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DEFINITION AND EMPIRICAL STRUCTURE OF THE RANGE OF STELLAR CHROMOSPHERES-CORONAE ACROSS THE H-R DIAGRAM: COOL STARS

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COOL STARS

ABSTRACT

Major advances in our understanding of non-radiative heating and other activity in stars cooler than T_{eff} = 10000 K has occurred in the last few years primarily as a result of the IUE and Einstein spacecraft, the VLA microwave facility, and new optical observing tecniques. I critically review this observational evidence and comment on the trends that are now becoming apparent. The evidence for non-radiatively heated outer atmospheric layers (chromospheres, transition regions, and coronae) in dwarf stars cooler than spectral type A7, in F and G giants, pre-main sequence stars, and close binary systems is unambiguous, as is the evidence for chromospheres in the K and M giants and supergiants. The existence of non-radiative heating in the outer layers of the A stars remains undetermined despite repeated searches at all wavelegenths. Two important trends in the data are the decrease in plasma emission measure with age on the main sequence and decreasing rotational velocity. Variability and atmospheric inhomogeneity are commonly seen, and there is considerable evidence that magnetic fields define the geometry and control the energy balance in the outer atmospheric layers. In addition, the microwave observations imply that non-thermal electrons are confined in coronal magnetic flux tubes in at least the cool dwarfs and RS CVn systems. The chromospheres in the K and M giants and supergiants are geometrically extended, as are the coronae in the RS CVn systems and probably also in other stars.

1. INTRODUCTION

In keeping with the tradition of these "Trieste" Workshops, I will attempt to give a comprehensive but provocative survey of an extremely broad field that has undergone a thorough revolution in the last few years. Despite this revolution, driven almost entirely by the data, as is usually the case, we remain indebted to the thorough investigation over the years of the closest star -- the Sun -- which has guided our thinking, provided deep insights into the phenomena that occur in real stellar atmospheres, and defined the terms that we use in describing phenomena in cool stars. It is therefore appropriate that this Workshop is being held at Sacramento Peak where the National Solar Observatory is a pioneer in both solar and solar-stellar research.

I will attempt to survey what we now know about chromospheres and coronae of cool stars, including interacting binary systems and apparently single stars on and evolved from the main sequence. Unfortunately, I will not say very much about pre-main sequence stars and stellar winds for lack of time and because others at this meeting are far better qualified than I to do so. This is an open invitation for them to fill in what I will leave out.

There are several themes in this review. First, the types of atmospheric regions and phenomena that have been investigated in detail on the Sun are indeed present in many if not most cool stars. Second, we must presume a priori that real cool stars are just as inhomogeneous and complex as the Sun even though we lack the spatial resolution to verify this. Thus, we should strive to incorporate inhomogeneity into our models or at least be suitably apologetic when we cannot take inhomogeneity into account. Third, we now have ample evidence that non-radiative heating and probably also non-radiative momentum deposition are fundamental phenomena in the atmospheres and winds of cool stars. Fourth, the evidence is accumulating rapidly that magnetic fields lie at the heart of much of the rich phenomenology in cool stars. This is not to say that magnetic fields control all phenomena, but rather that magnetic fields usually determine the geometry, time variability, non-radiative heating rates, inhomogeneity, and ultimately the global energy balance in stars located in a wide range of the cool half of the HR diagram. The only region of the HR diagram where the evidence for this is still weak is the upper right hand corner.

In approaching this topic we should be properly skeptical of both data and interpretation. A quick inspection of the literature of only ten years ago in this field (the outer atmospheres of cool stars) would demonstrate that, with hindsight, most of what was published then would now fall into four categories: (1) flagrantly wrong, (2) woefully inadequate, (3) hopelessly naive, or (4) outrageously simpleminded. It would not surprise me if a fearless reviewer of this topic in 1994 would say much the same thing about what is being published today. So, we should not fight overly tenaciously for our favorite models which, in a short period of time, will likely join the ever increasing garbage heap of astrophysical history.

Beginning in 1978, three events have totally changed our recognition and understanding of non-radiative activity and structure in cool stars. The International Ultraviolet Explorer (IUE) satellite launched in 1978 has obtained ultraviolet spectra of many stars of almost all types, providing evidence for 10^4 - 10^5 K plasma in the chromospheres and transition regions (TRs) of many of these stars. The Einstein (HEAO-2) satellite, also launched in 1978, has detected soft X-ray fluxes from many stars of almost all types, providing evidence for 10^6 - 10^8 K plasma in the coronae of many of these stars. Finally, the Very Large Array (VLA), dedicated in 1980, is observing microwave emission from an increasing number of cool stars and binary systems. These three events radically changed the data base concerning non-radiative activity from famine to feast. So much has been learned in the last few years that a comprehensive review of the topic is no longer feasible. Instead, for this workshop I will concentrate on the major achievements and the as yet unsolved problems.

Before proceeding, I should mention a number of reviews that provide more detailed treatments of different aspects of this topic. Broad surveys of X-ray emission from stellar coronae include those of Vaiana (1981, 1983), Golub (1983), Stern (1983), and Linsky (1981a,b). Gibson (1981, 1984), Gary (1984), and Mullan (1984a) have summarized the microwave observations of cool star coronae; and Linsky (1981c,1982), Brown (1983),and Baliunas (1983) have summarized the ultraviolet observations of stellar chromospheres and transition regions. The extensive evidence for mass loss in cool stars has been reviewed by Cassinelli (1979), Dupree (1982), and Hartmann (1981, 1983); and the direct and indirect evidence for magnetic fields in these stars has been summarized by Vogt (1983), Marcy (1983), Zwaan (1983), and Linsky (1983a). Linsky (1982) has discussed the energy balance in the outer atmospheres of cool stars. The X-ray, ultraviolet, and microwave emissions from the M dwarf flare stars have been reviewed by Gibson (1983), Johnson (1983), Worden (1983), Giampapa (1983a), and Linsky (1983b); and Giampapa (1983b) and Feigelson (1983) have reviewed similar data for the pre-main sequence stars. Finally, reviews of the emission from RS CVn binaries include those of Bopp (1983), Charles (1983), Linsky (1983a), and Mutel and Lestrade (1984); and Dupree (1983) has reviewed this topic for the contact binary systems.

2. DEFINITIONS

Throughout this review I will use the terms chromosphere, transition region, and corona in a precise way. Therefore, to avoid confusion I will begin by defining what I mean by these terms and mention why I make these distinctions and how these terms have developed historically. You can disagree with my definitions, but at least you will know what I mean when I use them.

Initially, the term chromosphere was coined to describe a region of the solar atmosphere extending some 10^4 km above the limb that is visible in emission lines of neutral and singly ionized atoms at the time of eclipse. Subsequently, it was recognized that this layer in the solar atmosphere gives rise to the core of many strong Fraunhofer lines seen in projection against the disk and many emission lines and continua in the ultraviolet. Thomas and Athay (1961) pointed out that the anomalously large scale heights (exponential decrease in intensity with height above the limb) of typical solar chromospheric emission lines requires either an energy source in addition to that supplied by radiation from the underlying photosphere (non-radiative heating) or a source of mechanical momentum. At the present time it is generally assumed that non-radiative heating is primarily responsible for the large extent of the solar chromosphere, although direct momentum transfer to the gas by mechanical waves may be important in cool giants and supergiants.

Thomas and Athay (1961) and Athay (1976) pointed out that the existence of the solar chromosphere and corona is a vivid manifestation of the failure of classical stellar atmospheres theory, with its assumptions of radiative equilibrium, hydrostatic equilibrium, and spherical symmetry, to predict the real Sun. Clearly a fundamental aspect of a chromosphere is the violation of these assunptions, particularly radiative equilibrium, and an important goal of stellar chromospheric research is to identify and quantify the non-radiative heating mechanisms responsible for the non-classical behavior of the Sun's outer atmosphere.

Praderie (1973) proposed a tentative definition of a stellar chromosphere as that layer in which both mass flux and non-radiative energy dissipation occur. By contrast, she proposed that a stellar photosphere is that region in which no non-radiative energy deposition occurs. Such a definition was motivated by the then prevailing belief that the dissipation of mechanical energy in acoustic or other types of waves (see Thomas and Athay 1961; Ulmschneider 1979) heats the chromosphere, and that turbulent convection generates the required mechanical energy flux. The non-radiative heating forces a rise in temperature over the monotonic outward decline otherwise expected in an LTE radiative equilibrium photosphere. The temperature inversion then produces in a complex way the emission lines and continua that we call the chromospheric spectrum.

One problem with the scenario discussed by Praderie (1973, 1977) is that temperature inversions are possible even in a purely radiative equilibrium atmosphere. In the most extreme example of the effect, originally described by Cayrel (1963, 1964), the local electron temperature in the outer layers can rise to the color temperature of the background photospheric radiation field. The Cayrel effect is opposed by surface line cooling (cf. Athay 1970) in solar-type stars. Thus our intuitive feeling that a chromosphere begins at the temperature minimum, where dT_e/dh changes from negative to positive values, may ignore much of the underlying physics.

I think that it is important to go beyond Praderie's definition of a chromosphere for the following reasons:

1. There is growing evidence for non-radiative heating in atmospheric

layers that we intuitively characterize as photospheres. Theoretical calculations of the propagation of acoustic waves in solar-type and cooler stars by Ulmschneider, Schmitz, and Hammer (1979), among others, predict that as much as 90% of the initial acoustic wave energy is dissipated in the photosphere (where $dT_e/dh < 0$) below the temperature minimum. The temperature gradient remains negative despite the mechanical heating because the high density photosphere is an efficient radiator of energy by H^- and other continua, and the acoustic dissipation rate is small compared with the local radiative heating, and cooling, rates. (By comparison, the lower density chromosphere is an inefficient radiator of energy and a small amount of heating is sufficient to produce a temperature inversion.) Also, analyses of the Ca II and Mg II resonance line wings suggest that the outer portions of the photospheres of many main-sequenc°Be and giant stars (Kelch et al. 1978, 1979) and both quiet and active regions of the solar chromosphere (Ayres and Linsky 1976; Morrison and Linsky 1978) are hotter than predicted by radiative equilibrium considerations. Thus, the assumption that non-radiative heating is unimportant in photospheres needs to be reconsidered.

2. Withbroe and Noyes (1977) have summarized the solar data that demonstrate the pervasive and fundamental role played by magnetic fields in defining the structure, mass balance, and energy flow of the chromosphere and corona. They point out that the differences in physical conditions in the chromospheric and coronal layers over different areas of the solar surface are intimately related to the strength and configuration of the local magnetic fields. A specific exmaple is the excellent correlation of Ca II K-line intensity with magnetic field strength (Skumanich et al. 1975), which demonstrates the close connection between magnetic field concentrations and non-radiative heating. Heating mechanisms involving magnetic fields include a range of MHD wave modes, ohmic dissipation of currents induced by evolving magnetic structures, and field reconnection. The latter two mechanisms do not involve mechanical waves directly. Consequently, the assunption that a mechanical energy source and a mass flux are necessary conditions for the existence of a chromosphere may not be valid.

3. It is important to differentiate between chromosphere and corona in a meaningful way.

With these problems in mind, I proposed (Linsky 1980) new tentative definitions of different atmospheric layers and have found no valid reasons for changing these definitions since that time. The defining characteristics are summarized in Table 1.

Table 1.

Atmospheric Regions

Parameter	Inner atmosphere	Outer atmosphere: Photosphere	Chromosphere	Transition region	Corona
Defining Characteristics					
Nonradiative heating	not present	present but not dominant	dominates the energy balance equation		
Temperature gradient		$\frac{dT}{dh} < 0$ except for Cayrel-type temperature inversions	$\frac{dT}{dh} > 0$ but gradual	$\frac{dT}{dh} > 0$ but steep	$\frac{dT}{dh} > 0$ but small
Geometrical extent (in units of the local P scale height)		many	several	much less than 1	many
Solar Example					
Dominant cooling terms for Sun		radiation in continua and lines	radiation in resonance and some subordinate lines, H^- and H continua	line radiation in UV and EUV	X-ray and EUV radiation, thermal conduction, thermally driven wind
Range of temperature in Sun		6000-4400 K	4400-25,000 K	25,000-1 × 10^6 K	1-3 × 10^6 K
Important structures seen in Sun		sunspots, faculae, granulation, flux tubes	network, plages spicules, prominences	network, active regions	magnetic loops, coronal holes

I use outer atmosphere as a generic term encompassing all of the layers described below. The specific quantity defining an outer atmosphere and separating it from the inner atmosphere of a star is the presence of significant non-radiative heating. I use the term non-radiative heating to include dissipation of mechanical waves, magnetic heating processes, thermal conduction, and even radiation from higher layers, for example X-rays from flares and coronae. The important point is that the heating does not involve the emergent photospheric radiation field directly.

By the term photosphere, I specify the atmospheric layers where non-radiative heating is present but not dominant. By this I mean that the non-radiative heating is not sufficiently large to force a temperature inversion. This definition is consistent with our intuitive feeling that a photosphere is a region of $dT_e/dh < 0$, such as usually occurs in radiative equilibrium. By this definition, layers in which temperature inversions occur within the radiative equilibrium constraint, such as by the Cayrel mechanism, are included within the term photosphere.

A necessary but not sufficient condition for the existence of a chromosphere is that non-radiative heating dominate the energy balance. By this I mean that the local non-radiative heating rate is sufficient to force a positive temperature gradient. Since this particular property does not uniquely distinguish a chromosphere from other layers, I propose another defining characteristic based on our understanding of the Sun. The first empirical aspect of the solar chromosphere that called attention to its anomalous character was its geometrical thickness. That is, the chromosphere extends over many pressure scale heights, and the temperature gradients are generally small. This is presumably due to the large opacity of the Lyman continuum and the resonance lines of HI, CaII and MgII. Since these lines, among others, and the Lyman continuum are relatively efficient radiators of energy, they act as thermostats to produce a gradual temperature increase with increasing height and decreasing density. In fact, it is useful to define the upper extent of a chromosphere as that height where the last of these resonance lines, Ly-alpha, becomes optically thin. At this point, typically above 20000 K, the atmosphere loses an important cooling mechanism (cf. Thomas and Athay 1961; Athay 1976) and the temperature rises steeply with height.

Therefore, I propose that the necessary and sufficient conditions for the existence of a chromosphere are that non-radiative heating dominate the energy balance and that temperature gradients be small compared with the local pressure scale height. Mass flux need not be an important term in the momentum equation, although in late K and M giants and supergiants there is evidence for supersonic winds in the chromosphere (Stencel 1978; Mullan 1978), and for large geometrical extent (Stencel et al. 1981; Carpenter, Brown, and Stencel 1985).

In the Sun the region immediately above the chromosphere is characterized by steep temperature gradients. In fact, the temperature rises from about 30000 K to 1×10^6 K in much less than a pressure scale height, presumably owing to the absence of efficient cooling agents. It seems reasonable, therefore, to define stellar transition regions as those layers where non-radiative heating is dominant (in the same sense as defined above), but the cooling mechanisms are sufficiently weak that the geometrical extent of the layer is smaller than a pressure scale height. Jordan (1980) has discussed the interrelationships between conductive heating, radiative cooling, and additional non-radiative heating terms in the context of the solar transition region. The role played by wave dissipation processes is unclear, although there appears to be insufficient mechanical energy available to balance the estimated cooling rates in either the solar TR or the corona (Athay and White 1978). Since the lower boundary temperature is governed by the ionization of hydrogen, one might expect TRs to begin near 30000 K. (This argument also suggests that the hotter O and WR stars may not have chromospheres as defined above owing to the absence of appreciable neutral hydrogen.)

The solar corona was initially identified by the presence of 10^6 K emission lines and its large geometrical extent. The high temperatures are a consequence of non-radiative heating processes that are largely or entirely magnetic in character (Withbroe and Noyes 1977; Vaiana and Rosner 1978), and cooling processes involving X-ray and EUV radiation, thermal conduction both down to the TR and out to space, and a thermally driven wind,all of which require 10^6 K temperatures to operate efficiently. The geometric extent of the corona is a consequence of the large pressure scale heights at high temperatures, conductive smoothing of temperature gradients, and perhaps also heating over large spatial scales.

It therefore seems natural to define a corona, in contradistinction to a chromosphere or a transition region, as a region heated by non-radiative processes that is characterized by small temperature gradients and sufficiently hot temperatures that the dominant cooling mechanisms include X-ray and EUV radiation, thermal conduction, or a thermally driven wind. For the solar corona these latter three terms are roughly comparable (Withbroe and Noyes 1977), but this need not be true in general. In addition, the interface temperature between a corona and the underlying TR need not be at 10^6 K, but will depend on the balance of heating and cooling rates, which controls the local temperature gradient.

It is important to recognize that the outer atmosphere layers of a star are probably inhomogeneous. In particular, magnetic loops dominate the Sun's coronal geometry (Rosner, Tucker, and Vaiana 1978), and emission from the solar TR may arise from less than 1% of the solar surface (Nicolas et al. 1979; Feldman et al. 1979).

3. TYPES OF EVIDENCE FOR NON-RADIATIVE ACTIVITY IN COOL STARS

I will define the term non-radiative activity to include those phenomena and physical properties that occur when the energy balance in a stellar atmosphere departs greatly from pure radiative equilibrium. Non-radiative heating produces the hot atmospheric layers that we have just defined as chromospheres, transition regions, and coronae. These layers are inhomogeneous and variable in time. In addition, momentum can be imparted to the outher layers of a star by a number of possible mechanisms to produce mass loss by a stellar wind. Except perhaps for the dusty M supergiants, the deposition of momentum in the winds of cool stars does not come directly from the stellar radiation field, and, therefore, could be considered an aspect of non-radiative activity. Thus in general terms the evidence for non-radiative activity consists of the following:

(1) Thermal radiation from plasmas substantially hotter than can be explained by an atmosphere in radiative equilibrium. The prime spectral diagnostics are X-ray and ultraviolet emission lines and continua, as well as thermal microwave emission. In addition, a few spectral features in the visible and near infrared, including the CaII H and K and infrared triplet lines, Hα, and HeI-10830 Å and HeI-5876 Å, are useful.

(2) Non-thermal radiation from relativistic particles in magnetic fields. Such radiation is detected during flares in the microwave and perhaps also in hard X-rays. Indeed, some portion of the "quiescent" microwave emission from M dwarfs could be non-thermal in character.

(3) Stochastic emission variations indicating flaring or rapid heatig of atmospheric structures like magnetic flux tubes or active regions. An atmosphere in radiative equilibrium should be a steady emitter, since the stellar luminosity changes only on very long, evolutionary timescales, except during rare explosive events. Radial and non-radial pulsations, on the other hand, can occur even for an atmosphere in radiative equilibrium and could be maintained by purely radiative processes.

(4) Large scale atmospheric inhomogeneities indicated by periodic variations of the stellar spectrum on a rotational time scale; for example, rotational modulation of the emission from bright active regions in the ultraviolet, X-ray, and microwave; or modulation of the optical continuum due to an inhomogeneous surface distribution of cool, dark starspots.

(5) Mass loss produced by such non-radiative acceleration processes as waves and an outwardly decreasing thermal pressure gradient.

In this review I will discuss the evidence for the first four points primarily by considering in turn the different spectral regions. As we proceed through this topic, it is important to keep in mind that the diagnostics of the heated or accelerated plasma may not be reliable for several reasons:

(1) Very small contrast between the sought after emission line and the background stellar photosphere -- a problem especially important in the ultraviolet for early F and A-type stars.

(2) Non-LTE effects. In some cases, non-LTE effects can produce a spurious emission spectral feature that appears to indicate heated plasma.

(3) Most stars are members of binary systems, and quite often the duplicity or multiplicity is not readily apparent either from optical imaging, composite colors, or variable radial velocities. Since the vast majority of stars are cool dwarfs that are faint in the optical but intrinsically bright in X-rays, ultraviolet emission lines, and microwave emission, one can easily be fooled into ascribing the evidence for hot plasma to the usually dominant primary star when, in fact, an unsuspected secondary star may be the source of much or all of the high temperature emission.

(4) Close companions can alter the adjacent stars by tidally-induced rapid rotation, mass exchange, or X-ray illumination and heating. Furthermore, as in the case of the RS CVn-type binaries, magnetic fields of the two stars may interact and heat plasma between the two stars.

(5) Interstellar and circumstellar absorption can decrease or totally eliminate measurable X-ray and UV radiation from a star. Absorption effects are especially important for distant stars in the galactic plane such as pre-main sequence stars.

(6) Instrumental problems can be very important. For example, sensitivity limitations can lead to sample bias or the inability to observe whole classes of objects. The failure to detect high-excitation emission features does not imply that a given star lacks hot plasma, but merely that the emission measure of the plasma must be less than an empirical upper limit. Furthermore, subtle imperfections in the instruments themselves can lead to false conclusions. An example is the UV light leakage in the Einstein High Resolution Imager (HRI) that falsely implied that Sirius A and Vega are X-ray sources.

4. EVIDENCE FOR HOT (10^6 - 10^8 K) CORONAL GAS: X-RAY EMISSION

X-ray emission in the continuum and discrete lines can be produced by thermal processes (free-free, free-bound, and bound-bound) and, in principle, by non-thermal processes involving high energy particles in magnetic fields. Both processes indicate a plasma heated by non-radiative processes. Early soft X-ray experiments on rockets and the ANS and SAS-3 satellites were able to detect only the very brightest X-ray sources among the nearby stars such as Capella and the dMe flare stars while flaring, but also curiously, Vega (AO V) and Sirius (A1 V + WD). Many of these early detections were serendipitous.The HEAO-1 A2 all sky survey discovered that the RS CVn binary systems as a class are luminous X-ray sources (log L_x = 30-31) (Walter et al. 1980), and detected several late-type dwarfs as quiescent and flaring sources.

Major progress required more sensitive imaging instruments, in particular the IPC and HRI focal plane instruments on Einstein (HEAO-2). These instruments detected X-ray emission from nearly every type of star except the luminous cool giants and supergiants (Vaiana 1981; Vaiana et al. 1981; Ayres et al. 1981; Helfand and Caillault 1982; Linsky 1981b), and in the process totally contradicted the previously held theory of acoustic wave heating of stellar coronae. The SSS instrument on Einstein obtained low resolution soft X-ray spectra of RS CVn systems, Algol, and one dMe star (Swank et al. 1981; Swank and Johnson 1982), while the higher resolution crystal spectrometer had the sensitivity to observe only Capella among the cool stars (Vedder and Canizares 1983). The EXOSAT spacecraft is now observing many targets, and future missions will include ROSAT, which will undertake an all sky survey, and the AXAF, which will have very high resolution imaging capability.

Linsky (1981b) has summarized the physical quantities which can be inferred from these data. The imaging instruments (primarily the IPC and HRI) are useful for identifying X-ray sources, studying their time variability, and measuring their broad band (0.25-4 keV) flux. The IPC also provided only a rough estimate of the plasma temperature and emission measure for coronae hotter than about 1×10^6 K. Low resolution spectroscopy (e.g.,the Einstein SSS) allows one to distinguish multi-temperature plasmas and the corresponding emission measures.

Even though the Einstein satellite has provided almost all of the information to date on stellar coronae, we clearly need greatly enhanced capability. For example, more sensitive imaging instruments are needed to study the luminous cool stars, A stars, and distant young stars. Significantly more sensitive spectroscopic instruments are needed. to determine the temperature distribution, electron densities (from density sensitive line ratios), flow velocities, and energy balance in stellar coronae. Even with such improvements, interstellar absorption will severely compromise our ability to detect distant soft sources near the galactic plane.

Einstein detected many dwarf stars of spectral type F, G, K, and M. The M stars are particularly interesting because they are very luminous in X-rays (log L_x = 27-30), but there is evidence that the coolest M dwarfs are much less luminous (Golub 1983). A number of early F dwarfs have been detected, and the hottest late-type dwarf star detected to date is probably α Aql (A7IV-V, T_{eff} = 7650 K) observed by Golub et al. (1983). Also, Canopus (FOII) has been detected as an X-ray source by Ayres et al. (1981).

The question of X-ray emission from the A dwarfs is not yet resolved. Pallavicini et al. (1981) noted that Vega (AOV) and Sirius A (A1V) were detected by the HRI (but not the IPC) at values of L_x/L_{bol} an order of magnitude below the 10^{-7} relation that characterizes the O and B stars. Golub et al. (1983) argued that these detections were real, but they later found that the HRI signal apparently was due to a spurious UV light leak. These authors also concluded that the X-ray emission detected from the other normal A-type stars at a level of log L_x = 29 is likely due to emission from known or suspected K and M dwarf companions, although two detected Ap stars in their sample exhibit no evidence of duplicity. We therefore have no unambiguous evidence as yet that A-type stars have 10^6 K coronae; we can only say that if such coronae exist, they must be of low luminosity, log $L_x < 27$.

To date the only evolved single stars detected as X-ray sources are F and G giants. Ayres et al. (1981) and Haisch and Simon (1982) have argued that a "dividing line" exists in the HR diagram (see Figure 1) separating the coronal stars (single giants earlier than about K1III and main sequence stars) from the non-coronal stars (giants later than about K2III and supergiants later than about G2Ib). Spectroscopic binaries, especially the tidally synchronous rapid rotators with periods less than 20 days, tend to be strong emitters (log L_x = 30-31); examples are the RS CVn, Algols, and W UMa systems.

Some important results concerning the hot plasma in the coronae of late-type stars include:

(1) There is a monotonic increase in L_x with decreasing age (see Stern 1983). This is based on systematic studies of the Hyades (age 4×10^8 yr, Stern et al. 1981), Ursa Major (age 1.6×10^8 yr, Walter et al. 1984), Pleiades (age 6×10^7 yr, Caillault and Helfand 1984), and Orion stars (age 10^6 yr).

(2) L_x increases monotonically with increasing rotational velocity. This result may explain the age effect, and suggests that the heating processes are magnetic in character with the fields regenerated by a dynamo-type mechanism. There remains a disagreement, however, whether the functional dependence of X-ray emission on rotation is of the form $L_x \sim (v \sin i)^2$ as proposed by Pallavicini et al. (1981) or $L_x/L_{bol} = f(\Omega)$ as proposed by Walter (1981, 1982). Also, there is evidence for saturation at high

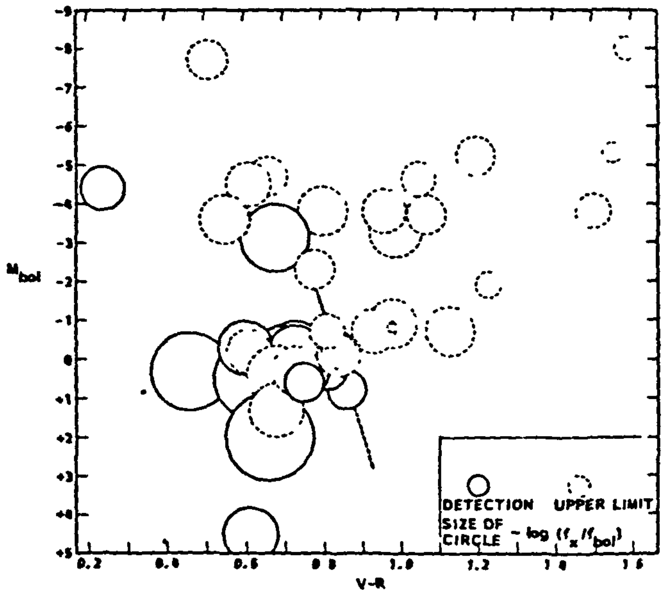


Figure 1. An HR diagram showing measured ratios of the soft X-ray flux (from Einstein) to the apparent stellar bolometric luminosity for apparently single stars from Haisch and Simon (1982). Solid line circles are detections and dashed line circles are upper limits. The sizes of the circles are proportional to log (f_x/f_{bol}). No apparently single stars are detected to the right of the "dividing line" to small upper limits in some cases.

rotational velocities and young ages (Rucinski 1984; Caillault and Helfand 1984).

(3) Swank et al. (1981) have found that the coronae of RS CVn and Algol systems are characterized by two temperatures (one component at roughly $5x10^6$ and the other hotter than $2x10^7$ K). Swank and Johnson (1982) found a similar result for the dMe star system Wolf 630 AB. However, the temperature of the hot component is poorly determined and it could in principle be non-thermal as suggested by the microwave data.

(4) In their study of the eclipsing system AR Lac, Walter, Gibson, and Basri (1983) found evidence for discrete active regions in the coronae of both stars and that the KO IV star possesses an extended component to its corona (see Figure 2).

(5) Coronal X-ray emission can be quiete variable, especially for the M dwarfs (e.g., Johnson 1981, 1983; Golub 1983) and RS CVn systems.

(6) Coronal magnetic field are needed both to confine the hot plasma and probably also to heat it.

5. EVIDENCE FOR HOT (10^6 - 10^8 K) CORONAL GAS: MICROWAVE EMISSION

The known or suspected mechanisms for microwave emission from stars include thermal bremsstrahlung, gyroresonance emission by thermal electrons spiraling in coronal magnetic fields, gyrosynchrotron emission from non-thermal electrons, and coherent processes. Prior to the commencement of VLA observations, the types of late-type stars detectable by interferometers such as the NRAO three-element interferometer or single disk radio telescopes were severely limited by sensitivity and source confusion. The only detected sources consisted of dMe and RS CVn systems while flaring, interacting binary systems, and two M supergiants with massive winds (α Ori and α Sco). The factor of 100 better sensitivity (a 3 sigma noise level of 0.1 mJy is achievable at 6 cm) and the factor of 400 better angular resolution of the VLA compared to a 100 m single disk telescope revolutionized the field of stellar radio astronomy just as Einstein revolutionized the field of stellar X-ray astronomy.

The VLA has now observed about a dozen dMe stars as quiescent and flaring radio sources (Gary and Linsky 1981; Linsky and Gary 1983; Topka and Marsh 1982; Fisher and Gibson 1983; Gibson 1983, 1984). These sources all appear to be variable. Since the dMe stars are detected at levels far above those predicted on the basis of bremsstrahlung from the coronal electrons inferred from the X-ray fluxes, and because the emission often is circularly polarized, these authors have argued that the quiescent flux likely is due to gyroresonant or synchrotron emission. The 6 cm luminosities for the quiescent emission lie in the range 1×10^{13} - 5×10^{14} ergs/s/Hz.

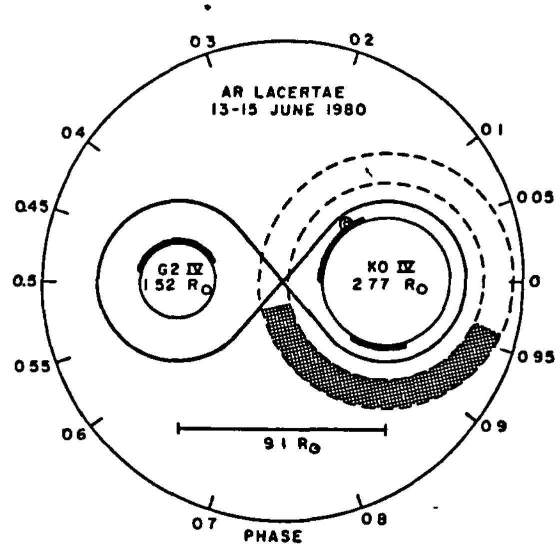


Figure 2. A scale drawing of the AR Laceratae system indicating coronal active regions. The line of sight at a given phase is found by lining up the phase indicated on the outer circle with the center of mass. The solid line is the Roche surface, the dashed lines surrounding the K star indicate the inner and the outer radii (1.5 and 2.0 R_K) of the extended component of the K star corona. Crudely indicated are the location and extent of the observed bright active regions in the chromospheres and coronae of both stars. Note that the extended component of the K star corona exceeds the Roche radius (from Walter, Gibson and Basri 1983).

Except for the Sun no single dwarf stars of spectral types F, G, and K have been definitely detected yet despite several searches (e.g., Linsky and Gary 1983). Luminosity upper limits for nearby stars as low as $3x10^{12}$ ergs/s/Hz at 6 cm have been achieved for such stars as ε Eri (K2V) and 61 Cyg AB (K5V + K7V), but these limits are still above those predicted on the basis of bremsstrahlung emission alone from their X-ray coronae. Gary and Linsky (1981) originally detected the young star χ^1 Ori (GOV), but repeated observations have revealed that the source is highly variable and the original detection could be explained by a flare on its M dwarf companion. No single A-type dwarfs have yet been detected. For comparison purposes, the Sun placed at a distance of d parsecs would have a typical quiet flux density of $0.01/d^2$ mJy, whereas the sensitivity limit of the VLA is now 0.1-0.2 mJy. Thus only stars that are considerably more luminous than the Sun at radio wavelengths can presently be detected as radio sources.

Among the late-type giants and supergiants, the only single (or widely separated binaries) detected are α Ori (M2Iab), α^1 Sco (M1Ib), α^1 Her (M5II), and α Boo (K2III) (cf. Newell and Hjellming 1982; Drake and Linsky 1983a). The emission mechanism is likely bremsstrahlung from a cool (6000-8000 K) chromosphere and wind. Also flares have been detected from α Ori, π Aur (M3II), and R Aql (gM5e-8e). None of the X-ray emitting F and G giants has yet been detected as a microwave source. On the other hand, RS CVn and Algol systems are readily detected as flaring and quiescent sources with single dish antennae and the Green Bank interferometer (Gisbon 1981; Feldman 1983) and now also as quiescent sources with the VLA. With increasing separation (longer period), the RS CVn systems are often less luminous. An exaple is the nearest long period system, Capella (G6III + F9III), with a period of 104 days that has not been detected despite several attempts (Drake and Linsky 1983b). The 0.25 mJy upper limit at 6 cm is barely consistent with the flux expected on the basis of bremsstrahlung from the X-ray corona alone. Figure 3 summarizes all of the non-thermal radio sources detected to date.

The following are some critical points learned from the data so far:

(1) Except for the K and M giants and supergiants, the emission seems to be coming from relativistic or very hot electrons confined by coronal magnetic fields. This conclusion is based on the large inferred brightness temperatures and detected circular polarization in some cases, indicative of gyro-synchrotron, gyroresonance, or maser emission. Furthermore, the maximum microwave emission of the eclipsing binary system YY Gem (dM1e + dM1e) occurs in phase with the meridian passage of the large starspot group and active region on the secondary star in the system (Linsky and Gary 1983).

(2) The microwave emission is highly variable on both short time scales ($\gtrsim$0.1 sec. flaring) (e.g., Lang et al. 1983) and long time scales of hours to days. The probable emission mechanisms (masering for the flares and gyrosynchrotron emission for the longer term variability) imply highly structured coronae similar to that of the Sun in which the local magnetic field confines and accelerates the emitting electrons.

(3) VLBI observations by Mutel et al. (1984) have shown that 20 cm emission from the RS CVn spectroscopic binary systems UX Ari and HR 1099 comes in part from large regions comparable in size to the binary separation. They argue on the basis of the deduced brightness temperatures and circular polarization that the emission is gyrosynchrotron radiation from a power law distribution of relativistic electrons.

(4) While the results to date are quite significant, stellar radio astronomy would greatly benefit from higher sensitivity, especially for VLBI measurements, and the ability to observe stars at large southern declinations.

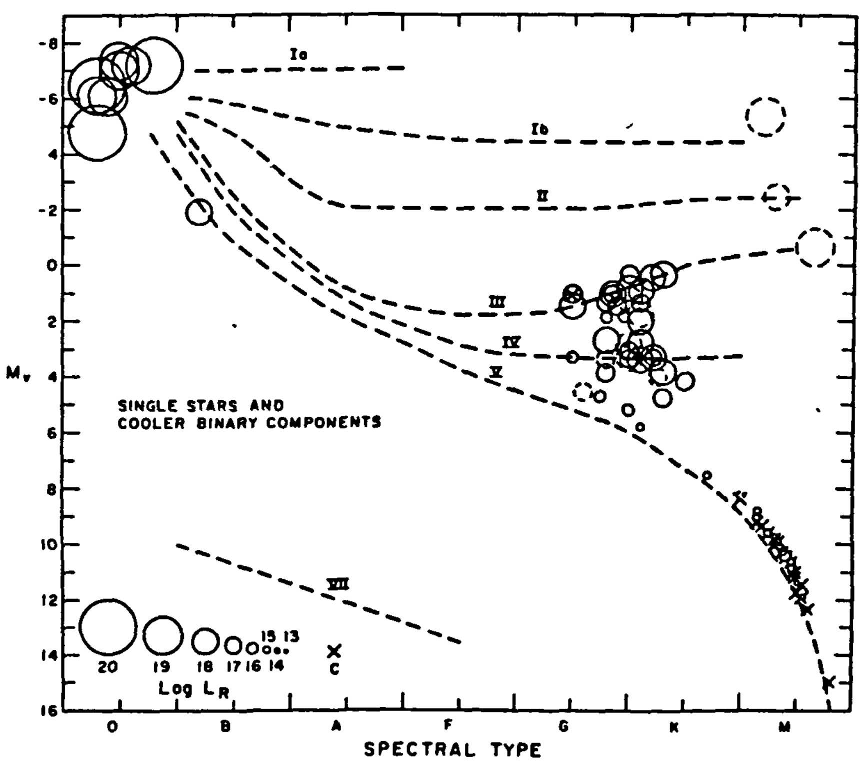


Figure 3. An HR diagram showing the location and the radio luminosity of all non-thermal radio stars detected to date (from Gibson 1984). A source is deemed to be non-thermal on the basis of a negative spectral index, circular polarization, high brightness temperature, or rapid variability. The five classes detected so far are the dMe flare stars, M giants and supergiants during flares, RS CVn binary systems, OB stars, and the magnetic B star σ Ori E.

6. EVIDENCE FOR 10^5 K (TRANSITION REGION) GAS AND 10^4 K (CHROMOSPHERIC) GAS: ULTRAVIOLET AND OPTICAL DATA

The available evidence for the existence of cromospheric (10^4 K) and transition region (TR, 10^5 K) plasma in the outer atmospheres of late-type stars consists primarily of emission lines observed in the ultraviolet. These lines are formed either by collisional excitation, recombination and subsequent cascade, or fluorescence. The first mechanism is generally thermal in character, although excitation by non-thermal electrons streaming down loops from the corona may contribute; the second and third mechanisms are also thermal but non-local in the sense that the ionizing or stimulating radiation originates elsewhere, often in a higher temperature plasma. For example, the HeI-10830 Å and HeII-1640 Å lines are likely formed at relatively cool temperatures following ionization by coronal X-rays and subsequent recombination. The CaII H and K lines and hydrogen Hα lines are among the few lines in the visible which indicate chromospheric plasma. In addition to spectral lines, chromospheric plasma can be observed by microwave emission and ultraviolet continuum emission -- the former has been detected so far only from K and M supergiants, and the latter so far only from dMe stars during flares.

The accumulation of evidence for the existence of non-radiatively heated chromospheres and TRs has been limited by our observational capability. Prior to observations from space, we could observe only relatively cool chromospheric plasmas using the CaII H and K lines and could obtain indirect evidence for hot coronae from the HeI-10830 Å line (Zirin 1982). Linsky and Avrett (1970) and Linsky (1977) have summarized these data and the usefulness of various spectroscopic diagnostics. The first few space observations by rockets, balloons and Copernicus, were superseded by IUE, which has observed hundreds of late-type stars in the 1200-3200 Å spectral region at both low and high resolution. These data in turn will be superseded by the more sensitive and versatile instruments on Space Telescope and the proposed Columbus mission. The capabilities of these instruments are summarized in Table 2.

It is important to recognize that instrumental spectral range and sensitivity limit the plasma temperatures that can be observed. For example, Copernicus was capable of observing only the Lyman alpha and Mg II lines in late-type stars (except for the very brightest stars like Capella), and thus could only observe plasma as hot as 10^4 K. IUE, on the other hand, can observe emission features of CIV at 1550 Å and NV at 1240 Å formed in plasma as hot as 150000 K. The 912-1216 Å spectral range of Columbus contains the strong resonance lines of OVI formed at 300000 K, and the 100-912 Å spectral range, also observable by Columbus, contains lines formed

Table 2

Capabilities for Observations of Ultraviolet Spectra

Mission	Years Operational	Focal Plane Instrument	Spectral Range (Å)	Spectral Resolution (λ/Δλ)
Copernicus (OAO-C)	1972-78		Mg II, Lα lines only	20,000 5,000
International Ultraviolet Explorer (IUE)	1978 →	Short Wavelength (SWP Camera)	1175-2000	10,000 250
		Long Wavelength (LWR,LWP Cameras)	2000-3000	10,000 400
Space Telescope (ST)	1987(?) →	High Resolution Spectrometer (HRS)	1175-2300 1175-1700	100,000 20,000 2,000
		Faint Object Spectrometer (FOS)	1150-8000	1,000 100
Columbus	1991 →		900-1200 1200-2000 100-2000	30,000 10,000 1,000

in coronal plasma as hot as 3×10^7 K (Fe XXIV). Some of the brighter spectral lines available in the 100-2000 Å range are indicated in Figure 4.

Even with the powerful spectrometers forthcoming on ST and Columbus, our ability to study non-radiative heating in stellar chromospheres and TRs will be limited. For one thing, use of ST will be severely constrained by intense competition for telescope time, so that it will be difficult to monitor specific stars for long periods of time or to observe a large sample of stars of a given type. Furthermore, it will be difficult to observe a large spectral interval at high resolution because the HRS can measure only a few Angstròms of spectrum at one time in the 100000 resolution mode. Even for the nearest stars, Columbus observations in the Lyman continum will be affected by interstellar absorption, but it should be able to observe a great many late-type stars at wavelengths below 300 Å. Finally, the poor contrast between ultraviolet emission lines and the very bright photospheric continuum in stars earlier than about spectral type FO severely hampers our ability to detect UV spectral signatures of non-radiative heating in these stars.

Emission lines formed in the chromospheres and TRs of main sequence stars later than spectral type FO are readily detected by IUE and the CaII H and K lines are easily observed by telescopes on the ground. The important lines from plasmas at 5000-10000 K are CaII (3933, 3968 Å), MgII (2796, 2803 Å), HI (1216 Å), CI (1657 Å), SiII (1808, 1817 Å), and OI (1305 Å multiplet). At higher temperatures (3×10^4 - 2×10^5 K) the strongest available emission lines are of CII (1335 Å), SiIII (1892 Å), CIII (1909 Å), SiIV (1393, 1403 Å), CIV (1548, 1550 Å), and NV (1238, 1242 Å).

The search for hot plasma in the early F and A-type stars with optical spectrographs and the IUE is severely hampered by the previously discussed contrast problem, and the existence of chromospheres and TRs on these stars is, therefore, an unanswered question at this time. This topic has been reviewed by Linsky (1981c) and most recently by Wolff (1983). The hottest stars exhibiting emission in the CaII H and K lines are the FO dwarf γ Vir N (B–V = 0.36, Warner 1968) and the FO supergiant, α Car (B–V = 0.15, Warner 1966). Occasionally, CaII emission has been reported in the A7III possible Scuti star γ Boo (B–V = 0.19, LeContel et al. 1970; Auvergne, Le Contel and Baglin 1979). Dravins, Lind and Särg (1977) demonstrated that transient emission occurs in the δ Scuti stars from shock waves formed when the photosphere has maximum outward acceleration. Careful studies of the CaII lines at high dispersion in the early A-type stars (e.g., Freire et al. 1978) and in A dwarfs in young clusters (Dravins 1981) show no evidence for emission.

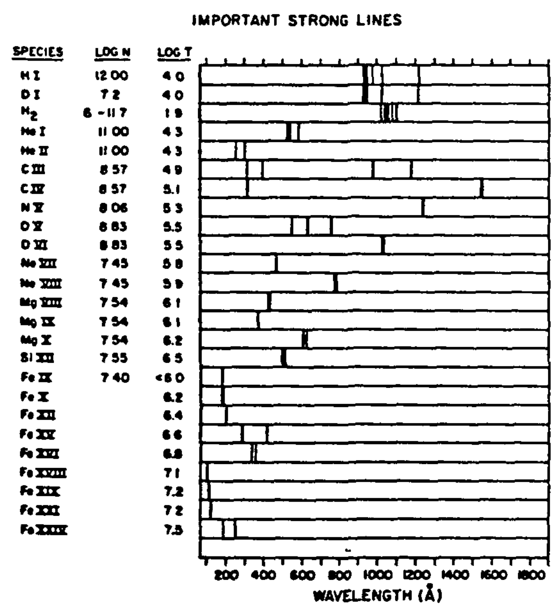


Figure 4. Wavelengths of important spectral lines of abundant elements and molecular hydrogen (H_2) that can be observed by the proposed Far Ultraviolet Spectroscopic Explorer (FUSE)/Columbus mission. Also indicated are the typical element abundances on a logarithmic scale where hydrogen is 12.00, and the temperatures of maximum fractional amount of each ion assuming collisional ionization equilibrium. Regions of continuous absorption by photoionization are indicated for hydrogen and helium. (From the Final Report of the FUSE Science Working Group.)

Extending the search for emission features in the A-type stars to shorter wavelengths offers some prospect for improvement, because the photospheric continuum becomes fainter toward shorter wavelengths. In their extensive MgII survey, Böhm-Vitense and Dettmann (1980) detected stars as early as Car (B-V = 0.34), but the hottest dwarf star that may contain MgII emission features is α Aql (B-V = 0.22), observed by Blanco et al. (1982). Since this rapidly rotating A7 IV-V star also has been detected at Lyman alpha (Blanco, Catalano and Marilli 1980) and in X-rays (Golub et al. 1983), it must contain non-radiatively heated plasma with temperatures of 10^4 K to in excess of 10^6 K. Accordingly, α Aql appears to be the earliest dwarf star that exhibits the non-radiatively heated atmospheric layers typical of the late-type stars.

Many investigators have searched the 1175-2000 Å region for evidence of emission in the CII, SiIV, and CIV lines. Among the earliest type stars detected are HD127739 (B-V = 0.35, Saxner 1981), and the Ursa Major Stream star α Crv (B-V = 0.32, Walter et al. 1984). Attempts to detect emission from A-type stars (e.g., Crivellari and Praderie 1982) have been unsuccessful so far. In particular, the detection of CIV emission in one spectrum of HD21389 (A0 Ia) by Underhill (1980) is probably spurious in view of the narrow line widths and unusual flux ratio. The disappearance of the strongest emission features into the photospheric continuum "noise" is nicely illustrated by comparison of the spectra of representative Ursa Major Cluster stars shown in Figure 5. A quantitative assessment of the problem is depicted in Figure 6, where the surface fluxes in the CIV and CII lines of the Ursa Major and Hyades dwarfs are compared against the surface flux in the adjacent continuum, which rises exponentially with decreasing B-V. These data, together with the absence of verifiable continuum emission in excess of that expected on the basis of radiative equilibrium, HeI-10830 Å features, or line variability (Wolff 1983), mean that we cannot yet determine whether the A-type stars (except for the very coolest) have non-radiatively heated atmospheres. On the other hand, many Ap stars have strong magnetic fields so that there are many different ways in which non-radiative heating could occur in such stars.

As a result of extensive observations of ultraviolet spectra and the CaII H and K lines, we have learned a great deal about the non-radiatively heated chromospheres and TRs of late-type stars. Since these results have been reviewed in detail by Brown (1983), Dupree (1982), and Linsky (1981c, 1982, 1983c), I list here only some of the highlights of this work.

(1) Emission lines indicative of chromospheric plasmas generally are observed in all stars later than early F spectral type and of all luminosity classes. Evidence for TRs (10^5 K plasma) generally is present in dwarf

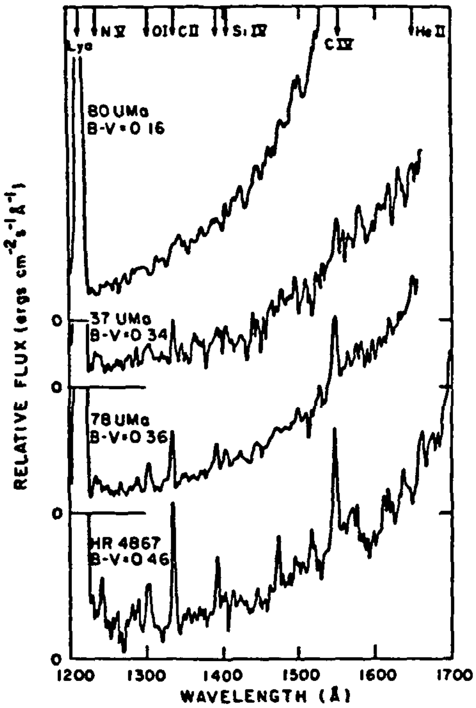


Figure 5. Short wavelength IUE spectra of four members of the Ursa Majoris Cluster. The zero level is indicated for each spectrum, but the vertical scales are different, for each. Strong chromospheric and transition region emission is visible in 78 UMa and HR 4867. Emission in the CIV (1550 Å) and CII (1335 Å) features is prominent in 37 UMa, but no emission, and possible absorption at OI and CII, are evident in 80 UMa (from Walter et al. 1984).

stars cooler than about F0V, and in the giants and supergiants of spectral types F and G. Linsky and Haisch (1979) proposed and Simon, Linsky and Stencel (1982) confirmed (see Figure 7) the existence of a dividing line in the HR diagram near spectral type K1III such that TR lines are generally not observed in single stars to the right (cooler) of this boundary. Whether the existence of the dividing line is due to the true absence of any plasma at 10^5 K in these stars or merely to the rapid decrease in the emission measure of such plasma with decreasing effective temperature, cannot be determined at this time. However, the upper limit to the CIV surface flux in α Boo (K2III) is only 1% that of the quiet Sun (Ayres, Simon, and Linsky 1982). The location of the boundary in the HR diagram is the same as the X-ray boundary proposed by Ayres et al. (1981). The absence or small amount of 10^5 K plasma in the cooler giants could be a result of the rapid decrease in rotational velocity as giants evolve across these "boundaries" (Gray 1981), leading to weakened dynamo generation of magnetic fields and thus decreased heating and open magnetic field configurations.

(2) Stars cooler and more luminous than these boundaries typically have large mass loss rates (Cassinelli 1979) as inferred from circumstellar absorption features and infrared emission from dust among the M supergiants or asymmetric CaII and MgII emission lines (Stencel 1978; Stencel and Mullan 1980) in the K stars. Stencel et al. (1981) and Carpenter, Brown, and Stencel (1985) have used line ratios within the CII-2325 Å multiplet to estimate electron densities in the chromospheres of late-type giants and supergiants. They find that stars hotter than the boundary have

high-density geometrically thin chromospheres, whereas stars cooler than the boundary have low density chromospheres that are geometrically extended (1-5 times the photospheric radius). These size scales are rough estimates since constant electron density was assumed. Brown and Carpenter (1984) have derived chromosperic temperatures of 7000 - 9000 K for these stars from CII 1335/2325 flux ratios.

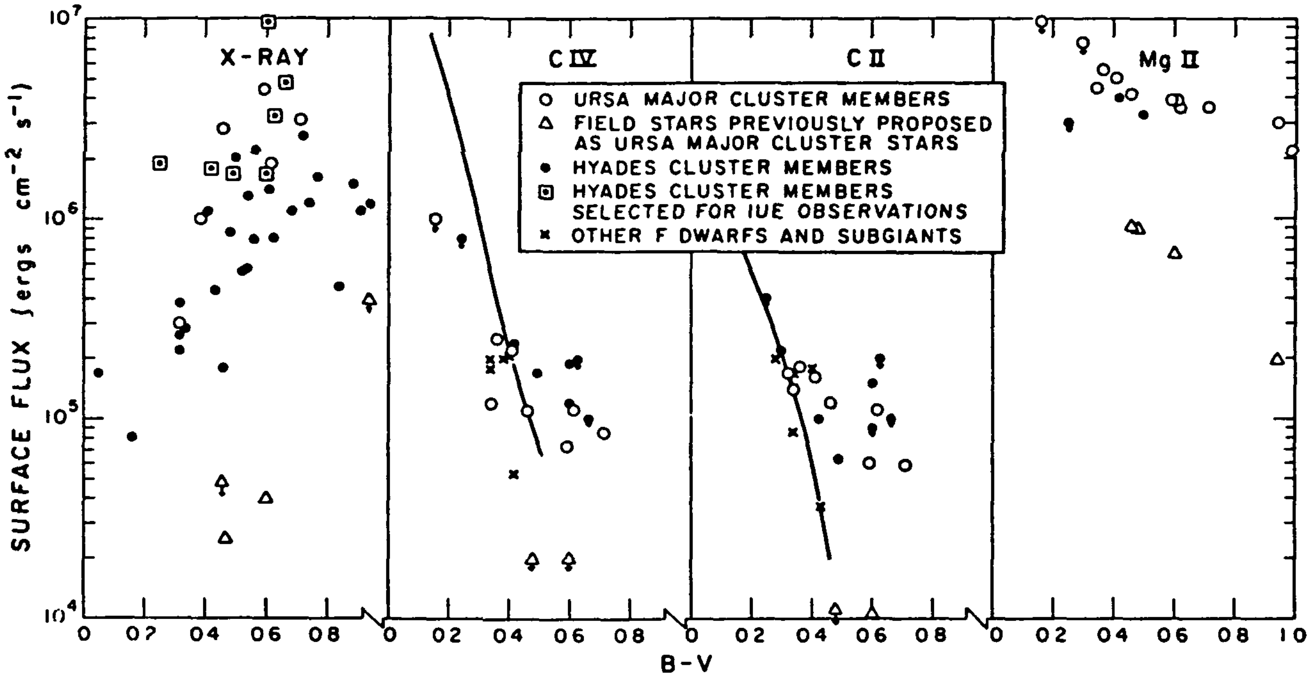


Figure 6. Comparison of surface fluxes in soft X-rays, CIV-1550 Å, CII-1335 Å, and the MgII-2800 Å doublet for Ursa Major Cluster members, probable field stars previously identified as Ursa Major members, Hyades, and selected field stars. X-ray surface fluxes of the ten Hyades that Zolcinsky et al. (1982) selected for IUE observations are denoted by boxes, and upper limits are indicated by arrows. The solid lines indicate the photospheric continuum emission and scattered light (per 6 Å interval) at CIV-1550 Å and CII-1335 Å obtained by averaging the measured flux for Ursa Major stars in 20 Å bands on both sides of the CIV and CII lines (from Walter et al. 1984).

(3) Hartmann, Dupree, and Raymond (1980, 1981) proposed a third class of stars, the hybrid stars, which show evidence for both strong mass loss and 10^5 K TR plasma. Prototypes of stars in this class are α Aqr (G2Ib) and α TrA (K4II). Proposed explanations for the hybrid nature of these stars include an Alfvén wave heated and accelerated wind (Hartmann et al. 1981), isolated hot flux tubes imbedded in a cool wind (Linsky 1982), shocks in an inhomogeneous wind (Mullan 1984b), or (in the particular case of α TrA) a previously unknown F dwarf companion (Ayres 1984a). We do not yet know whether any of these proposed explanations is correct.

(4) Surface fluxes for such TR emission features as CIV-1550 Å vary greatly from one star to another. Stars with very large surface fluxes include the dMe stars (Linsky et al. 1982), RS CVn systems (Simon and Linsky 1980), young stars like those in the Hyades (Zolcinski et al. 1982), and pre-main sequence stars (Giampapa 1983b). There is a clear increase in surface fluxes, and thus non-radiative heating rates, with decreasing age on the main sequence (e.g., Simon and Boesgaard 1983; Barry, Hege, and Cromwell 1984) but the $(age)^{-1/2}$ dependence proposed by Skumanich (1972) to describe the behavior of Ca II fluxes appears not to be valid for stars younger than the Hyades (Duncan 1983). The surface fluxes also increase with increasing rotational velocity, and Hartmann et al. (1984) have proposed a functional dependence of the Mg II emission on the Rossby number, further strengthening the association of magnetic fields with the non-radiative heating process.

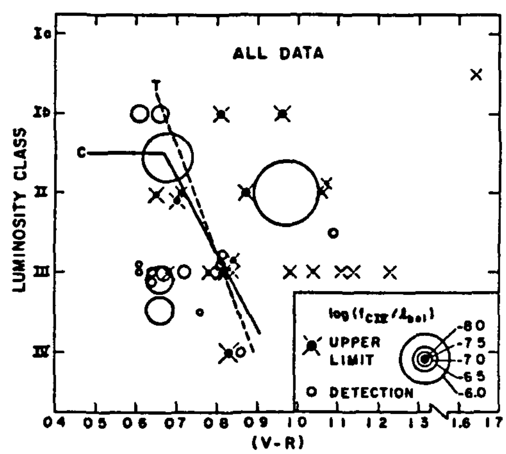


Figure 7

Figure 7. An HR diagram showing measured ratios of the CIV-1550 Å flux to the apparent stellar bolometric luminosity from Simon, Linsky and Stencel (1982). Open circles are detections and filled circles are upper limits. The line marked T is that originally proposed by Linsky and Haisch (1979) to separate stars with (to the left) and without (to the right) 10^5 K plasma. The line marked C was proposed by Ayres et al. (1981) to separate the stars that generally show soft X-ray emission (to the left) from stars that generally do not (to the right). All of the three detections to the right of the line marked T are previously unknown binary systems.

(5) The importance of magnetic fields in determining the geometric structure and energy balance in the chromospheres and TRs of late-type stars has been summarized by Linsky (1983a). This evidence is of several types. First, the existence of individual solar-like active regions on stars is revealed by the modulation of UV emission lines at the rotational period, in phase with the dark starspots deduced from the optical light curves (Baliunas and Dupree 1982; Marstad et al. 1982; Linsky 1983c). This is illustrated by observations of the RS CVn-type system II Peg (K2IV + ?) (see Figure 8) which has been used to locate the active region and the spots on the primary star (Figure 9). Second, the large dispersion in heating rates for stars of the same spectral type, which can be explained readily only by different magnetic field strengths and geometries on these stars, is contrary to the

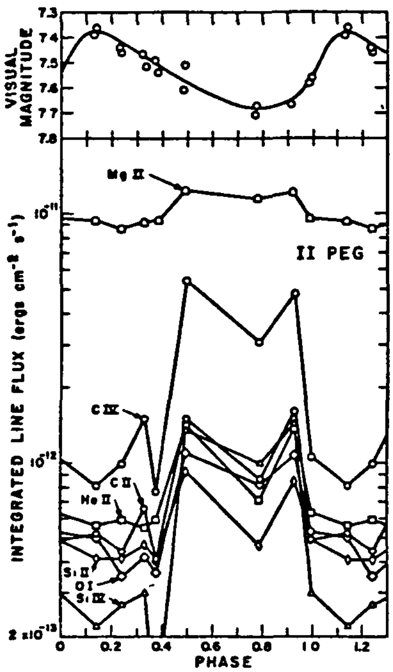


Figure 8. Lower panel: integrated emission line fluxes for II Peg obtained in October 1981 by Marstad et al (1982). Note the rapid rise in flux near phase 0.45 and rapid fall near phase 0.95 indicating the rotational modulation of a compact active region across the disk. Upper panel: photometric variation obtained with the FES simultaneously with the IUE spectra.

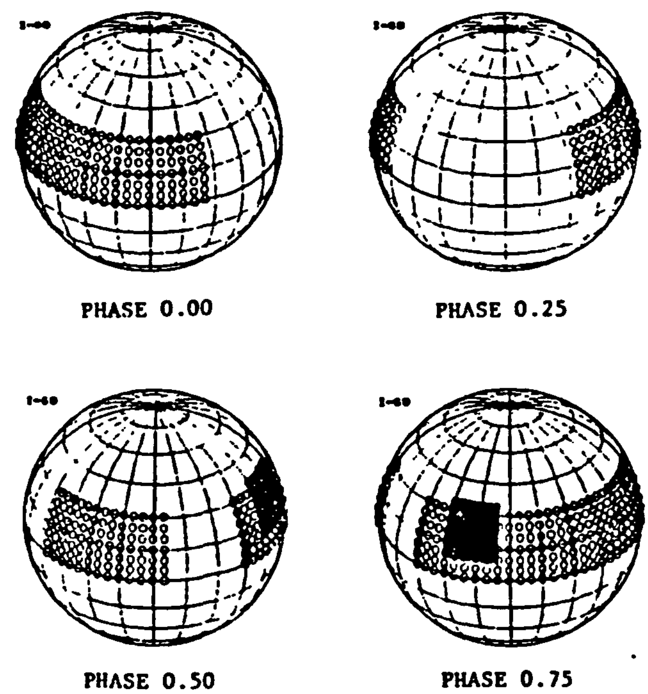


Figure 9. The location of the two spot groups (small circles) and the active region (solid black) derived by Marstad (1983) from the optical photometry and emission line flux versus phase observations of II Peg in October 1981. Note that the active region overlies a small portion of the larger spot group.

Figure 9

predictions of purely acoustic wave heating (Linsky and Ayres 1978; Basri and Linsky 1979). Third, the empirical functional dependence of chromospheric heating rates on gravity and effective temperature strongly suggests heating by slow mode MHD waves (Stein 1981; Ulmschneider and Stein 1982). Fourth, the existence of flaring in dMe, RS CVn, and T Tauri stars implies rapid conversion of magnetic energy to heat as is presumed to occur in solar flares. Finally, the existence of systematic redshifts of 10^4 - 10^5 K emission lines (Brown et al. 1984; Ayres et al. 1983; Ayres 1984b) (see Figure 10) likely is analogous to the downflows of hot plasma observed over solar active regions.

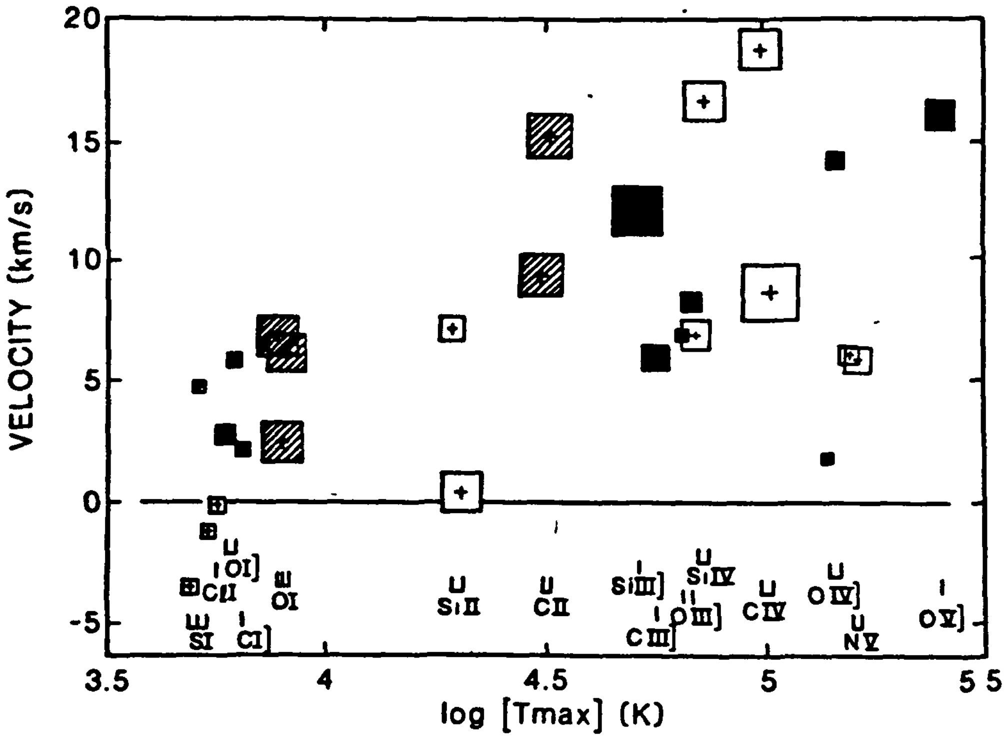
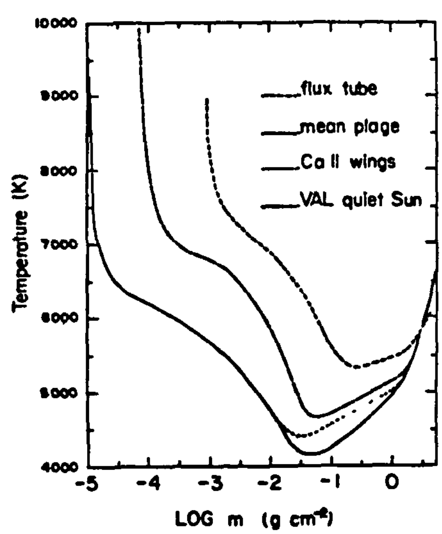


Figure 10. Redshifts of emission lines from the active F9 III star in the Capella (α Aur) system obtained by Ayres (1984b) from IUE high esolution 1200-2000 Å spectra. The redshifts were obtained from Gaussian profile fits to the observed profiles. Symbols with diagonal lines indicate lines that are very optically thick, and solid symbols indicate intersytem lines that must be optically thin. The agreement among all three types of lines indicates that the redshifts are due to downflowing matter in the chromosphere and transition region of this F9III star, presumably in magnetic flux tubes where the plasma is relatively dense and therefore bright.

Figure 11. Plage, flux tube, and quit Sun models. The solid line is the VAL quiet Sun model (Vernazza, Avrett, and Loeser, 1981). The short dashed lines (CaII wings) represent a modification of the VAL designed to reproduce the CaII H and K damping wings. The dash-dot curve is a plage model based on Lyman-alpha, CaII K, and MgII k data obtained by the LPSP experiment on OSO-8. The long dashed (higher) curve represent a flux tube model with a chromospheric portion matching the OSO-8 plage profiles with a 20% filling factor. The photospheric portion ($m > 0.3$ g/cm^2) is similar to the class of flux tube models advocated by Chapman (1977). From Chapman (1981), courtesy of Colorado Associated University Press.



7. EVIDENCE FOR NON-RADIATIVELY HEATED PHOTOSPHERES

I conclude this review with a brief summary of the evidence for non-radiative heating in stellar photospheres as defined in Section 2. Evidence for such heating could consist of a derived temperature structure that is hotter than predicted on the basis of radiative equilibrium alone. Alternatively, one could consider as evidence photospheric emission in a spectral interval that is brighter than predicted on the basis of a radiative equilibrium photospheric model. Either type of evidence requires an accurate radiative equilibrium model. This is a difficult requirement for two reasons: (1) Such models require an accurate and reasonably complete description of line blankenting taking non-LTE effects into account, at least in the important opacity sources. (2) The solar photosphere is highly inhomogeneous and the existence of non-radiatively heated flux tubes and efficient cooling by CO in the non-magnetic regions is a likely basis for thermal instability (Ayres 1981). Thus one-component radiative equilibrium models are not realistic pysically for the Sun and, therefore, for late-type stars in general. We are thus left with the following quandary: Against what are we to compare an empirical photospheric temperature distribution in order to infer the existence of non-radiative heating at photospheric levels?

For the Sun, Chapman (1981) derived empirical temperature structures for spatially averaged plages (active regions) and estimated temperature structures for isolated flux tubes by the analysis of the cores and wings of the CaII, MgII and Lyman alpha lines. These models are compared with quiet Sun models in Figure 11. Other models indicating photospheric temperature enhancements in magnetic regions have been computed by Vernazza, Avrett, and Loeser (1981), Morrison and Linsky (1978), and others. While such models are not directly compared to radiative equilibrium models, the systematic enhancement of the photospheric temperature structure in magnetic regions clearly suggests the presence of non-radiative heating, at least in the magnetic regions.

The extension of such arguments to late-type stars should be viewed with skepticism because of the difficulty of computing accurate radiative equilibrium models properly incorporating atmospheric inhomogeneity. Nevertheless, the models of dMe stars computed by Giampapa, Worden, and Linsky (1982) on the basis of the CaII and H lines have hotter temperatures in the temperature minimum region than dM stars of similar effective temperatures. A similar argument can be made for the active F-K dwarfs compared to the less active dwarfs (Kelch, Linsky, and Worden 1979) and the active subgiants in RS CVn systems compared to non-active stars of similar spectral type (Simon and Linsky 1980; Baliunas et al. 1979). Additional work along these lines should be undertaken.

The ultraviolet continua of A stars have been examined for evidence of temperatures in excess of those predicted by radiative equilibrium models. Praderie, Simonneau, and Snow (1975) proposed that emission in the short wavelength wing of the Lyman alpha line of Vega (AOV) implies non-radiative heating, but Snijders (1977) and Hubeny (1981) have shown that this spectral feature is consistent with non-LTE radiative equilibrium models. Again, further observational and theoretical work is needed.

AKNOWLEDGEMENTS

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REFERENCES

Athay, R. G.: 1970, Astrophys. J., 161, 713.
Athay, R. G.: 1976, "The Solar Chromosphere and Corona: Quiet Sun", (Dordrecht: Reidel).
Athay, R. G. and White, O. R.: 1978, Astrophys. J., 226, 1135.
Auvergne, M., Le Contel, J.-M., and Baglin, A.; 1979, Astron. Astrophys., 76, 15
Ayres, T. R.: 1981, Astrophys. J., 244, 1064.
Ayres, T. R.: 1984a, Astrophys. J. (Letters), submitted.
Ayres, T. R.: 1984b, Astrophys. J., in press.
Ayres, T. R. and Linsky, J. L.: 1976, Astrophys. J., 201, 212.
Ayres, T. R., Linsky, J. L., Vaiana, G. S., Golub, L., and Rosner, R.: 1981, Astrophys. J., 250, 293.
Ayres, T. R., Simon, T., and Linsky, J. L.: 1982, Astrophys. J., 263, 791.
Ayres, T. R., Stencel, R. E., Linsky, J. L., Simon, T., Jordan, C., Brown, A., and Engvold, O.: 1983, Astrophys. J., 274, 801.
Baliunas, S. L.: 1983, P.A.S.P., 95, 532.
Baliunas, S. L., Avrett, E. H., Hartmann, L., and Dupree, A. K.: 1979, Astrophys. J. (Letters), 233, L129.
Baliunas, S. L. and Dupree, A. K.: 1982, Astrophys. J., 252, 668.
Barry, D. C., Hege, K., and Cromwell, R. H.: 1984, Astrophys. J. (Letters), 277, L65.
Basri, G. S. and Linsky, J. L.: 1979, Astrophys. J., 234, 1023.
Blanco, C., Bruca, L., Catalano, S., and Marilli, E.: 1982, Astron. Astrophys., 115, 280.
Blanco, C., Catalano, S., and Marilli, E.: 1980, Proc. Second European IUE Conf. Tubingen, ESA SP-157, p.63.
Bohm-Vitense, E. and Dettmann, T.: 1980, Astrophys. J., 236, 560.
Brown, A.: 1983, in "Cool Stars, Stellar System, and the Sun", ed. S. L. Baliunas and L. Hartmann (Berlin: Springer-Verlag), p. 282.
Brown, A. and Carpenter, K. G.: 1984, Astrophys. J. (Letters), in press.
Brown, A., Jordan, C., Stencel, R.E., Linsky, J. L. and Ayres, T. R.: 1984, Astrophys. J., 283, 731.
Bopp, B. W.: 1983, in "Activity in Red Dwarf Stars", (IAU Colloq. No. 71), ed. P. B. Byrne and M. Rodono (Dordrecht: Reidel), p. 363.
Caillault, J. P. and Helfand, D. J.: 1984, Astrophys. J., in press.
Carpenter, K. G., Brown, A., and Stencel, R. E.: 1985, Astrophys. J., in press.
Cassinelli, J. P.: 1979, Ann. Rev. Astron. Astrophys., 17, 275.
Cayrel, R.: 1963, Comp. Rend. Acad. Sci. Paris, 257, 3309.

Cayrel, R.: 1964, SAO Spec. Rep,, 167, 169.

Chapman, G. A.: 1977, Astrophys. J. Suppl., 33, 35.

Chapman, G. A.: 1981, in "Solar Active Regions", ed. F. Q. Orrall (Boulder: Colorado Assoc. Univ. Press.), p. 43.

Charles, P. A.: 1983, in "Activity in Red Dwarf Stars" (IAU Colloq. No. 71), ed. P.B. Byrne and M. Rodono (Dordrecht: Reidel), p.415.

Crivellari, L. and Praderie, F.: 1982, Astron. Astrophys., 107, 75.

Drake, S. A. and Linsky, J. L.: 1983a, Astrophys. J. (Letters), 274, L77.

Drake, S.A. and Linsky, J. L.: 1983b, Bull. Am. Astron. Soc., 15, 947.

Dravins, D.: 1981, Astron. Astrophys., 96, 64.

Dravins, D., Lind, J., and Sarg, K.: 1977, Astron. Astrophys., 54, 381.

Duncan, D. K.: 1983, in "Cool Stars, Stellar Systems, and the Sun", ed. S. L. Baliunas and L. Hartmann (Berlin: Springer-Verlag), p.128.

Dupree, A. K.: 1982, in "Advances in Ultraviolet Astronomy: Four Years of IUE Research", NASA Conference Publication 2238, p. 3.

Dupree, A. K.: 1983, in "Activity in Red Dwarf Stars", (IAU Colloq. No. 71), ed. P. B. Byrne and M. Rodono (Dordrecht: Reidel), p.447.

Feigelson, E. D.: 1983, in "Cool Stars, Stellar System, and the Sun", ed. S. L. Baliunas and L. Hartmann (Berlin: Springer-Verlag), p. 27.

Feldman, P. A.: 1983, in "Activity in Red Dwarf Stars", (IAU Colloq. No. 71), ed. P. B. Byrne and M. Rodono, (Dordrecht: Reidel), p. 429.

Feldman, U., Doschek, G. A., Mariska, J. T.: 1979, Astrophys. J., 229, 369.

Fisher, P. L. and Gibson, D. M.: 1983, in "Cool Stars, Stellar Systems, and the Sun", eds. M. S. Giampapa and L. Golub, SAO Special Report 392, p. 109.

Freire, R., Czarny, J., Felenbok, P., and Prederie, F.: 1978, Astron. Astrophys., 68, 89.

Gary, D.: 1984, in "Proceedings of the Worshop on Stellar Continuum Radio Astronomy", Boulder, Colorado, August, 1984, to appear.

Gary, D. E. and Linsky, J. L.; 1981, Astrophys. J., 250, 284.

Giampapa, M. S.: 1983a, in "Activity in Red Dwarf Stars", (IAU Colloq. No. 71), ed. P. B. Byrne and M. Rodono (Dordrecht: Reidel), p. 223.

Giampapa, M. S.: 1983b, in "Cool Stars, Stellar Systems, and the Sun", ed. S. L. Baliunas and L. Hartmann (Berlin: Springer-Verlag), p. 14.

Giampapa, M. S., Worden, S. P., and Linsky, J. L.: 1982, Astrophys. J., 258, 740.

Gibson, D. M.: 1981, in "Solar Phenomena in Stars and Stellar Systems", ed.s R. M. Bonnet and A. K. Dupree (Dordrecht: Reidel), p. 545.

Gibson, D. M.: 1983, in "Activity in Red Dwarf Stars", (IAU Colloq. No. 71), eds. P. B. Byrne and M. Rodono (Dordrecht: Reidel), p. 273.

Gibson, D. M.: 1984, in "Proceedings of the Worshop on Stellar Continuum Radio Astronomy", Boulder, Colorado, August 1984, to appear.

Golub, L.: 1983, in "Activity in Red Dwarf Stars", (IAU Colloq. No. 71), eds. P. B. Byrne and M. Rodono (Dordrecht: Reidel), p. 83.

Golub, L., Harnden, F. R., Jr., Maxson, C. W., Rosner, R., Vaiana, G. S., Cash, W., Jr., and Snow, T. P., Jr.: 1983, Astrophys. J., 271, 264.

Gray, D. F. : 1981, Astrophys. J., 251, 155.

Haisch, B. M. and Simon, T.: 1982, Astrophys. J., 263, 252.

Hartmann, L.: 1981, in "Solar Phenomena in Stars and Stellar Systems", ed. R. M. Bonnet and A. K. Dupree (Dordrecht: Reidel), p. 331.

Hartmann, L.: 1983, in "Solar and Stellar Magnetic Fields: Origins and Coronal Effects", (IAU Symp. No. 102), ed. J. O. Stenflo (Dordrecht: Reidel),p. 419.

Hartmann, L., Baliunas, S. L., Duncan, D. K., and Noyes, R. W.: 1984, Astrophys, J., 279, 778.

Hartmann, L., Dupree, A. K., and Raymond, J. C.: 1980, Astrophys. J. (Letters), 236, L143.

Hartmann, L., Dupree, A. K., and Raymond, J. C.: 1981, Astrophys. J., 246, 193.

Helfand, D. J. and Caillault, J. P.: 1982, Astrophys. J., 253, 760.

Hubeny, I.: 1981, Astron. Astrophys., 98, 96.

Johnson, H. M.: 1981, Astrophys. J., 243, 234.

Johnson, H. M.: 1983, in "Activity in Red Dwarf Stars", (IAU Colloq. No. 71), ed. P. B. Byrne and M. Rodono (Dordrecht: Reidel), p. 109.

Jordan, C.: 1980, Astron. Astrophys., 86, 355.

Kelch, W. L., Linsky, J. L., and Worden, S. P.: 1979, Astrophys. J., 229, 700.

Kelch, W. L. et al.: 1978, Astrophys. J., 220, 962.

Lang, K. R., Bookbinder, J., Golub, L., and Davis, M.M.: 1983, Astrophys. J. (Letters), 272, L15.

LeContel, J. M., Praderie, F., Bijaoui, A., Dantel, M., and Sareyan, J. P.: 1970, Astron. Astrophys., 8, 159.

Linsky, J. L.: 1977, in "The Solar Outpunt and its Variations", ed. O. R. White (Boulder: Colorado Associated University Press), p. 477.

Linsky, J. L.: 1980, Ann. Rev. Astron. Astrophys., 18, 439.

Linsky, J. L.: 1981a, in "X-ray Astronomy with the Einstein Satellite", ed. R. Giacconi (Dordrecht: Reidel), p. 19.

Linsky, J., L.: 1981b, in "X-ray Astronomy in the 1980's", ed. S. S. Holt, NASA TM 83848, p. 13.

Linsky, J. L.: 1981c, in "Solar Phenomena in Stars and Stellar Systems", ed. R. M. Bonnet and A. K. Dupree (Dordrecht: Reidel), p. 99.

Linsky, J. L.: 1982, in "Advances in Ultraviolet Astronomy: Four Years of IUE Research", NASA Conference Pubblication 2238, p. 17.

Linsky, J. L.: 1983a, in "Solar and Stellar Magnetic Fields: Origins and Coronal Effects", (IAU Symp. No 102), ed. J. O. Stenflo (Dordrecht: Reidel), p. 313.

Linsky, J. L.: 1983b, in "Activity in Red Dwarf Stars", (IAU Colloq. No. 71), ed. P. B. Byrne and M. Rodono (Dordrecht: Reidel), p. 39.
Linsky, J. L.: 1983c, in "Cool Stars, Stellar Systems, and the Sun", ed. S. L. Baliunas and L. Hartmann (Berlin: Springer-Verlag), p. 244.
Linsky, J. L. and Avrett, E. H.: 1970, P.A.S.P., 82, 169.
Linsky, J. L. and Ayres, T. R.: 1978, Astrophys. J., 220, 619.
Linsky, J. L., and Bornmann, P. L., Carpenter, K. G., Wing, R. F., Giampapa, M. S., and Worden, S. P.: 1982, Astrophys. J., 260, 670.
Linsky, J. L. and Gary, D. E.: 1983, Astrophys. J., 274, 776.
Linsky, J. L. and Haisch, B. M.: 1979, Astrophys. J. (Letters), 229, L27.
Marcy, G. W.: 1983, in "Solar and Stellar Magnetic Fields: Origins and Coronal Effects", (IAU Symp. No. 102), ed. J. O. Stenflo (Dordrecht: Reidel), p. 3.
Marstad, N., Linsky, J. L., Simon, T., Rodono, M., Blanco, C., Catalano, S., Marilli, E., Andrews, A. D., Butler, C. J., and Byrne, P. B.: 1982, in "Advances in Ultraviolet Astronomy: Four Years of IUE Research", NASA Conf. Publ. No. 2238, p. 554.
Morrison, N. D. and Linsky, J. L.: 1978, Astrophys. J., 222, 723.
Mullan, D. J.: 1978, Astrophys. J., 226, 151.
Mullan, D. J.: 1984a, in "Proceedings of the Workshop on Stellar Continuum Radio Astronomy", Boulder, Colorado, August 1984, to appear.
Mullan, D. J.: 1984b, Astrophys. J., in press.
Mutel, R. L., Doiron, D. J., Lestrade, J. F., and Phillips, R. B.: 1984, Astrophys. J., 278, 220.
Mutel, R. L. and Lestrade, J. F.: 1984, Astrophys. J., in press.
Newell, R. T. and Hjellming, R. M.: 1982, Astrophys. J. (Letters), 263, L85.
Nicolas, K. R., Bartoe, J.-D. F., Brueckner, G. E., and Van Hoosier, M. E.: 1979, Astrophys. J., 233, 741.
Pallavicini, R., Golub, L., Rosner, R., Vaiana, G. S., Ayres, T. R., and Linsky, J. L.: 1981, Astrophys. J., 248, 279.
Praderie, F.: 1973, in "Stellar Chromospheres", ed. S. D.Jordan and E. H. Avrett, NASA SP-317, p. 79.
Praderie, F.: 1977, Mem Soc. Astron. Italiana, 553.
Praderie, F., Simonneau, E., and Snow, T. P.: 1975, Astrophys. Space Sci., 38, 337.
Rosner, T., Tucker, W. H., and Vaiana, G. S.: 1978, Astrophys. J., 220, 643.
Rucinski, S.: 1984, Astron. Astrophys., in press.
Saxner, M.: 1981, Astron. Astrophys., 104, 240.
Simon, T. and Boesgaard, A. M.: 1983, in "Solar and Stellar Magnetic Fields: Origins and Coronal Effects", (IAU Symp. No. 102), ed. J. O. Stenflo, (Dordrecht: Reidel), p. 161.

Simon, T. and Linsky, J. L.: 1980, Astrophys. J., 241, 759.
Simon, T., Linsky, J. L., and Stencel, R. E.: 1982, Astrophys. J., 257, 225.
Skumanich, A.: 1972, Astrophys. J., 171, 565.
Skumanich, A., Smythe, C., and Frazier, E. N.: 1975, Astrophys. J., 200, 747.
Snijders, M. A. J.: 1977, Astrophys. J. (Letters), 214, L.35.
Stein, R. F.: 1981, Astrophys. J., 246, 966.
Stencel, R. E.: 1978, Astrophys. J. (Letters), 223, L37.
Stencel, R. E., Linsky, J. L., Brown, A., Jordan, C., Carpenter, K. G., Wing, R. F., and Czyzak, S.: 1981, Mon. Not. Roy. Astr. Soc., 196, 47P.
Stencel, R. E. and Mullan, D. J.: 1980, Astrophys. J., 238, 221.
Stern, R. A.: 1983, in "Cool Stars, Stellar Systems, and the Sun", ed. S. L. Baliunas and L. Hartmann (Berlin: Springer-Verlag), p. 150.
Stern, R., Zolcinski, M. C., Antiochos, S. K., and Underwood, J. H.: 1981, Astrophys. J., 249, 647.
Swank, J. H. and Johnson, H. M.: 1982, Astrophys. J. (Letters), 259, L67.
Swank, J. H., Withe, N. E., Holt, S. S., and Becker, R. H.: 1981, Astrophys. J., 246, 208.
Thomas, R. N. and Athay, R. G.: 1961, Physics of the Solar Chromophere (New York: Interscience).
Topka, K. and Marsh, K. A.: 1982, Astrophys. J., 254, 641.
Ulmschneider, P.: 1979, Space Science Reviews, 24, 71.
Ulmschneider, P., Schmitz, F., and Hammer, R.: 1979, Astron. Astrophys., 74, 229.
Ulmschneider, P. and Stein, R. F.: 1982, Astron. Astrophys., 106, 9.
Underhill, A. B.: 1980, Astrophys. J. (Letters), 235, L149.
Vaiana, G. S.: 1981, in "X-ray Astronomy with the Einstein Satellite", ed. R. Giacconi (Dordrecht: Reidel), p. 1.
Vaiana, G. S.: 1983, in "Solar and Stellar Magnetic Fields: Origins and Coronal Effects", (IAU Symp. No. 102), ed. J. O. Stenflo (Dordrecht: Reidel), p. 165.
Vaiana, G. S. and Rosner, R.: 1978, Ann. Rev. Astron. Astrophys., 16, 393.
Vaiana, G. S. et al.: 1981, Astrophys. J., 245, 163.
Vedder, P. W. and Canizares, C. R.: 1983, Astrophys. J., 270, 666.
Vernazza, J. E., Avrett, E. H., and Loeser, R.: 1981, Astrophys. J. Suppl., 45, 635.
Vogt, S. S.: 1983, in "Activity in Red Dwarf Stars", (IAU Coll. No. 71), ed. P. B. Byrne and M. Rodono (Dordrecht: Reidel), p. 137.
Walter, F. M.: 1981, Astrophys. J., 245, 677.
Walter, F. M.: 1982, Astrophys. J., 253, 745.

Walter, F. M., Cash, W., Charles, P. A., and Bowyer, C. S.: 1980. Astrophys. J., 236, 212.
Walter, F. M., Gibson, D. M., and Basri, G. S.: 1983, Astrophys. J., 267, 665.
Walter, F. M., Linsky, J. L., Simon, T., Golub, L., and Vaiana, G. S.: 1984, Astrophys. J., 281, 815.
Warner, B.: 1966, Observatory, 86. 82.
Warner, B.: 1968, Observatory, 88, 217.
Withbroe, G. L. and Noyes, R. W.: 1977, Ann. Rev. Astron. Astrophys., 15, 363.
Wolff, S. C.: 1983, The A-Stars: Problems and Perspectives, NASA SP—463.
Worden, S. P.: 1983, in "Activity in Red Dwarf Stars", (IAU Colloq. No. 71), ed. P. B. Byrne and M. Rodono, (Dordrecht: Reidel), p. 207.
Zirin, H.: 1982, Astrophys.J., 260, 655.
Zolcinski, M. C., Antiochos, S. K., Stern, R. A., and Walker, A. B. C., Jr.: 1982, Astrophys. J., 258, 177.
Zwaan, C: 1983, in "Solar and Stellar Magnetic Fields: Origins and Coronal Effects", (IAU Symp. No. 102), ed. J. O. Stenflo (Dordrecht: Reidel), p. 85.