BOUNDARY CONDITIONS WITH MASS-LOSS : GENERAL CONSIDERATIONS

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I. INTRODUCTION

I begin by stating very explicitly and unambiguously that I completely disagree with any idea that a stellar atmosphere can be in any sense a boundary of the star, or that the atmosphere sets boundary conditions on stellar structure. Such an idea is what underlies all the single-layer, LTE atmospheric models, which misdirected atmospheric studies for so many years by introducing a false separation between "normal" and "extended" atmospheric phenomena. On the contrary, I assert that a more correct physical picture for the atmosphere than as a boundary comes from the characterization of star and atmosphere as :

(1) The STAR is : a concentration of matter and energy, C(M,E), in its parental environment, the interstellar medium (ISM) ; with boundary conditions on stellar structure being set by the way one models (a) storage modes for matter and energy in the star and ISM, and (b) energy generation in the star.

(2) The ATMOSPHERE is : (a) <u>functionally</u>, a transition-zone between star and ISM (Pecker, Praderie, Thomas, 1973) ; (b) <u>structurally</u>, a set of regions, each of which has distinctly different characteristics and reflects some aspect of the transition ; (c) <u>diagnostically</u>, the immediate place of origin of the fluxes, the analysis of which gives direct information on these regions and indirect information on thermodynamic structure of the star. In consequence, boundary conditions are imposed <u>on</u> the atmosphere by star and ISM, <u>not</u> imposed <u>by</u> the atmosphere on anything.

Equally explicitly, I emphasize that we do not know, a priori, either : (i) which of the several possible alternatives for thermodynamic structure of the star actually exists at each phase of the star's evolution ; (ii) or, in consequence, which variety of atmospheric regions is most important observationally for any given class of star. Thus our decisions on stellar structure and atmospheric regions must be empirical/observational, not a priori theoretical. We <u>observe</u> atmospher-

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ic regions, and we infer sub-atmospheric storage modes.

In this spirit, an alternative title to my remark, to parallel that of the preceding paper, might be : "Sensitivity of Atmospheric Structure to Lower (or Sub-atmospheric) Boundary Conditions". I focus on 4 points, and a summarizing slide prepared jointly by NASA, Pecker, and myself : (A) Non-Equilibrium thermodynamic alternatives on structure of, and fluxes from, the star as a C(M,E) in the ISM ; (B) Survey of atmospheric phenomena which guide an empirical choice among alternatives (A), hence boundary conditions on models ; (C) Pictorial caricature of the representation of the star as a system with matter-fluxes (OPEN system) and nonthermal kinetic energy storage modes ; (D) Mathematical representation of thermodynamic model and boundary conditions ; Summarizing-Slide, The Sun as a proto-example of the relation between sub-atmospheric storage modes and sequence of atmospheric regions.

II. POINTS OF FOCUS

A. NonEquilibrium Thermodynamic Alternatives on Structure of, and Fluxes from, the Star $\equiv$ C(M,E) :

Consider the models defined by various combinations of the (KIND, TYPE, DEGREE) alternatives of Table 1. We exclude those containing ISOLATED and EQUILIBRIUM because we observe the star. But any other choice must be empirical/observational, following the sequence of successive approximation : (1) choice of a combination and the implied boundary conditions ; (2) construction of a model, and of a diagnostic methodology consistent with the model to interpret observations, based on (1) ; (3) comparison of model to observations, seeking consistency or anomaly. To the degree of accuracy needed for the present discussion, and using our limited knowledge of general nonEquilibrium thermodynamic modeling, such successive approximation converges rapidly to show us those combinations of Table 1, hence which boundary conditions, we must study.

The great majority of stellar atmospheric models in the literature are based on the (closed, thermal storage, both linear and nonlinear nonEquilibrium) alternatives. In addition to chemical composition, these models depend upon just two parameters : F_R--- radiative flux, or T_{eff} ; gravity, g. The lower boundary condition in the atmosphere is a prescribed value for each of the two parameters. The outer boundary condition is no incident radiation on the star. The condition of radiative equilibrium ensures only thermal storage modes, because the computed T_e-gradients are too small to make thermal conduction be of importance. IF the models are nonlinear nonEquilibrium, they can provide a smooth transition from a static star to a static ISM. Any matter-flux comes wholly by thermal escape ; values computed from the outer-atmospheric properties of such models show these matter-fluxes to be negligible, in any observational way. Thus, these models are self-consistent : physically, and mathematically. But, those models for which density decreases monotonically outward (essentially all models) are unstable against arbitrarily-small outward radial velocities. The introduction of such small rad-

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TABLE 1

NonEquilibrium Thermodynamic Alternatives For C(M,E)

Kind of C		TYPE storage modes	DEGREE of nonEquilibrium
ISOLATED	: no fluxes	THERMAL only	EQUILIBRIUM
CLOSED	: only energy fluxes-- F_{rad}, F_{mech}	THERMAL + nonTHERMAL	LINEAR nonEquilibrium
		nonthermal kinetic energy : convection, pulsation, rotation, magnetic, hydromagnetic	nonLINEAR nonEquilibrium
OPEN	: energy and matter fluxes-- F_{rad}, F_{mech}, F_{mat}		

TABLE 2

Atmospheric Phenomena Guiding Choice Among Table 1 Alternatives

PHENOMENA	OBSERVED RANGE
$F_M(\text{obs}) \sim (10^4 - 10^7)\ F_M(\text{thermal})$	WR-OB-$\odot$-M
$F_M(\text{obs}) \rightarrow U \sim q$ at $R/R_o < 1.04$	WR-OB-$\odot$-M
C-C($T_e > T_{eff}$) ioniz. level	WR-OB-$\odot$-M
BaC excess	O-B_e-T Taur-Me
Balmer Line Emission	B_e-T Taur-Me
Nonthermal line widths	WR-OB-$\odot$-M

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ial velocities is the kind of thing which would result from admitting nonthermal sub-atmospheric storage modes.

Those presently-existing atmospheric models which are superposed upon sub-atmospheric models having nonthermal storage modes in the form of convection are not physically-consistent because of the imposed boundary conditions. As upper boundary conditions on the convection zone --- lower boundary conditions on the atmosphere --- they impose the condition F_M(matter-flux) = 0. That is, they impose the condition that the star be a CLOSED rather than an OPEN system, without asking the stability of such a condition against $F_M \neq 0$ and thus against its consistency.

Indeed, those CLOSED system models that have been enlarged to include kinetic-energy, as well as radiative-energy, fluxes provide counter-examples to demonstrate this inconsistency. The usual solar models having a convectively-induced acoustic mechanical energy flux produce chromospheres-coronas as a region of the atmosphere. Parker demonstrated that such models cannot match, statically, the ISM : but must produce a nonthermal matter-flux = "wind". Thus the star/Sun becomes an OPEN system ; and one must return to the convective nonthermal kinetic energy storage modes to include both matter- and nonthermal kinetic energy-fluxes. These must be part of the UPPER convective-zone, LOWER atmospheric boundary conditions. It is not so important whether such changes would introduce significant effect on the properties of the convective zone. It is important that without such fluxes, the stars would have no chromospheres-coronas ; with them, they have chromospheres-coronas, and all the attendant atmospheric features.

In summary : CLOSED stellar models can be constructed which are physically and mathematically self-consistent IF they have only thermal storage modes. But they are unstable against sub-atmospheric radial matter-, or nonthermal kinetic energy-, fluxes.

SOME nonthermal sub-atmospheric kinetic energy storage modes require, in parallel, chromospheres-coronas and matter-fluxes. In such situations, the proper lower atmospheric boundary conditions on models must be the non-restricted (by F_M = 0) upper boundary conditions on the sub-atmospheric nonthermal kinetic energy storage modes.

It is therefore essential to survey atmospheric phenomena, especially correlations between chromospheric-coronal and matter-flux phenomena, to ask whether all nonthermal kinetic energy and matter-fluxes produce such associations, so that the lower boundary conditions on them should be the upper boundary conditions on sub-atmospheric nonthermal kinetic energy storage modes ? Or, can we have nonthermal matter-fluxes without having chromospheres-coronas ? Current models of so-called radiation-presure origin of matter-fluxes indeed adopt this latter possibility. Unfortunately, just those hot (OB)stars, for whose description these radiation-pressure models were contrived, have been observed to have chromospheres-coronas. It is not generally agreed whether this conflict between observations and model-prediction comes from incomplete equations or inadequate boundary conditions for these models. I comment later on this point.

B. Survey of Atmospheric Phenomena guiding an Empirical Choice among Table 1 Alternatives :

The goal of such a survey is to decide whether observed atmospheric phenomena, across a sufficiently-broad range of spectral classes, suffice for us to conclude that nonthermal kinetic energy fluxes, and nonthermal matter-fluxes, are associated and characterize stars generally. If so, they imply equally-generally the existence of nonthermal storage modes in the sub-atmosphere, which couple directly to the atmosphere in the sense of providing both storage and fluxes there. If so, such coupling must be represented by the proper boundary conditions at the sub-atmosphere, atmosphere interface or transition. If so, we have then identified the "Universal" nonEquilibrium thermodynamic character of stars : they are OPEN, NonTHERMAL storage mode, NonLINEAR NonEquilibrium Concentrations. (The latter property follows immediately from recognizing the nonlinear character of distribution functions for photons, internal energy states, and particle velocities.)

It is necessary to define the meaning of chromosphere-corona characteristics associated with matter-fluxes. Nonthermal matter-flux characteristics are clear : macroscopic velocity fields comparable with, or exceeding, chromospheric-coronal, as well as photospheric, thermal velocities. If, in a macroscopic flow, having velocity gradients, velocities comparable with the local thermal velocity appear, mechanical energy dissipation begins --- and the local kinetic temperature of the gas rises. Such a rise in T_e above T_{eff} is the essential character of a chromosphere : because a rise to a value slightly smaller than T_{eff} can be induced wholly by nonlinear photon + atomic phenomena in a static atmosphere.

So, I present the following list, making no pretence that it is not highly selective, in no way complete. I could equally-well have used the similar list presented by Lamers in the Commission 44 session on stellar mass-loss. Refer to Table 2.

Table 2, by itself, is a bit cryptic ; hence, a brief explanation. The first line is clear ; observed matter-fluxes exceed by a very large factor those which would be produced by only thermal escape from the atmosphere. The second entry corresponds to a computation (Thomas, 1973), which considers the observed data on $F_M = 4\pi R^2 \rho U$ for a wide variety of stellar types. Because the photospheric thermal velocity, q, is much less than the escape velocity ; because the thermal velocity does not change much through the atmosphere unless/until the systematic velocity $U \sim q$; and because until this point $U \sim q$ the photospheric, radiative equilibrium density distribution does not change much ; we can use essentially isothermal density distributions to ask at what R/R(photosphere) $U \sim q$ from the observed F_M. Wholly empirically, for all stars for which F_M has been inferred, observationally, in some way, we

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obtain the result of line 2. This suggests that all these stars have chromospheres, which begin very near the photosphere. The third entry asks in what stellar classes we observe ionization levels significantly above those which would result for $T_e > T_{eff}$ (LTE or nonLTE calculation. The long-known observations of OVI in WR stars in the visual spectrum couple with recent satellite observations of OVI in OB stars (Lamers and Rogerson, 1975) in the far UV to demonstrate that T_e is at least some 2.10^5 K in the atmospheres of these hot stars, thus that they have chromospheres-coronas, for which the symbol C-C stands in Table 2. The fourth entry states a well known fact ; of which one possible explanation is a deep-lying chromosphere, such as suggested by Herbig (1962) long ago, for T Taur. The fifth entry is again a well-known observational fact which, we have suggested (Dumont et al., 1973), follows directly from a chromospheric interpretation of the BaC emission in these same stars. The fifth item is closely linked, suggesting that the deeper-lying the chromosphere, the greater the line-width, in either inhomogeneous (Thomas, 1973) or homogeneous (Dumont et al., 1977) atmospheres. Computations exist thus far only for the cool stars ; they are projected, for the hotter stars.

In short, a variety of atmospheric phenomena suggest that chromospheres-coronas, and matter-fluxes, arise from coupling between sub-atmospheric nonthermal storage modes and the atmosphere ; thus, that the star is an OPEN, NonTHERMAL storage mode, system. Let me return to Mrs. Gaposchkin's unpublished ejaculation, long ago, on seeing the first solar rocket spectrum : "the UV Sun is a WC6 star" (i.e. the Sun is also a symbiotic star) ; and re-phrase it, to be "the atmospheres of WC6 stars are visually deep-lying solar chromosphere-coronas, along with all their cousins". Boundary conditions, and equations to which the boundary conditions are applied, must reflect these empirical non-Equilibrium thermodynamic conclusions.

The boundary conditions for this (Open, nonthermal) model are, in parallel to those of the (Closed, thermal) model : prescribed values of F_M, F_{mech}, F_R, g at the sub-atmosphere, atmosphere interface for the lower boundary conditions ; no incident F_M (non-accreting) on the star, F_R (incident) equal to the statistical stellar contribution to the ISM for the upper boundary conditions. The condition of radiative equilibrium is replaced by including terms in both systematic and "turbulent" (viscous, or velocity gradient, terms ; acoustic terms ; "true" turbulence) velocities in the storage/transport equations describing the spatial/temporal evolution of the structure of star and atmosphere. One cannot, as is customary in the radiation pressure models, simply ignore the "turbulent" velocity terms, deleting them from the equations ; for this a priori exludes the production of chromospheres-coronas. Moreover, one cannot introduce the entropy as a state-parameter, as did Demarque in the preceding summary of boundary conditions on the interior, because in the nonlinear nonEquilibrium region, the entropy is undefined. In either of the (Closed, thermal) or (Open, nonthermal) models, one must admit the possibility of non-spherical-symmetry, for which F_M, F_{rad}, etc. depend on angular as well as radial coordinates. Whether one chooses to simply take these para-

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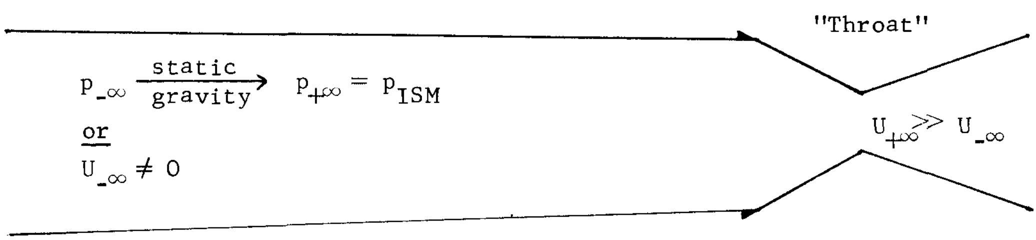
meters as given, or as coming from a solution of the sub-atmospheric nonthermal mode problem, is a choice which must reflect our degree of progress in modeling the stellar sub-atmosphere + interior. In the following illustrations, I take these F_M etc. as given.

C. Pictorial Caricature of a Representation of the Star as an (Open, nonthermal) System by an Imperfect Wind-Tunnel :

Consider the wind-tunnel analogy to the solar wind (Clauser, Germain, 1961), for which the equations, without "turbulent" terms, are essentially : ($q = \gamma p/\rho$ in 1a ; kT/M in 1b)

$$\left\{\frac{q^2}{U^2} - 1\right\} U\frac{dU}{dr} = \begin{cases} -\dfrac{q^2}{A}\, d\,\dfrac{A(r)}{dr} & \text{(1a) WIND-TUNNEL} \\ \dfrac{1}{r}\left[w_o^2\,\dfrac{r_o}{r}(1-\beta) - 2q^2\left(1 - \dfrac{d\ln T_e}{d\ln r^2}\right)\right] & \text{STAR (1b)} \end{cases}$$

and a schematic diagram is :



The caricature is both physical and mathematical. It is physical because it replaces the star-as-a-storage-pot by the storage section of the wind-tunnel (far left of the diagram), and replaces the atmospheric acceleration-to-escape-velocity by the converging-diverging nozzle (right part of diagram). The caricature is mathematical, because it ignores the 2-dimensional character of the diagram in writing the wind-tunnel equation.

The slope of the storage-converging section is <u>very</u> gradual, to represent the slow decrease of $(r\,w^2/r)/q^2$ in a "normal" = thermal-storage atmosphere. The smallest value of this ratio is some 400, in real stars ; for most hot stars, it exceeds 2000. In consequence, for such "normal" models, where $U_{-\infty} = 0$, and we can ensure that the "gravitational-decrease" of $p_{-\infty}$ brings it smoothly to $p_{+\infty}$, the wind-tunnel does not "flow" ; the atmosphere is static.

In Parker's solar chromosphere-coronal model, $p_{-\infty}$ is too large to

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decrease, gravitationally, to $p_{+\infty}$; so there is a flow ; because the "storage-section" is taken as the "hot" chromosphere-corona. The "perfect" wind-tunnel corresponding to Parker's model produces a continuously accelerating flow to supersonic velocity without shock-waves ; this requires both $U = q$ and $\sqrt{2}\, q = w$ (the escape velocity) to occur at the "throat". (For the moment, we ignore radiation-pressure, whose ratio to gravity is β).

But such a "perfect" wind-tunnel requires that $p_{-\infty}$ and $p_{+\infty}$ be specified, and A(r) designed to produce such shock-free, continuously-accelerating flow. Generally, if A(r) is also given a priori --- as in the stellar case, because gravity is fixed independently of the details of atmospheric structure, and q is constant in this outer atmospheric region --- such a "perfect" flow does not occur. If $w^2 (= w_o^2\, r_o/r)$ decreases to $2q^2$ before U increases to q , the flow is not continuously accelerated but decelerates after $w^2 = 2q^2$. Such alternative does not produce the large observed wind-velocities in the hot stars, which much exceed the escape velocity ; so, observationally, this alternative is not interesting. On the other hand, if U reaches q before w^2 reaches $2\, q^2$, shocks occur, and the resulting mechanical dissipation of energy heats the gas and raises q. The resulting behavior of U and q must be determined from a set of equations that are expanded over those above to include all forms of these energy dissipation terms --- which are essentially those included in "turbulence", plus heat-conduction, etc. Now, <u>this</u> alternative corresponds to the <u>observed</u> presence of chromospheres, even in these hot stars. Note that we <u>can</u> have chromosphères-coronas <u>without</u> a heating produced by the velocity in the matter-flux reaching the thermal velocity --- in this case the region of subsonic acceleration is extended, over the case of constant q. But we <u>cannot</u> have chromospheres-coronas without mechanical heating of some kind. Neither the "perfect" wind-tunnel, nor the accelerated-decelerated alternative, produce such heating : particularly, they do not produce such heating at such low atmospheric levels as correspond to Table 2 ; and especially they cannot produce such heating if there are no terms in the equations to describe such production.

So, we criticize the "perfect" wind-tunnel models, with or without radiation pressure, on three points. Physically, they do not produce chromospheric heating below the "critical point $w^2 = 2q^2$. Mathematically, they apply the wrong boundary conditions ($U = q$ where $w^2 = 2q^2$) to an incomplete set of equations.

Adding radiation pressure, $\beta \neq 0$, in these equations and under these boundary conditions does not change these essential criticisms, when they are taken in the context of observations. To move the "critical-point" deep-enough into the atmosphere to match the observed mass-fluxes requires values of some 0.95 for β. To say that there are some, <u>very</u> hot, stars for which such large β can be reached in a static atmosphere is not useful in a general sense, because Bo and O5 stars, which are <u>not</u> this hot, show chromospheres ; and these chromospheres must be explained. So, I prefer the above explanation : "imperfect wind-tunnels"; and the associated boundary-conditions applied to the complete equations.

D. Mathematical Representation of Thermodynamic Model and Boundary-Conditions in the One-Dimensional, Plane-Parallel Approximation :

The one-dimensional, plane-parallel approximation suffices for the present summary ; because our only objective is to show that an association, like the observed one, between matter-flux, nonthermal kinetic energy flux, and chromosphere-corona existence would be predicted by the model of a star as an open system with nonthermal kinetic energy storage modes and the associated boundary conditions. We have already shown that the observed matter-fluxes imply the beginning of chromosphere-corona well within the plane-parallel approximation limit. The one-dimensional approximation is highly-restrictive, especially under the variety of nonthermal storage modes possible, but only in the <u>details</u>, not the existence, of the stated association ; so it suffices for simplicity of illustration.

Then we can write the three equations which describe the storage/evolution of matter, thermal/microscopic energy, and nonthermal/macroscopic energy --- and their coupling --- as (Cannon and Thomas, 1977) :

Matter : $$\frac{d(U\rho)}{dx} = 0 \qquad ; \; (U\rho) \neq 0 \tag{2}$$

Microscopic energy :
$$\left\{\frac{d\lfloor U(\epsilon + p + p')\rfloor}{dx} - \frac{Ud(p + p')}{dx}\right\} = \left\{\frac{d}{dx}\left(\frac{\lambda dT_e}{dx}\right) + 4\pi\int (J_\nu - S_\nu)\frac{d\tau_\nu}{ds}\, d\nu\right\} \tag{3}$$

Macroscopic energy + Matter :

$$\rho(q^2 - U^2)\frac{dU}{dx} U^{-1} = \rho g + \frac{d}{dx}(p_r + p') \tag{4}$$

ϵ is the internal energy of the particles ; p' is the "generalized turbulent" pressure/energy (eg. Moyal, 1952), as is p the thermal pressure/energy, and p_r the radiation pressure/energy. In the static, thermal-storage-mode situation, the left-hand-sides of each of the above vanish, except for the q term in (4), which reduces to dp/dx. Thus, the left-hand-side gives the nonthermal-storage-mode presence and effects. Equation (4) represents the correction to equation (1), coming from the inclusion of these "generalized-turbulent" terms.

In the absence of the nonthermal modes, the terms in U and p' disappear ; and the boundary conditions are the values of g and of F_R , noting that

$$dF_R/dx = -4\pi\int (J_\nu - S_\nu)\,\frac{d\tau_\nu}{ds}\, d\nu \tag{5}$$

and that the thermal conductivity term (first term on right) in (3) is negligible. So one solves (3) with this given F_R (in the simplest opacity cases, like the grey case, T and ρ de-couple in this solution) to obtain $T_e(\tau)$; then uses this $T_e(\tau)$ in (4) to obtain $\rho(\tau)$. (2) is irrelevant, because U = 0 by assumption. One can, however, infer the outward variation of any small value of U imposed from below, by setting U = the imposed value of U, coupled with the static-atmosphere-inferred value of ρ at the given atmospheric level. Then, the variation of U follows that of this static atmosphere solution for ρ, until U becomes large enough to cause the left-hand sides of (3) - (4) to change the static-atmosphere solutions for T_e and ρ.

In essence, this last procedure corresponds to the situation with nonthermal storage modes. Hence, the boundary conditions for this case are simply values of F_M (or, alternatively, U) and F_{mech} added to the values of F_R and g. If only F_M is imposed, then the value of U increases to near q ; heating begins ; and T_e rises. But also, the solution of equation (4) begins to "oscillate". That is, because the right-hand-side is positive throughout this plane-parallel region, $dU/dx > 0$ so long as $q > U$. But when $U > q$, $dU/dx < 0$ and the flow decelerates, until $q > U$, when the process repeats. This is the well-known trans-sonic instability ; and the oscillation is accompanied by the production of many small shock-waves (eg. cf. the photographs in Charters and Thomas, 1945). So, to treat this problem completely, one must restore the complete set of time-dependent, 2- or 3-dimensional equations. But, in these regions, we have already produced the chromosphere, and the matter-flux has a significant ($U \sim q$) value. Hence, the stated association : matter-flux and chromospheres. If, in addition a non-zero F_{mech} produces an acoustic-wave component of p', chromospheric heating begins before $U \sim q$, as earlier mentioned in section C ; so that we have the further association with nonthermal mechanical energy fluxes. So, we see, pictorially as well as arithmetically, how this (open, nonthermal storage mode) model, plus an adequate set of boundary conditions can produce the kind of association observed.

Summarizing-Slide : The Sun as a Proto-Example of the Relation Between Sub-Atmospheric Nonthermal Storage Modes and Sequence of Atmospheric Regions. (See Figure 1.)

The slide follows a figure from work by Pecker and myself, and is reproduced courtesy of NASA (Pecker and Thomas, 1977). Going clock-wise from the right hand side of the figure, the Sun is divided into sectors. Each sector shows the kind of atmospheric region which would result if the sub-atmospheric nonthermal storage were as indicated in the sector. Thermal storage gives only photosphere ; nonthermal storage with one type of mode (convection, pulsation, or rotation) gives chromosphere-corona, matter-fluxes etc. but no magnetic "activity" ; two types of storage modes produce the "active" Sun etc. The implication of the increasingly-detailed structure coming from increasingly elaborate storage modes is clear. It is equally clear that such a sequence of phenomena and atmospheric regions hardly follows from considerations based on radiation pressure alone. It is equally clear that these "pictorial" considerations must be developed in detail ; and the relation between

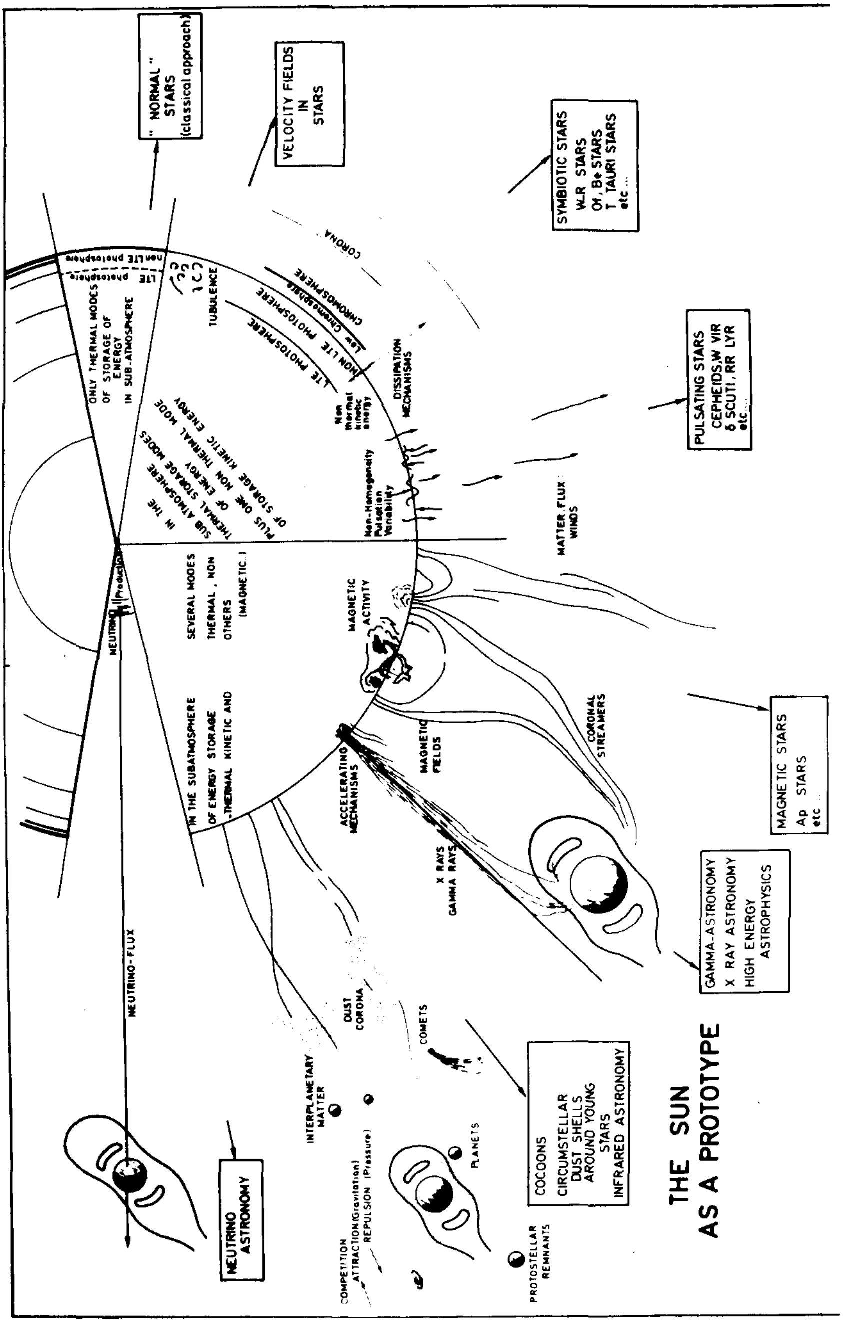

Figure 1. The Sun as a proto-example of the relation between sub-atmospheric non-thermal storage modes and sequence of atmospheric regions.

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atmosphere, sub-atmosphere, and interior examined in detail. Until the boundary conditions have been actually applied in detail, it is hardly worthwhile to debate whether the interior --- and its evolution --- is or is not altered as significantly as is the structure and evolution of the atmosphere.

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