NASA SP-317

STELLAR CHROMOSPHERES

A colloquium held at
GODDARD SPACE FLIGHT CENTER
February 21–24, 1972

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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The proceedings of the International Astronomical Union Colloquium
held at NASA Goddard Space Flight Center
February 21–24, 1972

Edited by

S. D. Jordan and E. H. Avrett

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PREFACE

IAU Colloquium 19 on "Stellar Chromospheres" was a natural extension of its predecessor "Spectrum Formation in Stars with Steady State Extended Atmospheres," held during April, 1969, in Munich, Germany. The present colloquium was co-sponsored by Commissions 36 and 29 of the International Astronomical Union. The official organizing committee comprised Y. Fujita, J. C. Pecker, F. Praderie, R. N. Thomas, and A. Underhill, with Underhill chairing a local, east coast organizing committee consisting of, besides herself, E. Avrett, S. Heap, S. Jordan, and D. Leckrone. The Colloquium honored Professor Cecilia Payne-Gaposhkin of the Smithsonian Astrophysical Observatory for her many outstanding contributions to astronomy. The aim of the organizers was to bring together experts on the complex radiative, hydrodynamical, and observational problems which the outer layers of stars provide, in the hope of clarifying both our present knowledge as well as where to go in the future. It is hoped that, to this end, these Proceedings will be helpful for students entering the field as well as research workers who were unable to attend.

There were no contributed papers other than the eight summary papers listed in the Contents. However, we would like to acknowledge, with our appreciation, the many participants who carefully edited their remarks and returned to us finished manuscripts complete with bibliographies, etc. We have attempted to retain the spirit and format of these manuscripts where they appear, while always being guided by the need to preserve the open, informal atmosphere of the discussions which did, in fact, prevail during the Colloquium. The final responsibility for editing is ours and, if minor changes have confused or obscured meaning, we offer the authors our apologies.

Several organizations participated in sponsoring, planning, financing, and running the Colloquium. In addition to official sponsorship by the IAU, the Goddard Space Flight Center and the Smithsonian Astrophysical Observatory were co-hosts, Goddard providing the site and direct support and the Smithsonian providing assistance in planning and a grant to defray expenses. Additional financial support was provided by a National Science Foundation Grant, and the cost of publishing the Proceedings was borne by Goddard.

Finally, it might be appropriate to point out a few salient features of the Colloquium which will certainly have bearing on future developments. The entire question of what, exactly, constitutes a chromosphere, both conceptually, in definition, and in physical actuality, as inferred from spectral diagnostics, was discussed avidly and ardently during the sessions. The final summary and the subsequent discussion illustrate how varied are the experiences and opinions of two highly respected experts in this area. In general, the difficulties, both theoretical and observational, of studying chromospheres *in detail* still leave open many important questions which await not only improved research techniques, but improved communications between the researchers. We hope these Proceedings will serve that function for all concerned.

The Editors
Greenbelt, Sept. 18, 1972

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PART I
SPECTROSCOPIC DIAGNOSTICS OF CHROMOSPHERES AND THE CHROMOSPHERIC ENERGY BALANCE

Chairman: **Roger Cayrel**

INTRODUCTORY COMMENTS BY SESSION CHAIRMAN CAYREL

I would like to define the topic for today and then turn to John Jefferies for the first introductory paper. I understand that today's topic is twofold. First, if there is a temperature rise in a layer of optical thickness of a few hundredths in the visible, what are the features of the spectrum which are most able to detect it? That I would say is the first point. The second point is how such a temperature rise can be driven either by a radiative mechanism or by dissipation of mechanical energy.

TEMPERATURE DISTRIBUTION IN A STELLAR ATMOSPHERE-DIAGNOSTIC BASIS

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Presented by John T. Jefferies

INTRODUCTION

As is well known, the word "chromosphere" was coined to denote the bright, thin, colored ring seen as the solar limb was obscured by the Moon at the time of a total eclipse. This region of the Sun's atmosphere was found to be the source of many strong emission lines – the flash spectrum – some persisting to such heights as to leave no doubt that their cores originated quite high in the chromosphere. The presence of such an emission line region is not unexpected; however, what gives the solar chromosphere special interest is the fact that its observed spectroscopic properties cannot be explained on the basis that it is a simple extension of a "classical" atmosphere for which radiative, hydrostatic, and local thermodynamic equilibrium all apply. Thus, the height above the limb to which most eclipse lines persist is inconsistent with the predicted density scale height. The observation of neutral and ionized helium lines in the flash spectrum demands temperatures far in excess of those predicted for a radiative equilibrium model. Further difficulty is encountered in attempting to explain in classical terms the shapes and strengths of certain chromospheric lines in the disk spectrum, notably the self reversals in the cores of H and K. Such observations, coupled with the recognition that the coronal temperature is in the range of millions of degrees and the discovery of the peculiar inhomogeneities in the chromospheric gas, e.g., the spicules and the supergranular flow pattern and such transitory phenomena as surges, flares and prominences, all contributed to the recognition that the properties of the chromosphere are controlled by factors that lie outside the scope of a classical atmosphere. Thus, the partitioning of the Sun into photosphere, chromosphere, and corona is seen to be far more fundamental than the simple geometrical division based on eclipse observation. It appears that there are different mechanisms at work in these layers, especially in the way energy is transferred.

We recognize now that some, at least, of the spectroscopic features of the solar chromosphere are consistent with the hypothesis that the temperature increases outward above some minimum value found a few hundred kilometers above the limb. The temperature rise is thought to be a result of the dissipation of mechanical energy generated in the photosphere, and if this is so we will naturally expect this process to take place in other stars, leading to the formation of stellar chromospheres. A direct approach to the study of these layers might be to concentrate on the kinematic motion of the line-forming layers as deduced from the shapes, strengths, and wavelength shifts of spectral lines. It is also fruitful, however, to consider the *symptom* of the dissipation of energy, namely the temperature rise, as a basis for comparison between solar and stellar chromospheres and this is the approach we shall adopt here. Thus, we shall consider a stellar chromosphere as a region where the temperature increases outward, and we shall examine spectroscopic methods for inferring the existence and properties of a temperature rise.

The following section sets out the physical basis for the discussion with some general considerations on how (or whether) the temperature structure of a gas controls the shapes of spectral lines. In particular, we shall discuss why some lines are very sensitive temperature indicators while others are much less so. Following that, we shall consider emission lines and what they can tell us about the atmosphere of the star, and we shall discuss methods for determining the temperature structure of the atmosphere from the analysis of line profiles. The final section contains a brief discussion of the information in the stellar continuum, together with some miscellaneous indicators.

THE INFLUENCE OF TEMPERATURE STRUCTURE ON LINE PROFILES

The monochromatic flux F_ν emerging from a plane parallel semi-infinite gas is given by

$$F_\nu = 2 \int_0^\infty S_\nu (\tau_\nu) E_2 (\tau_\nu) d\tau_\nu \ , \tag{1}$$

where τ_ν is the monochromatic optical depth, E_2 is the second exponential integral, and S_ν is the source function, defined as

$$S_\nu = \frac{\epsilon_\nu}{\kappa_\nu} \ , \tag{2}$$

where ϵ_ν and κ_ν represent respectively the monochromatic volume emissivity and the absorption coefficient per unit length in the gas. In general, both ϵ_ν and κ_ν will contain components from continuum and line processes; however we are here primarily interested in the cores of strong lines formed in the outer atmospheric layers, and we shall neglect the continuum contribution.

Clearly, the emergent flux will reflect the temperature distribution only to the extent that S_λ (or ϵ_λ and κ_λ) depends on the temperature. For a spectral line it is well known – see, e.g., Jefferies (1968) – that

$$S_\nu = \frac{2h\nu^3}{c^2}\left[\frac{g_2}{g_1}\,\frac{n_1}{n_2} - 1\right]^{-1} \psi(\nu) \quad , \qquad (3)$$

where n_1, n_2 are the concentrations of atoms in the lower and upper levels of the line g_1, g_2 are the statistical weights of the levels and $\psi(\nu)$ is a function which we shall set equal to unity, following Jefferies (1968) and Hummer (1969). This latter approximation implies that the line source function is independent of frequency over the core of the line, and we shall therefore drop the subscript ν. The physical basis of our arguments remains unchanged if we neglect stimulated emission, in which case equation (3) reduces to

$$S_\ell = \frac{2h\nu^3}{c^2}\,\frac{g_1}{g_2}\,\frac{n_2}{n_1} \quad . \qquad (4)$$

Thus, the dependence of the emergent flux on the temperature structure of the gas is fixed by the temperature dependence of the population ratio. Now this ratio can be expressed, formally, as

$$\frac{n_2}{n_1} = \frac{R_{12}}{R_{21}} \quad , \qquad (5)$$

where R_{ij} is the rate of all transition paths, direct and indirect, which carry the atom from level i to level j. Recognizing that there are, in general, two mechanisms (collisional and radiative) by which transitions can take place, we can write, equivalently,

$$\frac{n_2}{n_1} = \frac{\int_0^\infty J_\nu\,\kappa_\nu\,d\nu/h\nu + C_{12} + I_{12}}{A_{21} + C_{21} + I_{21}} \quad , \qquad (6)$$

where the C's are direct collisional rates and the first terms in numerator and denominator are respectively the direct radiative absorption and spontaneous transition rates, while the terms I_{ij} represent the rates of *indirect* transitions taking the atom from level i to level j. In this formulation, the "source" terms C_{12} and I_{12} represent the creation of fresh photons into the radiation field, while the sink terms C_{21} and I_{21} represent the destruction of absorbed photons by de-excitation of the atom. The source terms thus represent the ultimate source of the radiation in the gas.

Thomas (1957) distinguished two classes of lines according to whether direct collisional transitions or indirect processes are chiefly responsible for creation and destruction of photons. If $C_{12} \gg I_{12}$ and $C_{21} \gg I_{21}$, equation (3) reduces to

$$S_{\ell} = \frac{\int_0^{\infty} J_\nu \phi_\nu \, d\nu + \epsilon \, B_\nu(T)}{1 + \epsilon} , \tag{7}$$

where $B_\nu(T)$ is the Planck function at the local kinetic temperature T, ϕ_ν is a normalized profile of the absorption coefficient and the important parameter ϵ is defined as

$$\epsilon \simeq \frac{C_{21}}{A_{21}} \tag{8}$$

Thus, ϵ measures the importance of direct collisional relative to radiative de-excitations of an atom in the upper level of the line. In this case, therefore, the gas temperature enters directly into the line source function; the physical reason is that the collisions then control the production of new photons in the line, and the rate of these collision transitions depends on the kinetic temperature, through the Boltzmann distribution. Thus, for such a "collisionally controlled" line, the atmospheric temperature structure should be reflected in the line profile. The essential questions of interest to us here are, can we know *a priori* whether a line is "collisionally controlled," and, if so, exactly how is the temperature structure reflected in the profile of the observed line?

Thomas (1957) gave a partial analysis of the first question. In particular, he showed that, for stars of solar type and later, one would expect strong resonance lines of non-metals, and of ionized metals, to be collisionally controlled. The dichotomy depends on the atomic level structure and on the color temperature of the stellar continuum; as particularly important cases in this category, we identify the resonance lines of Ca^+, Mg^+, H, C, N, and O when formed in stars of solar type and later. Thomas also showed that the ratio of the populations of the levels of the resonance lines of neutral metals should be controlled less by collisions than by indirect processes, which should, in turn, be controlled by the strength of the continuum radiation field streaming through the gas. As a consequence, the source functions of such lines should *not* reflect the local temperature distribution in the region where the lines are formed, but rather the temperature in the region where the *continua* originate. Thomas' corresponding partitioning of lines into "collisional" and "photoelectric" control is important to keep in mind when designing observational programs, but it must be applied with an intelligent understanding of its basis. Thus, whether a given line falls into one or the other of the classifications depends on the gas temperature, the stellar continuum flux, and the local density; the classification is not an immutable property of the line. For example, the cooler the star, the closer a given line will be to collisional control.

Considerable insight into the question of just how sensitively the temperature structure is reflected in the line profile has been obtained over the past ten to fifteen years. For a collisionally controlled line, for which S_ℓ is given by equation (7), we can compute the emergent radiation for a given temperature model by solving (with appropriate boundary conditions) the transfer equation

$$\mu \frac{dI_\nu}{d\tau_\nu} = I_\nu - S_\ell = I_\nu - (1-\lambda)\int_0^\infty J_\nu \phi_\nu \, d\nu - \lambda B_\nu(T) \ , \quad (9)$$

where $\lambda = C_{21}/(A_{21} + C_{21})$ is the probability of a collisional de-excitation of an atom in the upper state of the line. We consider solutions of equation(9) for two general cases, an isothermal semi-infinite layer of gas, and secondly, a model in which the temperature increases outward.

ISOTHERMAL LAYER

Schematic results for an isothermal layer are illustrated in Figures I-1 and I-2 for a set of values of the scattering parameter λ. Two aspects of these figures should be particularly noted. Firstly, the line source function saturates to the Planck function at an optical depth of λ^{-1} as measured in the line center. This characteristic distance is known as the "thermalization length," corresponding physically to the average optical distance which a photon will travel from its point of creation as a new photon,

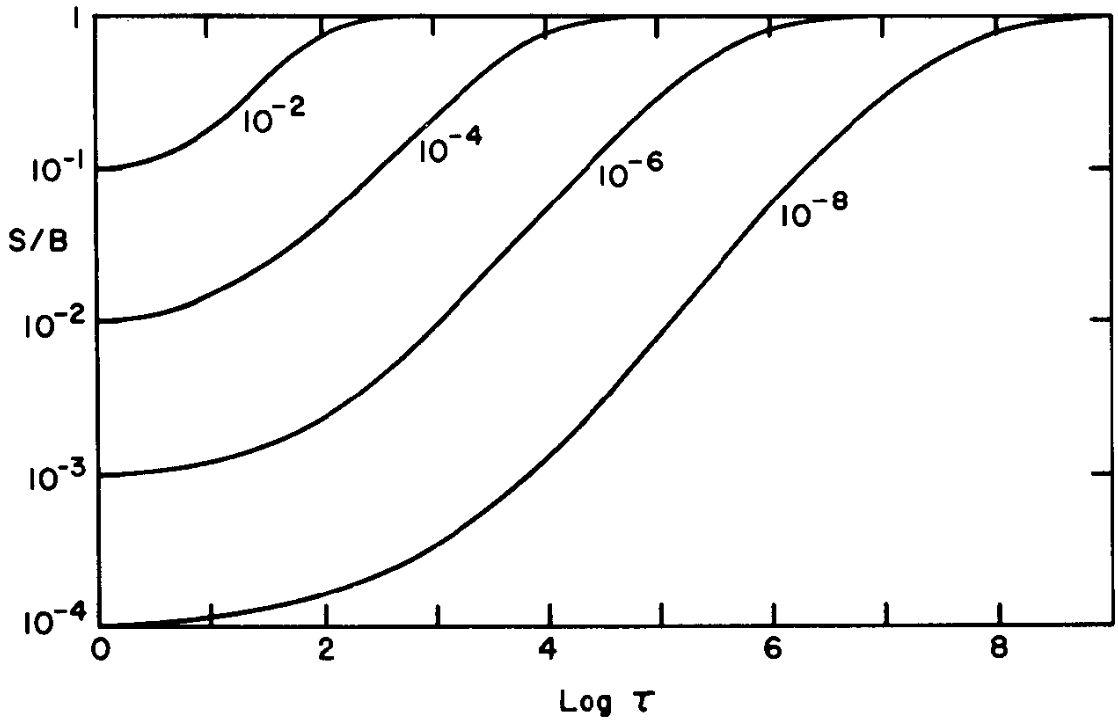

Figure I-1 The ratio of the line source function to the Planck function, for an isothermal gas, as a function of optical depth at the line center. The different curves refer to different values of the scattering parameter λ.

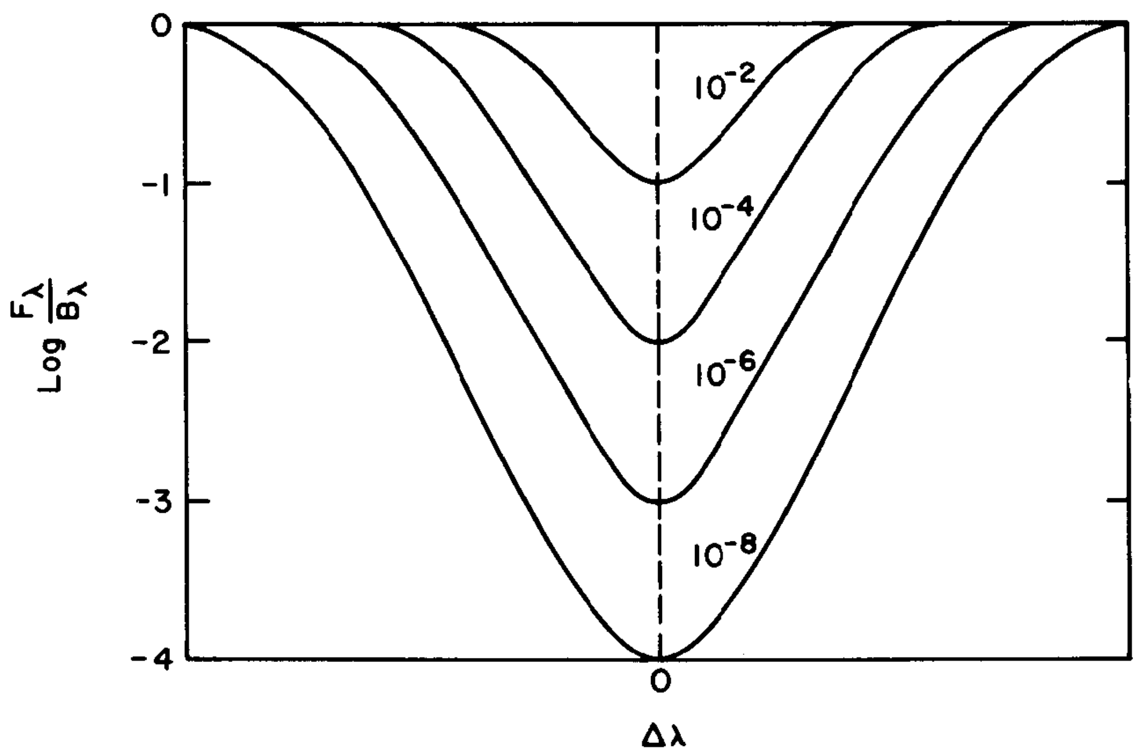

Figure I-2 The logarithm of the ratio of the emergent flux in the line to the Planck function, for an isothermal gas, as a function of wavelength. The profiles refer to different values of the scattering parameter λ.