5. Chromospheres, Winds and Mass Loss

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CHROMOSPHERES OF CHEMICALLY PECULIAR GIANT STARS

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Abstract. A review is given of the chromospheres of evolved stars with peculiar chemical abundances, emphasizing the observed dependence of chromospheric properties upon the evolutionary status of the stars. Some old and new physical processes which are potentially important in determining the observed chromospheric features are discussed.

A sample of intermediate mass stars with useful observations in the radio, infrared and ultraviolet wavelength regions is compiled. After a résumé of "normal" M giants on their first or second ascent of the giant branch, attention is focussed on the MS, S and C stars, currently believed to be manifestations of the "third dredge up" phase during double shell burning on the asymptotic giant branch, and differential comparisons are made between the various groups. A systematic study of the "warm" ($T > T_{eff}$) and "cool" ($T \leq T_{eff}$) chromospheric components is made.

Several conclusions have been drawn: (i) for M giants the chromospheric heating has a weak dependence on the fundamental stellar parameters (T_{eff}, $log\ g$), this is consistent with one heating mechanism (currently believed to be acoustic waves and/or remnant magnetic activity) which can account for the observed structure as a function of evolution, (ii) the heating drops sufficiently for the chromospheres to become progessively less ionized and more dusty as the star evolves, (iii) Carbon stars follow the same gradual trends of chromospheric heating with stellar parameters as the M stars, only when suitable corrections for chromospheric energy losses are applied, (iv) such corrections are inferred from spectral data (v) the few available MS and S stars have similar chromospheric activity (when accretion processes are unimportant) to M stars of similar effective temperature, (vi) the chromospheric spectra of the 3 S stars examined are consistent with photospheric studies suggesting that they are cool analogues of the Barium stars, (vii) it is not possible at present to place additional constraints on the evolutionary status of AGB stars on the basis of chromospheric data, (vii) questions concerning the nature of the temperature, density and velocity structure of MS, S and C stars and their chromospheric heating and mass loss processes must await answers from more sensitive observations, particularly in the UV, for instance with the *Hubble Space Telescope*.

1. INTRODUCTION

Detailed studies of the outer atmospheres of stars have been possible only over the last decade with the advent of data from the radio to ultraviolet (UV) wavelengths from telescopes such as the Very Large Array (VLA) and the International Ultraviolet Explorer satellite (IUE). IUE data have revealed information on the "warm" components (electron temperatures $T_e \geq T_{eff}$) of the outer atmospheres of stars across the HR diagram (Jordan and Linsky, 1987; Dupree and Reimers, 1987), and an overall picture has emerged concerning the nature of stellar outer atmospheres as a function of stellar parameters (e.g. $T_{eff}, Log\ g, v\ sin\ i$) and evolution. However, the majority of these studies focussed attention on stars which have not evolved beyond the K–giant phase of evolution. Other workers have studied very evolved stars using techniques which can detect cool material ($T \leq T_{eff}$) associated with the massive circumstellar outflows around such objects (see e.g. Olofsson, this volume, Mass Loss from Red Giants, Eds. Morris & Zuckerman, 1985, Late Stages of Stellar Evolution, Eds. Kwok & Pottasch, 1987).

Until fairly recently, few workers have studied outer atmospheres of late-M, MS, S, SC and C stars on the Asymptotic Giant Branch (AGB), because of the difficulty in detecting UV emission from these chromospherically "inactive" stars and because such stars do not (yet) possess the

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massive molecular envelopes associated with later stages of evolution. These stars are at a crucial evolutionary stage: theoretical models predict that essentially all stars with masses in the range $0.6M_{\odot} < M_{*} < 5M_{\odot}$ pass through this evolutionary phase (e.g. Lattanzio, 1988), where they undergo double shell burning and dredge-up with associated changes in surface abundances, substantial photospheric variability and mass loss which potentially can affect subsequent evolution. Helium flashes in the interiors of AGB stars are currently believed to be the primary source of "s-process" elements observed throughout the Galaxy (e.g. Audouze & Tinsley, 1976).

Currently there are two possible scenarios proposed to describe the observed distribution of peculiar red giants: traditional theory (Iben & Renzini, 1983) and analyses of photospheric abundances suggest that at least some stars follow the evolutionary sequence $M \rightarrow MS \rightarrow S \rightarrow SC \rightarrow C$ (e.g. Lambert, this volume). However, recent analyses of IRAS photometric and spectral data (Willems & de Jong, 1988) reveals that some S stars may not fit into this picture, and measurements of radial velocities in Barium stars and certain S stars (Jorissen & Mayor, 1988) suggest that Tc– deficient S stars may be "cool" counterparts of the K-giant Barium stars whose s–process abundances are currently believed to originate from mass transfer from a companion at earlier epochs (e.g. McClure, 1983; Smith & Lambert, 1988; Little-Marenin, this volume).

The definition of a "chromosphere" has recently required extension beyond the traditional models of solar–type structure, which are geometrically thin regions extending over several pressure heights with electron temperatures in the range $T_{min} \simeq 0.75T_{eff} < T_e < 8000K$ (e.g. Linsky, 1980), heated by some non-thermal process such as the damping of mechanical, probably magnetic, waves. Even for stars as warm as the Sun, observations of molecular spectra (particularly CO in the infrared (IR)) imply a large chromospheric surface coverage of cooler regions ($T_e \leq T_{eff}$) (e.g. Heasley et al. 1978; Ayres & Testerman, 1981; Tsuji, 1988), perhaps associated with a runaway cooling effect due to the formation of molecules (Ayres, 1981; Kneer, 1983; Muchmore, 1986; Muchmore, Nuth & Stencel, 1987). Data from the IRAS satellite have revealed cool ($\leq$ a few hundred K) "dusty" regions around cool giants later than ~M5 III (Stencel, Carpenter & Hagen, 1986), and radio and UV observations show evidence for geometrically extended warm regions ($T_e \leq 10^4K$) in the coolest giants (Drake & Linsky 1986, Drake 1985). In the present paper I consider regions between the photosphere ($\tau(5000)\text{Å} \sim 1$) and the inner circumstellar envelope (~ several stellar radii), and thus include all of these observations. This picture of a "chromosphere" is a highly complex region in the near vicinity of the star, spanning a wide range of physical conditions (pressures, temperatures, compositions) where a wide variety of important, but as yet poorly understood, physical processes are occuring.

Understanding the chromospheric structure of AGB stars will provide vital constraints on the non-thermal heating, cooling, and deposition of momentum in the outer atmospheres of these important objects, on the mass loss and subsequent stellar evolution. Morris (1987) remarks, in the context of mass loss mechanisms: "The cause of the matter ejection is, however, understood only in broad outline because the near-stellar arena from which the matter is expelled is complex and usually cannot be resolved spatially". The chromosphere (as defined above) is the region where most of the non-thermal energy generated in the sub-photospheric convection zone is deposited in heating the circumstellar material and lifting it from the gravitational field of the star. Until we can adequately describe this region we cannot say that we understand the mass loss processes from cool, evolved stars.

Basic questions concerning the chromospheres of stars evolving up the AGB are presently unanswered– some are addressed below: how do chromospheric properties (densities, temperatures, dust/gas ratio, velocity fields, inhomogeneities, geometry) vary with the evolutionary changes in luminosity, effective temperature, chemical composition, photospheric variability? What can be inferred concerning mechanisms and physical processes responsible for the observed structures? What effect does binarity have on chromospheres of AGB and other chemically peculiar evolved stars? Recent reviews of relevant work are given by de la Reza (1987) and Johnson (1987).

The paper is organized as follows: Section 2 describes the stellar sample adopted. In Section 3 the chromospheres of the "non-variable" oxygen rich M giants are reviewed. In Section 4 the MS and

S stars are discussed, and Section 5 deals with the C stars. Section 6 discusses physical processes which may account for some of the observed properties, and Section 7 describes the stellar data in an evolutionary context.

2. STELLAR SAMPLE AND CHROMOSPHERIC DATA

Since typical M supergiant stars probably have masses in excess of the theoretical upper limit for helium shell flashes (e.g. Iben & Renzini, 1983), and since galactic N-type carbon stars have masses typically $\sim 1.4M_{\odot}$ (Dean, 1976), I focus on M stars of luminosity class III to obtain a sample of AGB stars from early-M type through the carbon star phase which may represent an evolutionary sequence. The 42 stars examined are listed in Table 1, together with IRAS data (taken directly from the point-source catalogue and the LRS atlas). IUE and VLA data are listed in Table 2, together with sources listed individually.

The sample was chosen on the basis of stars having useful measurements from IUE, the VLA or both. H-α and the Ca II H and K lines and IR triplet can also provide useful constraints (Hagen, Stencel & Dickinson, 1983) These are not discussed in detail here since interpretation of these lines is less straightforward and there are observational problems with carbon stars (e.g. Johnson & Luttermoser 1987). Just 4 MS/S stars exist (all binaries) which satisfy these criteria, together with 13 carbon stars (3 R stars, 10 N stars). Note the observational bias of decreasing V-band flux (and hence distance, interstellar absorption, etc.) with more advanced phases of evolution. The discussion is therefore restricted to nearby stars and to long wavelength spectra obtained with IUE.

Photometric data are from the SIMBAD compliation of stellar data of the Centre du Données Stellaires, except where indicated. Angular diameters are from the Barnes-Evans V-R colour calibration (Barnes, Evans & Moffett, 1978) except other determinations are available. The UV data consist of observed ($F_{\oplus}$) and surface fluxes (F_{*}) ($erg\ cm^{-2}\ s^{-1}$) of Mg II (h+k), surface fluxes of the C II] λ2325 Å multiplet and Al II λ2670 Å, and the electron density N_e (cm^{-3}) derived from high-dispersion studies of the ratios within the C II] multiplet following early work by Stencel et al. (1981), modified using updated atomic data (Lennon et al., 1985)

Figure 1 identifies the stellar sample on the IRAS two–colour diagram of van der Veen and Habing (1988), revealing stars which have no detectable circumstellar (CS) dust (region I), "warm" dust associated with O-rich CS envelopes (regions II-IIIa), and warm (region VII) and cool (region VIa) C-rich CS envelopes. Only 6 stars have detectable silicate or silicon carbide (SiC) CS features in the LRS spectra (Table 1).

Figure 2 shows the fractional luminosity in the Mg II, C II] and Al II] chromospheric lines as a function of photometric colours and of the effective temperature (T_{eff}). Note the gradual decline in the fractional luminosity for the non-dusty or "clean" K and M stars, and the sharper decline for the dusty M and C stars.

3. THE "NON-VARIABLE" M GIANTS.

Strictly "non-variable" M giants do not exist (e.g. Querci, 1987); here I discuss M giants which are not regularly pulsating and whose variablity does not exceed a few tenths of a magnitude. Generally the chromospheric UV emission fluxes discussed below are relatively less variable than the underlying photosphere (Oznovich & Gibson, 1987), but sufficient data do not exist to discuss the variability of the radio and IR diagnostics.

"Warm" chromospheric components ($T_e > T_{eff}$)

"Warm" chromospheric regions around cool, low-gravity oxygen rich stars differ substantially from solar–like chromospheres (e.g. Judge 1988): Instead of an essentially hydrostatic chromosphere ($T_{eff} \leq T_e \leq 10^4 K$) overlaid by hotter material at transition region temperatures ($\sim 10^5 K$) and a hot ($\sim 10^6 K$) corona, the outer atmospheres of single K and M giants have a quite different structure in which no material hotter than $\sim 2 \times 10^4 K$ has been detected. Lines such as Mg II h and k therefore

Table 1
Basic data and IRAS fluxes for the program stars.

Name	spectrum	*log g*	T_{eff}	V	R	K	F_{12}	R_1	R_2	LRS	Notes
α Boo	K1 III	1.7	4250.0	−0.1	−1.0	−3.0	792.8	−1.73	−2.03		1
β UMi	K4 IIIBa			2.1	1.0	−1.2	160.3	−1.55	−2.08		
α Tau	K5 III SB	1.3	3850.0	0.9	−0.4	−2.8	699.4	−1.65	−1.95		2
β And	M0 III	1.6	3800.0	2.0	0.8	−1.8	286.4	−1.55	−2.03		4
μ UMa	M0 III SB	1.35	3850.0	3.0	1.8	−0.9	100.9	−1.50	−2.03	n/a	3
α Cet	M1.5 IIIa			2.5	1.2	−1.6	234.7	−1.55	−2.03		
β Peg	M2 II-III	1.2	3600.0	2.4	0.9	−2.2	387.3	−1.50	−2.00		4
π Aur	M3 III			4.3	2.6	−0.9	107.8	−1.47	−1.92		
σ Lib	M3 IIIa			3.3	1.7	−1.4	200.7	−1.68	−1.88		
μ Gem	M3 IIIab	1.0	3600.0	2.9	1.3	−1.9	304.5	−1.55	−2.08		7,8
γ Cru	M3.4 III			1.6	0.0		865.0	−1.47	−1.98		
δ^2 Lyr	M4 II		3385.0	4.3	2.5	−1.2	155.8	−1.38	−1.88		5
ρ Per	M4 II-III	0.8	3500.0	3.4	1.6	−1.9	308.6	−1.47	−1.92		6
β Gru	M5 III	0.3	3500.0	2.1	0.2		941.5	−1.50	−1.92	n/a	2
L^2 Pup	M5 IIIe			5.1	2.4	−1.8	2415.1	−1.15	−2.40	n/a	
W Cyg	M5 IIIe			5.4	3.0	−1.3	349.1	−0.97	−2.05	weak Si/C	
2 Cen	M5 III			4.2	2.1	−1.6	255.3	−1.60	−1.92		
R Lyr	M5 III			4.0	2.0	−2.1	370.8	−1.45	−1.85	n/a	
W Hya	M5 IIIe			7.0		−3.1	4200.0	−1.35	−2.03		
α Her A	M5 II	0.0	3220.0	3.5		−5.0	1515.1	−1.38	−1.77		5
g Her	M6 III	0.2	3250.0	5.0	2.5	−2.0	437.6	−1.17	−2.00		4
X Her	M6 III			5.7		−1.4	484.4	−0.75	−1.98	strong Si	
RZ Ari	M6 III	0.5	3295.0	5.9	3.5	−1.0	147.2	−1.47	−1.98		9
θ Aps	M7 III			5.5			733.8	−0.83	−2.00	Si	
R Dor	M8 IIIe			5.5	1.8	−3.8	5548.7	−1.25	−2.13	n/a	
4 o^1 Ori	$M3^-$ S III SB	0.8	3450.0	4.7	3.5	−0.5	83.6	−1.47	−1.70		4,a
HR 363	S3+/2- SB	1.0	3600.0	6.4	5.1	1.6	11.6	−1.45	−1.68		4,a
HD 35155	S3,2 SB		3660.0	6.8	5.4	2.1	8.0	−1.50	−1.60		10
HR 1105	S3.5/2 SB	0.9	3550.0	5.1	3.5	0.2	41.0	−1.45	−2.10		6
CIT6	C4,3					1.1	3319.5	−1.10	−1.63	C	
S Cen	C4,5=R5			7.6	6.0		8.9	−1.42	−1.25	n/a	
UV Cam	C5,3=R8			7.9			11.1	−1.45	−1.63		
UU Aur	C5,3		2825.0	5.3	3.3	−0.7	232.1	−1.27	−1.47	C	7
TX Pisc	C6,2		3030.0	5.0	3.2	−0.6	162.9	−1.53	−1.32	n/a	7
BL Ori	C6,2		2960.0	6.2	4.4	0.7	44.5	−1.25	−1.38		7
R Scl	C6,II		2550.0	5.8	3.7	0.0	162.1	−0.75	−0.45		7
TW Hor	C7,2			5.7	3.8	0.0	101.2	−1.00	−1.85		
NP Pup	C7,2			6.3	4.6	0.9	34.0	−1.05	−1.25		
U Hya	C7,3		2825.0	4.9	3.0	−0.7	205.5	−1.13	−1.58	n/a	7
T Ind	C7,3			6.0			47.2	−1.38	−1.15		
IRC+40540	C8,3.5					2.5	959.8	−0.78	−1.55		
IRC+10216	C9,5					1.3	47525.2	−0.78	−1.53	C	

Notes: Photometric data from SIMBAD except (a) from Eggen (1972). F_{12} is the IRAS 12μ flux, R_1 and R_2 the ratios $2.5log(F_{25}/F_{12})$ and $2.5log(F_{60}/F_{25})$ respectively. "Si" indicates that a silicate feature is present in the LRS spectrum, "C" a SiC feature. *log g* and T_{eff} are from the following sources: 1. See Judge (1986a) 2. See Judge (1986b) 3. Luck & Lambert (1982) 4. Smith & Lambert (1985). 5. Tsuji (1986) 6. Smith & Lambert (1986). 7. Lambert et al. (1986) 8. See Johnson & Luttermoser (1987) 9. Tsuji (1981) 10. See Johnson & Ake (1984).

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Table 2
IUE fluxes, electron densities and VLA ionization fractions.

Name	$F(Mg\ II)_\oplus$	$F(Mg\ II)_*$	$F(C\ II])_*$	$F(Al\ II])_*$	$log N_e$	F_{ion}	Notes
α Boo	9.0(−11)	1.7(5)	8.5(3)	2.7(3)	9.7	−0.5	1,2
β UMi	5.3(−11)	6.6(4)				−0.75	3,2
α Tau	1.7(−10)	7.0(4)	4.4(3)	2.2(3)	9.0	≤ −2.0	4,2
β And	4.2(−11)	3.7(4)	2.3(3)		9.0	≤ −1.5	5,2
μ UMa						≤ −0.3	2
α Cet						≤ −1.3	2
β Peg	≥ 5.8(−11)	≥ 3.3(4)			8.8	≤ −2.0	6,5,7,2
π Aur	≥ 1.6(−11)	≥ 5.0(4)				≤ −1.1	2
σ Lib						≤ −1.0	2
μ Gem	4.0(−11)	3.2(4)	3.2(3)			−1.42	8,2
γ Cru	1.6(−10)	1.6(4)	1.3(3)	6.4(2)	9.0		9,10
δ^2 Lyr	≥ 2.1(−11)	2.9(4)					11
ρ Per	3.4(−11)	2.1(4)	1.3(3)	6.6(2)	8.9	−2.39	12,2
β Gru	1.3(−10)	1.9(4)	1.9(3)	6.0(2)	8.5		4
L_2 Pup	5.1(−13)	9.2(1)		1.2(1)			11
W Cyg	2.4(−12)	1.7(3)					11
2 Cen	2.5(−11)	1.2(4)	1.2(3)	3.6(2)	8.0		12
R Lyr	2.8(−11)	1.3(4)	8.2(2)	4.1(2)	8.9		11
W Hya						≤ −4.1	13
α Her A						−1.95	2
g Her	6.5(−12)	2.0(3)	1.0(2)	8.0(1)	8.0		12
X Her	7.0(−13)						11
RZ Ari	4.1(−12)	3.9(3)	4.9(2)				8
θ Aps	1.6(−12)						8
R Dor	1.0(−12)	1.5(1)		2.4			11
4 o^1 Ori	2.5(−12)	3.6(4)	7.2(3)	≤ 2.3(3)			14
HR 363	1.6(−12)	5.9(4)	1.5(4)	≤ 3.7(3)			10
HD 35155	3.0(−12)	1.6(5)	1.3(4)	≤ 6.4(3)			15
HR 1105	5.0(−12)	2.2(4)	4.4(3)	≤ 1.1(3)			10
CIT6						≤ −3.3	13
S Cen	1.4(−13)	6.5(3)	6.5(3)	≤ 3.3(3)			8
UV Cam	8.4(−14)						8
UU Aur	2.2(−13)	4.4(2)	2.8(2)	8.8(1)			8
TX Pisc	2.3(−13)	4.4(2)	2.8(2)	≤ 5.5(1)			8,16
BL Ori	8.0(−14)	5.7(2)	4.5(2)	≤ 2.9(2)			8
R Scl						≤ −3.2	13
TW Hor	2.6(−13)	9.9(2)	6.2(2)	2.0(2)			8,16
NP Pup	2.2(−13)	3.1(3)	1.6(3)	6.2(2)			8,13
U Hya	2.7(−13)	4.9(2)	2.0(2)	9.8(1)			8
T Ind	1.8(−13)						8
IRC+40540						≤ −3.3	13
IRC+10216						≤ −3.3	13

Notes: Fluxes given in erg cm^{-2} s^{-1}, N_e in cm^{-3}, and F_{ion} is the log of the ionization fraction from the VLA observations. References are from: 1. Judge (1986a) 2. VLA data from Drake & Linsky (1986) 3. Oranje (1986) 4. Judge (1986b) 5. Brown & Carpenter (1984) and Carpenter, Brown & Stencel (1985) 6. Stencel et al. (1980) 7. Byrne et al. (1988) 8. Johnson & Luttermoser (1987) 9. Carpenter, Pesce, Stencel, Brown, Johansson & Wing (1988, preprint) 10. IUE Archive 11. Stencel, Carpenter & Hagen (1986) 12. Eaton & Johnson (1988) 13. VLA data from Drake, Linsky & Elitzur (1987) 14. Ake & Johnson (1988) 15. Johnson & Ake (1984) 16. Variable: mean data taken

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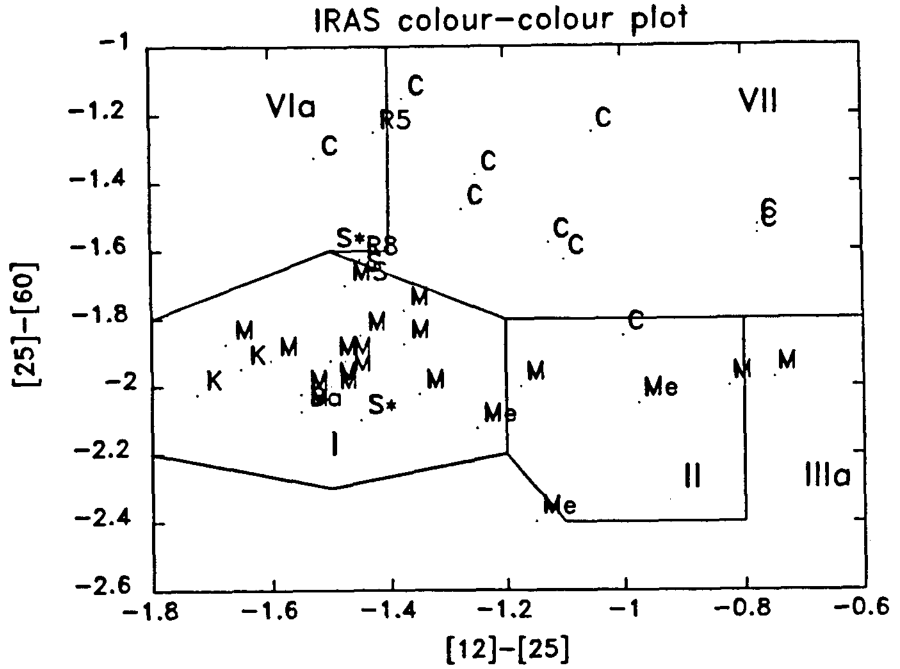

Figure 1. The IRAS colour-colour diagram of the stellar sample.

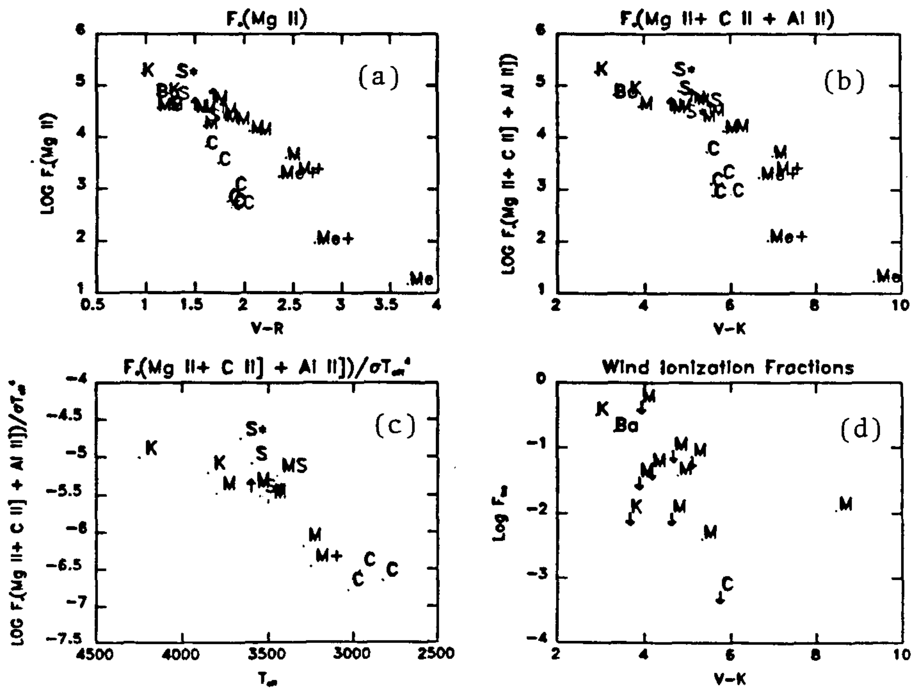

Figure 2. The behaviour of the observed chromospheric losses with photometric colours and T_{eff}. Binaries with evidence for accretion are marked with an asterisk, "dusty" M stars ([25] - [12] > −1.2) with a plus. All the C stars are "dusty" (see text).

remain optically thick relatively higher in the atmosphere where they show redward asymmetries indicative of substantial flows, which have been interpreted in terms of radially outflowing winds (Stencel and Mullan, 1980a,b; Drake and Linsky 1983; Drake 1985). Late-M giants show, in addition to the asymmetries, essentially permanent sharp circumstellar (CS) blue-shifted absorption features formed in the circumstellar envelope several stellar radii from the photosphere (e.g. Reimers, 1981).

In an evolutionary context the outer atmosphere becomes relatively "inactive" as a star spins down during its ascent of the giant branch through spectral types G-K III and it exhibits a "basal" level of activity perhaps related to purely non-magnetic waves (Schrijver, 1987) and /or a minimal level of dynamo activity associated with the reduced rotation rate (Rutten & Pylyser, 1988). Figure 2 shows quantitatively how the chromospheric heating falls off with later spectral type for M stars, analogous to a similar sample of stars studied by Steiman-Cameron, Johnson & Honeycutt (1985). This extends smoothly the earlier relation derived on the basis of G,K and warmer stars (e.g. Linsky & Ayres, 1978).

The chromospheric regions with $T_e \leq 2 \times 10^4$ become relatively more extended (in terms of $\Delta H/R_*$) in cool low gravity stars than in the dwarfs (Drake & Linsky, 1985; Judge 1986a,b), because (i) for a given chromospheric T_e and turbulent velocity field, the hydrostatic gas pressure scale height is inversely proportional to the stellar gravity g_* ($\Delta H_{scale} = P_g/g_*\rho$), i.e. proportional to the stellar radius *squared*; (ii) hydrodynamic "turbulence", as inferred by the observed widths of optically thin lines (e.g. Hartmann & Avrett 1984; Judge, 1986a,b), supports the chromospheric gas and momentum deposition drives a cool stellar wind, although the mechanisms remain poorly understood (e.g. Holzer, 1987). Judge (1988, in preparation) demonstrates that, even for α Ori (M2 Iab), which has a relatively massive stellar wind ($dM/dt \sim 10^{-6}\ M_\odot\ yr^{-1}$), hydrostatic equilibrium, when "turbulent" velocities are accounted for, dominates the momentum balance in the regions where UV photons are *created* owing to the $(density)^2$ dependence of the emissivity. The asymmetries in e.g. Mg II *k* are produced by scattering of photons at significantly lower column masses where the wind is well under way and where densities are so low that the contribution to the emissivity (or source function) is negligible.

Characteristics of "warm" chromospheric material are represented by IUE and VLA data. Several crucial types of data from observed emission lines are represented in Table 2. (i) For M stars Mg II integrated line fluxes represent a substantial fraction of the total non-thermal energy input above the photosphere (Linsky & Ayres, 1978, estimated the fraction to be $\sim 1/3$ from warmer stars, but Carpenter (1988) emphasizes that in the coolest M stars Fe II UV complexes contribute a comparable fraction to the total cooling). (ii) The electron density N_e yields a measure of the "mean" electron density in the "warm" chromosphere (proportional to the heating- see below). (iii) The ratios of line fluxes of C II] and Al II] with Mg II *h* & *k* yield constraints on the relative carbon abundance and on the effects of multiple scattering in the Mg II lines (the formation of Al II] and Mg II lines effectively differ only in their optical depths- the former are always optically thin in the chromosphere). The latter will be examined below in the context of the destruction of Mg II photons by absorption in "dusty" chromospheres, and depletion onto grains which may be formed at chromospheric heights.

The variation of the electron density N_e with *log g* is plotted in Figure 3(a), extending the sample of Byrne et al. (1988) to later spectral types. Judge (1987) argues that these (and other) global chromospheric properties can be understood in terms of Ayres' (1979) explanation of the Wilson-Bappu effect, since these warm UV-line emitting regions are (i) close to turbulently-supported hydrostatic equilibrium (hence the behaviour with gravity g_*), and (ii) are heated by the same mechanism, Schrijver's (1987) "basal" level of chromospheric heating. Also plotted (Figure 3(b)) is $log\ N_e$ vs. $0.5[log\ g.A_{Fe}] + log\ T_{eff}^n$, where g and T_{eff} are stellar gravities and effective temperatures, and A_{Fe} are the metallicities relative to the Sun. According to Ayres' scaling law ($N_e \propto \tilde{F} g^{1/2} A_{Fe}^{1/2} T_{eff}^n$ where $F_*(Mg+..) \propto T_{eff}^{2n+1}$, here $n \simeq 3$ is estimated from the K and M stars of Figure 2), Figure 3(b) should yield ordinates proportional to the heating parameter $\tilde{F}$ ($erg\ g^{-1}\ s^{-1}$). Despite $\sim \pm 0.3 dex$ uncertainties in Figure 3(b), I conclude that the data imply a steady decline in $\tilde{F}$ from α Boo (K1 III) to the M stars. This potentially valuable method of examining the heating

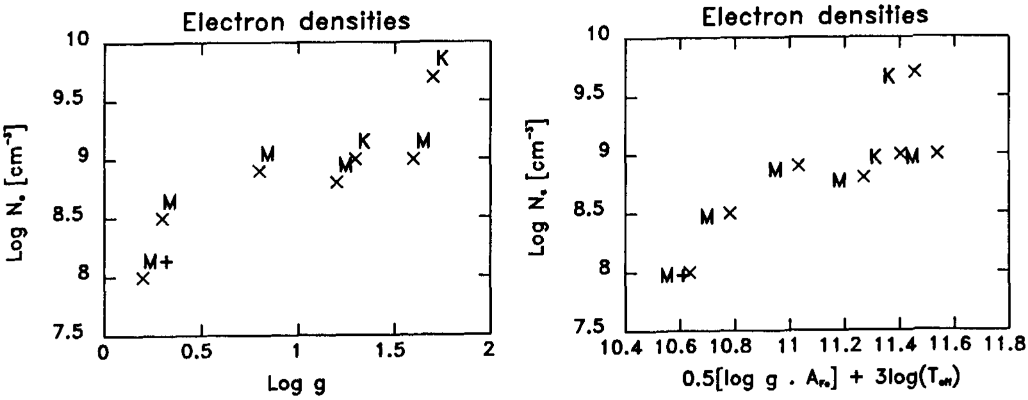

Figure 3. The variation of the observed chromospheric electron densities with (a) *log g*, and (b) 0.5[*log g*.A_{Fe}] + *log* T^n_{eff}, n=3 (see text).

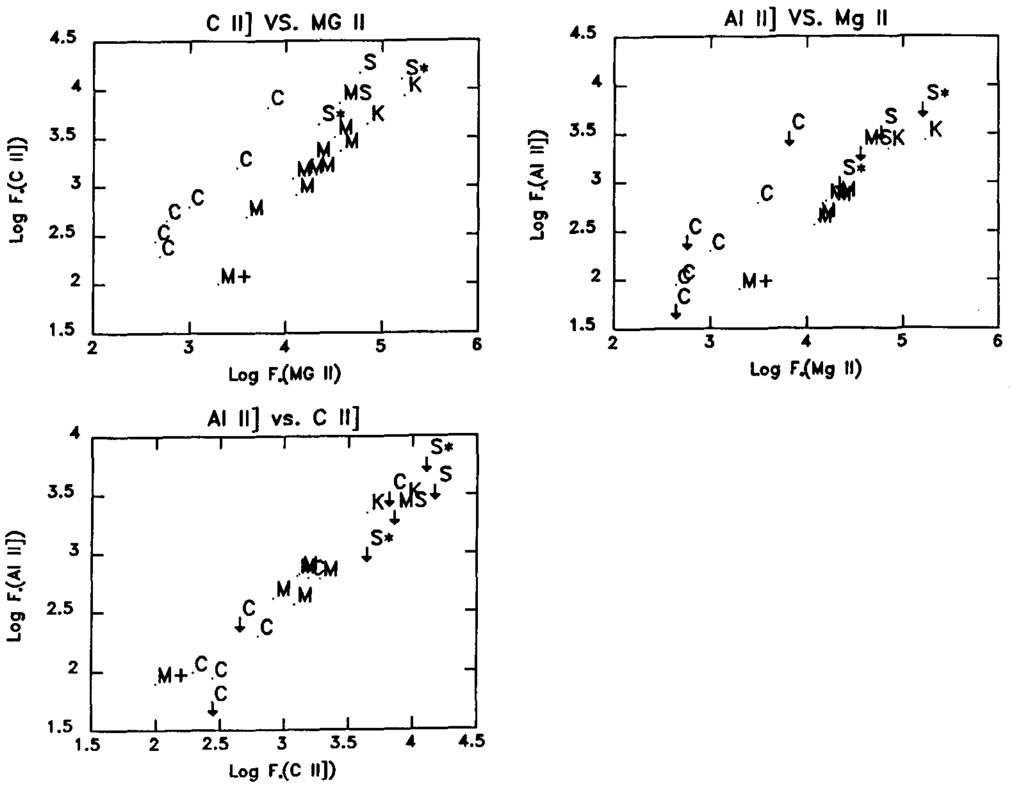

Figure 4. Flux-flux diagrams relating observed chromospheric losses in the lines of Mg II *h* & *k*, Al II] λ2670 and C II] λ2325.

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as a function of spectral type, T_{eff} and evolutionary status should be pursued further.

Pioneering studies with the VLA also reveal valuable constraints on the warm chromospheric gas (Drake & Linsky, 1986, Drake, Simon & Linsky, 1987; Drake, Linsky & Elitzur, 1987). Table 2 lists the ionization fraction F_{ion} derived by these authors, which represents a first attempt to parametrize the fractional ionization of the emitting regions. In chromospheric models concerned with UV emission lines the fractional ionization can change by several orders of magnitude over the emitting regions (e.g. Judge, 1987). Nevertheless F_{ion} provides a useful starting point for comparing various stars, and it is clear that the ionization fraction of material within several stellar radii (the radio photospheric angular diameters are typically twice the optical photospheric diameters) declines with later spectral type. In an absolute sense, one problem remains: for some stars listed in the Table, F_{ion} has been derived from the general formula for the *total* mass loss rate of Reimers (e.g. 1981), which may or may not be appropriate for these stars (e.g. Drake, 1986).

"Cool" chromospheric components ($T < T_{eff}$)

Three types of observations have been used to identify the presence of "cool" material above the photospheres of cool giants: (i) vibration-rotation IR molecular absorption bands, (ii) rotational molecular emission in the circumstellar envelopes (extending many stellar radii and the subject of Olofsson's review (this volume)), (iii) IR excesses due to circumstellar dust.

Tsuji (1987, 1988) provides evidence for a quasi-static, turbulent ($\xi_t \geq 5km/s$) new component in the outer atmospheres of M giants, from an analysis of equivalent widths, velocity profiles and variability of low-excitation CO lines compared with higher excitation lines. Tsuji argues that this new component could represent a transition zone between the warm chromosphere and cool wind. Although these spectra are certainly formed higher in the atmosphere than the photospheric lines, inspection of Tsuji's results reveal that, as expected by e.g. scaling from the work of Heasley et al. (1978), the absorbing layer has quite high column masses: for ρ Per (M4 II–III), a typical example, Tsuji's (1988) table 3 gives $log\ N_{CO} = 19.78cm^{-2}$, yielding a column mass of $log\ m \simeq 0.1gcm^{-2}$. The present author believes that, because of momentum and energy requirements, such large column masses imply that the absorbing regions lie close to the stellar photosphere, in disagreement with Tsuji's speculations, and that the absorbing regions co-exist with the warmer chromospheric regions with similar column masses inferred for the case of ρ Per e.g. from opacity sensitive line ratios of Fe II (Eaton & Johnson, 1988). This picture is consistent with Ayres' (1986) multi-component picture of α Boo (K1 III).

High quality IRAS data are available for $\simeq 5700$ oxygen rich giants and supergiants (Zuckerman, 1987; van der Veen & Habing, 1988). Analyses of data for individual stars have been made by Stencel, Carpenter and Hagen (1986), Stencel, Pesce and Hagen Bauer (1988) and recently by Kenyon, Fernandez-Castro and Stencel (1988) in studies of M–star components of symbiotic systems.

Kenyon et al. (1988) found that the onset of dust formation occurs near spectral type M5 III, as indicated by a [25/12] flux ratio > 0.25 (the Rayleigh- Jeans value for a photosphere near 2-3000 K) from the IRAS 25 and 12μ bands, i.e. essentially at the point where a star begins to pulsate as a long period variable (LPV), confirming earlier findings (e.g. Jura, 1986). From Figures 1 and 2 we find that *the M (and C) stars with dust have substantially reduced chromospheric UV emission* (in units of $F_*/\sigma T_{eff}^4$, but that the warm chromospheric components are not completely "quenched" in the late M giants, as discussed by Stencel et al. (1986). The crucial question of where the dust is formed is delayed until Section 6 where C stars will also be included.

4. MS AND S STARS.

Chromospheric data on MS and S stars are scarce, since the stars themselves are also rather scarce (Smith & Lambert, 1988, cite Stephenson, 1984, who lists 178 such stars with $V \leq 9.9m$). No SC stars have been observed in the UV, to the author's knowledge. These classes of stars include targets which should be examined in the UV with the Hubble Space Telescope, but some interesting results are available from IUE.

MS stars

4 o^1 Ori ($M3^{-}S$ III), examined in detail by Ake & Johnson (1988) following earlier work by Peery (1986), is the only MS star for which valuable UV chromospheric data exist. Ake & Johnson argue that, although the SWP continuum spectrum (1200-2000 Å) reveals a white dwarf companion, the emission lines and LWP spectrum show no evidence for binary interactions through mass exchange and accretion. The chromospheric profiles of Mg II *h* & *k* are similar to those found for normal M giants, but the C II] λ2325 multiplet is a factor of ~ 3 stronger relative to Mg II (and possibly Al II]) than in normal M giants (see Figures 2 and 4). These figures imply that 4 o^1 Ori has a slightly higher level of chromospheric activity (measured by e.g. $F_*(Mg\ II)$ or $F_*(Mg\ II)/\sigma T^4_{eff}$) than M stars of similar T_{eff}. This is probably "normal" chromospheric emission and not heating due to accretion since the flux of C IV λ1550 has relatively a much lower upper limit.

Smith & Lambert (1985) have determined CNO, Fe and s-process element abundances from IR spectra, in a differential analysis with α Tau (K5 III). Although the C abundance is enhanced it is only by a factor of 1.5 relative to α Tau (K5 III), insufficient to account for the enhanced C II] flux. Possible interpretations will be discussed in Section 6.

Ake & Johnson's SWP spectrum shows (weakly) the usual lines of C I (λ1657) and S I/Si II (λ1819) again with normal M-star intensities (compared with spectra of e.g. Stickland & Sanner, 1981). However, the usually dominant O I (λ1304) multiplet is clearly lower than in M stars of equivalent T_{eff}. A deep LWP high dispersion spectrum should be obtained which would potentially allow the measurement of the electron density, relative C II] abundance and chromospheric non-thermal line broadening parameters.

The IRAS data reveal that 4 o^1 Ori has a small 60μ excess which may indicate the presence of cool, relatively old dust perhaps from a previous mass-loss episode.

In a recent preprint, Smith & Lambert (1988) confirmed the presence of Tc in the photosphere of 4 o^1 Ori. They argue that MS and S stars with Tc are presently undergoing the thermally pulsing phase of the AGB, whereas the remaining MS and S stars ($\sim$ 37% of their sample) probably acquired s-process elements from accretion of material from a companion AGB star at an earlier epoch ($\Delta t \geq 1.5 \times 10^6\ yr$), which implies that the latter stars are cooler relatives of the Barium stars. Hence it appears that 4 o^1 Ori and other MS and S stars with Tc represent the first stage in the evolution from the M giant phase, following the "third dredge-up" (Smith & Lambert, 1986). Certainly, from the UV data for 4 o^1 Ori there is no evidence for significant mass transfer processes at the present time.

S stars

Tables 1 and 2 contain just three S stars which have been studied with IUE. The absence of Tc in HR 363 and HR 1105 (Smith & Lambert, 1985,1986) suggests that these stars are probably cool analogues of Barium stars, i.e. their s-process elements were accreted from their companions in an earlier period of mass transfer (Little, Little-Marenin & Hagen Bauer 1987; Smith & Lambert 1988). Except for HR 1105 these stars have excesses at 60μ indicative of cool dust perhaps associated with previous mass loss episodes of the companions, consistent with this picture.

HR 363, analysed by Ake, Johnson & Peery (1988), appears to be a non-accreting binary with an SWP spectrum similar to mid/late M giants, although Ake *et al.* note that their SWP image is flawed by a particle impact over the important Si II/S I blend near λ1820. Further IUE observations by Ake examined from the archive reveal "normal" Mg II *h* & *k* profiles but, as can be seen from Figures 2 and 4, HR 363 has a relatively "active" chromosphere compared to normal M stars. The C II] lines are substantially enhanced, relative to the Mg II lines.

HR 1105 (Ake et al., 1988) and HD 35155 (Johnson & Ake, 1984; Peery, 1986) clearly have SWP spectra more closely resembling symbiotic stars than normal M giants since they show strong high temperature lines of N V λ1240 and C IV λ1550 associated with accretion processes and X-ray heating (in the case of N V).

The chromospheric surface fluxes of HD 35155 exceed those of any star in the sample, indicating that the "chromospheric" line fluxes also probably result from accretion onto the white dwarf companion. The Mg II line profiles reveal just red wings in emission indicating a substantial wind from the primary (Johnson & Ake, 1984).

HR 1105, although having evidence for accretion in lines formed near 10^5 K, has chromospheric fluxes similar to normal M stars suggesting that the dominant contribution is from the normal chromosphere rather than accretion. The C II] lines are enhanced by a factor ~ 2 compared with Mg II, relative to the M stars.

5. C STARS.

By comparison with the M (and S) stars, the C stars clearly have very different UV spectra (See Johnson & Luttermoser, 1987 and Figures 2 and 4) and dust properties (Figure 1). C stars also differ fundamentally in their degree of variability of chromospheric emission: studies by Querci & Querci (1985) and Johnson et al. (1986) revealed striking changes in UV emission lines of factors up to 5–10, greater than corresponding changes in the optical and UV continuum, on timescales as small as days (possibly hours). For some time it has been known that neither the H-α nor Ca II H & K traditional chromospheric features are seen in cool C stars (e.g. see the discussion by Johnson & Luttermoser, 1987). This is almost certainly due to low chromospheric densities and temperatures which (because of the NLTE effect of photon escape in Ly-α), yields very low chromospheric opacity in H-α compared with the M stars of higher gravity and effective temperature, and because the higher chromospheric opacities in resonance lines enhance escape in subordinate lines (e.g. the Ca II IR triplet lines) which may not be observed in emission against a strong background continuum. Querci & Querci (1985) have also argued that the regions where the K line is formed are probably cooled by H^-, leading to no observable emission in the K lines.

Warm C stars (R stars) have been studied in the UV by Eaton et al. (1985), cool C stars (N stars) by Johnson & Luttermoser (1987). TX Psc, the brightest C star showing detectable UV emission will be discussed in some detail below.

Dust Properties

The carbon-rich dust environment of our sample of C stars is clearly evident from Figure 1: all the C stars in the sample are "dusty". The 60μ excesses can be interpreted as evidence for cool dusty regions well separated from the star (and hence not embedded in the "chromosphere"), suggesting evolution following an earlier period of mass loss as implied by Willems & de Jong (1988) who included additional evidence from LRS spectra. Note that Zuckerman & Dyck (1986) interpreted the 60μ excesses in *very* dusty C stars (as opposed to M stars) in terms of different emissivities of grains in C- and O-rich environments.

Ultraviolet and Radio Properties

Figures 2 and 4 contain several important clues to the nature of C star chromospheres. For stars with several IUE observations a mean value for the fluxes was adopted. (Johnson et al. (1986) found that the C II] and certain Fe II lines approximately follow the Mg II line variability). The most striking features are the *apparent drop in the UV fluxes of chromospheric lines* relative to the M stars, and the *large relative flux of the C II] intersystem lines* (e.g. Johnson & O'Brien, 1983; Johnson, 1987). Figure 2(b) shows, for the first time, how the fractional energy losses in the measured lines of M and C star chromospheres varies with the effective temperature of the stars. The C II] line fluxes are much stronger than can be accounted for by the relative C abundance in M and C stars ($\simeq 0.4 dex$, Lambert et al. (1986)). Figure 4 reveals other spectroscopic clues to the nature of C star chromospheres: the optically thin Al II] and C II] line fluxes follow a trend consistent with the M stars, but the Mg II lines do not. Below, evidence is presented showing that the probable cause of these peculiar line ratios and fluxes is absorption, perhaps by dust embedded in the chromospheric regions as well as by overlying circumstellar gas.

Upper limit radio free-free data is only available for a handful of C stars (Table 2): these however yield very low values for F_{ion} and the chromospheric emission measures for these stars (Drake, Linsky & Elitzur, 1987) and indicate that the regions within $1-2R_*$ are essentially neutral, unlike early M and K giants.

TX Psc: The best-studied C star.

TX Psc is the only C star (to the author's knowledge) in which chromospheric emission has been detected at high dispersion with IUE: Eriksson et al. (1986) obtained Mg II *h* & *k* profiles (Figure 5) and some lines of Fe II. Eriksson et al. derive several important conclusions: (a) the lines are severely affected by CS absorption lines of Mn I and Fe I (possibly by an order of magnitude); (b) the Mg II line wings are marginally blue-shifted perhaps indicating outflow deep in the chromosphere (see Figure 5), but that (c) the interpretation of the line profiles is quite non-unique.

Point (a) is the only process by which the k/h ratio can be very much less than unity, as observed, implying that the observed radiative losses plotted in Figure 2 for TX Psc (and by implication other C stars, given Figure 4) ***underestimate the true losses in Mg II by between factors of 2 to an order of magnitude.*** Additional absorption in the interstellar medium over the M star sample is also expected since TX Psc, the brightest of the C stars in the UV, is significantly more distant ($d \simeq 300$pc). Eriksson et al. also point out the possibility that extinction by the observed CS grains could potentially lead to underestimates of the chromospheric cooling rates. This is discussed further below.

Recently Luttermoser et al. (1988) used the code PANDORA (Vernazza, Avrett & Loeser, 1973) to construct a one-component chromospheric model for TX Psc, adopting the Mg II *h* & *k* profiles, the C II] integrated flux and the overall appearance of the 2000-3200 Å, Mg I 2852 Å and H-α regions as observational constraints. This is the coolest model chromosphere ever made with very low densities, and it provides a needed starting point for future modelling. (A similar model for a late-M giant is urgently needed for comparison). The authors concluded that a strongly-constrained model could be found (within the limitations of their modelling procedure and diagnostics used), to account for the diagnostics. They derive, however, a very curious velocity field, (stationary high in the chromosphere, expanding at 40 km s^{-1} near the temperature minimum region) which may be an artifact of assuming a ***smooth*** velocity field (see Section 6). In addition, the PANDORA program takes no account of "Doppler drifting" of photons in frequency (Avrett, 1988, private communication) which dominates the transfer problem under conditions of low density and high opacity (Basri, 1980).

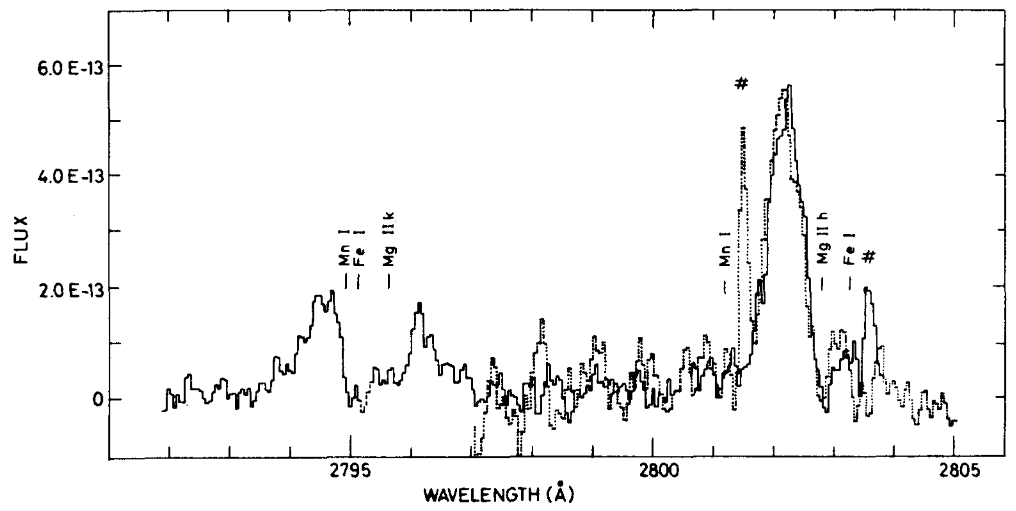

Figure 5. High dispersion spectra of Mg II *h* and *k* lines in TX Psc (Eriksson et al., 1986)

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6. CHROMOSPHERIC HEATING AND RELATED PHYSICAL PROCESSES.

As noted in previous sections there are several crucial unanswered questions: What is the *actual* level of chromospheric heating in C stars? How can we derive this from the observations? How does this vary as the star evolves from M to C type? What is the underlying cause of the chromospheric variability of C stars? Do the chromospheric observations shed light on the proposed evolutionary sequences? Where is the dust formed in the outer atmospheres of cool giants and does this agree with current ideas of mass loss? Here attempts are made to answer some of these from the available data.

Chromospheric Energy Losses of M and C stars.

There are several problems concerning the use of Mg II (+ Al II]+C II]) fluxes to indicate chromospheric radiative losses, including (a) Absorption of Mg II k photons by overlying CS gas by e.g. Mn I, Fe I; (b) Extinction of UV photons by CS grains; (c) emission in e.g. Fe II complexes which e.g. may progressively increase with lower gravity; (d) Absorption in the ISM; (e) depletion onto grains of Mg (and Al) in O-rich environments (Snow et al. (1987)), (e) chemical fractionation caused by grain expulsion (Stencel, Pesce & MacGregor, this volume).

Here a method is proposed to overcome (a) and (d) by using the Al II] intersystem line flux as an indicator of the Mg II $h + k$ flux: model calculations for low gravity stars (Judge, 1988, in preparation) reveal that, unlike the Sun (Linsky & Ayres, 1978), the Mg II lines are effectively thin in these chromospheres: hence the emergent flux at the top of the chromosphere is proportional to the ion abundance and upward collisional rate for both Al II] and Mg II, integrated over the heated regions. Since Mg II and Al II] have very similar fractional ion abundances (e.g. Judge, 1986a) and excitation energies, their ratio remains approximately constant, over reasonable temperature ranges, in the absence of substantial depletions. This is evident for the dust-free M stars in Figure 4. Thus, from Figure 4, I suggest that the M stars form a calibration curve from which the C star Mg flux can be read off, given the Al II] flux. *This implies an increase in the chromospheric losses of between a factor of 5 and 10 for the C stars*, precisely the amount by which the C stars are lower than the extrapolated radiative losses for the M stars. Thus, in the absence of interstellar and CS extinction, the C stars do not differ greatly from the late-M stars in terms of chromospheric "activity". The Mg lines fluxes are reduced certainly by line absorption (observed in TX Psc) and probably by dust extinction (see below).

The C II] lines, although stronger than Al II], are not well suited because they have potentially different ionization fractions, excitation potentials (the ratio with Mg II is too temperature-dependent), abundances, chromospheric partial pressures and depletions onto grains (the latter two depending on the C/O ratio). The partial pressures of C I and C II will increase *non-linearly* with the C/O ratio such that a substantial enhancement of C I and C II ions may be expected as C/O becomes > 1. This may partially explain the enhancements in the C II fluxes seen in the MS, S and C stars.

Chromospheric cooling in a haze of e.g. Fe II lines, difficult to estimate from IUE spectra, implies that using the Mg II lines (with corrections mentioned above) underestimates the chromospheric heating. However, the relative cooling between M and C stars should still be represented by Mg II unless a systematic change occurs in the major cooling routes owing to different chromospheric conditions. Although fluorescent processes, important for exciting many Fe II multiplets (e.g. Carpenter, 1988), are enhanced relative to collisional ones in lower gravity stars (Judge, 1988), they serve merely to redistribute thermally created photons. Since thermal creation terms are relatively the same for Fe II and Mg II at the same N_e and T_e (with the exception of certain Fe II lines pumped by H Ly-α) and since Fe II does not explicitly remove photons from Mg II, then adopting Mg II lines in a comparative study should yield reliable results, provided the H Ly-α losses are smaller than Mg (which is certainly the case for β Gru (M5 III) - Judge (1986b)).

Strong Fe II emission (e.g. in TW Hor- Querci & Querci, 1985) can potentially result from pumping by H Ly-α photons generated by large shock heating. This idea is consistent both with the factor ~ 10 variability of these lines in TW Hor (Querci & Querci, 1985) and perhaps with the observation that strong Fe II emission persists even in dusty stars in which Ca II *K* emission is absent (Hagen, Stencel & Dickinson, 1983). Quantitative work is needed on the Fe II spectrum.

Co-existing Chromospheric Dust and Warm Gas?

Using a sample of M giants and supergiants Stencel et al. (1986) examined the relation between 'cool' dust and 'warm' chromospheric emission in the UV, and specifically tested Jennings' (1973) interpretation of earlier data that energy which would normally heat chromospheric gas and emit in e.g. Ca II *H* and *K* lines is re-directed into warming dust in stars which show dust emission. They concluded that not *all* of the available energy is so directed, and that significant alteration of radiation loss channels may occur. The present review confirms and extends the study of Stencel et al. to include a larger sample of C stars.

However, arguments presented here suggest that the dusty star chromospheres are heated to a similar degree as the M stars, but that the overlying opacity of CS lines (Eriksson et al., 1985) and possibly chromospheric dust obscures the Mg II lines. I suggest an additional interpretation of the data: the reduction of the observed chromospheric losses in dusty stars may not be due to the cooling instability of molecular formation in the chromospheres (Stencel et al.), but instead due to underestimates of the actual radiative losses from the UV observations (Section 5).

In addition to straightforward extinction of UV photons by e.g. CS dust, preferential destruction of resonance line photons may occur in the case where dust co-exists in regions where the lines are optically thick (Hummer & Kunasz, 1980). Resonance line photons (e.g. Mg II *k*) travel substantially further in space than optically thin lines (e.g. Al II]), thereby suffering greater extinction. An order of magnitude calculation using the scaling laws of Faurobert & Frisch (1985) reveals that this process, already observed in planetary nebulae (e.g. Barlow, 1983), may be important in the chromospheric conditions considered here, adopting a reasonable dust opacity at 2800 Å of $10^{1\pm1} cm^2 g^{-1}$. *This may be a useful diagnostic of the presence of dust in the regions close to the star where UV photons are created.* Note that the line profile may be altered since emergent photons from different parts of the profile travel different path lengths through the chromospheric regions: calculations extending those of Hummer & Kunasz should be performed. Chromospheric modelling using resonance line profiles may be affected.

Shocks: a possible diagnostic and a *caveat* concerning line profiles

Previous discussions of blue– (or red–) shifted emission components in chromospheric lines e.g. Mg II *h* & *k* (e.g. Eriksson et al. (1986), Luttermoser et al., 1988) have considered velocity fields which vary continuously and smoothly, over a mean photon path length, λ_p. With this assumption a blue-shifted emission core always implies outflow with the observed velocity shift (i.e. ~ 40 km s^{-1} for the lower chromosphere of TX Psc).

However, a very different situation occurs if the velocity field changes sharply over a smaller scale than λ_p (I. Hubeny, private communication). In the case of shock fronts accelerating outwards (such shocks surely must exist to provide the heating), emergent scattered line photons can be blue-shifted substantially from line centre, yielding a blue asymmetry in an opposite sense to the "smooth" regime where outward acceleration would yield a redward enhancement (e.g. Stencel & Mullan, 1980a). This is analogous to the Fermi acceleration process for particles crossing a shock front (Neufeld & McKee, 1988).

The rather unphysical *ad-hoc* velocity field of TX Psc derived by Luttermoser et al. (1988) assuming a smooth velocity field suggests instead that, in the regions where the Mg II *h* and *k* emission wings are formed, shocks of sufficiently large scale are propagating outwards and accelerating the gas, leading collectively to the observed profile. Indeed, TX Psc could be exhibiting a profile equivalent to those obtained recently by Bookbinder et al. (1988) in Miras. Calculations are planned by I. Hubeny which can correctly treat the complex transfer problem in the regime considered here. Such calculations are of crucial importance not only in stars with global shocks but also in the mesoturbulent chromosphere of the Sun (P. Goutebroze, paper presented at SMM workshop, Washington, July 1988). This may require a re-thinking of current ideas based on line profiles of optically thick lines.

An observational test will be provided by comparing profiles of optically thin and thick lines: the discrepancy in the velocities between Mg II and the less thick Fe II lines observed by Eriksson et al. already suggest that the shock model is more appropriate. Deeper observations should be obtained with IUE.

Heating and Mass Loss Mechanisms.

It is inapproriate here to discuss detailed heating processes, instead I briefly mention some mechanisms in the light of the present conclusions. Contrary to some previous authors, I suggest that for non-Mira M and C stars the heating mechanism varies smoothly with the effective temperature as the star evolves, pointing to a common heating mechanism, probably damped "short period" acoustic waves generated at the top of the convection zone, leading to emission in the UV lines observed (see e.g. Querci & Querci, 1985). These authors also conclude that for stars such as TW Hor (and TX Psc) with substantial variability of UV lines, global chromospheric changes (perhaps larger scale shocks?) associated with aperiodic acoustic and/or slow-mode magnetic waves (perhaps generated by the semi-regular photospheric pulsations), probably account for this time-dependent heating. Solar-like magnetic activity is not likely, but cannot be ruled out entirely.

The substantial mass loss observed from non-regular pulsating stars remains a problem (Holzer, 1987): periodic short period acoustic waves damp too soon to provide the energy to lift gas from the gravitational field of the star, and Alfvèn waves produce excessive wind velocities which are not observed. Recent exploratory work on stochastically-changing short period acoustic waves (Cuntz, 1987) concludes that merging strong shocks can lead to mass loss events. This work should be pursued further, since potentially this can account for many of the observations described above.

7. AN EVOLUTIONARY PICTURE.

Arguments have been presented above to allow important chromospheric parameters (heating, dust content) to be estimated from observations. For warmer stars and less evolved stars chromospheres have provided, via e.g. rotation-activity relations (See Jordan & Linsky's 1987 review), information on the evolutionary status of stars. Are currently available chromospheric conditions of M, MS, S and C stars consistent with current evolutionary pictures and can we learn from these conditions about AGB evolution?

No definite answer to these questions is currently possible. However, Figure 2 and earlier discussions suggest some interesting possibilities:

If the chromospheric losses drop precipitously as a star becomes dusty (i.e. if one adopts the 'raw' Figure 2 to represent the radiative losses) then this suggests strongly that the chromosphere has evolved from the relatively active M star phase to the C phase of evolution, either by spin-down following mass- and angular momentum loss (in the case where remnant magnetic activity is responsible for the M star emission (Rutten & Pylyser, 1988)), or by reduction of the acoustic flux (if short-period acoustic waves are responsible for the heating- Schrijver, 1987).

If the chromospheric losses are, as suggested in Section 6, smoothly varying with effective temperature, then the evolution of a single star up the AGB will barely affect the chromospheric emission. Instead, other processes such as the formation of a CS shell and associated dust and line absorption will simply dominate the observed spectrum. In this case dynamo activity is unlikely to be the source of chromospheric heating since the massive circumstellar shells observed will have removed substantial angular momentum and velocity from the star.

Data on the 3 S stars available for study in the UV regions so far suggest that these particular stars are cooler brethren of the Barium stars in which peculiar surface abundances have been acquired from accretion of a previous AGB star companion. The proposed sequence M–S–C cannot therefore be tested using present observations of chromospheres.

Subsequent evolution of the stars and enrichment of the ISM depends on the mass loss process:

future observations may be able to tell us whether chromospheric dust exists close enough to the stellar surface to produce the observed large mass loss rates with current theories.

FUTURE WORK.

Much of the work described here is of an exploratory nature requiring substantially improved data and analyses. It is hoped that readers may be inspired to obtain data with instruments such as the *Hubble Space Telescope* to examine some of the ideas put forward in this new, exciting field.

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