The Structure of a Stationary Atmosphere with a Heat Source or Sink

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There are several methods for solving a structure of a stellar atmosphere in radiative equilibrium. Among them, the matrix method (Nariai and Shigeyama 1984, Nariai and Ito 1985) uses only the energy equation at the nodes; therefore, it is easy to extend this method to an atmosphere that is not in radiative equilibrium. The matrix method gives direct solutions for the cases of a gray model or a picket-fence model, and it is so effective that the calculation converges in 3 or 4 iterations in the case of a non-gray atmosphere with scattering even if the starting model is isothermal. In order to simplify the problem, in this paper, however, we will limit ourselves to the case of a gray atmosphere with pure absorption.

A plane-parallel stellar atmosphere is a semi-infinite medium. In the numerical calculation, we divide it into n finite elements and 1 semi-infinite element. Let us define a node as a point between two elements. Node 0 is defined as the boundary between the surface element and the vacuum. In total, we have $n+1$ nodes. The distribution of any physical quantity is represented by a vector of $n+1$ dimensions with its values at the $n+1$ nodes as elements. The mean intensity of radiation J is written in the ordinary expression as

$$J(\tau)=\frac{1}{2}\int_0^\infty B(t)K(|t-\tau|)dt \tag{1}$$

Let the value of B at node i be represented by b_i. Then, we can integrate equation (1) analytically if we assume an appropriate interpolation formula within each element. Linear interpolation was adopted in Nariai and Shigeyama(1984) while third order polynomials were used in Nariai and Ito(1985). Results can be expressed in a form

$$\mathbf{j}=\mathbf{A}\mathbf{b}+\mathbf{y}, \tag{2}$$

where the constant vector $\mathbf{y}$ is mainly determined by the gradient term in the semi-infinite element and its element is expressed approximately as

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$$y_i = 0.375\ F\ K_2(\tau_n - \tau_i), \tag{3}$$

where F is flux.

The equation of radiative equilibrium is written as $\mathbf{b}=\mathbf{j}$. When there is a heat source or sink, we add a term $\mathbf{q}$ to the right side of the equation so that

$$\mathbf{b} = \mathbf{j} + \mathbf{q}. \tag{4}$$

We can write the solution of the energy equation as

$$\mathbf{b} = (\mathbf{U}-\mathbf{A})^{-1}\mathbf{y} + (\mathbf{U}-\mathbf{A})^{-1}\mathbf{q}. \tag{5}$$

The first term is the solution of the equation of radiative equilibrium. The second term represents the effect of the perturbation by the source or sink layer in the atmosphere. When $\mathbf{q}$ represents a source term, the second term is positive at the surface, has a maximum near the center of the source region, and approaches a finite value with zero gradient at the bottom of the atmosphere ($\tau=\tau_n$).

Nariai and Murata (1987) solved the structure of an atmosphere in a binary system by treating the radiation from the other component explicitly in the radiative equilibrium equation. However, it is possible to treat the same problem as an example with a source term which is generated by the decay of the direct radiation from the other component.

An atmosphere that has quasi-steady horizontal flow is another interesting example. As the flow exchanges energy with the surrounding medium through radiation, entropy along the flow line is not constant, therefore, $\mathbf{q}$ is finite. An atmosphere with a sink layer gives a very low temperature in the line-forming region. Therefore, analysis of such an atmosphere by means of normal atmospheric model may lead to false abundance values. The sunspot penumbra may be interpreted with the present model. If the assumption of the existence of a penumbra type atmosphere in some part of the atmosphere of Ap stars is justified, abundances for Ap stars will have to be revised completely. The existence of strong magnetic field in Ap stars may justify such an assumption.

References

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