Session V

“NEXT GENERATION MODEL ATMOSPHERES”

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Abstract. Continued progress in the physical interpretation of solar and stellar observations, the increased speed of computing now available, and new highly efficient numerical procedures have all led to significant advances in stellar atmospheric modeling. This review attempts to summarize recent progress in the field and to describe the many interrelated physical processes that should be taken into account in next-generation modeling programs.

1. Introduction

Progress in stellar atmosphere research continues to depend on improvements in both observations and modeling. The two go hand in hand: model calculations provide a framework for interpreting observational data while the observations define the questions that the models need to address.

This review attempts to summarize the considerable advances made in atmospheric modeling in recent years, to indicate the current research efforts in this field, and to suggest ways that further progress can be made.

The field of atmospheric modeling has been developing in two complimentary directions: 1) the introduction of fast numerical methods along with the availability of computers with greatly increased speed has made it possible to solve problems in more realistic detail than has been possible before; and 2) progress has continued in the incorporation of physical processes that were treated by means of simplifying approximations before. The next few years should see a convergence of these two efforts, with the fast codes becoming more general and the general codes becoming faster.

The most recent review similar to the present one is that of Mihalas (1991), who gives an overview of past developments in the field and

K. G. Strassmeier and J. L. Linsky (eds.), Stellar Surface Structure, 503–518.

prospects for the future. The present review is more limited in scope: providing a guide to recent published research, and summarizing the many physical processes that should be taken into account in current and future model calculations.

2. Recent reviews

The review "Models of late-type stellar photospheres" by Gustafsson & Jørgensen (1994) provides a comprehensive discussion of recent research on models of the photospheres of F and later-type stars. Line blanketing, non-LTE effects, and dynamical processes are considered at length, along with abundance determinations and other topics. They give a list of the published grids (to 1994) of model photospheres for late-type stars. (One subsequent paper to be added to this list is that of Allard & Hauschildt (1995).) The photospheric models discussed in this review generally assume radiative equilibrium, with no mechanical heating.

The review "Basal heating in the atmospheres of cool stars – Observational evidence and theoretical support" by Schrijver (1995) presents evidence that in all stars with convective envelopes, there is a basal level of chromospheric heating from acoustic waves generated by turbulent convection, and further magnetic heating due to the interaction of convective motions with stellar rotation. This review also describes work by Ayres, Carlsson, Stein, and others on the cool component of the solar chromosphere, and the relationship between steady-state and time-dependent chromospheric models. These topics will be considered in Section 5 below.

The proceedings of a recent workshop on "Chromospheric Dynamics" (Carlsson, ed. (1994)) contain a number of papers that are relevant to chromospheric modeling, namely, papers on: observed motions of magnetic regions in the quiet solar chromosphere (Lites), observed internetwork motions (Rutten), numerical simulations of radiation shock dynamics in the solar chromosphere (Carlsson & Stein), and properties of the solar T_{min} region from infrared CO line observations (Uitenbroek & Noyes).

The volume "Mechanisms of Chromospheric and Coronal Heating" (Ulmschneider, et al., eds. (1991)) contains reviews and research reports on stellar chromospheric and coronal heating, covering developments to 1990.

"Stellar Atmospheres: Beyond Classical Models" (Crivellari, et al., eds. (1991)) covers many subjects of the present review, also to 1990. Major topics include:

- fast iterative methods based on accelerated lambda operator techniques
- non-LTE line blanketing
- 2-D and 3-D line formation

  - small scale effects
  - large scale effects (outflow from rotating stars; flow between binaries; accretion disks)

- time-dependent radiation hydrodynamics
- non-LTE spherical expanding atmospheres
- radiation-driven winds (and instabilities)
- dust-driven winds
- opacity data

A number of other books and conference publications have appeared in recent years containing papers in the field of model atmospheres: "Numerical Methods for Multidimensional Radiative Transfer Problems" (Rannacher, et al., eds. (1994)), "Molecules in the Stellar Environment" (Jørgensen, ed. (1994)), "The Atmospheres of Early Type Stars" (Heber & Jeffrey, eds. (1992)), "Properties of Hot Luminous Stars" (Garmany, ed. (1990)), "F, G, K Stars and T Tauri Stars" (Cram & Kuhi, eds. (1989)), "Physics of Formation of Fe II Lines Outside LTE" (Viotti, et al. eds. (1988)), "Numerical Radiative Transfer" (Kalkofen, ed. (1987)), and "Progress in Spectral Line Formation" (Beckman & Crivellari, eds. (1985)). This list does not include the series of workshops on Cool Stars, Stellar Systems, and the Sun, and several further IAU conferences.

3. Fast methods

The recent development of fast numerical methods for solving the non-LTE radiative transfer equations has made it possible to address more realistic problems of structure, dynamics, and energetics in stellar atmospheres than has been possible before.

Such numerical methods use fast and reliable iterative techniques to determine the non-local coupling between the radiative transfer and statistical equilibuium equations. Space here does not permit a description of these methods, and the reader is referred to the detailed discussions in many recent publications.

In the years 1994 and 1995 alone there are papers on this topic by: Auer, et al. (1994), Auer & Paletou (1994), Buchholz, et al. (1994), Crivellari & Simonneau (1995), Dykema, et al. (1995), Hauschildt, et al. (1995), Höflich (1995), Kiselman (1994), Paletou (1995), Paletou & Auer (1995), Rybicki & Hummer (1994), Trujillo Bueno & Fabiani Bendicho (1995), Ulmschneider (1994), and Väth (1994).

4. Dimensionality

4.1. 1-D

One-dimensional models usually have plane or spherical geometry, and can be either stationary (static or with steady flows) or time dependent. 1-D time-dependent models can include complex hydrodynamics, including different time scales for different physical processes.

When there is no information about spatial structure or local time variations, a model can attempt to represent the average stratification of a stellar atmosphere. Otherwise, separate 1-D models can be constructed for different atmospheric regions that are assumed to be independent of each other.

4.2. >1-D

When regions of dissimilar stratification are close enough to interact with each other, 2- or 3-dimensional modeling is needed. Recent results on 2-D and 3-D non-LTE line formation are given by Auer et al. (1994), Auer & Paletou (1994), Castor et al. (1992), Heinzel (1995), Kiselman & Nordlund (1995), Nordlund (1991), Paletou (1995), Paletou et al. (1993), Trujillo Bueno & Kneer (1990), and Väth (1994).

Detailed 3-D hydrodynamical modeling, including radiative transfer effects, have been applied with great success to solar and stellar convection and granulation simulations. See Chan et al. (1991), Dravins & Nordlund (1990) Rast et al. (1993), Nordlund & Dravins (1990), Nordlund et al. (1994), and Steffen et al. (1994).

5. Energy constraints

5.1. RADIATIVE EQUILIBRIUM MODELS

Most of the models for stellar photospheres discussed in the review of Gustafsson & Jørgensen (1994) assume radiative equilibuium, i.e., the atmospheric structure is determined so that the net radiative flux is constant with depth, at least in the outer layers. The effects of convective energy transport are often included as well in the deep layers. Departures from local thermodynamic equilibuium usually are not very large at photospheric depths so that LTE is often asssumed for simplicity. One of the most important effects in radiative equilibrium calculations is line blanketing. Anderson (1989) has constructed a solar atmospheric model in radiative equilibrium with non-LTE line blanketing, which in the relatively deep layers is close to the radiative equilibrium LTE line-blanketed model of Kurucz (1979). See also Anderson (1990), (1991). Non-LTE line-blanketed model atmospheres of hot stars are given by Grigsby et al. (1992), Hubeny & Lanz (1995), and Lanz & Hubeny (1995).

As discussed in the Schrijver (1995) review, there is evidence for nonradiative heating in the outer atmospheres of all stars with convective envelopes, causing a chromospheric temperature rise in the outer layers. Models assuming radiative equilibuium do not reproduce the outward increases in temperature inferred from stellar chromospheric observations.

5.2. SEMI-EMPIRICAL MODELS

In semi-empirical modeling, the temperature distribution, at least in the outer layers, is chosen by trial and error to obtain good agreement between calculated and observed spectra. This procedure replaces the constant net radiative flux constraint in determining the temperature distribution. The densities and other atmospheric quantities can be calculated in the same way as in radiative equilibrium models. An important quantity calculated from such models is the net radiative cooling rate, or the derivative of the radiative flux, which would be zero at all depths where radiative equilibrium prevails. This quantity gives the distribution of mechanical heating that would be needed to produce the given temperature distribution, thus providing some constraints on possible heating mechanisms. Anderson & Athay (1989) computed solar chromospheric models with the use of a prescribed nonradiative heating function in the energy equation, and found that a constant total heat flux in the chromosphere of 1.2×10^7 ergs cm^{-2} s^{-1} gives a chromospheric temperature distribution comparable to the average quiet-Sun distribution in semi-empirical models.

Semi-empirical models for different components of the solar atmosphere have been published by Holweger & Müller (1974), Vernazza et al. (1981), Maltby et al. (1986), Fontenla et al. (1993), and Hawley & Fisher (1994).

Linsky (1980) reviews the extensive research on stellar chromospheric models carried out in the 1970s. For recent work, see Harper (1994) and Harper et al. (1995), and references therein.

5.3. HYDRODYNAMICAL MODELS

Important advances have been made in hydrodynamic modeling of stellar atmospheres in which nonradiative heating is calculated as a result of wave dissipation. The 3-D hydrodynamic modeling cited above has been applied mostly to the deep photospheric layers, while higher layers have been modeled in a number of investigations by solving the 1-D time-dependent hydrodynamic equations.

Narain & Ulmschneider (1995) have recently reviewed the various hydrodynamic and electromagnetic heating mechanisms which are thought to be sources of chromospheric and coronal heating.

Model calculations based on chromospheric heating by acoustic shocks have been carried out by Rammacher & Ulmschneider (1992), Cheng (1992), Carlsson & Stein (1992), Fleck & Schmitz (1993), Judge & Cuntz (1993), Jordan (1993), Mullan & Cheng (1994), Kalkofen et al. (1994), Buchholz & Ulmschneider (1994), Cuntz et al. (1994), Cuntz & Ulmschneider (1994), Musielak et al. (1994), Sutmann & Ulmschneider (1995), (1995), and Carlsson & Stein (1995). Huang et al. (1995) discuss heating by magnetic tube waves in the solar atmosphere.

The results of Carlsson & Stein (1995) (see also Carlsson & Stein (1994)) are of particular interest in that 1) the calculations are based on more realistic physical processes than have been included before, and 2) the authors conclude that solar chromospheric emission comparable to observed values can be produced without any outward increase in the mean gas temperature, at least in magnetic field-free internetwork regions.

In their calculation, waves are generated deep in the photosphere by piston motions that reproduce the observed time sequence of Doppler shifts in a weak iron line. The resulting acoustic waves increase in amplitude with height, eventually becoming shocks which dissipate mechanical energy. They find that while the traveling shock waves produce short intervals of high temperature, much of the mechanical energy goes directly into radiation without enhancing the mean thermal energy of the chromosphere.

These results need to be confirmed by further detailed calculations, with attention to the various approximations that were made for simplicity. For example, Carlsson and Stein did not include either line blanketing or PRD effects (discussed below). Also, the calculations need to be extended to greater heights where it is clear from observations that there is a substantial increase in the mean gas temperature.

Since their results are intended to apply only to field-free internetwork regions of the Sun, the network contribution must be determined in order to compare with spatially averaged observations. The brightness temperature of the Sun, averaged over network and internetwork regions, is observed to increase with wavelength for $\lambda > 200\mu$m and to increase from center to limb at these wavelengths (see Bastian et al. (1993), Ewell et al. (1993), and Lindsey et al. (1995) and references therein). Since the observed radiation is continuum free-free emission, the observed brightness temperature should correspond to the mean gas temperature at unit optical depth. Semiempirical chromospheric models (e.g., Fontenla et al. (1993)) account for such observations by an increase of the temperature with height above around 550 km. However, it may be only the network component that is responsible for such enhanced brightness temperatures at sub-millimeter and millimeter wavelengths.

Hydrodynamic modeling appears to provide an explanation to the problem of interpreting the infrared CO lines in the Sun. These lines are formed in LTE, as shown by Ayres & Wiedemann (1989), so that the observed brightness temperature is roughly the gas temperature at the depth of formation. The strongest lines have central brightness temperatures of about 4100 K at disk center and values as low as 3700 K near the limb. A steady-state model based on the CO lines alone (see Avrett (1995)) has a temperature of 4100 K at a height of about 700 km, and lower temperatures at greater heights, while the other diagnostics used to construct semiempirical models indicate temperatures of roughly 5000 K at 700 km.

An explanation for these conflicting chromospheric diagnostics is that CO line absorption is enhanced at low temperatures and diminished at high temperatures at different times as waves travel through the atmosphere. Evidence for substantial time variations in brightness temperature at each position is shown in spatially and temporally resolved spectra obtained by Uitenbroek et al. (1994). Also see Uitenbroek & Noyes (1994), Cuntz & Muchmore (1994), Solanki et al. (1994), Ayres (1995), and particularly the review by Ayres in this volume.

Avrett et al. (1995) have attempted to model such CO time variations by studying the effects of acoustic waves with various periods traveling through the atmosphere. These calculations do not include the effects of hydrogen ionization that Carlsson & Stein (1995) have shown to be important in the higher layers, and they are similar to the earlier calculations of Muchmore et al. (1988), except that the effects of time-dependence in the formation of CO are included.

The calculations of Avrett et al. show that, while the fine-structure levels of the rotation-vibration bands have relative populations in LTE corresponding to the instantaneous local temperature, the total amount of CO cannot follow rapid temperature changes, so that it effectively corresponds to a time-averaged temperature structure. Variations in CO line intensities thus reflect local temperature changes rather than shifts in optical depth.

As discussed in the next section, a significant uncertainly in these calculations is the radiative cooling due to non-LTE line blanketing.

We conclude this section by stressing the importance of understanding the relationship between such time-dependent hydrodynamical models and the simpler time-averaged models derived from low-resolution spectra. Carlsson & Stein address this point by determining the average chromospheric temperature distribution that gives the same emission as the time-averaged emission produced by their acoustic shock model.

6. Lines

Large numbers of atomic and molecular lines must be included in realistic models in order to calculate photoionization and other rates, including radiative losses, and to calculate the emergent spectrum. Models should include not only the bound-free continua and strong lines, but large numbers of weak lines as well. See Kurucz (1991) and Bell et al. (1994) for discussions of the high-resolution solar spectrum. Also see the reviews by Bell and by Kurucz in this volume.

6.1. OPACITIES

Kurucz has compiled line opacity data for 42 million atomic lines (the first 9 ions of calcium through nickel) and for 14 million molecular lines (from 11 diatomic molecules). These data are avilable from Kurucz on the following CD-ROMs.
No. 1 Atomic data for opacity calculations.
No. 15 Diatomic molecular data for opacity calculations.
No. 18 SYNTHE spectrum synthesis programs and line data.
No. 20 Atomic data for Ca, Sc, Ti, V, and Cr.
No. 21 Atomic data for Mn and Co.
No. 22 Atomic data for Fe and Ni.
No. 23 Atomic line data.

See Kurucz (1994).

The SCAN molecular data base of Jørgensen (1994) contains about 70 million lines from 7 different diatomic and polyatomic molecules.

The RADEN molecular data base at Moscow State University (L. A. Kuznetsova and A. V. Stolyarov, lakuz@laser.chem.msu.su) contains information on about 300 diatomic molecules from more than 2600 publications.

The Opacity Project, reviewed by Seaton et al. (1994), has provided extensive calculations of atomic line data and photoionization cross sections based on the close coupling approach. See also Hummer (1991), Mendoza & Cunto (1993), and Rogers & Iglesias (1994). It should be pointed out that since the close coupling calculations are independent of laboratory data, the predicted wavelengths of lines can be substantially in error, particularly at long wavelengths. For example, the Ca II infrared triplet line at 854 nm is given a computed wavelength near 1 μm!

The review of Gustafsson & Jørgensen (1994) gives many additional sources of atomic and molecular opacity data.

6.2. STATISTICAL APPROXIMATIONS

Even using the fastest numerical methods now available, it is impractical to integrate line-by-line over the entire spectrum to determine photoionization and cooling rates. Two simpler approaches are commonly used: opacity distribution functions, and opacity sampling. The first is based on continuous distributions vs. wavelength of different opacity components, from high to low values. This approach assumes that, at a given frequency, the high and low opacities at one depth are correlated with the corresponding high and low opacities at every other depth, but this may be a poor approximation. Opacity sampling is more accurate, but ordinary statistical sampling typically requires the use of many wavelengths ($> 10^4$). Reliable results can be obtained with fewer wavelengths by various selection techniques (see, for example, Avrett et al. (1986)). Castelli & Kurucz (1994) show a comparison of the opacity distribution function and opacity sampling methods in calculating models for Vega. Plez et al (1992) and Jørgensen et al. (1992) use opacity sampling in calculating spherical models for giant and supergiant stars. Tsuji (1994) discusses the use of molecular opacity distributions. See Carbon (1984) for a general review.

6.3. NON-LTE EFFECTS

In general, one cannot assume LTE for the lines. The source function S (the ratio of the emission and absorption coefficients) is equal to the Planck function B in LTE, but equal to the mean intensity J in the case of pure scattering. At high densities deep in the atmosphere where collisions dominate, $S = B$, while at low densities in the outermost layers, $S = J$.

S should be determined by solving the coupled radiative transfer and statistical equilibrium equations. In general, such a non-LTE solution gives different values for the atomic and molecular number densities, and hence different opacities and optical depths, than are computed in LTE.

The most extensive study of non-LTE line blanketing has been carried out by Anderson (1989). He used a statistical approach in which large numbers of similar lines were treated together in multiplet groups between characteristic energy levels, then the combined transfer and statistical equilibrium equations were solved for these multiplets and energy levels. In this way the approximate non-LTE effects due to millions of lines were taken into account.

Anderson derived a very useful formula for a characteristic value of $\epsilon = C/A$, the effective collisional de-excitation rate divided by the corresponding Einstein A value for a line. Such a parameter can be used to express S in terms of J and B according to the two-level atom equation

$$S = \frac{J + \epsilon B}{1 + \epsilon} \tag{1}$$

Anderson finds that his statistical results are consistent with the following expression for the thermalization parameter

$$\epsilon = Q^{-1}(n_e/10^{13})(h\nu)^{-3} \tag{2}$$

where n_e is the electron number density and $h\nu$ is the transition energy in eV. For his solar-type model he finds that $Q = 6 \pm 1$ for the lines of Fe I, and $Q = 0.7 \pm 0.3$ for ionized species.

The problem with equation (2) is that ϵ is of order 10^{-2} or smaller in the temperature minimum region where $n_e \approx 10^{11}$. When a scattering albedo based on this value is used with Kurucz's line opacities, the ultraviolet lines calculated from a typical solar atmospheric model do not change from mostly absorption lines to mostly emission lines at around 170 nm as observed, but remain in absorption. This could be due to the failure of time-independent models to properly account for ultraviolet line emission, or simply an indication that the atomic line source functions are much closer to LTE in the temperature minimum region than equation (2) suggests.

Non-LTE line blanketing also has been considered by Höflich (1995) in detailed modeling of supernovae, having densities similar to those in the solar chromosphere. He solves the coupled equations of radiative transfer and statistical equilibrium together with the hydrodynamical and energy equations for a spherical expanding atmosphere, including relativistic terms. He solves the explicit non-LTE equations for many lines, and treats all others (from Kurucz's line list) by an equivalent two-level approach in which coefficients are adjusted to fit the calculated non-LTE lines. He finds that the thermalization parameter ϵ is 10 to 100 times larger than given by the two-level formula of Böhm (1961), which is roughly equivalent to Anderson's expression above.

The net radiative cooling rate is given by

$$\Phi = 4\pi \int \kappa_\nu (S_\nu - J_\nu)\, d\nu \tag{3}$$

where κ_ν is the total (line plus continuum) absorption coefficient, and the integral extends over the entire spectrum. In radiative equilibrium, $\Phi = 0$. Otherwise, Φ represents the sum of all mechanical and electromagnetic heating, and other energy deposition, such as the effects of radioactive decay.

The lines ordinarily contribute substantially to the radiative cooling rate since κ_ν is usually much larger in a line than in the nearby continuum, but the cooling is diminished when $S_\nu \approx J_\nu$ as a result of a high degree of scattering. Thus an accurate solution of the energy equation depends critically on non-LTE line blanketing.

6.4. PARTIAL FREQUENCY REDISTRIBUTION

The thermal motions of atoms which absorb and re-emit photons in a given line cause frequency redistribution within the narrow Doppler core of the line. In the far wings, however, frequency redistribution is limited and the scattering is essentially coherent. Complete frequency redistribution (CRD) over the entire line is a useful simplifying approximation, but one that is inappropriate for strong lines formed in low-density atmospheric regions.

The theory of partial frequency redistribution (PRD) is reasonably well understood – see the recent papers of Cooper et al. (1989) and Hubeny & Lites (1995), and the review by Linsky (1985) for early developments – but PRD calculations are far more complex than those assuming CRD.

The CRD line source function is frequency-independent while the S_ν determined from the more general PRD theory varies from core to wing. It is often important to include PRD interlocking between lines having an energy level in common, and between blended or partially overlapping lines (e.g., see Mauas et al. (1989)), and to include the detailed effects of Doppler shifts due to relative gas motions.

In PRD calculations, S_ν is usually closer to J_ν in the line wings than in CRD calculations. Thus, from equation (3), PRD usually gives smaller radiative losses than CRD, as recently demonstrated by Hünerth & Ulmschneider (1995). Thus, PRD is an additional effect to be taken into account as part of non-LTE line blanketing.

7. Multi-level, multi-ion calculations

Realistic calculations should be based on model atoms with a large number of energy levels in each stage of ionization. The 12 μm emission lines of Mg I remained unexplained until it was shown by Lemke & Holweger (1987), Chang et al. (1991), and Carlsson et al. (1992c) that the emission resulted from very high-lying atomic levels being almost in equilibrium with the Mg II continuum while the populations of lower levels were below equilibrium values due to radiative losses.

Multilevel atoms (and molecules) should include all important multiplets, line blends and splitting, and interactions between overlapping lines. Population inversions can occur, sometimes leading to negative total opacities, implying amplification of radiation in certain regions.

Many different atomic and molecular species must be included in order to obtain all the contributions to the electron number density, and to calculate photoionization and cooling rates.

8. Particle diffusion

The general form of the statistical equilibrium equation, including time and velocity terms, is

$$\frac{\partial}{\partial t}n_i + \frac{\partial}{\partial z}(n_i v) = \sum_{j\neq i}(n_j P_{ji} - n_i P_{ij}) + n_\kappa(R_{\kappa i} + C_{\kappa i}) - n_i(R_{i\kappa} + C_{i\kappa}) \quad (4)$$

where R and C are the bound-free radiative and collisional rates and P is the bound-bound rate (radiative plus collisional), all per particle in the initial state. (For simplicity this equation includes only the bound levels of one stage of ionization together with the next higher ionization stage.) The left side would be zero if there were no changes with time and no flow velocities. The second term on the left represents advection when v is the mass motion velocity, i.e., the increase in the number density n_i caused by inflowing particles.

Consider regions of the atmosphere where the temperature gradient is so large that there are significant temperature changes over distances smaller than a particle mean free path. Then v should be the sum of the mass motion velocity and the particle diffusion velocity, which can be determined from the temperature and density distributions. The atom and ion diffusion velocities are in opposite directions. Fontenla et al. (1990), (1991), (1993) have shown that particle diffusion in addition to thermal conduction in the solar chromosphere-corona transition region can transport sufficient energy from the corona to account for the emission in the hydrogen and helium resonance lines, and that these lines are formed at higher temperatures than without diffusion. As a result, the earlier semiempirical transition region models of Vernazza et al. (1981) have been updated by theoretical energy balance models that do not need a temperature plateau to account for the observed Lyman α emission. Lanzafame (1995) has applied these methods to the upper chromospheres and lower transition regions of dMe stars.

Large temperature gradients typically occur in the partially ionized regions where the resonance lines of hydrogen and helium are formed, so that particle diffusion should be taken into account in modeling the ionization equilibrium of these important elements. Similar conditions apply at the chromospheric shock front regions in hydrodynamic models.

9. Incident radiation

Coronal-line ionizing radiation penetrating into the upper layers of the solar chromosphere has been found to be largely responsible for the subordinate lines of He I and He II. See Avrett et al. (1994) and Wahlstrom & Carlsson (1994) for recent model calculations.

There are applications of incident radiation in other contexts as well, including backscattering from a wind and the irradiation of one star by another.

10. Concluding remarks

The task of summarizing the computer programs currently used for atmospheric modeling is not attempted in this review. Descriptions are given in the many papers cited above. Hummer & Hubeny (1991) discussed many of the modeling programs that are available, particularly those for hot stars and winds. Papers were given by Carlsson (1992), Anderson (1992), and Avrett & Loeser (1992) at the 7th Cool Star Workshop summarizing the MULTI, PAM, and PANDORA computer programs, respectively.

This review has attempted to discuss, or at least refer to, the many processes that are important in stellar atmospheric modeling. Next-generation model atmosphere programs should include all these processes in detail. No single existing program accomplishes this, but given the rapid pace of new development, significant progress can be expected within the next few years.

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