SPECTRAL DIAGNOSTICS FROM X-RAY TO RADIO WAVELENGTHS

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"Astronomers are a little like poets (indirectly from the Greek ωου, make): they MAKE the universe by interpreting messages, extrapolating spectra, and inventing "models" of the cosmos or of stars - fictional constructions whose observable part constitutes only a small fraction of the whole, and which only the inductive logic of the theoretician allows us to consider as representing unique physical reality." - Jean-Claude Fecker (1970)

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I. INTRODUCTION - WHAT IS A SPECTRAL DIAGNOSTIC?

Essentially everything we think we know about the physical properties of astrophysical plasmas is derived from the analysis of their emitted radiation. Thus the techniques for inferring these physical properties are the basic tools with which the stellar astrophysicist pursues his work of deducing models for stellar atmospheres and envelopes. This process of interpreting messages and inventing "models" inevitably involves numerous arbitrary assumptions and, therefore, has somewhat the character of the fictional constructions that Jean-Claude says the theoreticians among us consider as representing "unique physical reality".

My intention is not to initiate an epistemological debate, but rather to begin this review of a very complex and difficult subject with a healthy note of skepticism. It is essential to recognize the real limits to the accuracy and completeness with which one can diagnose an astrophysical plasma using spectra as a result of unresolved inhomogeneities, unknown flows, poorly known atomic parameters, insufficient data, and simplistic assumptions. Throughout this review I will call attention to these potential flaws in the application of the available spectral diagnostics.

What do I mean by the term "spectral diagnostic"? I propose as a working definition that a spectral diagnostic is an observable spectral quantity that can be used to measure a physical parameter characterizing the observed plasma. The term "spectral quantity" is used here generically to include continuum fluxes and shapes, line fluxes and ratios of line fluxes, line profiles, and variability in any of these quantities. How a diagnostic is interpreted is critical because the accuracy of the derived physical parameter depends upon the validity of the assumptions underlying the model. Since a given diagnostic usually measures only one physical parameter, many diagnostics located across the electromagnetic spectrum are generally required to obtain an accurate picture of the complex, multicomponent, dynamic, magnetized, nonLTE plasma in a stellar atmosphere. A valid model for the environment of a star must explain all the data and not violate physical principles before such a model can possibly represent "unique physical reality".

A final introductory point is that "seeing can be deceiving". Astronomers must live with the unpleasant fact that most phenomena and structures are not spatially resolved even on the Sun. Thus an observed spectrum is a composite of the spectra of individual unresolved structures. The observed mean spectrum may be quite different from the individual spectra and the inferred parameters of the plasma may be quite different from the mean values of parameters of the individual components of the plasma. A simple example of what I have in mind is that the unresolved image of a complex pattern of small red and blue features is the color purple, although purple is not present in the resolved image.
II. SPECTRAL DIAGNOSTICS OF THE THERMODYNAMIC PROPERTIES OF AN ATMOSPHERE

How are spectral lines excited?

The first step in establishing a spectral line as a diagnostic is to determine whether the upper state of the transition is excited primarily by collisions (typically by electrons), by a radiative process, or by recombination (either direct or cascade). In the following section I will concentrate on the ultraviolet portion of the spectrum, because it is well studied, the background photospheric continuum is weak for cool stars, and the spectrum consists of an interesting mix of lines formed by all three mechanisms. For a more complete description of the ultraviolet spectroscopy of cool stars I refer the reader to the reviews of Jordan, Judge and Johansson (1985) and Jordan and Linsky (1987).

Spectral lines in the x-ray region are produced primarily by electron collisional excitation in hot coronal plasmas. In the ultraviolet spectra of dwarf stars of spectral type F-M and of F-G giants, electron collisional excitation of such ions as CII, CIII, CIV, SiII, SiIII, SiIV, and NV present in their chromospheres and transition regions produces bright emission lines against the weak photospheric background. In the optical region spectral lines are also commonly produced by collisional excitation, but strong lines (e.g. CaII K) appear primarily in absorption against the bright background. For optically thick resonance lines, such as HI Lyman α, MgII h and k, and CaII H and K, resonance scattering can populate the excited state more rapidly than electron collisions by orders of magnitude, but the scattering process only redistributes in angle and frequency the photons that were originally created by a collisional excitation process. The fluxes of collisionally-excited lines provide useful data on the emission measure of the plasma over the range of temperatures for which the particular ion is abundant, and the analysis of a number of emission lines formed over a range of temperatures can permit one to determine the functional dependence of emission measure on temperature with a minimum of assumptions concerning the geometry. An example of this approach is the emission measure analysis of the G2 Ib-II star β Draconis by Brown et al. (1984) based upon their IUE high S/N and high resolution 1200-2000 Å spectrum.

Giant and supergiant stars somewhat cooler that β Draconis have very different ultraviolet spectra. Instead of collisionally-excited emission lines of multiply-ionized species, these stars have emission line spectra of neutral and singly-ionized atoms located in a cool (T<10,000K) plasma for which the additional excitation processes include direct photoexcitation and the absorption of a photon followed by emission in another spectral line (fluorescence). Fluorescent lines of OI, SII, FeII and FeI are among the brightest features in the 1200-3200 Å spectrum of Arcturus (K1 III) (Ayres, Simon and Linsky 1982; Carpenter, Wing and Stencel 1985) and the 2500-3230 Å spectra of such M giants as Betelgeuse (M2 Iab) and γ Crucis (M3 III) in the IUE Cool Star Atlas of Wing, Carpenter and Wahlgren (1983).
Carpenter and Johansson (1988) provide the most recent summary of fluorescent processes responsible for many of the observed emission features in the ultraviolet spectra of cool giants that are located to the right of the dividing line in the H-R diagram proposed by Linsky and Haisch (1979). Photo-excitation processes become more evident relative to the collisionally-excited lines in the ultraviolet spectra of low gravity stars owing to the low electron densities in their outer atmospheres (Judge 1988). It is the weakness of the collisionally-excited lines rather than the strength of the photoexcited lines that accounts for the qualitatively different spectra of cool giants compared with the higher gravity "coronal" stars (Judge 1987). In a broad sense, photoexcited line fluxes are diagnostics of column densities (∫n_H dX), whereas collisionally-excited line fluxes are diagnostics of emission measures (∫n_e^2 dX) and/or electron densities (see below).

Hydrogen Lyman α, in particular, is a prolific source of radiative excitations because this bright line can be quite broad (5 Å wide in the spectrum of γ Crucis) and there are numerous wavelength coincidences with allowed SI and FeII transitions (Judge 1988) originating in well populated levels between 0 and 3 eV. Johansson and Jordan (1984) studied many of these processes, and Carpenter and Johansson (1988) list 10 direct fluorescent channels and 4 secondary cascades leading to emission features at 1260-2856 Å that originate with a Lyman α photon. They also list 6 multiplets of FeII that are pumped by the FeII UV 1 and other multiplets. In addition to FeII, the lines of OI near 1304 Å are pumped by Lyman β which in turn pumps the SI lines near 1300 Å, several FeI multiplets are pumped by MgII, the fourth positive band of the molecule CO (1300-1800 Å) is pumped by Lyman α, OI, and CI, and there are other known fluorescent processes. These fluorescent emission lines provide information on the intensity of the pumping line deep in the stellar atmosphere and also on the line shapes and Doppler motions where the pumping occurs. This information is not easily acquired by any other means. The first detailed calculations of photo-excitation by Lyman α were by Judge (1988), and the first by Lyman β were by Haisch et al. (1977).

Spectral lines excited by recombination are important in low density nebulae such as planetary nebulae, HII regions surrounding hot stars, and recombing shocked plasmas such as Herbig-Haro objects. While this excitation process may not be too important for ultraviolet emission lines of late-type stars, the He I 10830 Å and HeII 1640 Å lines may be exceptions, since they can be formed in a recombination cascade following photoionisation of HeI or HeII by coronal back-radiation (e.g. Zirin 1975), although there are other possible explanations (e.g. O'Brien and Lambert 1986).

The above are examples of lines which are excited primarily by single processes, where the nonlocal coupling between radiative transitions, which occurs at large optical depths, can be neglected to a first approximation. However, in some important cases, for example the hydrogen spectrum in late-type stars, the lines and continua are strongly interlocked and the simple ideas outlined above cannot be applied directly. In
a pioneering analysis, Skumanich and Lites (1985, 1986) showed how to identify the major sources of line and continuum excitation by rewriting the coupled multilevel statistical equilibrium equations, once a solution is obtained, in terms of an equivalent 2-level atom model for each transition. In this way they can identify the sources of line excitation. For the case of the solar hydrogen spectrum they find that (a) Lyman α is excited mostly by collisions, and (b) Lyman β, Balmer α and the Lyman continuum are controlled by the Lyman α radiation field. Using this technique with further developments (Skumanich and Lites, in prep.), it should be possible to also use these strongly-coupled spectral diagnostics to obtain temperature- and density-corrections to empirical model atmospheres.

**Electron density diagnostics**

From the flux in a collisionally-excited line formed above 10,000K one can derive only a value for the emission measure \( \int n_e^2 \, dA \) within a limited temperature range. Additional information on the electron density of the emitting plasma (by observations or by some assumption such as hydrostatic equilibrium) is required in order to deduce the volume of the plasma in this temperature range and thus some information on the geometry (e.g. Jordan and Brown 1981). Ratios of fluxes of effectively thin lines of the same ion or ions abundant at the same temperature can be used to infer the local electron density when the populations of the respective upper states have different functional dependencies on the density. There is now such an extensive literature on this important topic that I will concentrate only on some aspects of the topic and refer the reader to several review papers for references to the original literature. I have found the reviews by Feldman (1981), Dere and Mason (1981), Dupree (1978), and Feldman, Doschek and Behring (1978) very useful. While Stark broadening of the hydrogen Balmer lines with principal quantum numbers greater than 16 and the merging together of the higher Balmer lines can be used to measure chromospheric densities (Feldman 1981), most density diagnostics involve the interpretation of line flux ratios, which are more easily observed in the disk-integrated spectra of stars.

One can understand the essential physics of the line ratio method by considering an atom with a ground state (1) and two excited states (2 and 3) which are, for illustrative purposes, only connected to the ground state. If we assume that the spectral lines are optically thin and that radiative excitation is unimportant, then the statistical equilibrium equations governing the populations of the ground and each excited state are \( n_e (A_{u1} + n_e C_{u1}) = n_e n_e C_{1u} \) and the emergent flux in each transition is \( F_{u1} = A_{u1} n_e \, h\nu \). The line flux ratio, \( R = F_{21}/F_{31} \), is then \( R = (A_{21}/A_{31}) [n_e C_{12} / (A_{21} + n_e C_{21})]/[n_e C_{13} / (A_{31} + n_e C_{31})] \). This ratio is sensitive to density within some density range when the atomic parameters for the two transitions differ significantly, but the ratio may also be temperature sensitive and thus model dependent. This ratio can be density sensitive when one transition is optically allowed and the other is either
an intersystem or a forbidden line. A good example is the BeII isoelectronic sequence ion CIll (cf. Keenan et al. 1984) for which the optically allowed \((2s2p \, ^1P_1 - 2s^2 \, ^1S)\)
977 \(\text{Å}\) resonance line has a spontaneous de-excitation rate \(A_{31} = 1.7 \times 10^5 \text{ s}^{-1}\), whereas the 1908 \(\text{Å}\) intersystem transition \((2s2p \, ^3P_0 - 2s^2 \, ^1S)\) has a rate \(A_{31} = 190 \text{ s}^{-1}\). In the
low density ("coronal") limit \(A_{31} > n_e C_{31}\) and \(A_{31} > n_e C_{31}\), the line flux ratio
is simply \(R = C_{12}/C_{13}\), which is independent of density. In this limit the fluxes of
both lines are proportional to the emission measure and thus behave as "allowed" lines.
On the other hand, in the high density limit \(A_{21} < n_e C_{21}\) and \(A_{31} < n_e C_{31}\), the
line flux ratio is also a constant, independent of density because both transitions are
collisionally de-excited and behave as "forbidden" transitions. The interesting regime
occurs at intermediate densities where \(A_{21} < n_e C_{21}\) but \(A_{31} > n_e C_{31}\). Now the line
flux ratio depends explicitly on \(n_e\) \([R = A_{21} C_{12} / n_e C_{21} C_{13} \sim 1 / n_e]\) One can define a
critical density, \(n_c^{(cr)} = A_{21}/C_{21}\) which is a practical lower limit to the density for
which \(R\) is a useful density diagnostic.

In the ultraviolet spectrum of the Sun and late-type stars there are a number of
density diagnostics involving the ratios of intersystem to permitted lines or to other
intersystem lines with different critical densities. Eleven of the important intersystem
lines are listed in Table 1 together with their corresponding isoelectronic sequence,
temperature at which the ion has peak abundance (\(T_m\)), critical density, and line ratios
that have been used in previous studies. It is preferable to use lines of the same ion
to avoid uncertainties in atomic abundances and different line formation temperatures.
This is often not feasible for instrumental reasons or because one line is below the Lyman
edge or at a long wavelength where the photospheric background is bright. Instead, two
lines of different ions formed at similar temperatures are used such as in the CIll
1908 \(\text{Å}/\text{SiII}\) 1402 \(\text{Å}\) and OIII 1666 \(\text{Å}/\text{SiII}\) 1402 \(\text{Å}\) ratios. The SiIII 1892 \(\text{Å}/\text{CIll}
1908 \(\text{Å}\) ratio is commonly used even though both lines are intersystem transitions,
because over a factor of 30 in \(n_e\) the CIll line is above its critical density, and thus acts
as a "forbidden" line, whereas the SiIII line is below its critical density, and thus acts
as an "allowed" line (Keenan, Dufon and Kingston 1987).

Most of the ratios listed in Table 1 have been used in analysing solar spectra,
because they can be observed with sufficient spectral resolution and signal-to-noise and
Lyman continuum absorption is unimportant. Except for the very brightest stars, IUE
spectra of late-type stars include lines useful for only a few density-sensitive ratios,
although Space Telescope will provide the required resolution and signal-to-noise to
analyse all but the OV 1218 \(\text{Å}/760 \text{Å} \) ratio. In particular, the OIII 1666 \(\text{Å}\) and OIV
1400 \(\text{Å}\) multiplets are usually too weak or blended to be useful and the NIII 1750 \(\text{Å},
NIV 1468 \(\text{Å}, \) OV 1218 \(\text{Å}, \) SIV 1406 \(\text{Å}, \) and SV 1199 \(\text{Å}\) lines are rarely detected with
IUE. It is tempting to use the CIll 1908 \(\text{Å}/1175 \text{Å} \) ratio, but the 1175 \(\text{Å}\) multiplet
lies at the edge of the MgF\(_2\) reflectivity where the calibration of IUE and HST are
uncertain and the temperature sensitivity of the 1175 \(\text{Å}\) multiplet may be different
<table>
<thead>
<tr>
<th>Ion</th>
<th>Wave Sequence</th>
<th>Wave (Å)</th>
<th>Transition</th>
<th>log(T&lt;sub&gt;max&lt;/sub&gt;)</th>
<th>log(n&lt;sub&gt;e&lt;/sub&gt;(e&lt;sub&gt;cr&lt;/sub&gt;))</th>
<th>Useful Line Ratios</th>
<th>Ref.</th>
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<tr>
<td>C III</td>
<td>Be I</td>
<td>1908</td>
<td>2s2p&lt;sup&gt;3&lt;/sup&gt;P&lt;sub&gt;1&lt;/sub&gt; - 2s&lt;sup&gt;2&lt;/sup&gt;1S&lt;sub&gt;0&lt;/sub&gt;</td>
<td>4.8</td>
<td>10.2</td>
<td>C III 1908/SI IV 1402</td>
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<td>N IV</td>
<td>Be I 1468</td>
<td>&quot;</td>
<td>5.1</td>
<td>10.8</td>
<td>C III 1908/1175</td>
<td></td>
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<tr>
<td></td>
<td>O V</td>
<td>Be I 1218</td>
<td>&quot;</td>
<td>5.3</td>
<td>11.0</td>
<td>O V 1218/1760</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>C II</td>
<td>B I 2325</td>
<td>2s2p&lt;sup&gt;3&lt;/sup&gt;4P - 2s2p&lt;sup&gt;2&lt;/sup&gt;3P</td>
<td>4.0</td>
<td>8.0</td>
<td>C II 2325/2327</td>
<td>3</td>
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<tr>
<td></td>
<td>N III</td>
<td>B I 1750</td>
<td>&quot;</td>
<td>4.9</td>
<td>10.8</td>
<td>N III 1750/1754</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>O IV</td>
<td>B I 1401</td>
<td>&quot;</td>
<td>5.1</td>
<td>11.7</td>
<td>O IV 1401/1407</td>
<td>4</td>
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<tr>
<td></td>
<td>O III</td>
<td>C I 1666</td>
<td>2s2p&lt;sup&gt;3&lt;/sup&gt;8S&lt;sub&gt;3&lt;/sub&gt; - 2s2p&lt;sup&gt;2&lt;/sup&gt;3P&lt;sub&gt;1&lt;/sub&gt;</td>
<td>4.9</td>
<td>10.5</td>
<td>O III 1666/SI IV 1403</td>
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<td>Si II</td>
<td>Na I</td>
<td>2335</td>
<td>3s3p&lt;sup&gt;3&lt;/sup&gt;4P - 3s&lt;sup&gt;2&lt;/sup&gt;3P&lt;sub&gt;1&lt;/sub&gt;</td>
<td>4.0</td>
<td>9.0</td>
<td>Si II 2335/2350</td>
<td>9</td>
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<td>S IV</td>
<td>Na I</td>
<td>1406</td>
<td>&quot;</td>
<td>5.1</td>
<td>12.5</td>
<td>S V 1199/N V 1242</td>
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<td>Si III</td>
<td>Mg I</td>
<td>1892</td>
<td>3s3p&lt;sup&gt;3&lt;/sup&gt;P&lt;sub&gt;1&lt;/sub&gt; - 3s&lt;sup&gt;2&lt;/sup&gt;1S&lt;sub&gt;0&lt;/sub&gt;</td>
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<td>11.7</td>
<td>Si III 1892/C III 1908</td>
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<tr>
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<td>Mg I</td>
<td>1199</td>
<td>&quot;</td>
<td>5.3</td>
<td>12.0</td>
<td>S V 1199/N V 1242</td>
<td>7</td>
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<tr>
<td>C V</td>
<td>He I</td>
<td>40.73</td>
<td>1s2p&lt;sup&gt;3&lt;/sup&gt;P&lt;sub&gt;1&lt;/sub&gt; - 1s&lt;sup&gt;2&lt;/sup&gt;1S&lt;sub&gt;0&lt;/sub&gt;</td>
<td>5.5</td>
<td>8.8</td>
<td>C V 40.73/41.47</td>
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<td>&quot;</td>
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<td>10.5</td>
<td>O VII 21.80/22.08</td>
<td>8</td>
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<tr>
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<td>He I</td>
<td>13.55</td>
<td>&quot;</td>
<td>6.2</td>
<td>11.8</td>
<td>Ne IX 13.55/13.70</td>
<td>8</td>
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<tr>
<td>Mg XI</td>
<td>He I</td>
<td>9.23</td>
<td>&quot;</td>
<td>6.4</td>
<td>12.7</td>
<td>Mg XI 9.23/9.32</td>
<td>8</td>
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<tr>
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<td>He I</td>
<td>6.09</td>
<td>&quot;</td>
<td>6.8</td>
<td>13.6</td>
<td>Si XIII 6.09/6.74</td>
<td>8</td>
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<tr>
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<td>He I</td>
<td>3.10</td>
<td>&quot;</td>
<td>7.4</td>
<td>15.4</td>
<td>Ca XIX 3.19/3.21</td>
<td>8</td>
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<tr>
<td>Fe XXV</td>
<td>He I</td>
<td>1.86</td>
<td>&quot;</td>
<td>7.7</td>
<td>16.8</td>
<td>Fe XXV 1.86/1.87</td>
<td>8</td>
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</table>

than the 1908 Å line. Also, the SiIII 1892 Å/CIII 1908 Å ratio may give unreliable results because the SiIII and CIII lines are formed at significantly different temperatures. Thus the most reliable density diagnostic for solar-like stars is the CIII 1908 Å/SiIV 1402 Å ratio, which has been used to infer densities near 60,000K for RS CVn stars (e.g. Byrne et al. 1987) and the G2 Ib-II star β Draconis (Brown et al. 1984). For cool giants g ratios of lines within the CII 2325 Å multiplet (Stencel et al. 1981; Judge 1986a,b) are useful diagnostics of n_e under chromospheric conditions of low temperature and high column densities. Care should be taken, however, with the interpretation of density and temperature diagnostics in chromospheres (Judge 1987), chiefly because collisionally-excited line fluxes are generated over regions where the emission measure rises exponentially with decreasing temperature.

There are a number of line ratios involving intersystem and forbidden lines that are sensitive to densities in hotter plasmas. In the ultraviolet the ratio of lines within the ground configuration of MgVI, SiVIII, SX, and FeXII have been used to infer coronal densities above the solar limb and may be detected in HST observations of cooler coronal stars. For the 50-800 Å spectral range Feldman et al. (1978) list density-sensitive ratios of the BeI, BI and CI isoelectronic sequences that may be studied with the proposed LYMAN mission. Density diagnostics in the 171-630 Å region useful for analysing hot solar flare plasmas are discussed by Dere et al. (1979). Finally, the x-ray region contains a number of useful ratios for FeXVIII-XXVI and other highly ionised species (cf. Feldman 1981). Of particular importance are the HeI sequence ions for which Gabriel and Jordan (1969) showed that ratios of forbidden to intersystem lines are density sensitive. The important ratios for the HeI sequence are listed in Table 1 with data from Pradhan and Shull (1981).

This discussion would not be complete without mention of the potential systematic errors involved in deriving meaningful densities from these diagnostics:

(1) High spectral resolution and signal-to-noise are needed to separate blends. Examples include blending of the CII 2325 Å multiplet with FeII and the blending of CIII 1866 Å with AlII 1870 Å and FeII 1863 Å.

(2) Ratios of lines widely separated in wavelength are sensitive to instrumental calibration errors or must be observed by two different instruments often at different times. An example is the CIII 1908 Å/1175 Å ratio. Such lines may also be sensitive to temperature in different ways because their excitation energies differ considerably.

(3) The observed ratios represent line of sight integrals through plasma which is inhomogeneous in temperature and density. The observed line ratio may reflect conditions that are not present anywhere along the line of sight and may not even provide a rough estimate of the mean density. This is especially true when line ratios are near their low or high density limits in some regions of the plasma.

(4) Permitted lines may be optically thick such that radiative excitation is important. For this reason the SiIII 1892 Å/1206 Å and CIII 1175 Å/977 Å ratios are not
often used.

(5) Raymond and Dupree (1978) have calculated the effect of flows through a steep temperature gradient in a plane-parallel transition region on the CIII 1175 Å/977 Å ratio. Flow speeds of 10 km s\(^{-1}\) are sufficient that the recombination time is slow compared to significant changes in the temperature and collisional excitation rates. Under these conditions the line ratio is altered significantly so that densities inferred from the observed ratios ignoring flows will not be accurate. Feldman (1981) and Dere and Mason (1981) have argued that this calculation is unrealistic because: (i) the solar transition region is inhomogeneous with magnetically-confined structures in which the flows are along the field lines where the temperature gradients are unlikely to be steep, (ii) ionisation equilibrium may not be a valid assumption when the temperature gradients are steep so that the temperature gradients inferred spectroscopically are not valid, (iii) flows will smooth out steep gradients, and (iv) temperature gradients may move with the flow decreasing the flow speed through the temperature gradient. Thus more realistic calculations are needed to determine the effect of flows on line ratios.

**Column density diagnostics**

Another useful class of diagnostics are line ratios that are proportional to the chromospheric column density \(\int n_H \, dz\). When this diagnostic and the emission measure for the same range of temperatures are available, then one can estimate the total number density in the plasma. For atoms or ions with both optically thin and optically thick lines with the same upper level, interlocking causes the ratio of the optically thin to optically thick lines to increase with increasing line opacity, which is proportional to the column density. One useful example is CI for which the 1994 Å intersystem transition \((2p3s \, ^{3}P\leftarrow 2p\leftarrow 1D\) and the 1657 Å permitted multiplet \((2p3s \, ^{3}P\leftarrow 2p\leftarrow ^{3}P\) share the same upper level (Jordan 1987). Another example is the OI ratio 1641 Å \((2p^{6}5p \, ^{2}S - 2p^{4} \, ^{1}D) / 1304 Å \,(2p^{5}5s \, ^{2}S - 2p^{4} \, ^{3}P)\). Both the 1994 Å/1657 Å and the 1641 Å/1304 Å ratios are larger in giant than in dwarf stars (Judge 1986a,b), indicating that column densities increase with decreasing gravity, as previously noted by Ayres, Linsky and Shines (1975) and others on the basis of semi-empirical chromospheric modelling.

**Can the thermodynamic properties be nonlocal?**

Calculations of the emergent spectrum from a stellar atmosphere generally assume that the thermodynamic properties of the plasma are local in the sense that the ionization and excitation of the constituents of the plasma are in equilibrium with the local density, temperature and radiation field (which is nonlocal) and that the velocity distribution of the electrons is Maxwellian (which defines the local temperature). Relaxation of the local thermodynamic assumption, beyond the inclusion of photo-excitation by the nonlocal radiation field, is painful because of the enormous computational problem
it engenders, but in the skeptical spirit of this paper I would like to ask whether this assumption is valid.

Shoub (1983) made some landmark calculations that demonstrate that this assumption may not be valid in the solar transition region and by implication in other stars as well. He computed the velocity distribution for electrons in models of the solar transition region. Since the energy dependence of the cross section for thermalising collisions between electrons is proportional to $E^{-2}$, downward-directed coronal electrons can travel to the lower transition region where their energies are many times larger than the local $kT$. Thus the electron velocity distributions develop asymmetric high-velocity tails that significantly enhance the collisional excitation and ionization rates when their thresholds are many times larger than $kT$. This can produce overionization and overexcitation for such species as HeI and HeII (cf. Jordan 1980), which have excitation and ionisation energies much larger than the local $kT$ at which these ions are estimated to be abundant. Additional calculations are needed to understand under what conditions nonlocal thermodynamics may be important and the resulting effects on conductive energy transport rates.

Evidence for thermal bifurcation/instability

Whenever theoretical models agree with observations, astrophysicists generally proceed on to other problems without considering whether the models are unique or the observations sufficient. However, observations of spectral features in previously unexplored regions of the electromagnetic spectrum can be sensitive to atmospheric properties that were not previously tested and thus lead to qualitatively different models that explain both the old and new data. A good example of this need to explain observations over a broad wavelength range is the recent study of the fundamental vibration-rotation bands located near 4.6 $\mu$m of the molecule carbon monoxide (CO) in the solar spectrum.

Ayres and Testerman (1981) called attention to the very low brightness temperatures ($T_\text{b}=37000$K) inferred from the core intensities of the strongest CO lines observed near the solar limb. Assuming that the CO lines are formed in LTE, they argued that these brightness temperatures are inconsistent with published one-component solar atmosphere models. They proposed instead that the CO lines are formed in a cool component of the solar atmosphere where the temperature decreases monotonically at least out to $\tau_{\text{5000}} < 10^{-6}$, whereas such ultraviolet emission lines as CaII H and K and MgII h and k are formed in discrete structures (perhaps magnetic flux tubes) that cover only a small fraction of the solar surface. Ayres, Testerman and Braulet (1986) confirmed this thermally bifurcated model with simultaneous, co-spatial observations at different positions on the solar disk of the CO bands and the CaII line. The main features of this model are that the CO lines are formed in a cool component without a chromospheric rise in temperature, whereas the ultraviolet emission lines are formed in a hot component in which a steep chromospheric rise in temperature occurs above a temper-
ature minimum \((T_{\text{min}} > 4500 \text{K})\) at the top of the photosphere. The reality of the cool component depends upon whether the CO lines are truly formed in LTE, in which case the low brightness temperatures in the line cores require low plasma temperatures. To test the LTE assumption, Ayres and Wiedemann (1988) solved the coupled equations of statistical equilibrium and radiative transfer for a model CO molecule consisting of 10 vibrational levels with 50 rotational levels each. For cool component models of the Sun and Arcturus, they found that departures from LTE produce only small decreases in the CO line core intensities. Thus the thermal bifurcation model has a strong empirical basis.

Is there a physical basis for thermal bifurcation? Ayres (1981) and Kneer (1983) argued that an optically thin plasma with \(T < 4500 \text{K}\) is radiatively unstable because of the extreme temperature sensitivity of CO molecule formation and the radiative cooling efficiency of the many lines in the CO fundamental vibration-rotation band. Thus in the absence of mechanical heating, the upper photosphere of a star with \(T_{\text{eff}} < 6000 \text{K}\) will reach radiative equilibrium at \(T < 3700 \text{K}\) controlled by CO cooling, \(H^-\) heating, and complex line blanketing processes. When mechanical heating is important, however, the top of the photosphere will heat up to above 4000K (forming a chromosphere) as mechanical heating will now be balanced by cooling in the \(H^-\) continuum and many spectral lines but not by CO which is no longer present. Since the mechanical heating will be largest in regions of strong magnetic fields, the hot component likely consists of spatially unresolved flux tubes. The hydrodynamical calculations of Muchmore and Ulmschneider (1985) and Muchmore (1986) indicate that CO causes thermal instability in the temperature range 3500-4500K and that the hot and cool components can have temperature differences as large as 1900K at the same height.

Does a thermally bifurcated model provide a better explanation for such well studied chromospheric diagnostics as the CaII H and K lines? The bright CaII emission lines observed in solar plages were previously explained with a semi-empirical (i.e. ad hoc) plage model with a steeper chromospheric temperature gradient than a semi-empirical quiet Sun model created to “explain” the quiet Sun H and K line profiles with very little emission in the line cores. Ayres et al. (1986) instead “explain” the plage and quiet Sun profiles as different spatial averages of unresolved flux tube and cool components. They find that the CaII plage profile can be explained by roughly equal amounts of both components, while the quiet Sun profile can be synthesised from a mixture of 7.5% flux tube and 92.5% cool component. The virtue of this picture is that it can explain both the ultraviolet and infrared spectra at the same time and it has a clear physical basis. However, the calculation ignores horizontal radiative transfer, which may be important for structures too small to be resolved with present techniques.

Can other molecules drive thermal instabilities in the outer atmospheres of stars much cooler than the Sun? Muchmore, Nuth and Stencel (1987) argue that SiO can play a similar role to CO in the atmospheres of M supergiants like Betelgeuse. The
critical temperature for the onset of thermal instability for SiO should be near 3600K, and SiO may be able to cool the atmosphere to near 1000K. They suggest a scenario for these stars in which a chain of molecular instabilities ("catastrophies") occur starting with CO and then in turn SiO, CS, OH, H2O, and finally silicate dust and perhaps SiO maser emission. In this way thermal instability and the onset of massive winds may be intimately coupled (Stencel, Carpenter and Hagen 1986).

Self-consistency across the electromagnetic spectrum

According to a legend, 12 blind people each touched a different portion of an elephant and each one "saw" it as a very different kind of beast. Models of astrophysical plasmas based upon the analysis of only a few diagnostics located in one narrow region of the spectrum can be as inaccurate as each of the elephant "models" for the same reason that the diagnostics sample only a small portion of the plasma. A more valid model requires diagnostics that sample many important regions of the plasma, but such diagnostics typically lie in very different regions of the electromagnetic spectrum.

The analysis of different diagnostics for the same plasma can provide a unifying picture by showing that a range of observables can be explained self-consistently as emission from the same particles. A good example is the tight correlation of the solar microwave and hard x-ray (100 keV) flare emissions that track each other even down to timescales of < 1 second (e.g. Dulk 1985). Stewart and Nelson (1979) and Nelson and Stewart (1979), for example, have shown that for extended solar bursts the 3.75-9.4 GHz microwave flux and the 100 keV x-ray flux are produced by the same population of energetic electrons having a power law energy spectrum with a slope of -4 above 100 keV.

In their very recent VLA survey of the microwave emission from a sample of 122 RS CVn binary systems, Drake, Simon and Linsky (1988) found a clear statistical correlation of the 5 GHz microwave flux with the soft x-ray emission from these systems previously obtained with the Einstein satellite. The remarkable aspect of the correlation between these two diagnostics of coronal plasma is that the soft x-ray emission has always been interpreted as thermal bremsstrahlung and line emission, whereas the microwave emission has generally been interpreted as gyrosynchrotron radiation by mildly relativistic electrons of a few MeV energy spiralling in magnetic fields of 10-100 Gauss (e.g. Owen, Jones and Gibson 1976; Dulk 1985). This latter interpretation is consistent with brightness temperatures near 10^6K deduced from 5 GHz VLBI observations of these systems (Mutel et al. 1985) and the moderate amounts of circular polarisation commonly detected.

Why should emission from thermal and nonthermal electrons be correlated? Undoubtedly, numerous elegant theoretical explanations could be advanced to explain this observational "discovery", but one should look deeper into the interpretation of the data before developing a model. Soft x-ray spectra of RS CVn systems obtained with
the Einstein Solid State Spectrometer (Swank et al. 1981) and the Exosat Transmission Grating Spectrometer (Brinkman et al. 1987) cannot be fitted by emission from a single-temperature plasma, but instead typically require a model with (at least) two plasma components, one with a temperature \( \log T_1 = 6.8 \) and the other with a higher temperature \( \log T_2 = 7.7 \). The temperature of the hot component, however, is not well determined. For the 7 RS CVn systems for which both SSS and microwave data exist, the nonflare radio flux correlates poorly with the cool component of the x-ray emission but well with the hot component.

Could this mean that the electrons responsible for the hot component also produce the microwave emission? Drake et al. (1988) propose that the microwave flux is indeed produced by gyro-synchrotron emission from these thermal electrons. To test this unconventional hypothesis, they consider the system UX Ari for which VLBI measurements (Muetel et al. 1985) indicate a core-halo structure. The dimensions of the halo and the observed microwave flux indicate a brightness temperature of \( \log (T_B) = 7.7 \), consistent with optically thick emission from the hot component electrons, and the derived magnetic field of 200 Gauss is consistent with a geometrically-extended corona for these systems. Thus the nonflare microwave and x-ray emission can be explained simply as due to the same electrons and all of the x-ray and microwave emission from these systems becomes self-consistent.

III. SPECTRAL DIAGNOSTICS OF MAGNETIC FIELDS

Solar physicists have long known that magnetic fields play essential roles in heating the chromosphere and corona, determining the geometry of structures in these regions, and otherwise influencing the dynamics and energetics of the diverse phenomena that are called "solar activity". The spatial correlation between magnetic fields and phenomena of specific regions on the Sun is well established, because the proximity of the Sun permits spatially resolved observations. X-ray, ultraviolet and radio observations of dwarf stars of spectral type F-M and certain giant stars, such as components of RS CVn-type binary systems, indicate active phenomena on these stars as well but often orders of magnitude more energetic, indicating that these stars probably also have strong magnetic fields.

Magnetic fields in the solar photosphere are measured from the difference in line profiles between right and left-handed circular polarization for absorption lines that are magnetically sensitive (i.e. large Landé g factors). This procedure provides useful results because the fields are presumed to be roughly homogeneous in the small regions on the Sun defined by the instrumental aperture and seeing, although the measured quantity is the magnetic flux rather than the field strength because the field may not fill the aperture. Application of similar methods for measuring magnetic field properties in solar-type dwarf stars have provided null results (e.g. Babcock 1958; Vogt 1980;
Borra, Edwards and Mayor (1984). This classical method has not led to positive results probably because for spatially-integrated stellar observations the contributions of oppositely-directed field elements cancel to high precision, just as they do in integrated solar light. Thus to measure magnetic fields on late-type stars, one must first devise a better spectral diagnostic. I describe next recently developed of diagnostics that use spectral line broadening and linear polarization. Other reviews of this topic include those of Linsky (1985) and Gray (1988).

**Zeeman broadening techniques using unpolarised light**

Robinson (1980) proposed that the average magnitude of the stellar photospheric magnetic field could be derived from a careful study in unpolarised light of the enhanced Zeeman broadening of a magnetically sensitive line (high Landé g factor) compared with another spectral line very similar in shape and formation, except for its small magnetic sensitivity. Extreme care must be taken in the diagnostic technique because the splitting of a simple Zeeman triplet is only 84 mA or 4.2 km s\(^{-1}\) for a 6000 Å line with g=2.5 in a 1000 G field. This splitting is small compared with stellar line profiles, so that the effect of the magnetic field is to broaden the profile slightly in the inner wings. Since the broadening depends upon the square of the wavelength, observations of infrared lines should have more pronounced broadening. Indeed, Saar and Linsky (1985) have resolved the Zeeman triplet pattern in TiI lines located near 2.2 μm in the spectrum of the dM3.5e flare star AD Leo, which they interpret as due to a field of 3800 ± 260 G covering 0.73 ± 0.06 of its surface. Stellar observations of the 12 μm MgI lines already detected in the solar spectrum (Brault and Noyes 1983) should reveal completely split Zeeman patterns.

Robinson's suggested technique was to observe a pair of spectral lines carefully selected to have similar equivalent widths, central intensities, heights of formation, and temperature sensitivities. He proposed to derive the magnetic field strength from the excess width determined from a Fourier analysis of the the two observed lines. This technique was then used by Robinson, Worden and Harvey (1980) to derive magnetic field strengths (B) and fractional disc filling factors (f) for two stars - ζ Boo A (G8V) and 70 Oph A (K0 V). Gray (1984) used a modified Fourier analysis technique to derive magnetic field parameters in 7 of 18 dwarf stars studied, and Marcy (1984) used a profile fitting variation of this technique to measure field parameters in 19 of 29 dwarf stars observed.

Because the observed quantity is a subtle increase in line width, the inferred magnetic field properties depend upon the accuracy of the diagnostic technique and systematic errors may be critical. Several authors (e.g., Kurucz and Hartmann 1984; Hartmann 1987) have raised the following questions:

1. Weak line blends, especially those located in the inner wings of the magnetically-sensitive line, can result in spurious magnetic fields in all stars, but especially in the
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coolest stars where line blending is nearly ubiquitous. Saar (1988) has studied this effect quantitatively. His solution for the problem (cf. Saar, Linsky and Beckers 1986) is a line difference technique in which one subtracts the profile of the same magnetically sensitive line in a less active star from that of a more active star of the same spectral type, after adjusting the profiles of the two stars for their different rotational and turbulent broadening. The difference profile is then analyzed for Zeeman broadening, but some limitations to this technique are discussed below.

(2) The spectral lines generally analyzed for Zeeman broadening are not weak and thus are saturated. Typically their equivalent widths place them on the flat part of the curve of growth, so that their shapes depend upon line optical depths and on the line/continuum opacity ratio. The Robinson (1980) technique implicitly assumes that both the magnetically-sensitive and insensitive lines are optically thin, but Hartmann (1987) showed that the difference between two lines with different degrees of saturation can be appreciable in the inner line wings and thus produce a spurious magnetic signature. This problem can be alleviated by comparing observed line profiles with computed profiles that include line saturation effects. This has been done by Saar (1988) using an analytical solution to the radiative transfer equation in which the LTE line source function depends linearly upon optical depth, and the line/continuum opacity ratio is assumed to be independent of depth. Baari and Marcy (1988) have instead solved for the Stokes vector in a full LTE model atmosphere in which all parameters are allowed to vary. Since this technique results in magnetic field parameters similar to those found by Saar for stars in common, Saar's simpler analytical technique appears to be approximately valid.

(3) The magnetic field parameters inferred from a comparison of observed and computed line profiles depend sensitively on the assumed stellar rotational velocity, microturbulent broadening and macroturbulent broadening. Thus even the model atmosphere technique has its limitations.

(4) The comparison of profiles of the same magnetically-sensitive line in two different stars does cancel the effects of line blends to first order, but the two stars may have somewhat different thermal structures and abundances and thus different line saturations and widths that must be corrected for.

(5) In order to measure small differences in line width due to Zeeman broadening, high quality observations are essential. Saar (1988) showed that for lines in the visible, the minimum requirements are signal/noise > 80, vsini < 8 km s\(^{-1}\), and a spectral resolution > 70,000.

(6) The thermal structure of the magnetic regions of a stellar atmosphere may differ considerably from that of the nonmagnetic regions, whereas all analytic approaches used to date assume the two atmospheric regions to be the same (except for the magnetic broadening). If the magnetic regions are hotter with a brighter continuum adjacent to the magnetically-sensitive line (analogous to solar faculae), then the magnetic regions
contribute disproportionately to the disk-integrated line profile, and the magnetic filling factors should be smaller than computed for a homogeneous atmosphere. This effect may explain the large filling factors (as large as f=0.9) that Saar et al. (1987) have deduced from infrared spectra of M dwarf stars. On the other hand, if the magnetic regions are cooler than the surrounding photosphere (e.g. pores on the Sun), then the filling factors have been underestimated.

(7) What is the proper physical interpretation of the derived magnetic field strengths? Because starspot are very dark in the visible, the disk-integrated line profiles include very little contribution from spots even when they cover a large portion of the stellar surface as is true for dMe stars. The inferred fields must, therefore, refer to penumbral spots or to localized magnetic regions perhaps analogous to the chromospheric network on the Sun. The empirical correlation of observed field strengths with the values computed by balancing magnetic with gas pressure forces in the photosphere (Saar and Linsky 1985 ; Saar et al. 1987) suggests that convective motions enhance the photospheric fields until pressure equilibrium is achieved. In the solar photosphere typical field strengths of 1200-1500 G in small structures (Tarbell and Title 1977) are consistent with this explanation. Thus we might expect that the inferred field strengths represent averages of this pressure equilibrium field over the whole stellar disk. The computed line profiles that are compared with observed profiles to determine the field parameters should thus be disk averages rather than profiles computed at an average viewing angle.

Circular and linear polarization techniques

While most recent empirical studies of magnetic fields in late-type stars are based on measurements of the excess Zeeman broadening of line profiles in unpolarised light, polarization techniques have been pushed to their limits in order to obtain information on the fields complementary to the broadening analyses. For example, Kemp et al. (1987) have found variable broad-band circular polarization of amplitude 0.002-0.004% in observations of the single-lined RS CVn system λ Andromedae (G8 III-IV). They interpret their net polarization signal as due to ordered magnetic fields, perhaps in large spots near the rotational pole and thus always near the limb, that are not fully cancelled in the disk-averaged flux because of their concentration near the limb.

Linear polarization from magnetic regions distributed across the disk does not cancel in integrated starlight, and has been recorded in broadband measurements for a few stars (e.g. Huovelin et al. 1988). While the interpretation of these data in terms of magnetic parameters is difficult and not unique (Landi Degl’Innocenti 1982), the polarization amplitude is a measure of the net tangential component of the magnetic field and will be largest when sufficient magnetic flux is concentrated asymmetrically near the stellar limb. In contrast, the magnetic filling factor derived from unpolarised line broadening measurements is weighted towards disk-center regions because of pro-
jection and limb-darkening effects. Thus the combination of simultaneous broad-band linear polarization data and line broadening data for the same star provides positional information from which a "magnetic image" may be constructed. Saar et al. (1988) have constructed a magnetic image of ξ Boo A (G8 V) on the basis of a coordinated observing campaign in June 1986.

IV. CONCLUDING THOUGHTS

The topic of spectral diagnostics is extremely broad and I have only covered a portion in the allotted time. In particular, I do not have the time to present recent interesting work on systematic flows (both winds and downflows in magnetic regions), turbulent broadening, and spectral line asymmetries (so-called C patterns) that have been used to infer the circulation patterns in stellar granulation (Dravins 1982; Gray 1988). For all diagnostics, one should be skeptical concerning the accuracy of the derived thermodynamic, magnetic and flow properties as the assumptions embedded in the underlying models may be inadequate or even erroneous, whereas the "inductive logic of the theoretician" would like the constructions based upon the diagnostics to represent "unique physical reality".

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