracy than by any other method for a large sample of red giant stars (*e.g.*, Knapp and Morris, 1985). Also, termianl flow velocities, which are confirmed to be rather small in most red giant stars, have been determined with high accuracy from the CO spectra (*e.g.*, Zuckerman, Dyck, Claussen, 1986), together with the stellar radial velocity. These results enable a comparison of the momentum in the outflow gas $\dot{M}v$ and momentum in the stellar radiation field L/c; a necessary condition for the winds to be accelerated by radiation pressure on dust seems to be fulfilled for a large number of stars, but not for all the stars (Zuckerman, Dyck, 1986a, Knapp, 1986). The answer to the question of whether the dust formation initiates mass-loss or vice versa seems to be not very clear yet. Molecules other than CO are also observed: For example, HCN was found not only in carbon-rich stars (*e.g.*, Rieu *et al.*, 1987) but also in oxygen-rich stars (Deguchi, Claussen, Goldsmith, 1986). While rich chemistry has been known in envelopes of carbon stars such as IRC+10216, it has recently been shown that the chemistry in oxygen-rich envelope such as of OH231.8+4.2 (M-giant star with bipolar nebulosity) is similarly rich (Morris *et al.*, 1987). Such information on gaseous component of the circumstellar matter should be most useful in our understanding on physics and chemistry of stellar envelopes when they are combined with the new information on dust component revealed by IRAS.

So far the three dimensional (*i.e.*, two spatial dimensions plus radial velocity) mapping of the circumstellar envelopes at sub-arc second resolution has been done by radio interferometry with SiO, H_2O, and OH masers: For example, VLBI observations of SiO masers showed that the masers occur within a few stellar radii but do not show any systematic expanding patern (Lane, 1984). Thus, SiO masers may originate in cloudlets of rather high density in the turbulent region of the inner circumstellar envelope (Alcock, Rose, 1986). MERLIN observations (*e.g.*, Chapman, Cohen, 1986; and references cited therein) clearly showed that OH maser at 1612MHz originates in a thin expanding shell at some 100 stellar radii while H_2O and OH main line masers in accelerating thick shell at some 20 stellar radii. The velocity extents of the maser emissions increase systematically with angular extent and, if this fact be interpreted as showing the continuous increase of expansion velocity, the driving force per unit mass must be increasing with the distance from the star. Thus, maser emissions are very useful in probing the inner circumstellar envelope where the acceleration may take place, but they are so far limited to oxygen-rich stars. However, recent discovery of HCN masers in carbon-rich stars (Guilloteau, Omont, Lucas, 1987; Izumiura *et al.*, 1987) has opened a new possibility of probing inner part of the circumstellar envelope of carbon stars. Also, a possible weak maser of CO has recently been found in a classical carbon star V Hydrae by Zuckerman and Dyck (1986b). A spatially resolved time series observation of CO in V Hya revealed that anomalous excitation, which may occasionally induce maser, should be closely

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related to the inhomogenous radiation field due to bipolar geometry, and thus V Hya may be a carbon star already at the initial phase to planetary nebula via bipolar object (Tsuji *et al.*, 1987). Such observations of masers and related phenomena in carbon stars will also provide new impacts on our understanding of molecular excitations and masers in stellar envelopes.

3. Envelopes of Red Giant Stars.

Now, radio interferometry revealed that the circumstellar matters are continuously accelerated until at least some 50 stellar radii before they gain the terminal flow velocity that is still observed at some 1000 stellar radii by radio thermal emissions. On the other hand, infrared interferometry revealed the presence of dust-free zone in the inner part of the envelope. Then, even if dust may play some role in accelerating the outflow, it could not provide the initial acceleration in the inner envelope. Thus, inner turbulent region revealed by SiO maser and infrared CO lines may have important key in our understanding of the origin of mass-outflow. Although little theoretical work has yet been done to have unified understanding on all these observations now available, one interesting suggestion in this regard is that the thermal instability due to molecular cooling plays an important role in determining the physical structure of the outer atmosphere of cool giant stars (Muchmore, Nuth, Stencel, 1987). Also, evidences of bipolar structure for the envelopes of red giant stars are increasing, and bipolar stage may represent an important phase of the evolution of mass-losing stars. Then, how to understand the formation of such a bipolar structure should be another important problem in the theory of stellar envelopes of red giant stars.

C. Supernovae Spectra (R. Harkness)

The computation of supernovae spectra is still a relatively young field. Initial modelling by means of LTE spectrum syntheses has been very successful in explaining the complex spectra of both Type Ia and Ib supernovae, while progress has been made in attempting non-LTE calculations for Type II supernovae. Of course, the explosion of SN 1987A in the Large Magellanic Cloud has intensified interest in this area, not only because SN 1987A has been observed in unprecedented detail, but because its spectral evolution and light curve appear to be unique. IUE observations of supernovae of all types have provided a new avenue of investigation. Supernovae represent some of the most extreme conditions for the theory of stellar atmospheres: rapid expansion, extended spherical geometry, non-thermal radioactive decay energy sources, extreme departures from LTE, unusual and radially stratified abundances.

1. Type Ia Supernovae

The spectra of 'normal' Type Ia supernovae are now relatively well understood. There seems little doubt that the explosion mechanism is the thermonuclear incineration of a white dwarf. Theoretical spectra of a carbon deflagration supernova model by Nomoto *et al.* (1984) show extremely good agreement with observations at the time near maximum light (Branch *et al.* 1985, Harkness 1985). The spectrum at this time is dominated by intermediate mass elements, and the models require a substantial fraction of the white dwarf be converted to these elements. Unfortunately, current theory suggests that the central ignition will lead to a supersonic combustion, or detonation, rather than a subsonic deflagration. The net result is that the entire white dwarf is burned to Ni^{56}, leaving no intermediate mass elements to account for the maximum light spectrum. It remains a puzzle as to how a detonation may be damped to allow production of the intermediate mass elements in the outer layers.

IUE observations show that all Type I supernovae have an 'ultraviolet deficit', or paucity of ultraviolet flux compared to that which one would expect

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on the basis of the optical colour temperature. It now seems, on the basis of theoretical atmosphere models, that the deficit arises quite naturally in moderately extended atmospheres and is due mainly to the strong near-uv resonance lines of Fe II, Ni II and perhaps other iron-peak elements such as Cr II and Mn II (Branch and Venkatakrishna 1986, Harkness 1986). In SN Ia there is no shortage of these elements, and indeed one problem is to prevent them from swamping the optical spectrum at maximum light. The strong abundance gradients in the partially burned outer layers require some mixing to take place, to homogenise the intermediate mass elements. If this mixing involves the almost pure Fe-Co-Ni core, the spectrum deteriorates. It may be that the dying combustion wave promotes this homogenisation as it disintegrates into small burning regions or blobs and this mechanism will require future study.

Most spectrum calculations to date have been confined to conditions near maximum light or very late phases (more than 100 days past maximum). Fu and Arnett (1986) consider the effects of flux dilution on the UBVRK colours of SN Ia from 20-50 days after maximum light. They find evidence for wavelength dependent flux dilution, the dilution increasing with increasing photon energy. Consequently, SN Ia may be dimmer than their infra-red colours would indicate, but brighter than their UBV colours would indicate.

Just a few years ago it seemed that all Type Ia supernovae shared a practically identical spectral and photometric development. However, counter-examples are beginning to show up (Branch 1987) and hopes of using these events as standard candles may begin to fade. Matching individual supernovae may shed some light on the role of mixing in the outer layers. Wide spectral coverage on a daily basis for the first four weeks of a typical SN Ia would allow very detailed models to be constructed. Observations of the first few days would be of the greatest interest, but obviously the hardest to obtain. It may be possible to detect the presence of a small amount of hydrogen at this time, lending further suppout to the theoretical model on an accreting white dwarf undergoing a runaway as it approaches the Chandrasekhar mass.

2. Type Ib Supernovae

Apart from the explosion of SN 1987A, the most exciting developments of the last few years concern a subtype of SN I now denoted as SN Ib. The prototype was observed in the summer of 1983 in NGC5236 (M83), and a second, very similar example SN 1984L was observed in NGC991 in August 1984 (Wheeler and Levreault 1985). Meanwhile, unrelated observations of SN 1985F showed a unique late-time spectrum of an unknown kind of supernova (Filippenko and Sargent 1986). The spectrum was dominated by [O I] and [Ca II], with no evidence for Hα which is usually the dominant feature of Type II events. The spectrum was also quite unlike the late-time spectrum of SN Ia, which is due principally to [Fe II] lines. When observations of SN 1983N made in February 1984 were reduced, it was found that the spectra were a close match to the Filippenko-Sargent object (Gaskell *et al.* 1986). Furthermore, analysis of SN 1984L also shows evidence of the emergence of a strong [O I] emission. The early-time spectra of 83N and 84L have also been shown to be dominated by He I lines, so this type of SN appears to be most consistent with the explosion of a Wolf-Rayet star (Harkness *et al.* 1987).

Atmosphere models of SN Ib are in a very early stage of development. It seems clear, however, that large departures from LTE are necessary for the formation of the helium lines and this poses a major computational challenge. From the light curve, one requires the synthesis of a substantial mass of Ni^{56} (but less than an SN Ia), which provides most of the energy input from maximum light onwards. The ultraviolet deficit at maximum light appears to be formed in the same manner as SN Ia.

Other 'peculiar' SN I such as SN 1983I and 1983V may be related to the

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apparently helium rich SN Ib. Atmosphere models with power-law density profiles consisting of helium/oxygen mixtures provide a fair match with the observations of these two events (Wheeler *et al.* 1987). It seems possible that these are directly related to normal SN Ib, but defferentiated by the extent to which the helium envelope has been removed through mass loss.

3. Type II*l* and IIp Supernovae

Type II supernovae are so defined by the presence of hydrogen lines in their spectra. The Type IIp (plateau light curve) events are consistent with explosions of red supergiants. Shock energy originating in a core collapse is deposited in a massive extended envelope. At maximum light the spectra tend to be somewhat featureless, with weak Balmer lines. SN II*l* (linear light curve) may represent lower envelope masses, but Doggett and Branch (1985) note that the light curves resemble Type I events and tend to be almost as bright, leading them to suggest that SN II*l* may be due to some kind of thermonuclear explosion, as opposed to the conventional core collapse model. The spectral development of the two subclasses is distinctly different, the metal lines being more dramatic in SN II*l*.

Non-LTE analysis of SN II is a much more practical proposition than for the Z = 1 composition of SN Ia. All supernova atmospheres are expected to be strongly scattering dominated. If true, distance estimates using the Baade method could be seriously in error. Shaviv *et al.* (1985), Hershkowitz *et al.* (1986a,b) and Hoflich *et al.* (1986) address the problem of non-LTE spectrum formation for low density hydrogen atmospheres. They find that deviations in level populations from LTE values generally increase with radius through the atmosphere. Near the surface NLTE effects occur because of the non-local nature of the radiation field and are enhanced by dilution of the radiation field due to sphericity. However, Hoflich *et al.* (1986) also find that electron scattering can act to restore LTE if a sufficiently extended scattering atmosphere exists above a low density photosphere. Furthermore, they note that for power law dinsity profiles, NLTE effects become more important with steeper dinsity gradients.

Hempe (1985, 1986) has calculated line profiles for Hα, Hβ formed in SN II model atmospheres with power-law density profiles.

4. Peculiar Supernovae and SN 1987A

Excellent spectral coverage of the LMC supernova 1987A has given us a new opportunity to unravel supernova spectrum formation. SN 1987A was not, however, a 'normal' Type II event. It was very subluminous and apparently originated in a blue supergiant. Spectra were obtained only 24 hours after the explosion, and were observed to undergo extremely rapid changes over the first few days as the shock heated photosphere cooled rapidly. Unlike normal Type IIs, the progenitor of SN 1987A is known to have had a small radius of about 2×10^{12}cm because the supernova was acquired visually just three hours after detection of a neutrino pulse presumably due to the core collapse. Adiabatic expansion losses were therefore very significant for this supernova. IUE data show the ultraviolet flux dropping hourly over the first two to three days. Initial ultraviolet spectra were unusual for a Type II, and then passed through a phase similar to the maximum light UV spectra of SN I. The optical spectra displayed distinct Balmer lines which became almost saturated before fading at about 10 days. He I 5876Å was visible for a couple of days, but no He lines have re-emerged. The spectrum after 10 days remained remarkably constant for the next three months, and most closely resembled that of a SN II*l* after maximum light.

Modelling the rapid spectral evolution of SN 1987A over the first 10 days presents a whole new challenge. It is likely that the full time dependence of the radiation field will be required to simulate this event, including non-LTE effects.

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As more and more high quality supernovae spectra are obtained it is becoming clear that many have some unique feature. Adapting conventional atmosphere theory to supernovae should continue to be a rewarding endeavour.

D. Numerical Methods in Radiative Transfer(W. Kalkofen)

This report surveys perturbation methods for the numerical solution of radiative transfer problems in unpolarized light, as well as solution methods for polarized radiation.

1. Perturbation Methods.

Recent theoretical and numerical developments in radiative transfer have been towards more efficient, faster methods for the solution of radiative transfer problems, such as line transfer in media in statistical equilibrium and the construction of model atmospheres in radiative equilibrium. The speed of these new methods is due to the use of approximate matrix operators that are simpler in structure and often lower in order than the corresponding exact operators, leading to equations that can be solved much more rapidly than the equations of conventional, direct methods. An apparent drawback is that even linear equations must be solved iteratively. But the timing advantage can be several orders of magnitude. In addition, a given problem can usually be separated into simple parts that can be solved still more efficiently on parallel processors, leading to further substantial savings in computer time. Problems that can be attacked with these methods are, for example, radiation in multi-dimensional media, time-dependent radiative transfer coupled with gas dynamics, and the radiation emerging from stochastic media. In the following we describe some of the recent methods, emphasizing the physical principles on which the approximate operators are built, and mention some of the applications.

A typical line transfer problem contains many scale lengths, which range from the monochromatic photon mean free paths in the core of a line to the thermalization length, *i.e.*, the distance over which information about the structure of a medium is communicated to the source function. These lengths must be represented in the operators used in the numerical solution. Operator perturbation methods based on integral equations contain these scales in different operators: the individual, monochromatic photon mean free paths are expressed mainly in the exact intergral operator; the thermalization distance, in the approximate operator. The exact operator is used in the solution of uncoupled, or low-order coupled, equations that determine the error made by a provisional solution in a conservation equation; the approximate operator is used in the calculation of corrections to a provisional solution.

The approximate operator of Scharmer's (1981, 1984) method, which has inspired many of the recent operator perturbation methods, simplifies the description of the transfer along a ray by equating the specific intensity at a given point to the source function at unit optical distance in the upstream direction. This construction leads to a nearly triangular matrix operator (in a semi-infinite atmosphere) and thus a system of equations that can be solved very rapidly, with timing that scales more nearly as the square of the order of the system than as its cube. -- An ingenious application of this efficient method is by Carlsson & Scharmer (1985; cf. also Scharmer & Carlsson 1985, Carlsson 1985) to line formation in stochastic velocity fields in the solar atmosphere.

The simplification of approximate integral operators has been carried to an extreme with a purely *diagonal* operator, in which the intensity at a given point is proportional to the source function. The proportionality factor is equal to unity for a source function in a saturated line, *e.g.*, deep inside an atmosphere, but near the surface it is reduced to account for escaping radiation. Olson *et*

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al. (1986) base this factor on the escape probability whereas Werner & Husfeld (1985), Werner (1986, 1987) and Hamann (1985, 1986, 1987) base it on the core *fraction of the* Λ*-operator. -- In the applications showing the features of the* method, Olson *et al.* solve a two-level atom problem, Werner constructs line-blanketed hydrogen model atmospheres in radiative, hydrostatic, and statistical equilibrium, and Hamann solves the multi-level equations for a spherically expanding pure helium atmosphere of a Wolf-Rayet star of given structure.

The distinctive and significant feature of *diagonal* operator for the desciption of the radiative transfer is that the system of equations for N depth points and K unknown functions, whose order would ordinarily be $N \times K$, is split into two systems, one of order N, the other of order K. This feature is of enormous advantage for model atoms with many levels since the computation time scales as the cube of the order of the system of equations. -- Avrett & Loeser (1987) reduce the size of the matrices in another way, by writing the equations for a multilevel atom as a series of (so-called equivalent) two-level atom problems. This also separates a problem into parts of order N and order K, but insteasd of solving the transfer equation *approximately* and the equations of statistical equilibrium *exactly*, Avrett & Loeser do the opposite, solving the transfer equation *exactly* and the equations of statistical equilibrium *approximately*. Of course, the converged solution in either case is the (numerically) exact solution of the problem.

One potential drawback of Scharmer's method is that for atoms with many levels the timing may approach that of th complete linearization method (Auer & Mihalas 1969). The reason is that the solution time for such problems is dominated by the time for solving a system of equations of high order. Thus for large atomic systems, the computation time of both methods scales the same way with the "size" of the problem (*i.e.*, as $[N{\times}K]^3$) . Diagonal operators avoid this difficulty. On the other hand, they may give slowly converging equations since the maximal eigenvalue of a critical matrix appearing in the expansion for the solution (cf. Kalkofen 1985) need not be small compared to unity. This is a problem studied by Olson *et al.* (1986) whose remedy is to extrapolate the solution based on several consecutive iterates (cf. also Auer 1987); this cuts the number of iterations necessary to reach a required accuracy considerably although, as with operator perturbation methods generally, convergence remains linear.

An operator perturbation method that solves only Feautrier (*i.e.*, second-order differential) equations, both scalar and low-order coupled equations, is offered by Kalkofen (1987) who derives the differential operator for the perturbed system of equations from an integral equationm formulation. His demonstration is for grey, scattering, radiative equilibrium atmosphere.

Nordlund (1985) describes a method in which he perturbs the transfer equation for a two-level atom along individual rays. This approach is suitable also for problems in more than one dimension. He applies it to the formation of an iron line in an atmosphere obtained from a three-dimensional hydrodynamic simulation of the solar granulation.

A differential equation method not based on the perturbation of an operator is proposed by Anderson (1985, 1987). His approach is analogous to that in the variable Eddington factor technique, applied here to frequencies. Anderson groups photons with similar interaction probabilities into blocks, defining block average coefficeints, and performs a Newton-Raphson iteration on the block equations. With an improved solution he updates the frequency averages. He has used this method to construct line-blanketed model atmospheres in which the fine-grained frequency set has 2000 grid points and the coarse-grained set, about 100 points. Thus the order of the system of equations is reduced by a

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factor of 20 (not counting angle points), implying a very significant reduction in the solution time.

2. Polarized Radiation.

Polarization plays a role in the Zeeman effect, *i.e.*, in line formation in a magnetic field, and in electron scattering near the surface of the solar atmosphere, for example. Solution methods for the transfer equation of polarized radiation must deal with the complication of an opacity that is a matrix and an intensity that forms a vector, given by the Stokes parameters. When departures from LTE combine with polarization the equations become still more complicated. Fortunately, it is often possible to make the weak-field approximation and thus to separate a transfer problem into two parts. In the first, the magnetic field is completely ignored and the source function of a line is computed as in standard non-LTE theory; in the second, the source function is given and the polarized radiation field is computed for given magnitude and orientation of the magnetic field. This approach is frequently used, *e.g.*, by Rees and Murphy (1987) who discuss several methods of solving the transfer equation for polarized radiation. In one method they transform the first-order differential equation for the Stokes vector into a second-order differential equation for the even part of the radiation field, *i.e.*, the analogue of the Feautrier equation. The difference equation form of this equation is block tridiagonal; thus the equation is solved by standard techniques. In another approach, they separate out the diagonal part of the absorption matrix to arrive at an equation with a diagonal transfer operator but with off-diagonal elements. For the formal integration of this equation, the off-diagonal terms are treated as known source terms. The result is an integral equation for the unknown Stokes vector. By using a quadrature scheme, such as piecewise linear expansion of the Stokes vector, a system of linear equations involving a block triangular matrix is derived from which the Stokes vector can be determined by means of a simple forward elimination.

A solution method that does not make the weak-field approximation is due to van Ballegooijen (1987). He supposes that the magnetic field is sufficiently strong to permit the assumption that the magnetic sublevels of the atom do not interfere with each other. Then the problem of this Zeeman effect with departures from LTE is completely described by a scalar line source function that depends only on optical depth. For this source function van Ballegooijen derives an integral equation which he solves by expanding the source function in piecewise linear and quadratic segments. — This method is a welcome addition to methods for polarized radiation; it is also very useful in allowing an assessment of the limits of applicability of the weak-field approximation.

A completely different method for solving the transfer equation of polarized radiation in the presence of departures from LTE is described by Schmidt & Wehrse (1987). Their method, which is well suited for homogeneous media, uses the eigenvalues and eigenvectors of the matrix multiplying the intensity, *i.e.*, the matrix that describes the opacity and the redistribution properties of the transfer. After diagonalizing with the modal matrix, the transfer equation together with the statistical equilibrium constraint can be solved analytically. If only the emergent intensity is wanted, the intensities elsewhere in the medium need not be calculated, a significant advantage of the method. However, for a multi-level atom in an inhomogeneous atmosphere this method is expensive since it requires the calculation of the eigenvalues of the interaction matrix at many grid points, a calculation that scales as the cube of the order of the matrix. An approach described by Peraiah (1987) achieves the same end, albeit after more matrix manipulations that are needed for insuring the stability of this doubling method. — Note that both Schmidt & Wehrse's and Peraiah's methods are very general; they can be used for transfer of polarized radiation with complete or partial redistribution in atmospheres with plane or spherical symmetry.

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Several recent conference proceedings and monographs contain papers on the subject of this review or on related topics. In particular:

Chromosheric Diagnostics and Modelling, 1985, B.W.Lites ed.,
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E. Line-blanketing in Expanding Atmospheres(D. C. Abbott)

1. Introduction.

"Line-blanketing" is the term for the effect of bound-bound transitions from spectral lines on the global properties of the atmosphere, such as the temperature, density, and emergent spectrum. It is well known from the study of radiative equilibrium, plane-parallel, static atmospheres that line-blanketing leads to two main results (*e.g.* Mihalas 1978): (i) flux blocking and redistribution, and (ii) heating and backwarming. The strength of these effects depends strongly on the fraction of the spectrum that is blocked, which means that the cumulative effect of many, relatively weak lines may dominate the process, as the strongest lines occupy only a small frequency interval of the spectrum.

In an expanding atmosphere, line-blanketing is enormously enhanced if two conditions are met: (i) the expansion velocities are large compared to the velocity width of the line profiles, and (ii) the expanding atmosphere is dense enough that the stronger lines are still optically thick. Two examples where these conditions are met are stellar winds from hot stars and the photospheric phase of novae and supernovae. Each optically thick line may cover a frequency interval that is a thousand times larger than in a static atmosphere. Large regions of the spectrum may contain no line-free continuum, as the overlapping lines form a "pseudo-continuum". Examples demonstrating this have been given by Abbott (1982, figure 7) for hot star winds, and by Karp *et al.* (1977, figure 3) for expanding atmospheres from supernovae. As there are no gaps in frequency between the strong lines under these circumstances, the importance of the cumulative contribution of many weak lines is greatly diminished.

A unique feature of expanding atmospheres is that the Doppler-shifted frequencies of distinct spectral lines can coincide, so that a given photon can interact with many lines before escaping from the atmosphere. The presence of this "multiply scattered" radiation field also means that the radiative excitation rates of distinct lines from distinct elements are coupled, so the statistical eqilibrium of all the species are interlocked. Line-blanketing in an expanding atmosphere also creates a very favorable environment for the transfer of momentum from the radiation to the gas, which is the driving agent in hot star winds. Finally, the interpretation of features in a region of a line pseudo-continuum can be very difficult. For example, an apparent emission feature may indicate an absence of lines, where the radiation leaks out.

2. Optically-Thin Expanding Atmospheres.

In many cases of interest, such as the OB stars, expansion is confined to

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the outer layers of the atmosphere, which are optically-thin to continuum opacity. These atmospheres can be modeled by a "core-halo" approach. The continuum radiation is formed in a "core" represented by a standard radiative-equilibrium, plane-parallel, hydrostatic atmosphere. The expanding part of the atmosphere forms an extended "halo" about this core, which contains many optically-thick lines, but negligible continuum absorption or emission processes. Models which self-consistently solve for the radiation hydrodynamics of the expanding atmosphere were first developed by Castor, Abbott, and Klein (1975). Recent refinements to the model include correctly accounting for multiple scattering of radiation (Abbott and Lucy 1985, Puls 1987), and solving for the non-LTE statistical equilibrium of the thousands of transitions formed in the wind (Pauldrach 1987, Puls 1987). These models provide a detailed description of the radiation that is reflected back onto the core by line scattering and electron scattering in the wind. This reflected radiation field can greatly modify the structure of the hydrostatic atmosphere where the photospheric spectrum originates (*e.g.* Hummer 1982, Abbott and Hummer 1985), a process called "wind-blanketing".

Wind-blanketing mainly heats the atmosphere, while changing the shape of the emergent spectrum only somewhat. A wind-blanketed model atmosphere which fits the photospheric spectrum will have a lower effective temperature than a standard unblanketed model. In the case of the star Zeta Puppis (O4f), wind-blanketing decreased the inferred effective temperature by 4500 K or about 10% (Bohannan *et al.* 1986), while in Alpha Cam (O9.5I) the effective temperature was reduced by roughly 7% (Voels *et al.* 1986). For the more luminous OB stars, spectral classification is truly three-dimensional, with the mass loss rate, the gravity, and the effective temperature all playing important roles in determining the emergent photospheric spectrum.

3. Optically-Thick Expanding Atmospheres.

In many cases of interest, such as Wolf-Rayet stars, Luminous Blue Variable stars, as well as Novae and Supernovae, the expanding atmosphere is optically thick to continuum opacity. The photosphere is formed out in the wind. Line-blanketing will be of great inportance in these objects from the outer atmosphere all the way through the depth of continuum formation. Models which can accurately treat the radiation-hydrodynamics of expanding, optically-thick winds are still under development.

Models of optically-thick expanding atmospheres were calculated with a Monte Carlo code which extends the method of Abbott and Lucy (1985) to account for continuum absorption opacity under the assumption of LTE (see also Lucy 1987). The preliminary result from a supernova model calculation (Abbott 1987) shows tremendous flux-blocking in the UV, where it is impossible to ascribe the observed features to any one element, because there are overlapping, optically thick lines from many different elements at virtually all frequencies. The flux-blocking is much more severe in these models than in hot stars because the atmosphere is less extended, so the scattered photons tend to diffuse back down in the atmosphere to be thermalized, rather than to escape. This in turn leads to significant backwarming, and the temperature at depth is roughly 15% higher in the line-blanketed model, as reflected in the heightened continuum at optical wavelengths. The development of models which can correctly account for line-blanketing in optically thick winds is clearly a fruitful area of research for the coming years.

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