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THE SUN AS A STAR

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INTRODUCTION: THE SOLAR-STELLAR CONNECTION

In the final part of this volume we return to the question posed at its beginning: How does the Sun serve as a guide to the study of the atmospheres of other stars? The question has been discussed in various preceding chapters in connection with specific solar nonthermal phenomena. We now address it explicitly by summarizing this book on solar astrophysics from the point of view of stellar applications.

The most important contribution that solar astrophysics can make to stellar astrophysics is to lead the way to an improved methodology for the interpretation of stellar observations and for the construction of stellar atmospheric models.

Contemporary solar physics focuses on the multitude of nonthermal phenomena shown by the Sun; stellar physics will be greatly enriched if it can incorporate insights obtained from solar *understanding* of the *processes* that underly these phenomena. Conversely, the stars let us study the same processes, in less detail but over a much wider range of environments, provided by the stars' variety of mass, rotation, magnetism, composition, stellar companions, and evolutionary history.

This is a new solar-stellar connection, emphasizing astrophysical processes. It differs from the solar-stellar connection of old, which concentrated on the equilibrium structure of stellar photospheres. In this introduction, we first review the old connection before outlining the new connection and its observational and interpretational consequences, which are then discussed in the remainder of this chapter.

The Classical Solar-Stellar Connection: Equilibrium Modeling of Photospheres

The old connection was a matter of course when solar astrophysics was centered on the study of unresolved observations of the photosphere, with the goal to understand the formation of the spectral lines and the continuum radiation field in terms of atomic physics and the physical conditions of the photosphere. The classical theory of stellar photospheres is based on these studies. We would now call this thermal modeling, because it ignores all nonthermal phenomena by assuming hydrostatic equilibrium and radiative/convective equilibrium. This modeling has had considerable success, and it is extensively used in stellar research, particularly in determining stellar atmospheric parameters such as temperature, pressure, and chemical composition. However, the methodology of classical modeling is far from complete. We outline its basic assumptions and briefly discuss its current state and future improvements.

The basic assumptions of classical modeling are as follows:

1. Radiative/Convective Equilibrium. Energy is carried only by the radiation field, except in layers where a test of convective stability fails. A phenomenological, incomplete model of convection is used to describe energy transport when convection is present. There is no adequate model for convective/radiative energy transport, and

certainly no worker in the field has attempted to derive selfconsistent models which include *all* the consequences of convective instability.

2. Hydrostatic Equilibrium. The atmosphere is stratified in spherically-symmetrical layers with the sum of the gas pressure gradient and radiation pressure gradient balanced by the force of gravity. In a few cases, a "turbulent pressure," crudely representing the Reynolds stress associated with convection, is also included.
3. Constitutive Relations. These consist of the equation to state and a specification of the interaction between radiation and matter. Most classical models are based on an equation of state which reflects Maxwell-Boltzmann-Saha equilibria (detailed balance) and an interaction described in terms of local thermodynamic equilibrium (LTE). However, the low particle densities and anisotropic radiation fields of stellar atmospheres generally imply that detailed balance does not apply. In this case, the only safe way to introduce constitutive relations is to work with the microscopic statistical equilibrium equations for all important atomic states, and to solve these simultaneously with the radiation transfer equation and the equations of hydrostatic and convective/radiative equilibrium. This is the program of "non-LTE classical model photospheres"; it is mathematically complex, and it has been most highly developed for the Sun. The classical solar-stellar connection is therefore still present with some modifications. We discuss it separately for the lower and the upper photosphere.

The current state of the art in modeling the solar photosphere is represented by the elaborate LTE models of Kurucz (1974) and Gustafsson and Bell (1979). A vast number of lines ($\approx 2 \times 10^6$) is explicitly included to reproduce line blanketing; the latter authors concluded that yet more weak lines are needed in the UV to match the solar spectrum.

The next improvement will be to include the effects of departures from LTE on line blanketing. These have been studied in most detail so far by Athay (1970b); this study is also discussed in his book (Athay, 1972), and reviewed by him in Chapter 4. In the deep photosphere, LTE is not a bad assumption for the line source functions ($S_\ell = B_\nu$) if the local mean intensities J_ℓ of the lines and J_ν of the continuum are correctly computed, because there the line blocking ($J_\ell \neq J_\nu$) is more important than the non-LTE imbalance in transitions ($S_\ell \neq B_\nu$). Line blocking actually heats the atmosphere relative to a continuum-only radiative equilibrium model ("backwarming"), because $J_\ell > J_\nu$ for most lines, especially for the weak violet lines which represent the most important contribution in the deep photosphere.

Figure 19-1 shows a comparison of representative one-dimensional models of the deep photosphere. The differences between the various types are of order 100 K throughout the photosphere, which is not more than the uncertainty of each model itself within its own assumptions. This agreement shows that equilibrium modeling gives a reasonable temperature structure for the deep solar photosphere; the mean radial structure is apparently close to thermal. This implies, in turn, that stellar equilibrium models are useful, perhaps "astonishingly good" (Gustafsson and Bell, 1979), for those analyses of stellar photospheres that are not concerned with nonthermal phenomena, notably studies of stellar chemical composition.

How does one improve the classical modeling further? The most obvious shortcoming is the simplistic description of convection, the neglect of its consequences, and the related issue of turbulence. Convective overshooting results in an appreciable amount of convective energy transport in the lower solar photosphere (Edmonds, 1974) but is neglected in mixing length theory; the theory of penetrative convection is far from complete (see Chapter 9 by Moore). The physical fluctuations observed in solar granulation enter the modeling equations nonlinearly and should be included through convection theory; the same holds for granular motions. These contribute significantly to the observed nonthermal line

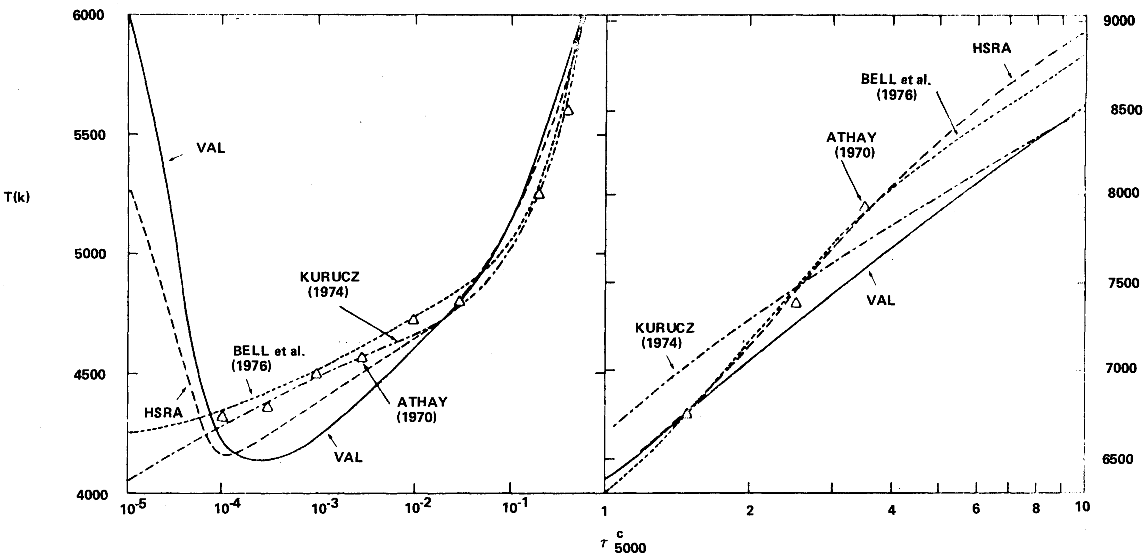

Figure 19-1. Representative one-dimensional models of the solar photosphere. The models by Kurucz (1974) and Bell et al. (1976; see also Gustafsson and Bell, 1979) are theoretical line blanketed LTE models. Athay's (1970b) radiative equilibrium model ignores convection but includes non-LTE line blanketing by the strongest lines and representative groups of other lines. The Harvard-Smithsonian Reference Atmosphere (HSRA, Gingerich et al., 1971) is a semiempirical model based on continuum observations. The VAL model (Vernazza, Avrett and Loeser, 1976, model M) is a semiempirical model based on continuum and line observations (from figures 19 and 20 of Vernazza et al., 1976).

broadening, and perhaps account for all of it, as suggested by Nordlund (see Chapter 2 by Beckers). Turbulence is included as an ad hoc empirical parameter in all classical models, which, therefore, are not fully self-consistent (and should not, therefore, be called "theoretical" or "thermal").

Theoretical modeling of the upper photosphere is yet more complicated. As described by Athay in Chapter 4, the non-LTE imbalance in the stronger line transitions (those at the shoulder of the curve of growth) become important near $\tau^{c}_{5000} = 10^{-4}$, generally resulting in "surface cooling." To compute line blanketing near the temperature minimum thus requires detailed non-LTE studies for many lines. It has, in addition, become clear that the effects of frequency coherence must be explicitly included for most resonance lines (see Milkey, 1976). Nevertheless, non-LTE partial redistribution (PRD) line transfer is the least uncertain of the complications. The departures from LTE in the H^- continuum are important but their role is still controversial (see Chapter 12 by Jordan). Waves are important too, at least as a probable contributor to line broadening (see Chapter 2 by Beckers), possibly as a dissipator of large amounts of energy (Chapter 12). The magnetic flux tubes expand to a nonnegligible filling factor (see Chapter 17 by Spruit), making any one-dimensional modeling whatsoever questionable. Thus, radiative equilibrium modeling of the upper photosphere will certainly not produce a relevant description of this layer. Its usefulness is restricted to comparison with more realistic models: "the model serves simply to demonstrate its own obsolescence" (Pecker, 1965). Ideally, the differences could be used to infer the amount of local storage and the rate of dissipation of (magneto-) mechanical energy, and should indicate from where the chromosphere and corona get their energy. In practice, as discussed in

Chapter 4 by Athay, neither the current empirical models nor the best radiative equilibrium models are accurate enough to meet this goal. Such comparisons for stars are certainly premature.

The New Solar-Stellar Connection: Nonequilibrium Astrophysical Processes

Contemporary solar physics no longer concentrates on the spatially averaged optical spectrum of the photosphere, but instead on the host of nonthermal phenomena and nonequilibrium processes that are displayed primarily by the outer solar atmosphere, where physical conditions are not controlled by the bulk of the radiative flux but by the magnetic field, mechanical energy, and matter fluxes that have their origin in the convection zone. For a long time, these problems seemed exclusively solar. In the meantime, astrophysics diversified and began studying newly discovered exotic objects such as quasars and pulsars, and the primordial universe. But progress from discovery to understanding requires solid astrophysics, and the exotic objects generally require new nonequilibrium astrophysics. Also, the space revolution now enables us to study the outer atmospheres of the other stars too, resulting in the current shift in emphasis, for all stars, toward their nonthermal phenomena.

In this new era, solar physics remains "the mother of astrophysics" (Parker, 1978), because studies of the detailed structure of the solar atmosphere are among the few astronomical studies which give insight into the *processes* responsible for the occurrence of nonthermal phenomena, so ubiquitous in the universe. There can be little doubt that many of the *new concepts* which are required for progress in these new astrophysical domains will often be conceived, and almost invariably tested, by studies of the Sun. This is so, first, because the solar atmosphere is a domain enormously rich in nonequilibrium processes, and second, because the Sun's proximity makes its atmosphere relatively easy to observe. We measure its wind in situ; we explore its electromagnetic spectrum over the whole spectral range, with high resolution in three spatial dimensions and in time, wavelength, and polarization as well. This has led to the discovery of all the unexpected and interesting phenomena that are described in this book. The major topics of solar physics reviewed in the preceding chapters—the dynamics of the convection zone, including the generation there of oscillations, waves, and the concentrated magnetic fine structure; the activity cycle and the solar eruptions; the nonthermal structure and dynamics of the whole outer atmosphere, from the upper photosphere to the wind—these topics all represent scientific problems which are highly relevant to astrophysics in general, with each topic abounding in well-observed nonthermal phenomena that are direct manifestations of basic astrophysical processes. *Solar phenomena frequently offer an opportunity unique in the whole cosmos to observe in detail universal astrophysical processes at work at their characteristic physical scales.*

An understanding at microscopic scales is often an essential prelude to understanding the macroscopic effects of nonthermal processes, and, in fact, to understanding the global structure of the object under study. Studies of the detailed structure of the solar atmosphere are, therefore, not merely studies of small deviations from an equilibrium structure. They also lay the foundations of nonequilibrium astrophysics, by contributing new methodology and insights that are of wide applicability. Thus, the classical solar-stellar connection, emphasizing the spatially averaged optical spectrum and the equilibrium structure of photospheres, is being extended to wider horizons by connecting the astrophysics of processes observed at their characteristic scales on the Sun with the astrophysics of other objects, often exotic and always remote, that are governed by similar processes but are impossible to study empirically with adequate detail.

The Observational Solar-Stellar Connection: Flux Spectroscopy

Although the proximity of the Sun lets us study the details of many astrophysical processes on their characteristic scales, many phenomena are still inadequately resolved. The maturing of solar space technology, adding spatial resolution to the opening up of new spectral domains, changes this situation. NASA's Solar Optical Telescope (SOT) promises 0.1 arcsec *spatial* resolution, equaling the continuum opacity scale height and the mean free photon path length in the deep photosphere. The SOT should show, finally, what the Sun really looks like, and resolve most fine structure (a notable exception are the tiny flare kernels), and not only in snapshots but over extended periods of time. For example, the SOT will enable the study of the slender photospheric flux tubes, now barely glimpsed as filigree, that are the roots of the corona.

For stars other than the Sun we are less fortunate. There is clearly no hope of observing stars with the spatial resolution that we find necessary to study the fundamental nonthermal processes on the Sun. A SOT resolution element covers less than 10^{-8} of the solar disk, yet exceeds the apparent solid angle subtended by even the largest stars! The basic techniques of stellar observation—photometry, polarimetry, and spectrometry in all spectral domains—permit high resolution in magnitude, wavelength, polarization, and time, but only for the total emergent flux. While solar studies have turned away from just spectral resolution to require high spatial resolution as well, the latter will continue to be absent in stellar data. This constraint lies at the heart of the new solar-stellar astrophysical symbiosis. It implies that, in bridging the gap between studying solar physical processes at their characteristic scales and studying unresolved stars, we need to translate solar results into flux diagnostics. Observationally, this usually means conversion to spectral diagnostics because *spectral* resolution remains the pertinent domain of resolution for stars.

While solar physics and the new solar-stellar connection have the study of nonthermal *processes* as their primary subject, stellar physics is currently in the exciting stage which precedes this emphasis, that of discovering nonthermal *phenomena*. This is, of course, because stellar space instruments now reveal the spectral domains of stellar radiation which originate in outer atmospheres. Figure 19-2 shows Malitson's (1977) compilation of the solar flux spectrum. The quiet Sun continua are formed above the temperature minimum shortward of 1626 Å, and longward of 150 μm (Vernazza et al., 1976, figures 23b and 29). These continua directly exhibit the nonthermal heating of the outer atmosphere. In addition, the X-ray, EUV, and radio parts of the solar flux spectrum display large fluctuations when the Sun is active. Thus, the solar example illustrates that high spectral resolution is not needed in the new spectral domains to discover nonthermal phenomena, but eventually it will help to explain the underlying processes. In contrast, the signatures of the photospheric nonthermal phenomena in the optical part of the spectrum are generally limited to slight changes in line profiles, requiring good to very high spectral resolution. Fortunately, this is now also becoming possible. Thus, throughout the spectrum, techniques are becoming available that enable a redirection of the emphasis of stellar analysis, first from classical photospheres to nonthermal outer atmospheres, then from nonthermal phenomena to nonequilibrium processes. We discuss these techniques within the solar-stellar connection in the next section of this chapter.

The Interpretational Solar-Stellar Connection: One-Dimensional Modeling

The fact that stellar data are always averaged over the true scales of the important processes implies that "one-dimensional" modeling, i.e., modeling the radial variation of the horizontally and temporally averaged mean state, remains by default of paramount importance in the analysis of stellar atmospheres. Ideally, the solar guidance to one-dimensional modeling should come from averaging truly nonthermal models which self-consistently specify the multidimensional, dynamical atmospheric structure in terms of specific nonthermal processes. However, a complete model incorporating all inhomogeneous and time-dependent processes is still far off! Unfortunately, such a model is not even an important goal of solar physics, because solar physicists' main

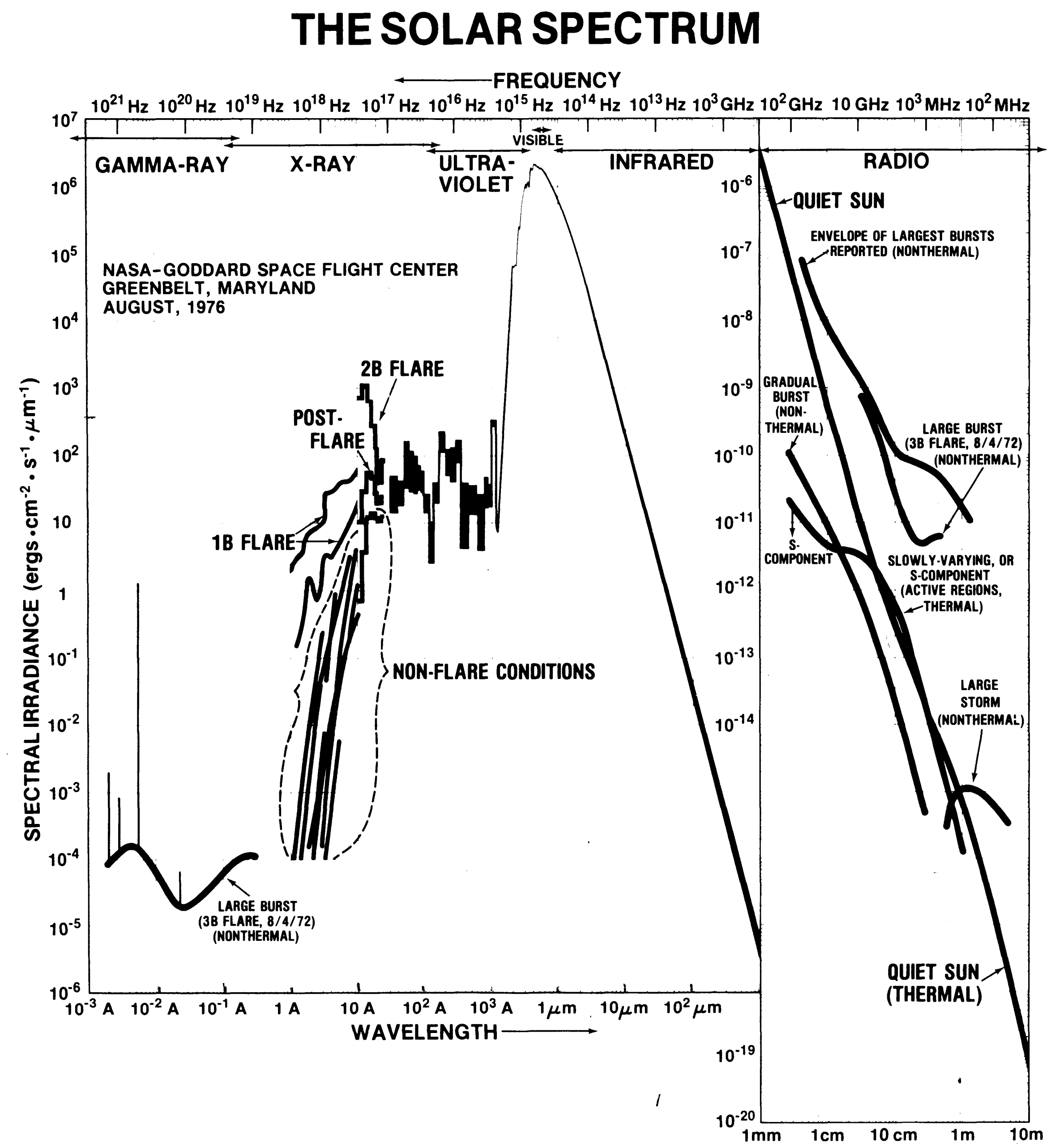

Figure 19-2. The solar irradiance spectrum, compiled from data in "The Solar Output and Its Variation" (White, 1977). Reprinted courtesy of Harriet H. Malitson, Goddard Space Flight Center.

interests generally lie in the processes themselves, not in their grand average. However, to use solar studies as a stepping-stone to studies of stellar atmospheres, it is important to evaluate spatial and temporal averages of solar nonthermal models, to show to what extent one-dimensional modeling is worthwhile, and to guide stellar methodology. The last section of this chapter represents an attempt toward this goal.

It is particularly instructive to compare the results of such fully consistent treatments with the conclusions of semiempirical diagnostic methods. Semiempirical models represent an intermediate class of models between thermal and nonthermal models. They crudely account for the existence of the mean macroscopic effects of nonthermal phenomena without specifying their nature or cause. Such models are not self-consistent: they ignore the detailed physics of inhomogeneous structure, magnetic fields, ordered nonthermal motions, differential rotation, etc., but they, nevertheless, try to include the changes in the mean state of the atmosphere that are due to these phenomena. This is done by introducing ad hoc modeling constructs, such as turbulence or a nonthermal chromospheric-coronal temperature rise. Semiempirical models are designed to reproduce spatially averaged observations, and to represent the horizontally averaged radial structure of the true atmosphere. The success of such models in attaining these two goals depends on the appropriateness of the adopted semiempirical constructs.

In recent years there has been a major thrust in stellar atmospheric studies to apply semiempirical solar diagnostics. Solar one-dimensional semiempirical models are also becoming increasingly sophisticated, employing continuum data throughout the spectrum and detailed non-LTE-PRD line profile analysis. However, a point of diminishing returns may soon be reached, since the diagnostic techniques do not reflect the actual physics. The time-dependent, inhomogeneous nonthermal processes that underly turbulence or the heating of the outer atmosphere may enter the equations in complex nonlinear ways, so that an overly simplified set of constructs may lead to a totally misleading mean model. This obvious point has to be stressed. History shows that we have to be very careful with assumptions that are taken originally for the sake of tractability only. For example, it is clear a priori that photons that leave a star cannot be described by equilibrium thermodynamics, and from quantum mechanics we learn that frequency coherence occurs wherever radiative damping is important. Nevertheless, LTE and CRD (complete redistribution) were standard assumptions for a long time, not proven, not tested, and often wrong. No argument serves to justify a tractability assumption other than a detailed analysis which relaxes the assumption. Thus, the relevance of semiempirical modeling has to be tested through nonthermal modeling; the relevance of one-dimensional modeling has to be tested through inhomogeneous modeling. The Sun represents the primary testing ground for both, the only one for the latter.

A point of diminishing returns may well have been reached in one-dimensional semiempirical modeling of the solar atmosphere; we will discuss this issue in the last section. The trend to apply solar semiempirical diagnostics to the stars will continue as observations of integrated starlight are made in new spectral domains, and with higher spectral resolution and quality. Stellar studies are probably not yet at the point of diminishing returns, although there can be little doubt that we are misled in some important directions by the inappropriateness of semiempirical modeling techniques. To set, or keep, stellar interpretational methodology on the right track will be a major contribution of solar astrophysics in the new solar-stellar connection.

OBSERVING THE SUN AS A STAR

In this section we discuss observational aspects of the new solar-stellar relationship, and we briefly review nonthermal characteristics of the Sun when seen as a star, i.e., when observing the solar flux spectrum.* We concentrate on *spectroscopy* because, as stressed above, spatially averaged spectroscopy is the main domain of observational overlap between the Sun and the stars.

Currently, the new space observations open our eyes to the nonthermal outer atmospheres of stars; eventually, the medium of translating solar insights into the underlying processes to stellar studies will be *resolved line spectrometry*, in which the profiles of the lines are employed as gauges of the temperature, pressure, velocity, and

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*"Flux" is a loose term, used both for the radiance (emittance) of a unit area of the solar surface, and the irradiance per unit area on Earth. The former is best called "surface flux"; the latter would be α^2 times smaller, with α the angular radius of the Sun, if the solar radiance were the same everywhere over the solar surface. We use "flux" here in the sense of the irradiance of the top of the Earth's atmosphere.

magnetic field and their variations, throughout the spectrum and throughout the atmosphere. This requires spectrometry with *high spectral purity*, i.e., with high spectral resolution, a stray-light-free, clean instrumental profile, a large signal to noise ratio, and accurate wavelength calibration. We discuss some of the latest techniques and their current state of development, dividing the subject into stellar and solar instrumentation.

Solar-Like Stellar Spectrometry

Solar-like spectrometry of stars with high spectral purity (say $\lambda/\Delta\lambda > 2 \times 10^5$, signal to noise ratio > 500) is just becoming possible in the visual and the near infrared. These new techniques promise to revolutionize optical studies of stars, because they furnish diagnostics of nonequilibrium processes in photospheres.

Such high precision is not yet available in the other parts of the spectrum. However, these other parts originate in the outer regions of stellar atmospheres, where the nonthermal effects are not hidden in minuscule line profile detail, and where moderate spectral purity has already proved to be very informative. This is currently demonstrated by the International Ultraviolet Explorer (IUE). Of course, many new problems are arising that may ultimately require higher spectral purity in these spectral regimes as well.

A good general reference to modern stellar high resolution techniques is the report of the Trieste meeting (Hack, 1978).

Optical Resolved Line Spectrometry. Steps on the way to solar-like quality in optical stellar spectroscopy were the use of double pass échelle scanners (e.g., Smith, 1976), of solar spectrometers for bright stars (Goldberg et al., 1975; Chiu et al., 1977; Freire et al., 1977, 1978), and of the triple Fabry-Perot PEPSIOS Interferometer (Kurucz et al., 1977). Although the spectral purity obtained was sometimes overstated, and, in fact, sometimes inferior to results of careful conventional photographic Coudé spectroscopy (Griffin and Griffin, 1978, 1979b, 1979c, 1980a, 1980b), a recent comparison of four techniques for observing spectral lines of Arcturus (Gray et al., 1979) shows convergence to a new standard of accuracy. The 40 year old solar Utrecht Atlas now has its stellar counterparts in the atlasses of α Boo and α CMI (Griffin, 1968; Griffin and Griffin, 1979a). The latter are based on the highly precise recent photoelectric data from stars.

The best current technique is the use of linear diode arrays, such as the Reticon, in a Coudé or échelle spectrograph, either bare or as the back-end in a Digicon image tube. The first setup is slower for weak exposures in the blue, but superior throughout the optical spectrum when a large signal to noise ratio is required (Vogt et al., 1978). Multielement detection is, of course, much faster than scanning with a single detector, except for Fourier Transform spectrometry which cuts the integration time by putting all spectral elements simultaneously on one detector, marking their identity through modulation. The latter technique, usually in the form of Michelson interferometry, is best in the infrared where detector noise is worse than photon noise, so that diluting it over many spectral elements constitutes Fellgett's (1951) multiplex advantage; but its use for very high spectral purity expands toward the violet. An additional advantage is that the built-in laser offers precise absolute wavelength calibration.

The current breakthrough of optical stellar spectroscopy toward high spectral purity is primarily due to the progress of digital detection technology (see Ford, 1979); but there are also important advances in the techniques of guiding and image slicing, in the fabrication of ghost-free holographic gratings and large échelle gratings, in the design of new spectrometers of various types, and in the automation of data acquisition and reduction. This is a rapidly evolving field, extending solar-like quality spectrometry to more than just the brightest stars; the advent of the large telescopes of the next generation which incorporate the new technology should eventually enable precision spectrometry to be achieved for any type of star.

Nonoptical Spectrometry. In the ultraviolet the best current instruments are BUSS (Kondo et al.,

1979) and IUE (Boggess et al., 1978); both use a cross-dispersed échelle format with a SEC Vidicon detector. These instruments accomplish quality resolved line spectroscopy of nonthermal regimes of outer stellar atmospheres throughout the Hertzsprung-Russell diagram, and their success demonstrates how the capability of using solar-like interpretational diagnostics enriches stellar astrophysics. Higher resolution, precision, and sensitivity will eventually come, for example, with the Space Telescope instrumentation.

At the ends of the spectrum, in the X-ray and radio domains, we have no "resolved line" spectroscopy yet. However, we do have detection of stellar emission at these X-ray and radio wavelengths, though without adequate spectral resolution for detailed diagnostic studies of the sort performed with EUV data. The Einstein Observatory has now filled the Hertzsprung-Russell diagram with stellar coronae (Vaiana et al., 1980); radio detections of active giants and binaries offer new diagnostic possibilities (see Hjellming and Gibson, 1980).

Stellar-Like Solar Spectrometry

The basic techniques of stellar observation are applied to the Sun in a highly precise fashion, taking advantage of the large photon flux. Stokes vector magnetographs, high dispersion, stigmatic mixed order spectrographs, tunable, narrow band imaging filters, imaging hard X-ray spectrometers, and other instruments of this genre are often peculiar to solar physics, without direct stellar application. However, their techniques serve as an example: many instrumental concepts are first tested on the Sun, and then are improved in sensitivity to observe the stars. Such sequences have been followed in most spectral domains, for example, in X-ray instrumentation from the first NRL solar sounding rockets (1949) to the Einstein Observatory, in the ultraviolet from the NRL solar rockets (1946) to IUE, in the radio domain from Christiansen's Cross to the VLA.

The solar parallel to stellar resolved line spectrometry is spatially averaged spectrometry, in which the inhomogeneous fine structure is not resolved. A special solar-stellar issue is the observation of the Sun as an unresolved star, doing away also with the solar center to limb variations. We illustrate these topics in this section by concentrating on optical spectroscopy, because it reaches the highest spectral purity. We shall also discuss two solar optical spectrometers.

Spatially Averaged Solar Spectrometry. Very high spectral resolution ($\lambda/\Delta\lambda > 4 \times 10^5$) and signal to noise ratio (>1000) are obtained at the cost of spatial and temporal resolution, in this solar variety of resolved line spectroscopy. It differs from stellar high resolution flux spectrometry only in its higher precision and its resolution of the center to limb variation. *Line profile shapes* are studied in detail, on the assumption that the spectral details of the spatial and temporal mean are significant. Such spectroscopy of the Sun has been valuble in various aspects.

First, it has been the basis of the development of radiative transfer methodology, from the classical theory of stellar atmopheres to the non-LTE formalisms of today; as such it underlies the classical solar-stellar connection. The assumption that the mean is significant has been quite fruitful in this field. For example, the archetype solar example of this assumption is to use a homogeneous model atmosphere to explain the spatially averaged self reversals of the cores of the Ca II H and K resonance lines. Solar observations of high spatial resolution show that these reversals are due to an intricate fine structure of enormous spatial and temporal variation, of which the mean profile is quite unrepresentative. Nevertheless, modeling the unresolved reversals has been of prime importance in the development of non-LTE and PRD methodology.

Second, spatially averaged solar continuum and line spectroscopy supply the observational constraints for semiempirical one-dimensional modeling, which currently provides the most refined picture of the overall structure of the solar atmosphere. The Ca II H and K lines again furnish an example: one-dimensional models have been derived, for the Sun and for other cool stars, from spatially averaged photoelectric observations of the extended wings of H and K, which span the upper photosphere in their height of formation.

Third, solar spatially averaged spectroscopy is useful in defining stellar nonthermal diagnostics. A Ca II H and K example in this respect is the use of their emission cores as an index to the spatial extent of plage-like areas on the surface of cool stars.

Solar Atlases. A traditional format of solar spatially averaged spectrometry has been the "atlas," and producing atlases of the solar spectrum has been a traditional pastime for solar spectroscopists. Now, with solar physics concentrating on spatially resolved dynamical phenomena, the quest for ultimate atlases of the mean spectrum is less popular; but it should be stressed that such atlases remain useful within the solar-stellar connection, in the definition and solar calibration of spatially averaged spectral diagnostics.

Table 19-1 gives a selection of the currently available solar spectrum atlases. One should note that the "ultimate" atlas has not yet appeared. It should provide the *absolute* intentsity spectrum with high purity, for a selection of disk positions covering the center to limb variation; it should include spectral line identifications; and it should appear on magnetic tape. Ideally, one should have such atlases also of the sunspot spectrum, the mean plage spectrum, etc., for various viewing angles, throughout the spectrum, and with polarization information (cf. Rutten, 1978).

Table 19-1

Solar Spectrum Atlases

Beckers, J.M., Bridges, C.A., Gilliam, L.B., 1976, *A High Resolution Spectral Atlas of the Solar Irradiance from 380 to 700 Nanometers,* Sacramento Peak Observatory, Sunspot.

Optical flux spectrum; graphical edition with line identifications; tabular edition with intensity calibration; also on magnetic tape.

Brault, J.W., Testerman, L., 1972, *Kitt Peak Solar Atlas 2942 to 10014 Å, Preliminary Edition,* Kitt Peak National Observatory, Tucson.

Optical intensity spectrum, for the viewing angles μ = 1 and μ = 0.2; no calibration; available only on microfilm.

Delbouille, L., Roland, G., 1963, *Photometric Atlas of the Solar Spectrum from λ 7498 to λ 12016,* Institut d'Astrophysique, Liège.

Near-infrared intensity spectrum of the center of the disk; no calibration.

Delbouille, L., Roland, G., Neven, L., 1973, *Photometric Atlas of the Solar Spectrum from λ 3000 to λ 10000,* Institut d'Astrophysique, Liège.

Optical spectrum of the center of the disk; yet incomplete; available also on magnetic tape.

Hall, D.N.B., 1970, *An Atlas of Infrared Spectra of the Solar Photosphere and of Sunspot Umbrae, in the Spectral Intervals 4040-5095, 5550-6700, 7400-8790 cm^{-1},* Kitt Peak National Observatory, Tucson.

Infrared intensity spectrum of the photosphere, of sunspots, and their ratio, near the center of the disk; no calibration; line identifications added; also on magnetic tape.

Kohl, J.L., Parkinson, W.H., Kurucz, R.L., 1978, *Center and Limb Solar Spectrum in High Spectral Resolution 225.2 nm - 319.6 nm,* Center for Astrophysics, Cambridge, Mass.

UV intensity spectrum for viewing angles μ = 1 and μ = 0.23; intensity calibration; line identifications and LTE prediction added; also on magnetic tape.

Migeotte, M., Neven, L., Swensson, J., 1956, *The Solar Spectrum from 2.8 to 23.7 Microns,* Institut d'Astrophysique, Liege.

Infrared intensity spectrum of the center of the disk; no calibration.

Tousey, R., Milone, E.F., Purcell, J.D., Palm Schneider, W., Tilford, S.G., 1974, *An Atlas of the Solar Ultraviolet Spectrum between 2226 and 2992 Angstroms,* Naval Research Laboratory, Washington, D.C.

UV flux spectrum; intensity calibration.

Solar Spectrometers. We discuss two particular solar optical spectrometers, each of which represents the state of the art within its domain, and each of which sets an example for stellar spectrometer design. The first is the Kitt Peak Fourier Transform Spectrometer (Brault, 1978), which is built for spectral purity. It is a one-meter path difference Michelson interferometer, unsurpassed in spectral resolution, cleanliness of the instrumental profile, spectral range, and wavelength precision, and it is also usable for polarization measurements, even as a full Stokes polarimeter. However, it has no stigmatic capability. Two-dimensional imaging is feasible through replacing the single detector by an array detector, resulting in a Fourier Transform Spectrometer-per-pixel, but at the cost of an "embarrassingly large" data flow to be transformed by computer afterward. The instrument is the ultimate device for spatially averaged spectroscopy. It should soon produce the ultimate mean intensity solar spectral atlas defined above; and it is a direct and inspiring example to stellar high resolution spectroscopy.

The second example is the Sacramento Peak Échelle Spectrograph (Dunn, 1969), which, in contrast, was built for spatial imaging. The instantaneous imaging is one-dimensional, along the slit over which the solar image is stepped to build up a two-dimensional image. The advantage over two-dimensional filtergrams is that the full spectral detail is present. An important feature is the flexible selection of spectral diagnostics. This is important, because on one hand detection of a full-length spectrum at high resolution, in wavelength as well as in position along the slit, is quite unmanageable; and, on the other hand, diagnostically sound studies of solar phenomena usually require simultaneous observation of specially selected segments of the spectrum. This is because line profile diagnostics are never unique, requiring line pairs, for example, Ca II H and K together with the Ca II infrared multiplet (see Athay, 1976). The same holds for stellar interpretation, making free selection of spectral features desirable. In the Sacramento Peak spectrograph this selection is achieved by using the orders of an échelle grating without cross-dispersion. All orders overlap, and one may select short spectral ranges from each with narrow band filters, or with slits in a parallel predisperser spectrum. As a result, virtually any combination of specially chosen diagnostic lines, of widely different wavelengths, can be selected to lie close together on film or on a detector array. The same trick applied to stellar spectrometers results in the same advantage: high resolution detection of only those lines chosen, limiting the data flow, from the 10^6-10^7 pixels needed to detect a two-dimensional IUE-like échelle format working in crossed dispersion at full resolution, to only 10^3-10^4 *selected* pixels that are linearly arranged.

How to Observe the Solar Flux Spectrum. Observations of the solar flux (integrated sunlight, solar irradiance) have, in addition to applications in cometary and planetary physics, a two-fold astrophysical utilization: they reflect global properties of solar parameters, such as the magnetic field or the coronal heating rate, and they serve as an intermediate step between solar and stellar atmospheric diagnostics.

Interest in the former aspect has increased markedly in recent years with the recognition of the importance of solar variability, particularly over the solar rotation period, over the solar activity cycle, or over even longer intervals, and with the parallel increase of interest in stellar activity cycles prompted by O.C. Wilson's (e.g., 1978) monitoring of stellar Ca II H and K emission. A general reference to this subject is the excellent collection of reviews of the Solar Output Workshop in "The Solar Output and Its Variations" (White, 1977).

Interest in the latter aspect rises with the need to translate solar astrophysics into stellar diagnostics of nonthermal phenomena, as stressed above.

Although, perhaps surprisingly, it is not easy to observe the solar flux spectrum, there are various schemes available. We will briefly discuss them following Oranje (1981). One may observe the Moon with a stellar spectrograph (Wilson, 1978), or more stellar-like solar system objects such as Uranus and Neptune, which have a higher albedo. One is then limited by the low spectral purity, by solar standards, of the instrument. Another method is to use a solar spectrometer and add together spectra covering the whole disk (Sheeley, 1967), but this is very laborious. Ideally one should like to convert a normal solar intensity spectrometer into a flux spectrometer without sacrificing its spectral purity, but this is not trivial. If one discards the telescope objective to feed the solar irradiance onto the spectrograph slit (Bumba et al., 1967; Severny, 1969; Livingston et al., 1977; White and Livingston, 1978), a pinhole solar image is produced on the grating. Grating inhomogeneities will affect the weighting over the solar disk, and the slit should be either wide enough so that diffracted limb photons do not miss the grating, or narrow enough that they fall within the flat top of the diffraction pattern (White and Livingston, 1978). In the first case there is loss of resolution; in the second, loss of photons. Bappu and Sivaraman (1977) used a diffusing screen, also with large loss of light. Jebsen and Mitchell (1978) employed twelve flat mirrors to put multiple images on the grating. Beckers et al., (1976, volume I) avoided the imaging on the grating by using a microscope objective to project a 50 μm solar image between the slit jaws, but found that too much light was lost at the grating because of the mismatch in f ratio of the telescope and the spectrograph. Their flux atlas (Beckers et al., 1976, volume II) was made instead with a cylindrical lens giving a 50 μm line image parallel to the slit ("the world's smallest and most astigmatic solar telescope"). A pinhole image is then still present along the ruling of the grating.

It is also of interest to achieve partial integration, for instance, only over active regions, or over the quiet areas alone. Oranje (1981) uses a combination of White's (1964) averaging technique and the slit illumination of Beckers et al., (1976) with a cylindrical lens, to obtain spatial averages of freely chosen parts of the disk.

Solar Flux Diagnostics of Nonthermal Phenomena

What would we have known of the solar atmosphere if we had only been able to observe the Sun as we observe the other stars? We would have compared the solar flux spectrum to the predictions of equilibrium model atmospheres and, in the era of ground based astronomy, would have concluded that these models are quite good, disagreeing only in details such as the predicted width of the lines and the shape of the cores of the strongest resonance lines. In the era of space observations the discovery of an extended, hot, and highly variable outer atmosphere would have been a surprise. We would yet have no inkling of the utterly discrete nature of the magnetic field, and its consequential importance in setting the inhomogeneous structure of the outer atmosphere and the activity phenomena.

This would be our current situation for the other stars, except for the fact that we do resolve solar fine structure, and through solar-stellar analogy we *can* surmise more of stellar nonthermal structure than by flux spectroscopy alone. Thus, in discussing solar flux spectroscopy, the question of interest is how its diagnostics represent the actual inhomogeneous structure, and whether they contain information on the underlying processes.

We restrict our discussion to three topics, each representative of an atmospheric regime: turbulence as a measure of subphotospheric dynamics, chromospheric emission features as a diagnostic of the amount of surface magnetic flux, and X-ray emission as a diagnostic to the large-scale topology of the coronal magnetic field. We discuss the first of these diagnostics, turbulence, in most detail because it is the most unsatisfactory; the other ones are covered in detail in the chapters of Part II.

Subphotospheric Dynamics and Turbulence. The major nonequilibrium aspect of the solar photosphere is that it is in a continuous, very complex state of motion. Chapter 2 by Beckers and

Chapter 3 by Deubner review the many resolved contributions: differential rotation, granulation and supergranulation, various oscillations, and possibly pulsations and large-scale flows. In addition, there are the (currently) unresolved motions inferred from residual line broadening, line asymmetries, and the variation of line wavelength shifts from disk center to the limb (Chapter 2). Each of these separate components represents a highly complex gasdynamical phenomenon requiring detailed analysis; but in the solar flux spectrum their only signatures are nonthermal line broadening, line asymmetries, and line shifts. The first, in the form of "turbulence," is most familiar and will be discussed here; but, in fact, the other two diagnostics are much more promising to nonequilibrium studies of stellar photospheres. For example, detailed properties of convective motions, changes of granular contrast with wavelength, etc. can be diagnosed from the bisector shape and shift of various classes of lines in solar flux spectra (Dravins et al., 1980); precise monitoring of very small wavelength shifts in the solar flux spectrum resolves the discrete 5-minute oscillation modes of high radial and low azimuthal order (Claverie et al., 1979).

Beckers summarizes the various contributions of solar motion fields to the total kinematic power, for two heights in the photosphere in Figures 2-11 and 2-12. These graphs are schematic rather than definite; but they show that in the deep photosphere granulation is the dominant contributor of the resolved motions. If the "limb effect" is also of granular origin (Chapter 2), granulation constitutes the larger part of the total power. At the higher level (Figure 2-12), the 5-minute oscillation contributes significantly to the total vertical power. This indicates that granular and oscillatory motions make up a significant part of spatially averaged line broadening measured as "turbulence." Indeed, there is a lively debate now whether or not all solar turbulence can be explained by granulation alone (Nordlund, 1980), or by granulation and 5-minute oscillations together (e.g., Mattig, 1980), or whether there is an appreciable amount of "microvelocities" present also (e.g. Keil, 1980; Cram et al., 1979). Such a component has been tentatively included as a Kolmogoroff turbulence spectrum in Beckers's Figures 2-11 and 2-12.

This leads to the conclusion that granulation and oscillations are at least important contributors to turbulence and to the suggestion therefore that the nonthermal broadening of lines in the flux spectrum could be a useful stellar diagnostic of the dynamics of subphotospheric layers, where both phenomena arise in the case of the Sun. Eventually this prospect may come true, but in practice turbulence is not at all a useful diagnostic yet. This negative view will be briefly advocated here because, while everybody knows that turbulence is an unpleasant ad hoc parameter, the solar example clarifies just how suspect its usage is.

Turbulence is of course nothing but a convenient parameterization of poorly understood line broadening that has no physical meaning in itself. It just indicates the size of the errors made by equilibrium modeling. The neglect of nonthermal motions contributes to these errors, but not exclusively. At best, turbulence gives a rough indication of their general magnitude; at worst, turbulence measures modeling errors that have nothing to do with gasdynamics. Such errors can arise from neglecting departures from LTE or from complete redistribution, or from the use of incorrect damping formalisms, or from other invalid assumptions or procedures in spectral line computation which show up in the comparison with observations.

The turbulence formalism itself is correct only for stochastic "truly" turbulent motions, which are certainly not the only constituent of solar turbulence, nor of the line broadening of supergiants for which the "turbulence" tends to be highly supersonic (see Gray, 1978). (The solar turbulence does nowhere exceed the sound speed much, although it equals it in the transition region; see Figure 4-9 of Chapter 4 by Athay.) The assumption that a convolution suffices (for the local line absorption coefficient for microturbulence, with the emergent line profile for macroturbulence) neglects correlations of motions with brightness fluctuations or with temperature and pressure variations, as, in fact, are observed to occur in granulation. There is no reason to apply only the micro and macro "filters" and leave out the "meso"-scale motions; also, what is macro- or mesoscale to one line, or to one part of a line, will be microscale to another (see Canfield and Beckers, 1976).

Such distrust is strengthened by judging turbulence in the solar-stellar connection. A stellar-like measurement of the solar turbulence (Gray, 1977) gives values of turbulence parameters which differ significantly from the best solar determination of comparable interpretational simplicity (Holweger et al., 1978). The latter analysis employs observed equivalent widths in an LTE study which attributes residual discrepancies only to erroneous oscillator strengths, deriving solar microturbulent and macroturbulent values regarded as definitive. However, such complacency vanishes with increased sophistication, observationally or interpretationally, because one then finds that not the certainty but the uncertainty of the turbulence increases. In studying spatially averaged line profiles from the Sun, there are many more observables than in studying equivalent widths, but they do not increase redundancy, because the number of free fudge parameters in the solar turbulence formalism is just increased accordingly. Stellar microturbulence is usually a single constant, derived from the location of the shoulder of the curve of growth; in contrast solar microturbulence is taken to be a rapidly varying function of both height and viewing angle (see Figure 2-10 of Chapter 2 by Beckers). While these dependences are, of course, present in the processes which underly line broadening, and so should indeed be incorporated, we stress that so far solar turbulence modeling employs these dependences purely to increase fitting freedom: an increase of observational sophistication leading to an increase of fudging, not of understanding. A similar setback accompanies an increase in interpretational sophistication. In PRD line computations, it is not all clear to what extent turbulence affects redistribution in frequency and angle. It is commonly assumed that microturbulence acts just as thermal motions in Doppler redistribution, but Magnan (1975) has shown this to be incorrect, and it may well be that the extent of frequency redistribution through random nonthermal motions differs much from the case in which "turbulence" corrects erroneous line widths. For example, Rutten and Milkey (1979) find that the microturbulence above the temperature minimum cannot be equated with Doppler redistribution of lines seen near the limb. Thus, the interpretational progress from CRD to PRD line computation implies, unfortunately, increased sensitivity to the conceptual errors of turbulence, just as it implies increased sensitivity to the poorly known collisional damping.

Altogether, there is no doubt that the granulation and the 5-minute oscillation contribute a significant part of the photospheric turbulence, but proper modeling of these components is a prerequisite before studying what is left when they are taken out, and before employing observed stellar turbulence as a *physical* diagnostic of stellar photospheric or subphotospheric dynamics.

Chromospheric Diagnostics and the Magnetic Field. However we define the chromosphere (see the opening section of Chapter 4 by Athay), it is the layer where the existence of a nonthermal outer atmosphere becomes evident. Any chromospheric diagnostic is, therefore, a nonthermal one, noting that the chromosphere lies between the almost thermal photosphere and the utterly nonthermal transition zone-corona-wind complex above it. Spectral signatures of the chromosphere generally remain unchanged when spatially integrated. Such characteristics are the emission peaks in the Ca II H and K lines and the helium lines in the optical spectrum, the Mg II h and k cores in the UV, and a multitude of EUV emission lines (see Chapter 4 by Athay for details).

Shifting upward from photosphere to chromosphere, there is a bifurcation in the inhomogeneous structure that leaves its marks on the flux spectrum. As with the photospheric granulation and oscillations, there is a globally present, more or less evenly distributed component in the form of the quiet Sun network; but the chromospheric flux diagnostics are also sensitive to the presence of active regions on the disk. These leave no clear signature in the photospheric flux spectrum. There is, therefore, an irregularly patterned, spatially and temporally varying extra component, which modulates the flux diagnostics with extra information. For example, the strengths of the solar Ca II H and K and Mg II h and k flux profile core emissions correlate well with the total plage area which varies with activity, thus permitting one to monitor stellar activity cycles, of which Wilson's (1978) compilation is the landmark example. Such monitoring can also yield stellar active region statistics, and the rotation periods of slowly rotating stars (see Chapter 6 by Zwaan). Yet, the chromospheric flux diagnostics contain more information than just the total plage area. As discussed by Athay in Chapter 4, plages appear very different in different lines and in different parts of the same line, depending on the particular height of formation, temperature sensitivity, and density sensitivity of the spectral features. Thus, there are observational constraints to plage structure. This is extremely important because such studies may give insight into the chromospheric properties of the *magnetic field* of solar-like stars.

The magnetic field generally plays no major role in determining the large-scale structure of the photosphere where gas pressure dominates, but it is concentrated there in the tiny, strong field flux tubes, and organized into the network and activity patterns which set the structure of the corona, in which the magnetic pressure dominates. It is in the chromosphere that we observe the transition. Observational diagnostics for studying the structure and dynamics of the flaring flux tubes and their discrete patterns are needed in order to tie the domains together, connecting the large-scale nonthermal structure of the outer atmosphere to the subphotospheric dynamical processes in which it is rooted.

X-Ray Emission and the Coronal Topology. The current X-ray survey of stellar coronae by the Einstein Observatory represents a landmark in the study of nonthermal outer atmospheres of cool stars, just as the Skylab X-ray data represented a landmark in the study of the solar corona. Zirker, in discussing observations of the corona and the wind in Chapter 5, poses the following major questions: Where and how is the corona heated? Where and how is the solar wind accelerated? Why do the corona and the wind change with time scales ranging from hours to decades? Does the solar magnetic field influence the equilibrium of the solar corona and the wind in an essential way? Obviously, X-ray observations have played a major part in the posing of these questions, and they will certainly contribute to their answers. The same holds for the problems posed by solar flares, of which the observations are discussed in Chapter 7 by Brown, Smith, and Spicer.

The large-scale pattern of inhomogeneous structure that leaves signatures in the solar flux spectrum increases further in complexity from chromosphere to corona: from bifurcation (network and active regions) to the trifurcation of the solar corona reviewed by Zirker: quiet corona, active regions, and coronal holes. This pattern again modulates the flux spectrum in time, so that disentangling similar components in stellar flux spectra is perhaps feasible; and again there are many spectral characteristics which may enable the physical modeling of each component for stars too. Unfortunately, however, there is still no direct diagnostic of the magnetic field, which controls the physics of the corona to a large degree (Chapters 5 and 14). Accepting that the X-ray fine structure follows the field patterns closely, it is clear that there is an essential split into open streamer configurations underlying the holes and the wind, and the closed loop configurations of the active and quiet regions; but, as Zirker points out in the last section of Chapter 5 by quoting Chiuderi et al. (1977), knowledge of the field alignment alone does not suffice to understand the field's structure. Monitoring the X-ray emission of other stars with solar-like coronae may help, by establishing how such large-scale field configurations may vary from star to star.

This overview of solar-stellar observation leads to the conclusion that current observations of the Sun and the stars have greatly broadened the subject of nonequilibrium astrophysics. We can anticipate an exciting decade of discovery on the nature of the interaction of a star with its environment, on the physics of nonthermal stellar atmospheres, and on stellar structure. These prospects are discussed in the following sections.

THE SUN AS AN ASTROPHYSICAL LABORATORY

As emphasized above, the excitement of solar astrophysics lies in the fact that the Sun, almost uniquely in the cosmos, lets us study, in detail, astrophysical processes on the scale and in the environment that is of astrophysical interest. Because of this, solar studies have very often provided both inspiration for and crucial tests of concepts that later have become important in the general framework of astrophysics. We are sure that solar astrophysics will continue to represent a major contribution to general astrophysics as new solar phenomena are discovered, and as long-known phenomena are observed with better instruments, and interpreted with improved theories.

In the section, we discuss several examples of solar investigators that have become, or clearly soon will become, of interest in general astrophysics. Rather than attempt to provide a detailed map of the "two-way street" joining solar and stellar astrophysics (this would amount to a major astrophysical treatise), we will focus on only a few areas of solar research, and discuss their astrophysical implications based on foundations laid in the previous chapters of this volume. We propose to discuss three broad areas:

1. Non-LTE radiative transfer theory, because this is a relatively recently introduced and widely used astrophysical theory with deep roots in solar physics, which is now "mature" and which has led to a "revolution" in the study of stellar atmospheres (Mihalas, 1974).
2. Compressible, radiative gasdynamics, because this is a field of enormous contemporary interest in astrophysics, and several solar studies have had a strong impact on current ideas in the fields of convection, atmospheric oscillations, and the nature of solar mass loss.
3. Magnetogasdynamics and plasma physics, because it is becoming more apparent that this very difficult field will assume ever increasing importance in astrophysics, and solar studies clearly have enormous potential to shed light on important aspects of this discipline.

In this section we will constantly refer to previous chapters of this book. Our objective here is not to summarize these previous sections, but to place the predominantly solar flavor of those sections squarely in the broader astrophysical context. The final section of this chapter will extend this program by trying to place the Sun itself in the context of other stars.

Non-LTE Radiative Transfer

None-LTE radiative transfer theory has been with us for a long time. For example, Milne (1930) wrote down the equations of statistical equilibrium and radiative transfer in terms of atomic rate coefficients, and showed how the source function consisted of a nonlocal "scattering" part, and a local "collisional" part. However, Milne did not recognize the importance of the nonlocal nature of the scattering part, and so he became one of the early proponents of the restrictive and often invalid assumption of LTE. Although many of the first users of LTE were aware of its pitfalls, the concept became engrained in astrophysics during the period 1930-1960, and many spirited defenses of it were exhibited. It remained for astronomers seeking to understand the physics of the solar chromosphere to demonstrate the inadequacy of both the attempts to justify LTE, and the use of LTE itself, in more general studies of radiative transfer in stellar atmospheres.

Another early direction of non-LTE research involved the study of radiative transfer in gaseous nebulae by Menzel and his coworkers (e.g., Menzel, 1966). This work, which led to many important advances in fundamental atomic physics, was restricted by the lack of suitable analytical tools to algebraic solutions of the statistical equilibrium equations. Thus, only limiting cases of optically thick or optically thin media were studied. This limitation led to erroneous conclusions about the structure of the solar chromosphere (see Thomas and Athay, 1961).

It was the extension of this work by Menzel and his coworkers into the domain of optically thick, but not totally opaque, spectral line formation that marked a turning point in the use of non-LTE methods. This extension was initiated by the desire of Thomas and his coworkers (e.g., Thomas and Athay, 1961; Thomas, 1965) to provide a reliable analysis of spectroscopic observations of the solar chromosphere at a total solar eclipse. It was shown that these data demanded chromospheric physical conditions that invalidated the assumption of LTE, and a crude non-LTE diagnostic scheme was gradually assembled. By considering microscopic processes in detail, the solar physicists provided a self-consistent model of the solar chromosphere which was quite unlike previous models (Thomas and Athay 1961, Chapter 9), and which bears a close similarity to modern refined models (Praderie and Thomas, 1976; Vernazza et al., 1976).

It is important to emphasize that prior to this analysis, apparently self-consistent analyses of eclipse observations had been made, giving completely erroneous results. It was only by developing self-consistent and physically-appropriate diagnostics that these errors were revealed. It seems very probable that contemporary astrophysics contains other examples of this kind; we will identify a few candidates in the later parts of this section.

Nowadays, of course, non-LTE methods are used routinely in the spectroscopic study of stellar chromospheres (e.g., Linsky, 1980). However, there has been strong resistance to the idea that non-LTE methods must be used in studies of stellar photospheres, often "justified" by physical arguments. The experience gained in solar chromospheric studies should make us wary of any post hoc attempt to justify LTE. It is true that there are distinct advantages in the simplicity of LTE methods, but simplicity is not a valid reason for adopting a diagnostic technique. The invalid assumption of LTE may be responsible for errors in the inference of stellar atmospheric temperatures, gravities, and even abundances (e.g., Mihalas and Athay, 1973). There is no doubt that the use of LTE in the construction of model stellar atmospheres renders these models most uncertain in precisely those layers where important spectral lines are formed, and where it is particularly desirable to identify any deviations from radiative equilibrium that results from nonradiative heating (see Jordan, Chapter 12).

Although one may regard non-LTE theory as a mature field, it is important to realize that there are still important unsolved problems. Thomas and Athay (1961, chapter 10) listed four important limitations to the early non-LTE work, and we can now identify several others that have been investigated, and will be studied still further in the future.

The Influence of Systematic Velocity Fields. One of the main causes of asymmetries in solar and stellar spectral lines is the existence of systematic velocity gradients in the radiating atmospheres. Such velocity fields enter the equations of non-LTE radiative transfer in several places, and while there has been a lot of work on the general problem of velocity fields and spectral line formation, much remains to be done, both in the study of idealized problems and in the application of refined diagnostics to the interpretation of high quality spectroscopic data.

The primary effect of a velocity field is to Doppler-shift the line absorption profile. Since the solar atmosphere contains a three-dimensional, time-dependent macroscopic velocity field, the emerging spectral line profile is strongly distorted. It is impossible (in theory and in practice) to deduce precisely the three-dimensional atmospheric velocity field from observations of the emergent spectrum. Nevertheless, there have been many studies that relate properties of the emergent line profiles to atmospheric velocity fields via crude diagnostic methods (e.g., the displacement of the line profile bisector), and these have contributed to our understanding of the physical processes occurring in the solar atmosphere. These crude diagnostics are most reliable when they address the formation of spectral lines in the presence of small velocity gradients along the line of sight, and arising from spatially resolved structures in the field of view.

A second effect of a velocity field that is peculiar to non-LTE line formation is the coupling between the amplitude of the line sources function and the velocity field that results from the appearance of the absorption profile in the scattering integral. Athay (1970a) and others have shown that, because of the symmetry of the absorption profile in the local rest frame, this coupling is relatively weak. It may even be safely neglected in studies that are concerned solely with the inference of velocity fields from line shifts and asymmetries; but it is clear that even a weak coupling cannot be ignored in studies that correlate the line shifts and intensity changes, since the latter may result from pressure and temperature changes, and in part from the velocity fields themselves, and the two effects must be disentangled.

A third effect, which is not peculiar to non-LTE (although it is strongly modified by non-LTE effects), is the coupling of the Doppler shifts in the line absorption profile to changes in the shape and strength of the line produced by temperature and pressure fluctuations that must accompany the velocity fields. Many studies of the formation of solar spectral lines, and essentially all studies of the formation of stellar spectral lines, adopt what Cram et al. (1979) called the "kinematic" approximation, in which it is assumed that the only effect of atmospheric dynamical processes is a Doppler shift. But in many circumstances, there are strong correlations between Doppler shifts due to velocity fields and line shape changes due to other factors which lead to diagnostically important consequences. Among these are (1) the solar limb shift, which appears to result from intensity-Doppler shift correlations in the solar granulation (see Beckers, Chapter 2), and (2) the asymmetry of the flux profile of the solar Ca II K line, which appears to result from temperature-velocity-pressure correlations in waves in the solar chromosphere (Cram et al., 1977). Both of these phenomena require further study in the solar atmosphere, since both promise to provide powerful diagnostic tools to study analogous small-scale processes in stellar atmospheres (e.g. Dravins, 1974; Stencel and Mullan, 1980). The entire murky field of stellar atmospheric "turbulence" involves precisely the problems alluded to in this paragraph. It is unlikely that our understanding of this phenomenon will be clarified until reliable dynamical models are coupled with accurate radiative transfer solutions, so that the range of temperature-pressure-velocity interactions in the line formation process can be categorized, and the ones that are relevant in "turbulence" thus identified.

A fourth effect of velocity fields in non-LTE theory is the introduction of time-dependent terms into the equations of statistical equilibrium. Numericaly, the inclusion of these terms is quite straightforward (e.g., Cannon and Cram, 1974) and they may, in some circumstances, lead to important effects. The time evolution of level populations is of particular importance in diagnostics of the chromosphere-corona transition zone in the presence of dynamical processes, because atoms moving through the steep temperature and density gradients are ionized and recombine in radically different environments (Raymond and Dupree, 1978).

The Assumption of Complete Redistribution (CRD). Much work has been devoted to the relaxation of this assumption. Phenomenological models for partial redistribution (PRD) were developed by Hummer (1962), and the past decade or so has seen the introduction of powerful numerical methods that can account for the frequency and angular dependence of the source function that is implied by Hummer's models. There are certain circumstances in which PRD line formation models are significantly different from CRD models (see Mihalas, 1978). One of the diagnostically important circumtances involves the inner wings of strong resonance lines; examples that have received a lot of study in the solar atmosphere include the Hydrogen Lyman lines (Basri et al., 1979), and the resonance doublets of Mg II and Ca II (Shine et al., 1975). There are significant effects on both the absolute intensity and the limb darkening of these inner wings, and the use of PRD methods has resolved a number of hitherto perplexing problems on the formation of these lines in the solar atmosphere (e.g., Vardavas and Cram, 1974).

The introduction of PRD diagnostics into research on strong resonance lines in stellar chromospheres has also led to significant changes there (Linsky, 1980). An important example is is the inference of stellar atmospheric temperature minima: CRD diagnostics based on the inner wings of Ca II and Mg II lines generally lead to models that are too cool, and thus lead to major errors in estimates of the nonradiative heating (or cooling) of the upper photosphere and lower chromosphere. A second example is the fact that the outer edges of the Ca II resonance line emission cores are steeper in PRD models; this feature is important in the Wilson-Bappu effect (e.g., Wilson, 1973, p. 331), and its successful modeling has given astronomers greater confidence in their understanding of this important phenomenon (Ayres, 1979). Several unsolved problems remain in the theory and application of PRD non-LTE methods, and it is probable that significant errors are still being made in both solar and stellar diagnostics because of inadequate treatments of scattering in the formation of spectral lines and continua.

The Use of the Equivalent Two-Level Atom Formulation. While much of the basic physics of non-LTE theory can be illustrated with this crude atomic model, there are only a few spectral lines that may be quantitatively diagnosed with it (these include Ca II, Mg II, and Na I resonance lines in cool stars, and some of the prominent UV resonance lines in hot stars). A detailed account of the various effects of multilevel structure may be found in Athay (1972; also see Chapter 4). Examples of studies that have used multilevel models include Lites (1972, solar Fe I), Cram et al. (1980, solar Fe II), Vernazza et al. (1980, solar H I and other species), and stellar work by Mihalas and coworkers (e.g. Mihalas, 1978).

The basic influence of multilevel structure is to provide alternative paths for atoms to arrive in, or to leave from, a particular atomic configuration. These paths may involve comparable rates, and an accurate quantitative value for the level population is determined only by including all of them. The values of level populations influence the ionization equilibrium, the source function, and the line optical depth scales. Current refined models of the upper photosphere and temperature minimum regions of the solar atmosphere are strongly influenced by the multilevel, non-LTE ionization equilibrium of the dominant electron donors (Vernazza et al., 1980). A similar multilevel, multispecies treatment of the upper photosphere and temperature minimum region will have to be introduced in stellar models when attempts are made to refine atmospheric models on the basis of observations of their UV continua.

The Use of a Plane-Parallel Model Atmosphere. The obvious structuring of the solar surface when observed with high spatial resolution invites an attempt to study radiative transfer in model atmospheres that are not only radially inhomogeneous, but all structured in the horizontal direction. There are several studies of such "multidimensional" radiative transfer based on the assumption of LTE. Even in this simple case, there are subtle, nonlinear effects that demonstrate the need for great caution in the interpretation of the radiation field emitted from a structured atmosphere (e.g. Wilson and Williams, 1972).

Theoretical studies of non-LTE radiative transfer in structured model atmospheres have uncovered even greater subtleties, and illustrative examples have been published showing that one might even infer that a structure is cool and falling when it is, in fact, hot and rising (Cannon, 1976). A recent study by Kneer (1980) shows that nonlocal control of the non-LTE source function can lead to important smoothing of the radiation field, so that the observed emergent intensity does not accurately reflect the structure of the underlying state variables. Naturally, this effect will be important in solar studies, where we wish to interpret spatially resolved observations. It will also be important in stellar diagnostics, since the mean values may be distorted by the horizontal radiative transfer. However, the non-LTE aspects of multidimensional radiative transfer may not be of prime importance. Rather, the greatest diagnostic challenge arises because the very existence of atmospheric inhomogeneities leads to major uncertainties, as a result of the nonunique and nonlinear relations between the atmospheric state variables and the flux-integrated emergent radiation, even if LTE is valid (e.g., Mihalas et al., 1978; Nelson, 1978).

Incorporation of Non-LTE into Gasdynamic Models. Radiative gasdynamics, even within the limits of LTE, is a difficult subject. Theoretical and observational studies in the terrestrial laboratory have led to the development of a number of important concepts (e.g., Pomraning, 1973), but there are several differences between the terrestrial and the solar astrophysical environment that can be clarified only by special studies. Most important among these is the fact that radiation dominates the energy equation in most parts of a stellar atmosphere, while in the laboratory the radiation is typically a small part of the energy equation. Moreover, the energetically important radiation fields in stellar atmospheres are generally neither optically thin nor optically thick, so that there is an intimate coupling between the gasdynamics and the radiative transfer.

Non-LTE further complicates the above picture. The two main effects of non-LTE in radiative gasdynamics are (1) the nonlocal radiative control of the state of the gas, and (2) the introduction of new spatial and temporal scales. The first effect is manisfested in, for example, an equation of state that cannot be written in terms of purely local variables; moreover, the extensive properties of the atmospheric plasma (such as specific heat, opacity, etc.) cannot be locally specified, nor can they be tabulated. The second effect leads to new dynamical phenomena, such as the precursors described by Klein et al. (1976). There is a pressing need for further exploratory studies of radiative gasdynamics with both LTE and non-LTE radiative transfer. Without these studies, we will never develop the physical insight necessary to account for such important processes as solar and stellar chromospheric heating and mass loss.

Radiative Transfer in the Presence of Magnetic and Electric Fields. The most direct way to study the magnetic and electric fields in the solar atmosphere is to study the signature they imprint on the shape and state of polarization of spectral line profiles. The longitudinal Zeeman effect has been usefully exploited in many studies of the structure and evolution of the photospheric magnetic fields, and there have been a few successful attempts to perform vector magnetic field measurements. Unfortunately, to date, all of these studies are compromised by the absence of a reliable diagnostic program that can let the observer relate the observed spectral properties to atmospheric magnetic fields with confidence.

The provision of adequate diagnostics will require work in several directions. While there are phenomenological models for the interaction of radiation with atoms in the presence of magnetic and electric fields, there is, as yet, no axiomatic quantum theory (Landi and Landi, 1975). This deficiency is a source of concern, since there may be collective effects that can significantly influence the polarization signature and the damping of spectral lines. Related problems stem from the absence of a satisfactory theory for collisional rates among atomic substates; uncertainties in these rates may lead to important diagnostic errors in non-LTE analyses. There are other difficulties related to the fact that the non-LTE problem for polarized light must treat the atomic sublevels separately, so that the problem is intrinsically multilevel, and accurate diagnostics (as opposed to exploratory studies) require advanced computational techniques. It is evident that the observational study of solar atmospheric magnetic fields (and, in the future, macroscopic electric fields) will be retarded until there are major advances in our understanding of non-LTE radiative transfer in the presence of such fields. Solar studies will continue to provide almost all quantitative data on magnetic fields in stellar atmospheres, since there are major problems to be solved before we can hope to measure the structured magnetic fields of other stars (see Robinson et al., 1980). Nevertheless, it is important that we have a good understanding of the diagnostic problem to allow the reliable interpretation of the existing kinds of stellar observation.

In summary, we see that while there have been impressive improvements in our understanding of non-LTE radiative transfer theory, there are still important problems that require further study. One of the most difficult aspects of non-LTE theory is the fact that, ultimately, a comprehensive and quantitative diagnostic scheme will certainly require that many of the above problems be solved simultaneously. While this may be feasible with the latest computers and numerical techniques (e.g. Cannon, 1976), one wonders whether there is not another more effective way to proceed. We would like to suggest that a judicious mixture of refined studies of idealized model problems with a coarser application in the analysis of the actual atmospheric state may be fruitful, using the refined studies to isolate the important processes and to show which effects may be safely neglected in a given situation. Solar studies will be of particular importance in such a program, since they can be used to guide the selection of relevant parameters in refined studies and, then, to evaluate the errors and uncertainties that are made in coarser applications. It is probable that the next few years will see a tendency to use detailed solar studies to understand or even to calibrate the necessarily coarser diagnostics used in stellar studies. Such symbiosis promises to lead to major improvements in our understanding of such persistent problems as stellar atmospheric "turbulence."

Radiative Gasdynamics

The Sun and most other stars (neutron stars and the cores of white dwarfs are notable exceptions) are composed entirely of a compressible gas, whose state is strongly influenced by radiative energy transfer. The fundamental equations describing the behavior of such a physical system may be readily derived (e.g. Burgers, 1969), and there is no major controversy associated with this procedure. On the other hand, as emphasized by Liepmann (1979), these equations admit an enormous variety of solutions. The central problem of cosmical gasdynamics, then, is to follow a line of investigation that extracts from this host of solutions those that are most relevant in astrophysics. Observations should be used to make this selection; too often, theorists have appealed to simplicity and tractability of the simplified system.

The diversity of modern studies of radiative gasdynamics in the context of the Sun and other stars has been displayed in several chapters of this volume. Here, we propose to summarize three classes of problems discussed in those chapters, with an emphasis on the role played by solar studies as the prototype for studies of other stars.

Convection. Among the most fundamental of astrophysical concepts are those related to the interpretation of the Hertzprung-Russell diagram in terms of stellar evolution. These concepts rest squarely on the theory of convection in stars, since convection plays a dominant role in energy transport at some time in the life of all stars, and is responsible for the internal mixing of processed nuclei that is thought to account for the circuitous path of a star as it evolves in the H-R plane. The Sun provides us with a unique laboratory, where we may study stellar convection close up; it is sobering to find that there is little, if any, correspondence between the nature of solar convection as we observe it, and the theoretical descriptions that are the basis of stellar convection theory.

This disparity is not necessarily important. For example, Gough (1977) and others have pointed out that, for the most part, the interior of a convecting star will be adiabatically stratified, and that a detailed theory is not required to relate the temperature gradient and heat flux in such circumstances. However, Gough (1977) also emphasized that it is necessary to have a good theory for the transition zone between the convective envelope and the atmosphere, so that solar models may be extrapolated to other solar type stars. Models of red giants, for example, certainly require more refined models of convection. Thus, even if it is indeed true that "mixing length theory is likely to stay with us for a long time" (Gough, 1977), solar studies should be actively pursued with the aim of clarifying the nature of stellar convection processes and improving the theory of stellar convection.

There are two rather distinct points of contact between theory and solar observations, one related to granulation and supergranulation, and the other to the global circulation of the Sun. The former field was discussed by Moore (see Chapter 9), who presented a very plausible account of the observed granulation and supergranulation in terms of penetrative convection. He emphasized that the morphology and evolution of granulation does not correspond to the eddies envisaged in in mixing length models, but rather appears to reflect dynamical instabilities of unsteady cells. The appearance of characteristic scales of motion in the photosphere is not presently understood, but it is another observed property that is in strong disaccord with mixing length theory. While Moore provided a compelling picture, he did not offer a detailed physical model of granulation and supergranulation. In fact, he asserted that "observational results will surely run far in advance of theory for the next few years." In these circumstances, it is evident that solar studies will be of the greatest importance, for only they will provide the detailed observations necessary to test the detailed theories that will be developed, albeit slowly.

As described by Gilman (see Chapter 8), a similar somber picture describes theoretical studies of the global circulation of the Sun. Furthermore, there is in this field a paucity of reliable observations of the kinds of things urgently required by the theorists: the directions and amplitudes of meridional flows, the degree of variability of the solar rotation rate, the physical parameters of giant cells. Therefore, the development of theories in this field will be even more difficult than in the interpretation of granulation and supergranulation. But recent observations of stars have demonstrated that stellar cycles analogous to the solar cycle are widespread among late-type stars, and there is increasing acceptance of the idea that stellar atmospheric heating and local structure may be intimately connected to the presence of atmospheric magnetic fields (e.g. Vaiana and Rosner, 1978). A satisfactory understanding of these phenomena must be based on a reliable model for the internal circulation and convection of stellar envelopes.

The discussions by Moore and by Gilman imply that a promising line of theoretical investigation involves both a solution of the radiative, compressible gasdynamic equations that describe only the actual scales of interest, and also the parameterization of the smaller scales that are not of direct observational interest but, nevertheless, are of crucial importance in controlling the behavior of the larger structures. This method does seem to be widely applied in terrestrial laboratory and engineering investigations, and certainly represents a line that should be followed in astrophysical studies. However, theorists should be cautioned to be wary of the differences in scale between terrestrial and cosmic objects which may make it dangerous to extrapolate laboratory models that are fairly well understood into the astrophysical domain. In the pursuit of this line of attack, observational solar studies will be of value not only in testing the results of theoretical modeling, but also in the calibration of the small-scale processes that are included in the models.

Oscillations. Observation shows that the Sun supports an enormous variety of oscillations, ranging from low order pulsations of the entire Sun to localized high frequency magnetoacoustic waves in discrete magnetic structures in the solar atmosphere. The central importance of these oscillations in contemporary solar physics is demonstrated by the large proportion of chapters in this volume that deal with the various aspects of waves in the solar interior and atmosphere. In this section, we briefly discuss two aspects of these previous chapters–oscillations in the interior, and oscillations in the atmosphere–against the backdrop of studies of oscillations in other stars.

There is a long history of investigations of waves in stars other than the Sun, almost exclusively related to the theory of pulsations of Cepheid variables and related objects (RR Lyrae, δ Scuti, β Cephei, etc.). The thrust of this work (see, e.g., Cox, 1980) has been principally directed toward the development of models for radial pulsations, and there now exists an impressive body of work that rather satisfactorily accounts for the structure, excitation, and amplitude of stellar radial oscillations as these relate to the internal structure of the stars. Unfortunately, the understanding of the effect of these waves on the stellar atmosphere is much less satisfactory.

Recently, there has been growing interest in nonradial pulsations of stars. This development has been spurred by observations of photometric and spectroscopic time variations that are not explainable in terms of radial modes (e.g., Smith, 1978). To date, the stellar observations have revealed the presence of low-order nonradial modes; the observation of high order modes, should they exist, is frustrated by the fact that only the stellar flux spectrum can be observed, so that high order modes suffer enormous cancellation. But with increased instrumental sensitivity, it should be possible to discover high order modes: the work of Claverlie et al. (1979) shows that it is possible to observe the high order solar 5-minute oscillation in the solar flux spectrum if one has a suitable instrument (i.e., an instrument able to measure line shifts of a fraction of a meter/second over a time base of several days). There are no obvious limitations to the construction of such an instrument for stellar studies, although there are, of course, practical problems stemming from the low photon flux from stars.

We expect that there will be a rapid growth of observational and theoretical studies of nonradial stellar oscillations, principally devoted to the refined "seismology" of stellar interiors that is afforded by the observation of a pulsation spectrum, but also allowing a fresh attack on the interpretation of stellar atmospheric "macroturbulence." With the expected improvements in the quality of data on solar and stellar pulsations, it is reasonable to expect that the next decade or so will see new theoretical work that will entail a parallel refinement of models of pulsation and of stellar interiors, and uncover the mechanisms that excite the nonradial oscillations of the Sun and other stars. The work of Ulrich and Rhodes (1977) shows how fruitful this approach has been already in solar studies.

As noted above, there is no satisfactory understanding of the effects of global oscillations on the stellar atmosphere. This situation reflects, in large part, the enormous problems associated with the theoretical study of compressible gasdynamics in a radiating atmosphere. Similar problems attend the theoretical investigation of other kinds of atmospheric oscillations, such as short period acoustic waves and gravity waves generated in the convection zone (see Stein and Leibacher, Chapter 11) and various magnetoacoustic waves. Nevertheless, study of such waves in stellar atmospheres is an important problem. The dissipation of the energy flux in some presently unidentified wavemode is a favored mechanism for heating the chromospheres of the Sun and other stars. There is growing support for the idea that waves may transfer sufficient momentum in some stellar atmospheres to promote mass loss, and there can be little doubt that waves of diverse kinds are responsible in some measure for the nonthermal broadening of stellar spectral lines, the so-called stellar atmospheric "turbulence."

In the study of waves in stellar atmospheres, the Sun provides the only opportunity to effectively separate the wavemodes themselves, and then to determine which of these modes is relevant in heating, transfer of momentum, and turbulence. In other stars, it is essentially impossible to effect a clear separation of modes since there is no unique modal signature of most kinds of waves in the radiated stellar flux spectrum. Thus, the Sun is the focus of studies of waves in stellar atmospheres. Extrapolations from these solar studies to other stars have been undertaken (e.g., Ulmschneider, 1979) but these are of a gross exploratory nature, and they do not yet make sufficiently refined predictions to permit unambiguous confirmation of their general validity.

Nevertheless, since solar studies have not proved to be as decisive as we might have hoped (e.g., despite many years of research, we still have not decided whether short period acoustic waves heat the solar chromosphere–see Jordan, Chapter 12), there is strong motivation to exploit stellar observations. Gray (1978) has systematized the available data on stellar atmospheric turbulence, and there may be a clue in this material to the dominant wavemodes in stars. Smith (1980) has found, for example, that the systematic increase of "macroturbulence" with decreasing gravity in cool giant stars may be closely related to a systematic pattern of changes in the amplitude and structure of stellar analogs of solar nonradial oscillations. There have also been attempts to systematize the connection between stellar atmospheric heating and mass loss rates (e.g., Linsky, 1980; Stencel and Mullan, 1980), but at the present time the most striking property of the relevant observational material is its defiance of attempts to categorize it in terms of classical stellar atmospheric parameters (e.g., Vaiana et al., 1980). As other authors in this volume have discussed, there are strong indications that there are more physical processes involved in the structure and dynamics of the solar atmosphere, and other stellar atmospheres, than would have been considered even one decade ago.

Mass Loss. The amount of matter ejected from the Sun in the solar wind is small. It involves a minute fraction of the energy output of the Sun, it does not influence the evolution of the present Sun, and it is dwarfed by the spectacular outflows from some other kinds of stars. Nevertheless, the solar wind is of enormous interest, both as a major component of the solar system, and as the only example of a stellar wind that can be studied in detail.

A recurring theme in the several chapters of this volume that deals with solar mass loss (i.e., the solar wind) is the fact that we do not have, at present, a very satisfactory understanding of the physics of the solar wind. Parker's (1963) theory of coronal hydrodynamic expansion, as inspirational as it has been, does not account quantitatively for the observed properties of the solar wind. A number of modifications to that theory have been explored (see Holweg, Chapter 15), but, nevertheless, some of the most fundamental observational constraints, such as the near-Earth state of the wind, or the relation between wind speed and and near-Sun magnetic field geometry, are still not matched by the models.

It is thus reasonable to ask if studies of the solar wind have much to offer astrophysicists who would like to understand stellar winds. In particular, one could ask whether refined solar wind models are of any relevance whatever to the interpretation of stellar wind observations which, of necessity, refer to only the crudest, global parameters of such winds. The answer depends on what one means by the word "interpretation." Thomas (1981) argues that our understanding of the relation between stellar winds and other stellar parameters is so rudimentary that the first step in the "interpretation" of stellar data should involve an emphasis on empirical modeling and the fundamental gross thermodynamics of the wind/atmosphere/interior connection, rather than theoretical, quantitative modeling that excludes a priori some of the most basic physics. On the other hand, since we have access to a broader and more reliable solar data base, theoretical solar models may be constructed with some confidence that they are amenable to verification and refutation. In fact, the eventual understanding of empirical models of stellar winds in terms of physical processes will require the solution of the problems at the forefront of solar research. While stellar work should concentrate currently on providing a reliable empirical model of the gross radial variation of the state variables in the outer stellar atmosphere, solar work can concentrate on investigating the physical mechanisms that are responsible for the particular gross radial variation in the solar atmosphere. Because many of these physical mechanisms act on spatial scales that are small and temporal scales that are rapid, refined solar studies demand a parallel study of both the fine structure and the gross radial structure that results from it.

Most of the discussion of solar coronal and wind physics that appears in this volume does not address some of the questions that are most relevant to stellar astrophysicists. In particular, as Kopp (Chapter 16) has stated, solar wind models involve, in addition to specified equations and boundary conditions, two additional constraints:

"the temperature and electron density at the coronal base." With these, one may construct "self-consistent" wind models, but this is of little value to a stellar astrophysicist who cannot measure the coronal base pressure and temperature, and who is interested in being able to predict the wind properties from parameters that are more "fundamental" than these. The challenge to solar physicists is to provide a theory of the solar wind that rests on such "fundamental" parameters.

There have been a few attempts to provide such a theory. In essence, these attempts (e.g., Ulmschneider, 1967; Hearn and Vardavas, 1980) take the flux of mechanical energy that enters the photosphere as a fundamental parameter. This energy is dissipated in the atmosphere according to a postulated mechanism, to produce a hot corona which, in turn, is responsible for mass loss via the hydrodynamic coronal expansion mechanism described by Parker (1963). There are two major problems with this approach: (1) As several authors in this volume have pointed out, there exists no reliable theory for solar chromospheric and coronal heating (e.g., Wentzel, Chapter 14). There is thus no basis for theoretical predictions of the coronal temperature and density, so that the mass loss models rest on unreliable or demonstrably irrelevant physical processes. (2) Furthermore, there is no reason to expect that such models contain all the relevant physics, either for the solar wind or for stellar winds in general. There will be a transfer of momentum associated with the energy transfer, and this will change the atmospheric structure. Magnetic fields change the forms of energy and momentum fluxes, and also influence the flow patterns. Because the Sun is an open system (Thomas, 1981) there will be mass transfer through the atmosphere. These processes are all ignored in existing studies.

Stellar observations may offer some clues to potentially rewarding lines of solar research. Very large mass loss rates, sometimes more than 10^{10} times the solar rate, are inferred for both very hot and very cold stars, particularly low gravity supergiants. Although there is evidence for the widespread existence of stellar atmospheric heating (chromospheric and coronal), there is no clear empirical relation between the maximum coronal temperature (which is very hard to determine in many kinds of stars) and the mass loss rate. In fact, there appears to be an anticorrelation between mass loss rate and the quantity of matter at coronal temperatures among some latetype giants (Haisch et al., 1980). The dMe stars, which have strong chromospheric and coronal spectral features, do not lose mass at detectable rates. On the other hand, T Tauri stars, which are thought to be stars rather similar to the Sun when it was young, have both high mass loss rates and strong chromospheric and transition zone spectral features.

The stellar data, taken all together, do not provide much support for mass loss models which require a strong relation between coronal temperature and density, and the resulting mass loss rate. Neither does the Sun, for it is the relatively cool coronal holes that appear to be the source of most of the solar wind (see Zirker, Chapter 5). This empirical result contrasts with models based on hydrodynamic expansion, which predict a tight relation between mass loss rate and coronal conditions (although the relation may be hidden by rather small uncertainties in measurements of the former—see Parker, 1963, Chapter 15). There are other problems, too. Stellar mass loss rates are often observed to be variable, and in the few cases where the stellar wind structure can be probed by a nearby companion, there is evidence that the stellar wind contains structure. Variability and structure are also prominent properties of the solar wind.

There are, therefore, intriguing similarities between the solar wind and the winds of other stars. Moreover, these similarities are prominent in general global properties, such as variability, wind structure, and the relationship to the underlying atmospheric structure. These global properties are poorly understood, both in the Sun and in other stars. We conclude that there are major difficiencies in our theoretical understanding of the solar wind. These lie not so much in our understanding of the wind outside the "critical point," and near the Earth, but rather in our understanding of the origins of the wind near the Sun. There must be an intimate connection between the structure of the solar wind outside the critical point, and physical processes occurring in the atmosphere below this region. This connection is poorly understood, and, at present, the subject of few penetrating investigations. We believe that studies of this connection in the Sun will shed light on some of the most pressing problems of stellar winds.

Magnetogasdynamics and Plasma Physics

Magnetic fields and electric currents play a major role, perhaps as important as gravitational fields, in determining the structure and evolution of stars, galaxies, and other astronomical objects. Parker (1979, p. 2) has vividly sketched the role of magnetic fields:

> The magnetic field exists in the universe as an "organism," feeding on the general energy flow from stars and galaxies. The presence of a small amount of weak field causes a small amount of energy to be diverted into generating more field, and that small diversion is responsible for the restless activity in the solar system, in the galaxy, and in the universe. Over astronomical dimensions the magnetic field takes on qualitative characteristics that are unknown in the terrestrial laboratory. The cosmos becomes the laboratory, then, in which to discover and understand the magnetic field and to apprehend its consequences.

Despite the obvious importance of magnetic and electric fields, the study of cosmical electrodynamics has not been a central theme in astrophysics. There are two main reasons for this: (1) The paucity of accurate and extensive observational data has permitted the development of models which "explain" the limited data without including electrodynamic processes (see Spicer and Brown, Chapter 18). (2) The subject of electrodynamics is vast and difficult, and there are many unresolved theoretical and observational problems.

Nevertheless, the need to account for new observational data and the explosion of theoretical and experimental research in plasma laboratories will promote a growing interest in cosmical electrodynamics. Solar physics will be of central importance in this growth, since there exists already a solid background of work on solar magnetism and related phenomena, and the proximity of the Sun allows detailed tests of theoretical ideas before they are extrapolated to distant and therefore less well-observed cosmical objects.

The study of solar magnetism divides naturally into two rather separate domains: (1) the generation and structuring of magnetic fields inside the Sun, and (2) the effects of magnetic fields on the atmospheric structure. These domains reflect a dichotomy in the underlying plasma processes. In the former case, the theoretical description may be derived from magnetohydrodynamics, while in the later case there is growing evidence that the "anomalous" plasma properties that excite so much attention in contemporary terrestrial plasma research find analogs in the solar atmosphere. It is convenient to separate the discussion in this section into these two parts.

Before we begin these discussions, it is of some interest to discuss what Alfvén (1967) has called the "two approaches to cosmical electrodynamics," and to emphasize that there is no essential parallel between the two domains identified above, and these "two approaches." Alfvén's two approaches are distinguished by the following properties: The first approach is based on theoretical investigations that extend the kinetic theory of ordinary gases; it involves mathematically elegant models that are developed with very little contact with experimental plasma physics, and which neglect awkward and complicated phenomena. On the other hand, the second approach is based on an intimate dialogue between laboratory plasma studies and theoretical modeling; the models are not elegant, because the empirical studies show that plasma physics involves an enormous variety of complex phenomena.

Alfvén eloquently advocates the second approach, and there is no doubt that it is superior to "speculative astrophysics" along the lines of the first approach. Studies of plasma processes in the solar atmosphere are increasingly inclined to follow the second approach (see Spicer and Brown, Chapter 18), probably because the observational data are good enough both to demand such an approach, and to show how it can be undertaken. Studies of the generation and structuring of the internal solar magnetic field are more likely to follow the first approach, for reasons outlined by Parker (1978, p. 30): "Observations of the active magnetic fields of the universe tell us that the behaviour is complex. . . . In most cases the observations do not define the circumstances well enough. . . . We concentrate on the basic physics." The high density and high conductivity of the solar interior implies that MHD is a valid approximation, but MHD is one of highly developed mathematical theories criticized as being part of the first approach. Observations of the structure of magnetic fields emerging at the solar surface teach us that, even though the mathematical elegance of MHD theory is, in principle, available, relevant theoretical models must be complex, and developed with the empirical spirit of the second approach.

Origins and Structure of Solar Magnetic Fields. The patterns of temporal and spatial structure of magnetic fields at the solar surface reflect the processes that generate and determine the structure of the fields in the solar interior. It is widely believed that the basic interior processes are related to a turbulent dynamo, which cyclically produces and amplifies magnetic flux in the manner discussed by Gilman (see Chapter 8), although alternative models have been proposed.

The details of the action of this dynamo are almost totally obscure. Most quantitative modeling of the solar dynamo is based on the approximation of "mean field electrodynamics" (Rädler, 1968), but the prominent structuring of the solar magnetic field demands a model that is not predicated on weak fluctuations about a mean field. Mean field models can be adjusted to account for the cyclic behavior of the solar magnetic field, and also for the patterns of flux emergence, but these successes are due to the selection of free parameters such as the distribution of angular momentum inside the Sun. Current solar dynamo models may not be relevant to the physics of solar magnetism. There have been some attempts to study a "flux rope" dynamo, and these may provide greater insight into the workings of the solar dynamo, although like other models that follow Alfvén's second approach, they are mathematically inelegant, incompletely specified, and dauntingly complex (e.g., Piddington, 1978).

Interest in the generation and structuring of the solar magnetic field is currently intense, for two reasons:

1. There is an impressive body of evidence suggesting that the solar cycle is irregular, sometimes involving a lot of "activity" and sometimes almost none (e.g., Eddy, 1978). There is also a large body of evidence, some of it hotly disputed, which strongly suggests that there is a connection between the degree of solar activity and the climate and weather of the Earth (cf., Herman and Goldberg, 1978). There is certainly an intimate relation between solar activity and the behavior of the interplanetary medium and planetary magnetospheres. Intense theoretical and observational research efforts are in progress in an attempt to understand both the origins of the irregularities in the solar cycle, and the physical connections between the solar cycle and related events throughout the solar system.
2. Wilson (1978) has been measuring the intensities of the emission reversals in the Ca II resonance lines in several late-type stars for more than one decade. He has found that these intensities vary on time scales ranging from days to several years. Many stars exhibit cyclic intensity variations, which appear to be direct analogs of the solar cycle, although the amplitude, period, and envelope of the stellar cycle may be quite different from those of the Sun. At present, there is insufficient data to attempt to systematize the forms of the stellar cycles, and there is need for more data on the relations between cycle structure and fundamental stellar properties such as age,

mass, and rotation rate. Stellar cycles are of interest because they provide further tests for theories of solar activity, and because there is growing evidence that magnetic fields and related phenomena are enormously important in the outer atmospheres of many stars.

Atmospheric Magnetic Fields. The richness of cosmic electrodynamic phenomena is amply exhibited in the solar atmosphere. From filigree to flares, the patterns of mass, momentum, and energy transport in the solar atmosphere are modified by the presence of magnetic fields and electric currents. One of the central themes of contemporary solar physics is to understand these phenomena. Many chapters of this volume discuss this work in detail. The question that can be asked is whether studies of the solar phenomena have much to contribute to the general understanding of the structure and evolution of stellar atmospheres.

The answer, we feel, is definitely yes. It has long been clear that magnetic effects are very important in the atmosphere of the magnetic A stars (Cameron, 1967), but until recently, there was not hard evidence for the widespread occurrence of stellar analogs of solar-type electrodynamic phenomena. Compelling evidence now comes from several directions: flare stars have been studied in great detail, and there are several empirical results suggesting very close similarities between solar and stellar flares (Mullan, 1977); stellar cycles have been detected in several solar-type stars (Wilson, 1978), and there is evidence of chromospheric variability in many other stars, strongly indicative of transient atmospheric heating such as occurs in solar flares and plages; finally, there is the detection by the Einstein X-ray satellite of a vast number of stars that emit X-rays, and while this is not direct evidence for atmospheric magnetic fields, it strongly suggests that they are present (Vaiana et al., 1980).

Increased interest in stellar magnetic fields comes at a time when solar physicists are also revising their ideas concerning the importance of solar magnetic fields. For a long time, many solar physicists tended to equate solar magnetic phenomena with solar activity, and to regard the "quiet" Sun as an essentially nonmagnetic object. But the detection of strong photospheric magnetic fields in the network boundaries, even in the quiet Sun, and space observations that show that the chromosphere-corona transition region and the corona itself are highly structured by magnetic fields in both quiet and active regions have inspired a revision of this idea. It is now recognized that many phenomena of the quiet Sun are modified or even controlled by electrodynamic processes.

It is not possible to review here all of the physical processes involved in solar atmospheric magnetism: the chapters by Spruit (Chapter 17) and Spicer and Brown (Chapter 18) will give the reader a fair picture of the directions of current research. It is of interest, however, to summarize the basic effects of solar magnetic fields on the solar atmosphere, in order to provide a backdrop for studies of magnetic effects in other stellar atmospheres. An easy way to provide this summary is to trace the outward evolution of magnetic fields in the solar atmosphere.

1. Photospheric magnetic fields can be arranged in an ordered sequence, characterized by the total magnetic flux in the magnetic elements that make up most of the photospheric field (see Zwaan, Chapter 6). This sequence may be modified by effects related to the temporal evolution of the structures, especially when they are newly emerged. The field modifies the temperature and gas pressure of the photosphere, presumably by interacting with the outward convective heat flux (see Spruit, Chapter 17). It would be impossible to detect the photospheric magnetic field or its influence on photospheric structure if we could not resolve the surface of the Sun. In this respect, one could argue that photospheric magnetic fields are of no direct interest to stellar studies, although there are stars that show more prominent effects, including starspots that modulate the stellar luminosity as the star rotates (Bopp and Evans, 1973).
2. In the solar chromosphere, the magnetic field spreads out as the exterior gas pressure be-

comes less able to confine the intense magnetic pressure. There is a strong correlation between the presence of magnetic field and the intensity of chromospheric radiation, a correlation that holds in both the quiet network and in active region plages. There is growing evidence that even in the centers of the network cells, far from the photospheric loci of the magnetic elements, the field may have spread sufficiently so that the upper chromosphere is pervaded by magnetic field. The field in the boundary regions and in plages is clearly involved in a poorly understood atmospheric heating process. Now it is thought that the field in the cell interiors may also modify the propagation and subsequent dissipation of the mechanical energy flux required for chromospheric heating. It has been sometimes proposed that the magnetic field is essential for chromospheric heating, but most estimates of the distribution of chromospheric heating conclude that the greatest energy requirements occur in the deepest parts, where the obvious effects of the field are well confined to plages and network. It is difficult to determine empirically the contribution of radiation from magnetically influenced chromospheric regions to the solar flux spectrum. Observations by White and Livingston (1978) show that there is a clear correlation between the strength of solar Ca II emission and the solar cycle; Zwaan (1977) has argued that the fact that there are solar-type stars with even lower levels of chromospheric emission than the weak emission of the quiet Sun indicates that there is a strong, magnetically related emission component in even the quiet Sun. Detectable chromospheric activity in solar-type stars (and possibly all stars) may require the presence of a magnetic field, but there is insufficient data to investigate this speculation.

3. The solar corona is strongly modified by the presence of a magnetic field. In fact, the past decade of research on the solar corona has led to a fundamental revision of our ideas: "Introduction of structure is not to be regarded as a refinement of theories based on spatial homogeneity, but rather as a fundamental change in our understanding of the physics of the corona" (Vaiana and Rosner, 1978). This revision, which results from empirical studies of the corona, particularly with imaging X-ray telescopes, has led to fundamental changes in the theoretical study of the corona. The canonical theory of coronal heating by the dissipation of acoustic or gravity waves is being replaced by theories that treat the dissipation of electric currents, either in magnetogasdynamic waves or in plasma instabilities. Solar physicists almost universally picture the corona as a magnetically dominated plasma, and there is a productive dialogue between laboratory plasma physicists and coronal physicists. A strong case can be made that the observation of widespread coronal X-ray emission from stars is evidence for the widespread occurrence of stellar coronae that are in many respects similar to that of the Sun: by inference, then, stellar coronae may be strongly influenced by magnetic fields (Vaiana et al., 1980).
4. The solar wind is a magnetically dominated plasma. Magnetic effects are of crucial importance in the momentum and energy budget of the wind (see Holweg, Chapter 15), and are responsible for much of the gross structure of the wind, and for all of the microstructure. In situ measurements of the interplanetary plasma, magnetic field, and electric currents provide an enormous data base for the application of Alfvén's "second" approach to cosmical electrodynamics. Since the entire solar wind system would be undetectable if we were not close to the Sun, we can only speculate on the possible role of magnetic fields in the more prominent winds of other stars. Electrodynamic effects are not included in models for stellar winds, although it is improbable that the magnetically dominated solar wind is not at least a crude guide to the kinds of processes occurring in other stellar winds.

This attempt to place solar electrodynamics in the context of stellar atmospheres implies that stellar analogs of solar magnetic phenomena are probably widespread. It also shows, however, that there is currently no unimpeachable evidence that such phenomena do play an important role in the atmospheres of stars (apart from a few cases). Given the current observational evidence, most astrophysicists will probably choose the easy path (or appeal to Occam's razor!) and press forward with gasdynamic models that generally exclude magnetic effects. But as stellar observations improve, and where theory encounters increasing difficulties in explaining the new data, it is almost certain that what has been learned in studies of solar magnetism and plasma physics will find wide application in a new generation of stellar atmospheric models.

THE SUN AS A STAR

Solar physics stands apart from stellar astrophysics because the Sun can be studied in much greater detail than other stars, and because the Sun is uniquely important to our life on Earth. Because of these special circumstances, solar physics has become an inward looking discipline, at least in relation to the broad field of stellar astrophysics. This has led some astronomers (Pecker and Thomas, 1976) to the conclusion that solar physics suffers from "ghettosis," a disease whose symptoms are the isolation of solar theory and observation from the mainstream of stellar astrophysics, and whose prognosis is the slow decline of solar physics as an important part of astronomy. Although there are indeed serious problems with solar physics as a discipline, this diagnosis is far too pessimistic. It overlooks, for example, the enormous interest in and the importance of solar studies in the context of solar system, in particular, the study of solar-terrestrial relations. Even if there were no other stars, the Sun would be the subject of intense interest!

On the other hand, there has occurred in recent years a serious breakdown of communication between solar physicists and other astrophysicists. Solar physics is often perceived to be focused on the "meteorology" of the solar atmosphere, to be obsessed with the close scrutiny of astrophysically insignificant phenomena. Evidence for this narrowness is easy to find: solar physicists have their own journal, "Solar Physics," and a stellar astrophysicist who reads this journal will usually become lost in a maze of jargon and references to phenomena that certainly hold no immediate or obvious interest. One could refer to Bruzek and Durrant's *Illustrated Glossary* (1977) to clarify the jargon, but the basic problem of apparent irrelevance to stellar astrophysics would remain.

To close the gap between solar physics and stellar astrophysics, we have to identify those aspects of solar physics that are of immediate interest to stellar astrophysics. When this is done, solar physicists would be wise to concentrate more of their research in these directions, for then solar physics will become a more widely applicable discipline. On the other hand, if solar physics had been wholly devoted to problems of "general astrophysical interest," we would now have extremely precise (but uncertain) estimates of the abundances of all the elements in the solar photosphere, and no knowledge of the corona or solar neutrinos. Thus, some aspects of solar physics are not presently of great general interest, but we can safely predict that they will soon become so.

In this section we want to reexamine solar physics in the context of stellar astrophysics. Our approach involves three phases:

1. A reexaminiation of stellar astrophysics in the light of recent discoveries regarding the nature of stellar atmospheres,
2. An attempt to place solar physics in context in this "modern" picture of stellar atmospheres, and
3. A summary of the relation between the "details" of solar physics and those global solar properties that are identified as relevant in modern stellar astrophysics.

By following a program of this kind, we hope to show where solar physics will fit into the next decade of stellar atmospheric research, and to identify some of the promising directions for relevant observational and theoretical research.

New Directions of Stellar Atmospheric Physics

The old, or "classical," model of a stellar atmosphere involves a thin, passive layer of gas enveloping the star. It assumes that the structure of the layer is completely determined by the conditions of hydrostatic and radiative equilibrium. It permits stellar astrophysicists to make a three-dimensional classification of stars, by relating spectral type, spectral class, and metalicity to effective temperature, surface gravity, and the abundance of trace elements in the atmosphere. The theoretical basis of the models is well defined, and mathematically talented stellar astrophysicists can construct tables of ever more refined model atmospheres (e.g., Kurucz, 1979). These models are widely used: they provide a way to calibrate observational quantities such as the color of the stellar radiation, or the strength of stellar spectral lines, in terms of fundamental stellar parameters. These calibrations have been a very important step in the development of current ideas concerning the structure and evolution of stars and the galaxy.

This classical picture is currently being completely repainted. New observations of stellar atmospheres, particularly with instruments located outside the Earth's atmosphere, show that stellar atmospheres are not passive; they are dynamical structures exhibiting all of the richness of the phenomena long observed in the solar atmosphere, but often in much more spectacular ways.

These discoveries have revitalized the observational study of stellar atmospheres. A few years ago, the thrust of most stellar observations was the basically routine measurement of stellar colors and line profiles, with the aim toward improving the classical classification of a star, or verifying a refinement of the classical theory. Now, stellar observers concentrate on the quest for empirical data that can help unravel the problems of stellar mass loss, stellar atmospheric heating, and stellar variability. It is too soon to predict how much these new studies will influence the conclusions derived from classical studies; at present, our understanding of the new observations is too rudimentary, and the first tasks will be attempts to find order in the chaos.

In another volume of this series, Thomas (1982) discusses these new results. He points out the growing evidence for deviations from the classical model: superionization as evidence for the breakdown of radiative equilibrium, and systematic velocity fields–generally but not always outflows–as evidence for the breakdown of hydrostatic equilibrium. Attempts to systematize these observational properties have been uniformly unsuccessful. For example, stars emitting X-rays can be found in all parts of the H-R diagram, and there is no obvious trend in the strength of the X-ray emission with the taxonomic criteria used to construct the H-R diagram. Indeed, there is a wide range of X-ray luminosities among stars that lie close to each other in the H-R diagram (Vaiana et al., 1980). Similarly, any apparent trends in the inferred mass loss rates have to be measured against the observed fact that mass loss rates can vary markedly with time in a given star, and that stars of similar spectral type and class can exhibit widely different mass loss rates.

Thomas (1982) does identify three empirical results that must be considered in attempts to understand the new stellar astrophysics.

1. Stars exhibit considerable individuality, in contrast to the results of classical taxonomy which permitted the assignment of most stars to a relatively few classes; the phenomena of superionization and systematic velocity fields are characteristics of individual stars, and any attempt to systematize them cuts across some other classification dimension. This individuality has a close parallel in biology: species are defined by certain characteristics, while other more detailed characteristics identify the individuals of a particular species. It might be useful to note that the study of individual differences within species has led to important revelations into the nature of biological structure and the mechanisms of biological evolution (Mayr, 1978).
2. Stars exhibit variability. Poets have often sung of the constant stars, and evidence of stellar

variability was viewed with great consternation by the ancients. Now there is growing evidence of variability among stars of all types and classes. It is true that the variability is often manifested in only minor changes in the stellar spectrum. For example, evidence of stellar cycles in visible stellar spectra is found in only a few strong spectral lines (Wilson, 1978), yet these cycles may be extremely important in the overall behavior of stellar atmospheres. Another example is the relatively minor spectral signature of nonradial oscillations in the B stars (Smith, 1978); these oscillations may be implicated in atmospheric heating and mass loss from such stars. Variability, per se, is the intriguing property. The amplitude of the variability in the observed spectrum may give a totally misleading picture of the implications of its existence.

3. "Peculiarity" is a matter of degree. Peculiar stars have generally been regarded as objects apart from the mainstream of stellar astrophysics. However, it has become clear that the classical symptoms of peculiarity—superionization or subionization, variability, odd spectral line shapes and strengths, associated nebulosity etc.—are found in many stars. The prominence of a particular peculiarity may be greater or smaller in a given star, and this range is a legitimate subject for scientific enquiry. But the more significant fact, from the point of view of modern stellar astrophysics, must be simply the existence of the indicators of "peculiarity" in so many stars. The detection of symptoms of peculiarity in a given star now depends on the sensitivity of the instrument used to observe it, and peculiarity is no longer a pathological state.

To summarize: there is widespread evidence for departures from radiative equilibrium, and equally widespread evidence for departures from hydrostatic equilibrium. The evidence is contained in the radiation fields of the stars, and it has been long suppressed because astronomers have not had access to the spectral regions where it is prominent (i.e., in the far UV and X-ray spectrum), or to the sensitive techniques to measure its subtle manifestations in the visible spectrum. Observational studies of the consequences of these departures reveal three important characteristics: (1) The size of the departures vary from star to star in a way that has little relation to the classical properties of the stars; (2) The size varies with time in a given star; and (3) The effects of the departures result in a crude continuum of spectral signatures, prominent in some stars and undetectable in others.

The Sun's Place in Modern Stellar Astrophysics

It is not hard to see how solar physics fits into these new directions of stellar astrophysics. We have known for four decades that the outer atmosphere of the Sun exhibits enormous departures from radiative equilibrium, and for two decades we have known of departures from hydrostatic equilibrium manifested in the solar wind. Moreover, the most striking consequences of these departures in the solar atmosphere involve spatial structure and temporal variability, which can be related to the star-to-star and time-to-time variation of comparable properties in the stars.

The Sun, therefore, exhibits all of the features of the new stellar astrophysics. The occupation of many solar physicists with solar phenomena that were apparently of little relevance to classical stellar astrophysics now proves to be of great benefit. We can use the Sun as a paradigm in attempts to understand the revolutionary discoveries in stellar astrophysics. One of the main applications of the solar paradigm, at present, is to suggest a pattern of atmospheric structure that may be an almost ubiquitous consequence of departures from radiative and hydrostatic equilibrium.

In particular, the gross temperature distribution in the solar atmosphere, characterized by the pattern of photosphere—chromosphere—corona, results from the general energy balance of the atmosphere. Because the emissivity of the atmospheric plasma falls with the outward decrease in density, a given mechanical heating rate produces a greater temperature rise in the outer layers. In the Sun, the emissivity of coronal material is so low that a nonradiative energy input of less than 10^{-6} of the solar radiant energy flux suffices to raise the coronal temperature to over 10^6 K. We expect that any nonradiative heating in other stars will lead to a temperature structure similar to that in the solar atmosphere, although there will be differences from star to star, resulting from differences in heating processes, density structure, and photospheric conditions.

In the solar atmosphere, departures from hydrostatic equilibrium are prominent in two different ways: there is a pervasive temporal and spatial dependence of the velocity field whose amplitude seems to be limited roughly to the local sound speed in any particular layer, and there is the structured but basically radial flow of the supersonic solar wind. The former velocity field is not responsible for a major change in the hydrostatic density distribution in the atmosphere; the Reynolds' stress associated with a flow at the sound speed will, in the most extreme case, only double the pressure scale height. Nevertheless, dynamically induced extension of the atmospheric scale height is clearly evident in the solar transition zone, where spicules may extend for several thousand kilometers above their internal scale heights. However, the major distortion to the hydrostatic density distribution in the solar atmosphere occurs only where the solar wind becomes supersonic, in the outer corona.

It is important to separate these two kinds of departures from hydrostatic equilibrium. The space- and time-dependent subsonic velocity fields in the solar atmosphere are associated with convective overshoot, pulsations, magnetogasdynamic waves, jets, and other dynamical phenomena. Even though they do not grossly distort the hydrostatic density distribution, they can transport substantial fluxes of mass, momentum, and energy through the atmosphere. In fact, it is not unreasonable to argue that there would be no superionization or radial outflow without these kinds of motions.

It is tempting to identify this class of motions with the well-known but poorly understood phenomenon of stellar atmospheric turbulence. The empirical signature of stellar atmospheric turbulence is the widening of spectral lines beyond the thermal broadening associated with the spectroscopically diagnosed kinetic temperatures. There are many physical processes that could contribute to such widening, but it seems probable that Doppler shifts associated with spatially and temporally inhomogeneous velocity fields are a major component (this is not an endorsement of the conventional methods used to relate observed widening to estimates of velocity amplitudes via micro- and macroturbulence). Certainly in the solar atmosphere, the velocity fields that can be seen directly in spatially resolved observations do contribute to widening of the spectral lines in the solar flux spectrum (see Beckers, Chapter 2), and there is no reason to doubt the existence of a similar effect in stellar spectra. Stellar atmospheric turbulence appears to be ubiquitous (Gray, 1978). Moreover, it shares with superionization and mass loss the property of being extremely difficult to systematize in relation to the classical parameters of the H-R diagram.

The solar paradigm suggests a pattern not only for the temperature structure in a stellar atmosphere, but also the density and velocity structure. But as Thomas (1982) has emphasized, we should be careful not to confuse the empirical paradigm—the Sun has a superheated chromosphere and corona, it has stellar atmospheric turbulence, its density distribution departs from hydrostatic, and it loses mass—with suggested explanations of this structure. In particular, there is a widely held belief that in all stellar atmospheres these three things are intimately connected, insofar as stellar atmospheric turbulence is a manifestation of a mechanical heating agency, which produces the superheating by mechanical dissipation, which in turn produces mass loss by hydrodynamic expansion. Yet, if there is such an intimate connection, empirical evidence for it has been very hard to find, in the Sun and in other stars. In fact, attempts to empirically systematize the relations between these phenomena are so frustating that we can only conclude that the connection is by no means as obvious as had been assumed.

Given the present disturbed climate of stellar atmospheric physics, it is prudent to avoid such speculations, and to seek to understand the observational evidence in a way that is as free as possible from preconceived bias. The central diagnostic problem in stellar astrophysics is to infer from the stellar spectrum the distribution of temperature, density, and velocity fields in the stellar atmosphere. This is an extremely difficult task, since the problem of inverting spectral information is intrinsically ill posed, and it has no unique solution. Additional constraints must be imposed, and those that are most economical are (1) the supposition that the general radial stratification of the solar atmosphere (in terms of temperature, density, and velocity) is an example of a universal atmospheric structure; (2) the adoption of a few simple thermodynamic guidelines, such as requirements of continuity in velocity and density; and (3) an approach that seeks a crude but holistic model, rather than a precise specification of the physical conditions in a narrow layer of the atmosphere.

The solar paradigm may find applications beyond stellar atmospheric physics. For example, there are indications that the Galaxy possesses a "corona" and a "halo" that may be (rough) analogs of solar structures. Active galaxies also exhibit spectral symptoms of superionization, turbulence, and systematic mass flow, and there are quasar models whose structure is suprisingly like that of the solar paradigm. There are even suggestions that such fundamental ideas as thermodynamic irreversibility can be understood in terms of the consequences of the flow of matter and energy from the stars into the expanding universe (Gal-Or, 1976). Although these exotic corners of astrophysics appear to be rather remote from solar physics, concepts developed in the solar context will continue to be a major part of astronomy. The problems raised by new observations of stellar atmospheres will lead to renewed interest in solar physics as a part of stellar astrophysics.

The Origins of the Global Solar Structure

The preceding section underscores the importance of research into the physical origins of the global structure of the solar atmosphere. Left to themselves, solar physicists could well concentrate on sharply focused problems, such as the time evolution of solar granulation, the physics of chromospheric flux tubes, the nature of fluctuations in the solar wind, and the energy release mechanisms of solar flares. But the awareness of the close similarities between the global structure of the solar atmosphere and that of other stars should encourage solar physicists to investigate the broader relations between these detailed processes and the general structure which is the interface between solar and stellar astrophysics.

One must appreciate the two phases to this proposed program of solar physics: first, the study of phenomena in detail, to uncover the basic physics on the scales at which it primarily acts, and second, the integration of the consequences of these phenomena into an explanation of the global stratification of the solar atmosphere. We take exception to Thomas' (1982) contention that reviews of solar phenomena ". . . become lost in the questions of nonradial fine structure, setting aside the overall, radial, outward progression of velocity and temperature. . . " and therefore represent a ". . . misleading use of solar analogy to emphasize departure from an overall, radial, distribution of atmospheric regions." Thomas' position is based on a healthy suspicion of theoretical models for stellar atmospheres, including the solar atmosphere; but in relation to what solar physics has to offer stellar astrophysics, we believe this view is shortsighted. We have high quality observations of the fine structure of the solar atmosphere that are simply unavailable for other stars, and that if we are ever to understand the physical processes responsible for the overall, radial structure, we must understand how the fine scale phenomena lead to atmospheric heating and velocity fields.

There are even cases in which an understanding of nonradial structure is essential in understanding the gross stellar observations. An important example is the question of the origin of the variations observed in the Ca II resonance line cores in late-type stellar spectra (Wilson, 1978). Since the work of Jefferies and Thomas (1960), it has been clear that one possible cause of variations in Ca II emission core strengths could be the coupling of the non-LTE line source function to variations in the radial temperature profile in the chromosphere. Linsky (1980) and his coworkers have exploited this possibility in a large number of semiempirical studies of stellar chromospheres. But there is an alternative explanation that finds increasing acceptance: the Ca II emission is produced in quiet and active regions analogous to those on the Sun, and the main cause of variations is changes in the relative areas of the two atmospheric states. It requires only a small step from this proposition to the important realization that observations of the Ca II variations may then be translated into rough estimates of the variations in the amount of magnetic flux penetrating the stellar photosphere, and, hence, can be used as crucial input data for theoretical studies of the origins of stellar magnetism. Also there is increasing evidence that magnetism may be a vital factor in the determination of the overall structure of many stellar atmospheres.

In the remainder of this section we summarize the relations between the fine scale and the overall structure in the solar atmosphere. This serves two purposes: it brings the various chapters of the volume together, and it lets us identify some of the critical problems at the solar-stellar interface. Our approach starts from the photosphere and works outward: as we proceed through the atmosphere we will attempt to identify the small-scale processes that dominate the gross radial variation in temperature, density, and velocity.

1. Photosphere. In the deepest visible layers of the solar atmosphere, we observe the transition from convective to radiative domination of the energy flux. The relative contributions of the two processes as a function of height are not known accurately (Edmonds, 1974). It is known that the mechanical energy flux falls to less than about 1 percent of the radiative flux, but this value is still enormous in comparison with the total energy requirements for outer atmospheric heating. Photospheric velocity amplitudes may be as large as 50 percent of the sound speed; such velocities lead to easily observable Doppler effects, but do not appreciably alter the density distribution. Mass transfer rates in the photosphere are very large compared with the mass flux in the solar wind; it is clear that essentially all upflowing matter eventually falls again. The structure of the photosphere is quite well matched by radiative models based on the classical assumptions.

2. Chromosphere. By some definitions, the chromosphere is that part of the solar atmosphere where departures from radiative equilibrium first become prominent. One of the most frustrating aspects of modern solar physics is the fact that despite years of intensive effort, it has been impossible to reliably identify the small-scale dynamical processes that are primarily responsible for the nonradiative heating. In the chromosphere, the intimate connection between magnetic fields and atmospheric heating rates first becomes obvious. Chromospheric velocity amplitudes are somewhat larger than those in the photosphere, with values up to and even larger (e.g., spicules) than the sound speed. Just as in the photosphere, the mass transfer rates are orders of magnitude larger than the solar mass loss rate, so that there is a vertical circulation of matter. In general, there is insufficient observational evidence to describe the thermodynamic history of matter as it follows this circulation.

3. Corona. The temperature of the solar atmosphere leaps by two orders of magnitude between the chromosphere and the corona. It is thought that this sudden jump reflects the inability of the low density, optically thin chromospheric plasma to radiate the dissipated magneto-mechanical energy. The transition zone between the chromosphere and corona is a fascinating region where a multitude of dynamical processes occur. The conventional picture of a passive, plane parallel transition zone structured by thermal conduction is replaced by a complex model with energy fluxes strongly modified by the magnetic fields (e.g., Feldman et al., 1979). Velocity amplitudes in the transition zone and inner corona are of the order of the local sound speed (up to 100 km s^{-1}) in the corona. In the inner corona, the circulating mass flow still dominates the mass loss rate of the solar wind.

4. Wind. The layers of the corona where the systematic flow of the solar wind begins to compete with the small-scale circulating flows are almost totally unknown territory. We do not know the temperature profile in the region from 1 solar radius to 10 solar radii above the solar limb, apart from crude estimates derived from the density stratification and the ionization state of the solar wind at Earth. We do not know the velocity fields in these layers, apart from extrapolations back from the Earth. The failure of solar wind models to match conditions at Earth probably reflects our lack of understanding of this critical region. Despite concerted efforts, solar physicists can offer little insight into the physics at the base of the solar wind. The outer parts of the wind are better understood, although there are intriguing questions concerning the interface between the solar wind and the interstellar medium.

5. Activity. Solar activity changes the atmospheric structure in all layers. Activity involves a slow evolution of the atmosphere in response to the emergence and dispersal of magnetic flux, and occasional rapid and violent readjustments of the atmosphere (flares) when magnetic instabilities arise. The slow changes produce sunspots, plages, and intense X-ray emission from the corona, while the flares lead to outbursts of electromagnetic radiation and particles. It is becoming increasingly accepted by solar physicists that solar activity is not a special state of the solar atmosphere; rather, the phenomena that are so prominent around a large activity center occur in scaled-down form throughout the solar atmosphere, even in the quietest areas. Solar activity is the manifestation of electrodynamic processes in the solar atmosphere; without a thorough understanding of these processes it is impossible to fully understand the structure of the solar atmosphere.

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