WHAT SHOULD WE DO TO KNOW MORE ABOUT CHROMOSPHERES AND CORONAE OF STARS?

by

Richard N. Thomas

*Joint Institute for Laboratory Astrophysics**
Boulder, Colorado

ABSTRACT

Chromospheres-coronas satisfy the last two of the proposed classification schemes: inadequacy of the classical atmosphere (CA) model to represent observations and a priori rejection of the CA model. So we survey the question of what is required for more knowledge from the standpoint of asking what conceptual modifications will increase knowledge and what new observations are required. We stress that continued progress requires a continual interchange of ideas between the solar situation and the range of stellar situations.

Key words: chromospheres, coronas, classical atmosphere model.

The general subject of today's discussion is: "What do we know about chromospheres and coronae of stars?" Thus, as Françoise Praderie emphasized in the preceding summary paper, we restrict attention today to a particular kind of extended stellar atmosphere, one which can fall into either classification 3 or 4 of the alternatives I proposed the first day of this conference. I would like to emphasize to you that we are, at least implicitly, making a much stronger restriction of the kind of stellar configuration to be discussed than we would have, with the same literal title, in a discussion of extended stellar atmospheres 25, or even 15, years ago. The

---

*Of the National Bureau of Standards and the University of Colorado.

fact that it is a stronger restriction means, of course, that we think we know more today about chromospheres and coronae than we did 25, or even 15, years ago. I think we all generally understand that by "chromosphere" and "corona" in today's thinking, we mean an extended stellar atmosphere that arises as a consequence of a departure from strictly radiative or convective equilibrium because of a local dissipation of mechanical energy. In the chromosphere and corona, we have a reversal of the photospheric temperature gradient: $dT_e/dh > 0$. Overall, the evolution of thought during the last 25 years has centered on how deep in the atmosphere this region $dT_e/dh > 0$ can be pushed, and how many phenomena arise because of this outward rise in T_e. In this symposium where we ask what the problems of extended stellar atmospheres are, the important thing is not just the fact that we know more about this particular kind of extended stellar atmosphere, but also the way in which that knowledge has evolved. The path has not been simply one of acquiring new data, but also one of more critical analysis of old data and old concepts. So as we explore my topic today--What should we do to know more about chromospheres and coronae?--we might follow the same path: examining concepts as well as data.

Even 40 years ago, most astronomers would have said that stellar chromospheres and coronae satisfied classification 3 of extended stellar atmospheres--inadequacy of the CA model to represent observations--even though neither observations nor the idea of the CA model were as clear as they are today. Twenty-five or even 15 years ago, most astronomers would have admitted that a stellar chromosphere probably satisfied the category 4 criterion: *a priori* rejection of the CA model. But the conceptual basis for rejecting the CA model 40 and 25 years ago differed considerably from that which has evolved over the last 25 years. At that time, the admission of inadequacy rested upon the ad hoc construction of a phenomenon outside either our laboratory experience or conceptual understanding--the "turbulent" models of '40, 25, 15 and even more recent years ago--and the inability to see how it could arise from the CA model because we didn't understand what it was. So the chromosphere probably departed from the CA conditions, but probably because HE was invalid, while RE and LTE probably remained valid. Today, however, we profess to a very explicit physical understanding of why the atmosphere is extended, relative to the physical picture underlying the CA model. We have simply dropped the notions that either RE or CE provide all the energy transport in the atmosphere, and that LTE under the RE distribution of T_e describes the state of the gas. We have admitted the possibility that various kinds of instabilities arising even in the CA model may amplify, producing a local dissipation of mechanical energy, and that excitation conditions may differ from the CA strictures. By loosening the strictures placed on the diagnostic framework, we permit a tightening on the physical picture of the model.

The dropping of LTE--which has loomed large, sometimes almost irrelevantly so--in the discussions this week has a different kind of significance than that of RE. The RE, HE questions relate to the aerodynamical phenomena and give us the extended or non-extended configuration of the atmosphere; they tell us how the configuration occurs. Dropping LTE simply lets us state, unbiasedly and correctly, what the configuration and state of the gas is.

So we restrict attention to a kind of extended stellar atmosphere, whose general physical cause we think we understand. But when we ask what we know about chromospheres and coronae, it is the details of the phenomenon and the variation in details from spectral type to spectral type that we must investigate. In this connection, I have stressed the points in the preceding paragraphs for two reasons.

First, we have reached the stage of being willing to accept the above implications on what we mean by stellar chromospheres and coronae through a combination of two kinds of investigation: on the one hand, an analysis of physical self-consistency of atmospheric model and of spectroscopic diagnostics; on the other hand, an application of this analysis to solar observations and models. To this, we have added also observationally-less-detailed, exploratory investigations of other stellar atmospheres. But by and large, the situation is as I said: a compound of general theory and solar interpretive-observational work. Then, we have generalized and extrapolated to various stellar cases--testing, substantiating, modifying as we have been able.

Second, Françoise Praderie has given us a very complete summary of what we know about chromospheres and coronae of stars. In addition, in the process of asking what the spectral indicators of the presence of chromospheres and coronae are, she has gone a long way toward answering the question of what we must do to learn more: How do we extend the observation of these spectral indicators. It would be pointless for me, here, to follow her discussion by simply commenting on the various indicators she has summarized.

So, in considering this path of evolution of our knowledge, to answer the question of what we must do to learn more about chromospheres and coronae, I lean heavily on the evolution of thinking about the solar case. And, in the context of the specific features discussed by Françoise, we continue this extrapolation-generalization from the solar case.

I would stress that we must adopt a conceptual generalization from solar considerations, not necessarily a literal one. In such a literal approach, we would assume that all chromospheres must originate from the detailed causes underlying the solar chromosphere, and must have the detailed structure of the solar chromosphere. Such a literal approach, for example, is found in the 1955 IAU *Joint Discussion on Turbulence in Stellar Atmospheres*, held at Dublin. On the other hand, my own thinking has always centered around the notion that the common feature of chromospheres and coronae is simply a mechanical energy supply, which may arise in many different ways in many different spectral classes. I have repeatedly cited the sun and the Wolf-Rayet stars as probably lying near the two extremes of the kind of steady-state atmospheres produced by aerodynamical effects. In the sun, we consider only departures from RE; in the WR stars, departures from both RE and He. I consider to be most misleading the kinds of arguments cited that expect chromospheres-coronae only in stars of spectral class FO and later, based on the notion of acoustic waves from an atmospheric convection zone as the source of chromospheres-coronae. Such arguments confuse the existence of sources of mechanical instability with the details of one such source. I have stressed this point in the first paper of the series: Superthermic Phenomena in Stellar Atmospheres (Thomas 1948) and in the introduction to our survey of the physics underlying the solar chromosphere (Thomas and Athay 1961). Parker makes the same point in the concluding chapter of his monograph on the solar wind (Parker 1963). The two symposia on cosmical gas dynamics devoted to aerodynamical phenomena in stellar atmospheres developed this outlook (Thomas 1961, 1967). The symposium on Wolf-Rayet stars held in 1968 brought together much material that strengthened the case for considering the line-forming region of the WR atmosphere simply as an extended chromosphere (Gebbie and Thomas 1968). So what I would stress to you here, when we ask what we should do to know more about stellar chromospheres and coronae, is that it is not only a matter of getting more and better observations of known indicators. It is equally a matter of becoming very clear about the kind of evolution in our thinking that led us to focus on the true nature of the chromosphere-coronal phenomenon, hence the kind of parameters that might tell us more about them.

Tables I and II summarize the evolution of our thinking on the solar chromosphere-corona. Table I concentrates on the "classical" problem, referring to the concepts of 40 and 25 years ago that I stressed above. Points 1 and 2 of Table II [corresponding to points 1 and 2 of Table I] refer to the resolution of these problems.

The dilemma and resolution summarized in the tables in points 1 and 2 require little discussion. In essence, the "classical" dilemma of the extended solar atmosphere comes from looking at an apparent gross anomaly--the atmospheric extent--which is significant enough to vitiate the CA model, through a set of glasses tinted with the CA predictions: the excitation state of the outer atmosphere must not exceed that of the photosphere, and the outer atmosphere must be so thin as to be transparent, certainly in its effect on the disk spectrum, likely in considering the eclipse line spectrum. Given these observations, and given these strictures on interpretation, the only resolution was to "invent" a new kind of phenomenon, "astronomical turbulence," whose physical properties were constructed explicitly to (1) satisfy the observations as interpreted within the diagnostic strictures, and (2) beg the question of physical consistency by postulating unknown physical interactions. (1) refers to the requirement that emission gradient be interpreted as density gradient. (2) refers to the requirement that "astronomical turbulence," with characteristic random velocity exceeding the thermal velocity of the medium, somehow have any mechanical energy dissipation suppressed. The "secondary" classical dilemma, that associated with the symbiotic behavior of excitation state, was relegated to secondary status mainly because we retained the CA-tinted glasses, even in studying this non-CA phenomenon. The final resolution of these two aspects of the dilemma came when the diagnostic approach was freed from all a priori imposition of the strictures of the CA model, under the principle that no one of the CA assumptions should be more sacred than any other, when it became

TABLE I. SCHEMATIC EVOLUTION

How Astronomers Viewed the Solar

Original Observational Problem	Original Interpretation
1. Anomalous extent of atmosphere:	"Turbulent" momentum support.
a. Apparent scale-height of order 1000 km.	No energy dissipation by such turbulence
(i) Differential scale-heights from different lines, and continua	
b. Isothermal scale-height of order 100 km.	
2. Symbiotic excitation phenomena	
a. Presence of He I, He II	UV excess in sun
b. T_{ex} as low as 3000° for some metals	Line-blanketing depression of T [boundary]
c. Excitation increases outward	
(i) Spectral lines of "coronium"	

necessary to relax any one of them. Lifting the restriction on excitation state and opacity of the atmosphere permitted the density gradient to depart from the emission gradient, and a distribution of T_e to be sought which made the observations coherent. It is interesting to note that the path of resolution was not really so logical as stated, but came as a shocked necessity to permit $dT_e/dh > 0$ from the

OF THINKING ON SOLAR CHROMOSPHERE

Chromospheric Problem 25 Years Ago

Original Physical Problem	Perturbing Questions
Physical model of such "turbulence"	How to tell T_e, T_k from V_{turb} How to avoid mechanical energy dissipation, hence rise in T_k, T_e
Origin of such excess	Why should excitation increase outward in such a model?
Self-consistent calculation	Why such different values from different lines?

identification of the coronal lines. But it took some time to admit this situation to the region where the dilemma was quantitatively the most evident--the chromosphere--and to recognize that these regions could have an effect on the disk spectrum.

Points 3-5 of Table II refer to observational details that arose later, somewhat after the classi-

TABLE II, SCHEMATIC EVOLUTION OF

	Change in "Observational" View
Original Observational Problem	Refined Observation
1. Anomalous extent of atmosphere:	"True" scale-heights differ from observed
a. Apparent scale-height of order 1000 km.	Differs from line to line
(i) Differential scale-heights from different lines, and continua	
b. Isothermal scale-height of order 100 km.	Atmosphere not isothermal, but HE not bad approximation up to 1000 km. Any turbulence definitely subsonic
2. Symbiotic excitation phenomena	Symbiotic appearance exists
a. Presence of He I, He II	Same
b. T_{ex} as low as 3000° for some metals	Same
c. Excitation increases outward	Same; identification of "coronium" lines
(i) Spectral lines of "coronium"	
3. Emission lines in rocket UV, on disk	Same form as Ca^+ cores
4. Correlation between H and K lines and magnetic field	Profile changes over disk
5. Non-spherically symmetric emission	Same

of Solar Chromosphere Today

Physical Interpretation	Questions Remaining
Compound of outward increase in excitation, coming from $dT_e/dh > 0$, and of self-absorption, non-LTE Above	Refined observation still needed
Mechanical energy supply; $dT_e/dh > 0$ Non-LTE ionization equilibrium	Source, and interpretation, of any turbulence
Compound of $dT_e/dh > 0$ and non-LTE coming from boundary	Better observations More detailed non-LTE calculations for complex ions
$dT_e/dh > 0$; collisions + radiative excitation	Influence of inhomogeneous atmosphere
Non-LTE coming from boundary	
Line-blanketing effect small on non-LTE theory	Detailed calculation More refined observation
Consequence of $dT_e/dh > 0$	Detailed model
Consequence of $dT_e/dh > 0$	Detailed calculation Questions of line-broadening
Non-uniform mechanical dissipation under influence of magnetic field	Detailed mechanism and model
Inhomogeneous mechanical heating; inhomogeneous mechanical structure	Detailed observation Detailed model

cal dilemma represented by points 1 and 2 was well on the way toward resolution. But had the observational material underlying these points 3-5 been available 25, possibly even 15 years ago, we must be honest and realistic enough to admit that the same CA-tinted glasses would probably have inhibited their correct interpretation. This suggests that a useful way to compare the path of evolution of thinking on the solar chromosphere-corona to that on the stellar, would be to compare the full range of "anomalous" phenomena for each, using always as reference the CA model. After all, when we discuss "extended stellar atmospheres," we do so relative to the "non-extended" CA model atmosphere.

If we adopt this approach, we recognize that we can group the apparent anomalies under three headings: "apparent" macroscopic structural anomalies; symbiotic excitation anomalies, usually microscopic, at least in implication; and basic conceptual anomalies. Consider these, specifically.

THE OUTER SOLAR ATMOSPHERE

A. *"Apparent" Structural Anomalies*

1. Overall extent of the atmosphere:
   - Emission scale-heights large relative to the scale-height of an isothermal atmosphere, using a temperature derived from either a CA theory or a CA-interpreted observation.
   - Differing emission scale-heights from different lines and differing elements.
2. Gross structural inhomogeneities:
   - Mainly apparent in those observations capable of resolving small fractions of the solar disk.
3. Differential brightness correlated with differential values of local magnetic fields:
   - Again, mainly apparent in those observations capable of resolving small fractions of the solar disk.
4. Differential macroscopic velocity fields:
   - Two kinds of measures exist; those depending on resolving small fractions of the solar disk, and those not so depending.
   - a. Non-dependent on disk resolution:
     - Inferences of differential macroscopic fields from conclusions on line-broadening

mechanisms; either for a line-profile, or a total energy lying in the line.

Inferences based on asymmetries of line profile, which are interpreted in terms of differential motions.

b. Dependent on disk-resolution:

Indirect inferences in the Doppler cores of spectral lines based on limb-darkening data.

Direct measures based on line-shifts on different parts of the disk.

I have grouped items 3 and 4 in this heading of "structural" anomalies because of the evident temptation to associate structural behavior with kinematic behavior of the atmosphere, on the one hand; and the problem of separating thermal motion from other velocity fields, on the other hand. Uncertainty on thermal motions introduces uncertainty in what the extent of the atmosphere should be, even in HE.

B. Symbiotic Excitation Anomalies

1. Low-excitation indicators:
    a. The low residual intensities, or low values of T_{ex}, in most strong lines of the disk spectrum; values much below the CA-derived boundary values for T_e.
    b. The persistence to great heights of a significant population of the second quantum level of hydrogen.
2. High-excitation indicators:
    a. The presence of HE I 10830 in the disk spectrum, and of lines of He I and He II in the eclipse spectrum as low as 1300 km above the limb.
    b. The intensity in the continuum, on the disk, in the rocket UV and in the radio regions.
    c. The presence of highly-ionized elements in the eclipse spectrum, and in the rocket UV spectrum of disk and limb.
3. Mixed:

    The self-reversed emission cores of Ca^+ and Mg^+ in the disk spectrum coupled with the low values of T_{ex}; the absence of such emission cores in hydrogen Balmer lines and in other strong lines; self-reversed emission lines for hydrogen Lyman [and possibly other strong] lines in rocket UV disk spectrum.

C. *Basic Conceptual Anomalies*

1. The presence of a wide variety of emission lines in the solar rocket UV disk spectrum.
2. Evidence for a continuous outward mass flow from the sun.

REMARKS

I have deliberately omitted features of the "non-quiet" sun, and associated high-energy phenomena, to remain in keeping with the "steady-state" restriction of this meeting. Such an attitude may well be as subject to the same criticism that has been directed to the attitude that holds too strongly to an attempt to retain the CA model, which I have criticized here. But, I adopt it.

At first sight, some items in the categories A-C might equally well, or even better, be placed in another. For example: emission lines is placed in C rather than in B; the magnetic-correlation item (A3) is in A rather than in B. But consider the logic of the categories.

In category A, I tried to group those features bearing directly--either diagnostically or causally--with the atmospheric extent. Thus all material relating to velocity fields comes there, regardless of whether the velocity field is implied to extend the atmosphere by a momentum action, as in a flow field or "turbulence," or whether it might be, or might produce, a thermal field. I include item A3 here because, although there have been suggestions in the literature that the magnetic field somehow directly modifies the source function, it seems much more likely that it affects the velocity fields present--either macroscopic or thermal--and the energy dissipation from them.

In category B, I tried to group those features giving direct empirical evidence on the excitation--when properly interpreted, of course. The point of using the term "symbiotic" is that it describes very aptly what we have in such an atmosphere. There is a competition between the processes controlled by radiative effects--the photospheric radiation field corresponding to RE and the radiative transfer effects of the boundary--and those processes introduced by the mechanical dissipation of energy.

In category C, I have placed those features which, when present in stellar spectra, immediately suggest the presence of chromospheres and coronae, simply by their presence. The inference is not completely certain; some further criteria are required. But their presence stands as a stimulating and embarrassing beacon into our inquiry as to the adequacy of the CA model for any particular star. Embarrassing, because on a literal CA model, they cannot exist; stimulating, because of the attempts to see how little of the CA structure can be changed to accomodate them.

In a broad sense, we have now two questions to answer. (1) What can we say about the broad array of data, suggesting anomalies, that exists for stellar chromospheres-coronae? (2) In what ways are we trying to make these data more coherent for the solar case, in order to make the solar picture more quantitatively detailed; and how is this applicable to the stellar situation, again in the broad sense? Consider these in turn; my remarks on the first need only be a summary, drawing on the material already presented by Francoise Praderie.

THE EXTENDED STELLAR ATMOSPHERE

A. *"Apparent" Structural Anomalies*

1. Overall extent of the atmosphere:
   - Apparent density gradient inferred from transmission characteristics of the eclipsing atmosphere in binaries.
     - "Cool" atmospheres such as ζ Aur, 31 Cyg.
     - "Hot" atmospheres such as V444 Cyg.
   - Differential size of continuum-emitting, and line-emitting, atmosphere, from interferometric studies.
2. Macroscopic velocity fields:
   - a. Curve-of-growth studies:
     - Large "turbulent" velocities, some superthermic, from data on supergiants. Superthermic relative to a temperature derived from CA-theory or CA-interpretation.
     - "Turbulent" velocities from curve-of-growth eclipse studies.
   - b. Line-profile studies:
     - Large "turbulence" values necessary to match line-profiles.

  - c. Evidence on systematic flow fields from line-displacements, either from element to element, or between emission and absorption components. Visual and rocket UV.

B. Symbiotic Excitation Anomalies

1. Low-excitation indicators:
   - a. Low residual intensities, or low values of T_{ex}, in strong spectral lines, relative to T_e inferred from continuum.
   - b. Apparent indications of anomalously high number of second-quantum level population of hydrogen.
2. High-excitation indicators:
   - a. Presence of λ10830 of He I in cool stars.
   - b. UV and IR excesses in certain spectral classes, especially in supergiants.
   - c. The Russell-Adams effect.
   - d. A higher ionization and excitation level in the line spectrum than in the continuum.
3. Mixed:
   - a. All the features of the "standard" symbiotic stars.
   - b. The self-reversed emission cores of Ca^+ H and K; in addition, there are other lines that seem to show such self-reversal.
   - c. The appearance of He I emission lines in the carbon, cool star R Cor Bor.

C. Basic Conceptual Anomalies

1. The presence of emission lines generally, both in the visual and in the rocket UV.
2. Evidence, in some stars, of a continuous outward mass flow.

When we compare the two tabulations for the solar and the stellar cases, we are struck by the similarities of "anomalous phenomena." When we discuss interpretations, we are struck by the repetition of the "inertia" encountered in the early days of solar work now in the stellar case. Consider the kinds of attempts being made to clarify the above anomalies, with respect to these two points of similarity. Again, I would stress that all these considerations are based on similarity of general problem--the evidence that a mechanical dissipation of energy produces an outward rise in

T_e--not on any required identity of details of mechanical energy supply.

RESOLUTION AND INTERPRETATION OF ANOMALOUS FEATURES

1. *Distribution of T_e*

We have remarked, at the outset, the generally accepted interpretation of a chromosphere-corona today is an outer extended atmosphere arising because of an outward increase in T_e, coming from a mechanical dissipation of energy. So, a primary problem is to establish, for any given star, whether T_e does indeed increase outward, and the details of its distribution.

a. Empirical

For the sun, we still do not have a complete specification of the value of T_e [min] and the details of its behavior in this region. A great deal of effort is being devoted to the problem. Some aspects can be duplicated in the stellar case.

From the Continuum. In those spectral regions where τ_ν does not reach 1 near T_e [min], limb-darkening studies are required for precise work. Eclipse studies are required, generally, to go far into the atmosphere, except in those spectral regions of great opacity, such as the rocket UV and the radio region. For intermediate regions, where $\tau_\nu \sim 1$ does correspond to T_e [min], such as is--apparently--the case in the submm region and that near $\lambda \sim 1200A$, unresolved disk studies can be used in a scheme of successive approximation. All these procedures can be followed in the solar case; presently the most fruitful lines of further effort appear to lie in higher geometrical resolution studies. In most stellar cases, we are confined to integrated-disk results. So, one is forced to use $F[\lambda]$ rather than $I_\lambda[\mu]$, and an iterative scheme. But indications of stars having both UV and IR excesses already suggest, as in the solar case, the presence of an outward rise in T_e as the simplest explanation. Extending observations to the rocket UV, and farther into the mm and radio regions, increases the supply of data. For two classes of stars, we gain additional information, of the limb-darkening type. One class is the eclipsing binaries, for which change in spectral features during ingress and egress can be studied. A second class consists of those stars for which the new refinements in interferometry can be applied (e.g., Hanbury Brown 1968).

From the lines. The interpretation of such lines as Ca^+ H and K, the Mg^+ lines, the Balmer lines of hydrogen, the Lyman lines of hydrogen, and the NaD lines are more and more discussed in the literature. Difficulties still appear to exist equally in obtaining very high resolution profiles for the stellar case, and being absolutely sure of the details of the theory for both solar and stellar cases. Here, the solar case--where good spectral resolution exists--provides absolutely invaluable "calibration" of the theory against a solar model coming from the continuum. The self-reversed emission core of, e.g., Ca^+ now seems universally accepted as an indicator of the presence of a chromosphere--for, say, the period of the last 12 years. It is however not quite so clear how we interpret the details of the K_2 and H_2 regions outside the emission cores in terms of T_e [min]. In addition to those complications arising because the observed profiles represent the integral over sizeable portions of the disk, more problems arise in the theory: the accuracy of the assumption of complete redistribution for scattering, the problem of line broadening (which couples this problem of the T_e distribution to that of velocity fields), and the question of interlocking with other levels. All these are theoretical problems, but their solution clearly underlies the empirical analysis. And equally clearly, they are the same problem for sun and stars, so that solar and stellar investigations can hardly be separated.

b. Theoretical

We have already remarked on those theoretical aspects underlying the diagnostic spectroscopy here; consider those aspects dealing with theoretical model atmospheres.

One aspect is the problem placed into focus by Cayrel (1963) for the sun, but of long-standing for the planetary nebulae: the balance between quantity and quality of radiation in fixing T_e, and the question of getting some nontrivial outward rise in T_e due to it alone. Clearly, such a rise could introduce confusion in deciding on the presence of a chromosphere. So, the problem must be completely clarified; it is not so, at present (cf. Jordan 1969a, 1969b).

A second aspect is the T_e-distribution arising from the mechanical heating. I do not propose here to summarize all the aspects of the problem, aerodynamical and astronomical. One recent summary for the solar case lies in Jordan's thesis. The papers by Lighthill and Moore in the 1965 Cosmical Gas Dynamics Symposium focus attention on the problem of whether the particular acoustic heating in the sun arises in the convective, or in the overshoot, region of the solar atmosphere--a most important concept in extending solar thinking to the stellar case.

Again, I hope it is clear to you that the solar case can be utilized as a guide to stellar problems. More often than not, we are trying to extend to the astronomical environment, or develop completely afresh, physical ideas for which the theory is complex and for which we have only little intuition. The solar case provides a useful testing ground because of the wealth of geometrical and spectral resolution.

2. *Velocity Fields*

We have four main interrelated questions we need to answer on velocity fields. (a) How to separate thermal from macroscopic velocity fields? (b) How to separate the effects of increased kinetic temperature, and of momentum input causing departure from HE, on the atmospheric extent? (c) How to separate the required velocity field from radiation transfer effects in line-broadening mechanisms? (d) What is the origin and aerodynamic behavior of velocity fields?

Questions (a) and (c) overlap in their concern with specifying just what random, macroscopic velocity field must be introduced in addition to the thermal field. If we already knew the thermal field--as is the a priori assumption in the CA approach, or as we might possibly learn if we could get a complete atmospheric model from the preceding point (1)--it would be easier to infer the macroscopic field. Also, in principle, the separation of thermal and random macroscopic fields should be straightforward because of the differential mass dependence. Unfortunately there are two severely complicating factors: radiation transfer effects, and the effects of atmospheric inhomogeneities. Examples of each of these, for the sun, lie in Redman's [1942] attempts to use eclipse profiles of hydrogen, helium, and metals to infer T_e; and early attempts to identify the yellow coronal line by comparison of its width with that of known coronal iron lines (cf., the summary by Billings 1966). We have already commented on the coupling between uncertainties in line-formation theory and derived velocities, even under the non-LTE approach. The LTE approach gives too shallow lines, hence interpretation of observed line profiles or equivalent widths by an LTE diagnostics gives spurious microturbulent velocities. So we need to pay careful attention to comparison between theory and observation in a known atmosphere before we can be certain of results on an unknown atmosphere. We note that certain stellar eclipsing binaries provide line profiles and equivalent widths that change during the course of the eclipse, and so can presumably be used in a way similar to solar studies. Groth will be reviewing one aspect of this, at this symposium. Kuhi has summarized the situation for the WR stars (1968). So we can advance our knowledge of stellar chromospheres in this respect, by obtaining better observations, and devoting attention to the interpretive problems I have just summarized.

Items (a) and (b) overlap in their concern with what fixes the density gradient of the atmosphere. The problem couples closely to that of specifying the excitation state of the atmosphere, as a function of height. Again, the solar studies provide a useful guide.

Item (d) is almost wholly a theoretical problem at the present time, using as a boundary condition the mechanical energy and momentum supply required to satisfy the results of aspect (1) and (a)-(c) above. Although considerable work has been done on solar-type chromosphere-coronal aerodynamics, much more remains to be done. And the field is essentially virgin on most other chromosphere-coronal types. For example, although much has been done on the aerodynamics of the nonatmospheric regions of cepheids, the atmosphere has thus far been treated in only cursory detail. Possibly Hillendahl's remarks later in the session will cause this comment to be revised.

3. *Inhomogeneities, With and Without Magnetic Fields*

I do not intend to comment in any way on this most important point, except to say that the only direct information we have, comes from solar studies based on resolution of the disk. Possibly stellar eclipse studies can somehow be interpreted to give indirect information; certainly, we have evidence that the atmospheres are not spherically symmetric.

So what we need are ingenious ideas for empirical inference; or theoretical generalization from experience with the solar case.

4. Excitation Anomalies

There is a temptation to spend a great deal of time on this subject; indeed, I would like to see several days devoted to it. Clearly, to map out excitation stratification effects we need a detailed study of line profiles, studies of lines of different regions of origin in the atmosphere, and stellar eclipse studies. Again, I refer you to the evolution of our thinking on the solar chromosphere as the best example of how an apparently complex situation can be untangled (even though I would be the last to claim that we have done so, in detail, as yet). And I refer you to the WR atmosphere, as the best example of a situation where we cannot yet agree completely on the direction of change of excitation with height in the atmosphere, in more than an overall way. So I think it best to simply say: Consider the excitation problem, in all its aspects, observational and theoretical, when we ask what we can do to know more about stellar chromospheres and coronae. And I would emphasize very heavily any stellar spectrum that shows symbiotic effects as a strong candidate for having a chromosphere-corona.

5. Basic Conceptual Anomalies

In a discussion of a number of points above, we emphasized how to pin down the details of the chromosphere-corona. At the present time, in the great majority of the stellar situations, our first problem is simply to identify which star falls into the extended-atmosphere class, and then of these, which have chromospheres-coronae. Thus, we would like to develop some criteria, based on outstanding features that would help this identification. In the last sentence of (4) above, I suggested that symbiotic spectral features might well be one such criterion. This is a conjecture. Certainly, stars with chromospheres-coronae exhibit some symbiotic features; it is not clear that the converse is true, that all symbiotic stars have chromospheres-coronae. The problem remains to be investigated.

In just this category fall those features that I have labelled basic conceptual anomalies. We know that stars with chromospheres-coronae exhibit emission lines, and probably exhibit a steady-state mass-loss. The basic properties of each of these two phenomena are directly tied to a high-temperature outer atmosphere. The question is, can we apply the converse, and use these two phenomena as indicators of chromospheres-coronae.

Consider the emission lines. We must distinguish between intrinsic emission lines, and those arising wholly from a geometrical effect--a situation where the opacity in the lines so greatly exceeds that in the continuum over a much larger disk that an emission line results. Then we would first need a method to distinguish an intrinsic emission line from a geometrically induced one. Next, we would need to determine whether intrinsic emission lines come only from a reversal of a T_e-gradient, a chromosphere-corona. We know that in certain situations, fluorescence processes can produce emission; Anne Underhill has discussed examples of these. So we would need a means for discarding such fluorescent-produced lines. Then we are left with the Schuster mechanism which, in the literature, seems to be the favored mechanism, especially among those trying to retain the CA model. Katharine Gebbie and I think we have shown this mechanism can be rejected, in all but exceptionally unlikely cases, in stellar atmospheres (1968). So, we are left to devise methods for distinguishing between intrinsic and "geometrical" emission lines. One approach to this has been described by us some years ago (C. Pecker-Wimel and Thomas 1963); the group under Rense at the University of Colorado has been testing its utility in the solar rocket UV spectrum. Mrs. Gebbie and I are continuing with this problem of trying to decide the use of emission lines as an a priori chromosphere indicator. You have heard from Rybicki of the work by him and Hummer on investigations of the properties of intrinsic emission lines, which can be adapted to chromospheric situations. A number of people in JILA have been working on these problems including, beside Hummer, Mrs. Gebbie, and myself, Castor, Paczynski, Lindsey Smith, van Blerkom. By the time this symposium is over, you will have heard from, or about, a number of other workers elsewhere. Again, reference should be made to Françoise Praderie's summary.

Consider the steady-state mass loss. The physics of the problem are summarized in Parker's book (1963). Again, we see the utility of the solar-stellar comparison. The recent observations of supergiants (Morton 1967; Stecher and West 1968) exhibiting evidence of expansion in the rocket UV but not in the visual--thus implying stratification of velocity field--coupled with the observed suggestion of UV and IR excesses in the continuum present the kind of observational situation we face. Clearly, the point is to try to put all these observations together into a coherent picture, in the same kind of way Delache has tried for the sun. Again, we come together with Françoise Praderie's summary.

I hope, therefore, I have made it clear to you why I believe the best answer to the question: What can we do to know more about stellar chromospheres and coronae lies in continuing this parallel investigation of stellar and solar situation--depending upon the solar studies for high resolution of detail in one specific situation, and upon stellar studies for extrapolating and expanding the varieties of possible causes and configurations of chromospheres-coronae.

REFERENCES

Billings, D. E. 1966, *A Guide to the Solar Corona*, Academic Press.

Cayrel, R. 1963, *Cr. Ac. Sci. Paris*, 257, 3309.

Gebbie, K. B. and Thomas, R. N. 1968, *Ap. J.* 154, 285.

Gebbie, K. B. and Thomas, R. N. 1968, *Proceedings of the Symposium on Wolf-Rayet Stars*, National Bureau of Standards Special Publication 307.

Hanbury Brown, R. 1968, in Gebbie, K. B. and Thomas, R. N., *Proceedings of the Symposium on Wolf-Rayet Stars*, National Bureau of Standards Special Publication 307, p. 79.

IAU, 1957, *Joint Discussion on Turbulence in STellar Atmospheres*, Transactions of the IAU, 1955, IX, 727, Cambridge University Press.

Jordan, S. D. 1969a, in press, *Ap. J.*, 1969b, in press, *Ap. J.*, 1968, Thesis, University of Colorado.

Kuhi, L. V. 1968, in Gebbie, K. B. and Thomas, R. N., *Proceedings of the Symposium on Wolf-Rayet Stars*, National Bureau of Standards Special Publication 307, p. 103.

Morton, D. C. 1967, *Ap. J.* 147, 1017.

Parker, E. N. 1963, *Interplanetary Dynamical Processes*, Interscience Publishers.

Pecker-Wimel, C. and Thomas, R. N. 1963, *Ap. J.* 137, 967.

Redman, R. O. 1942, *MNRAS* 102, 134.

Stecher, T. P. and West, D. K. 1968, in Gebbie, K. B. and Thomas, R. N., *Proceedings of the Symposium on Wolf-Rayet Stars*, National Bureau of Standards Special Publication 307, p. 65.

Thomas, R. N. 1948, *Ap. J.* 108, 130.

Thomas, R. N. 1961, *Proceedings of the Fourth Symposium on Cosmical Gas Dynamics*, Supp. to Nuovo Cimento XXII.

Thomas, R. N. and Athay, R. G. 1961, *Physics of the Solar Chromsophere*, Interscience Publishers.

Thomas, R. N. 1967, *Proceedings of the Fifth Symposium on Cosmical Gas Dynamics*, Academic Press.

DISCUSSION

Hillendahl: For γ Boo (period 6^h) one would expect the K line emission to change with a "period" of about 1^h. This will be explained in my talk later.

Praderie: We observed this star with an exposure time of 3^m at intervals of half an hour. With this high time resolution we found that the Ca II changes sometimes, but not periodically.

Underhill: Can we find from the spectral lines available for analysis in stars of type A and earlier clear indications for an increase of temperature by a significant factor, that is 1.5 times or larger? I doubt it. Consequently it seems to me we have no need for the early type stars to think in terms of chromospheres with a large difference between temperature in the photosphere and the chromosphere.

You have mentioned the often quoted remark that the velocity of outward motion is larger for ions of higher ionization potential in P Cygni stars. This remark is without sound observational basis. In a study of P Cygni to appear in BAN Vol. 20 M. de Groot shows that the clearest monotonic relation is obtained by plotting the expansion velocity versus (IP + EP). The meaning of this empirical relationship cannot be deduced satisfactorily by any simple theoretical considerations.

Thomas: I would like to call your attention to the proceedings of a symposium of Wolf-Rayet stars held at Boulder in 1968 (NBS Special Publication 307, 1968). One of its aims was to consider that the atmospheres of these stars are simply chromospheres.

Praderie: The observation of P Cygni profiles in the UV spectrum of early type stars does show a dependence of expansion velocity on ionization potential.

Underhill: The UV observations are not sufficient to permit such a general conclusion.

Hearn: In the solar spectrum or in the spectrum of late type stars, the observation of He I λ10830 in absorption is a clear indication of a chromosphere. But for early type stars special conditions are indicated only if this line appears in emission.

Athay: It is important in discussing stellar chromospheres to remember that a chromosphere represents some type of equilibrium between a mechanical energy input and an energy output, most probably radiative. The temperature structure of a chromosphere will depend on both input and output. The temperature of the solar chromosphere is determined largely by the fact that hydrogen is an efficient radiator at temperatures a few thousand degrees above the photospheric temperature. In early type stars hydrogen is highly ionized and no longer an efficient radiator. Thus a given mechanical energy input will produce a chromosphere that differs greatly in its general properties from the solar chromosphere. It is possible that even small amounts of mechanical energy could produce important chromospheric phenomena in such stars.

Osterbrock: Observations in the near UV have contributed much to our knowledge of the solar chromosphere. I would like to call attention to the OAO UV measurements made by the University of Wisconsin group. They now have results extending down to about 1500A for over 100 stars, including several late type stars, and though the resolution is low it seems likely, that these observations will be very useful in trying to understand stellar chromospheres.

Skumanich: Observations show a change of the Ca II emission line of 61 Cyg in an interval of 5 years.

Meyer: In the case of the sun a combination of magnetic fields and shock waves is a sufficient mechanism to produce the heating of the chromosphere and corona. If there are similar magnetic fields in stars this mechanism could be applied.

Hillendahl: There is a thesis by D. M. Pyper on magnetic A-type stars. She gets indications for shock waves.

Hearn: Are there serious arguments against the hypothesis that all stars or most stars have chromospheres?

Thomas: We do know that the sun has a chromosphere, which is produced by the mechanical energy of the convection zone. We further know that all late type stars do have convection zones. Heating of chromospheres by mechanical energy is the only known process. We don't know a specific heating mechanism for early type stars, but that doesn't mean one doesn't exist. Personally, I have pushed studies of aerodynamic phenomena in all stellar atmospheres simply to try to identify such mechanical heating mechanisms; I have always argued that we must be prepared for chromospheres in all stars--but we must find the specific source of their energy supply.