FINAL TECHNICAL REPORT

to the

National Aeronautics and Space Administration

on Grant NAG 5-266

to the Ohio State University Research Foundation
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Title: "MEASUREMENTS OF CHROMOSPHERIC DENSITIES AND GEOMETRICAL EXTENSIONS OF LATE-TYPE GIANT AND SUPER-GIANT STARS"

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CONTENTS

I. INTRODUCTION

The research described in this document is based upon observations made with the International Ultraviolet Explorer (IUE) satellite. The work has been a collaborative effort between scientists at the Ohio State University, the University of Colorado, and the University of Oxford in England. The subject grant, NAG 5-266, covers only a portion of Ohio State University's contribution to this work.

Support by NASA for this work began in the Spring of 1981 with the award of two grants, one to the University of Colorado (P.I.'s: R. E. Stencel and J. L. Linsky) and one to the Ohio State University (P.I.: R. F. Wing, and Co-I: K. G. Carpenter). Originally, this had been a joint proposal by the four investigators under the title, "Measurements of the Chromospheric Densities and Geometrical Extensions of Late-Type Giant and Supergiant Stars Using C II Lines as Diagnostics", and the work has continued as a fully collaborative venture. The Ohio State University portion of the funding was transmitted as Supplements Nos. 3 and 4 to NSG 5368, with Robert F. Wing as Principal Investigator.

One year later, in the Spring of 1982, the IUE Observatory approved a continuation proposal entitled "Further Measurements of Chromospheric Densities and Geometrical Extensions of Late-Type Giant and Super Giant Stars Using C II Line Ratios" by the same four Colorado/Ohio State investigators. We requested that the Ohio State portion of the funding be transmitted as a further supplement to NSG 5368, but it was sent instead as a new grant, NAG 5-266. Consequently, this Report is separated from others describing the same science.

II. SUMMARY OF RESULTS

Multiplet (UV 0.01) of the C II ion has proved to be one of the most interesting and useful groups of atomic lines that can be studied in the ultraviolet spectra of late-type stars accessible to the IUE satellite. Its strongest line, at 2325 Å, was listed as the "strongest unidentified line" in our high-resolution spectra of γ Crucis and other cool giant stars observed during IUE's first year of operation (Wing and Carpenter, B.A.A.S. 10, 444, 1978). Two years later these lines were identified as intercombination lines of C II by Brown and Jordan of Oxford and by Stencel and Linsky of JILA. By analogy with similar transitions in B I, N III, amd O IV, which had been studied in the context of the solar atmosphere, the lines of the C II multiplet were expected to be useful indicators of the electron density. Efforts were then made to measure the C II lines on all suitable existing IUE exposures, to calculate theoretical line ratios as a function of electron density and temperature, and to compare the theoretical ratios with observation.

The first results of this study were very encouraging and were reported by Stencel, Linsky, Brown, Jordan, Carpenter, Wing, and Czyzak (Monthly Notices Roy. Astron. Soc. 196, 47P, 1981). As shown in Figure 1, the relative strengths of the five lines of C II (UV 0.01) vary from object to object and in particular are quite different in the low-density planetary nebula as compared to the late-type giants. Figure 2 shows that the various line ratios (designated R_1, R_2, and R_3, and defined in the figure) are calculated to be very sensitive to electron density in the range 10^7 - 10^9 cm^{-3}. In the high-density limit the ratios approach the values observed in the solar chromosphere, while in the low-density limit they agree with the ratios measured in the planetary nebula NGC 6572. Evidently the chromospheres of red giant stars have intermediate densities — precisely in the range where the C II lines are most sensitive.

Subsequently, we showed that the C II lines can give an indication of the geometrical size of the emitting region. Since the integrated intensity

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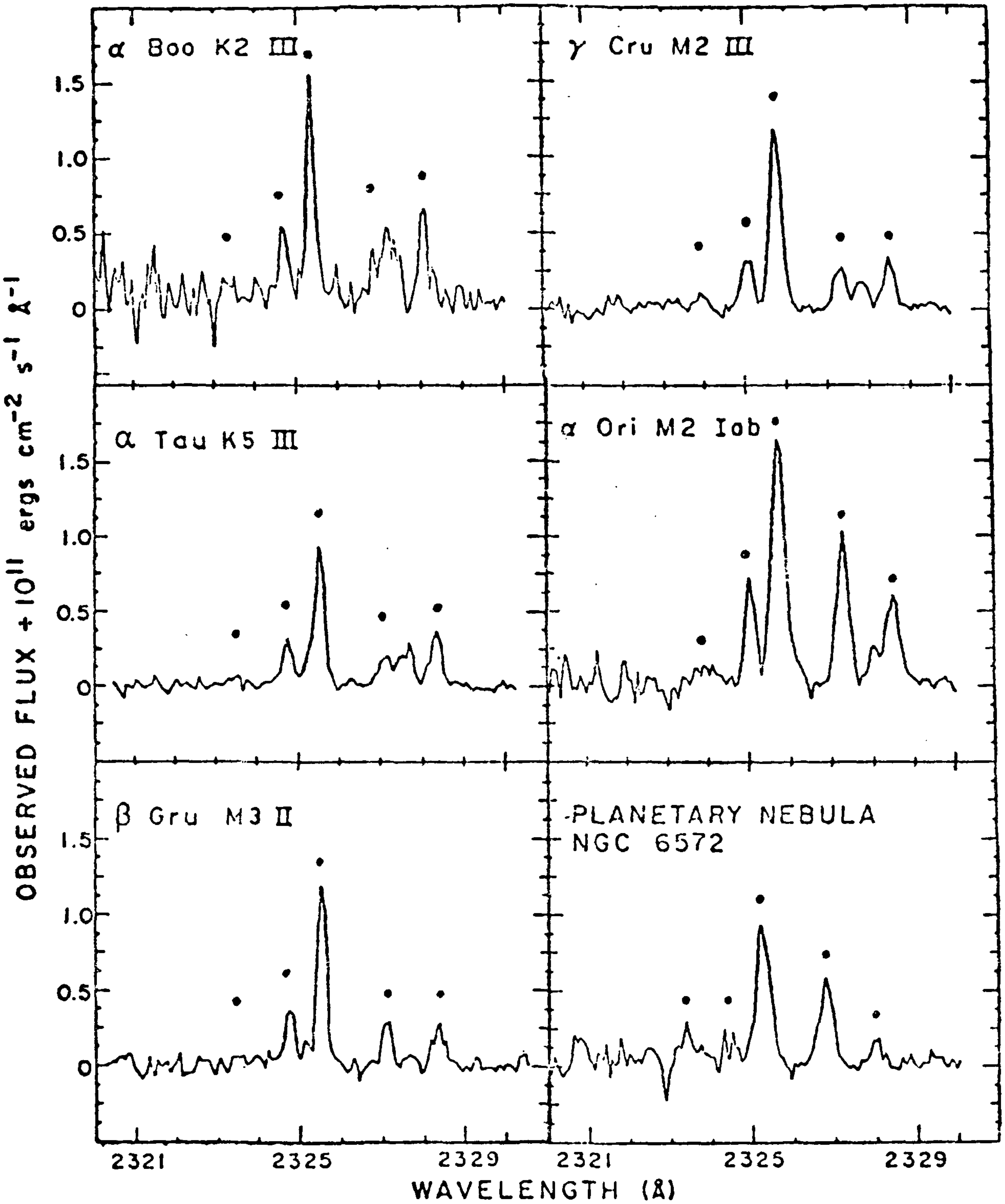

Figure 1. Emission lines of C II UV multiplet 0.01 observed in several late-type stars and a planetary nebula. Note that the ratio 2325/2327 is closer to unity in the nebula than in any of the class III objects, and is intermediate in Alpha Ori. From Stencel, Linsky, Jordan, Brown, Carpenter, Wing and Czyzak (1981).

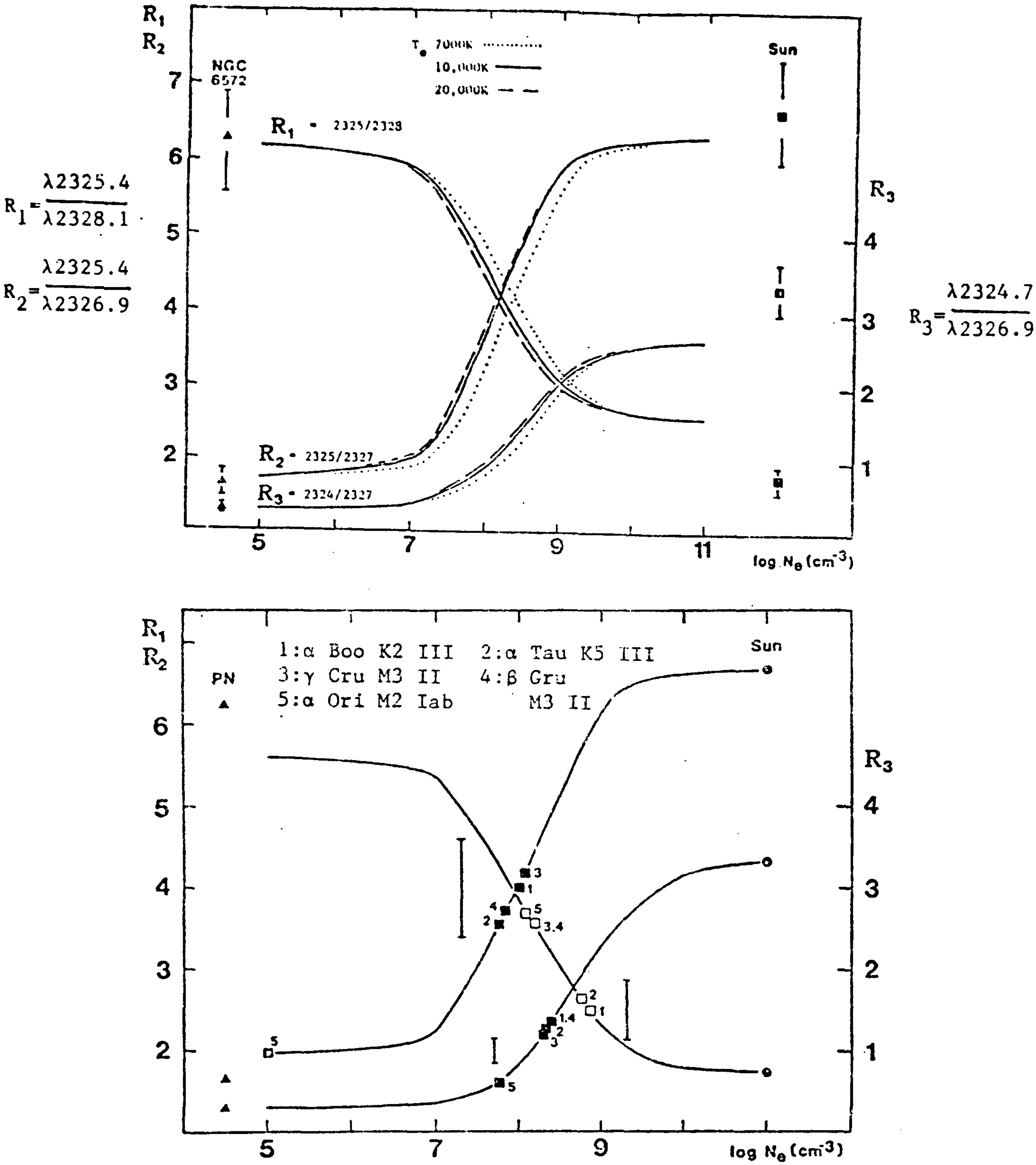

Figure 2. Upper diagram: calculated line ratios for three pairs of lines within the C II UV 0.01 multiplet, plotted against log N_e. Note the great sensitivity of these ratios to N_e between 10^7 and 10^9 cm^{-3}. The sensitivity to temperature, on the other hand, is small. Lower diagram: As above, for T_e = 10,000 K, except that the A-values have been adjusted empirically to force better agreement between calculated and observed solar ratios. The error bars represent $\pm$15%. From Stencel et al. (1981).

in the multiplet is proportional to the number of C II ions, while the ratios discussed above indicate the electron density, one can combine these data to determine the path length over which the lines are formed and hence the thickness of the chromosphere. This calculation is best done in conjunction with observations of the C II line at 1335 Å, since then the temperature is no longer a free parameter. The important result which soon emerged from this work is that the chromospheres of red giant and supergiant stars are greatly extended, on the order of one stellar radius in thickness, in contrast to the solar chromosphere, the thickness of which is only a few percent of the solar radius.

Recent work on the C II lines has concentrated on acquisition of data on additional stars (a slow process, since exposures of several hours are required to record even the brightest late-type stars adequately at 2325 Å at high resolution) and the reduction of these spectra. We have also developed an improved treatment of the carbon and hydrogen ionization equilibria, which permits a more accurate estimate of the extent of the chromosphere. As reported by Stencel and Carpenter (NASA CP-2238, p. 243, 1982), a distinction can now be made between the giants earlier than about K2 III, which like the Sun have thin chromospheres surrounded by hot coronae, and the cooler giants which have thick chromospheres surrounded by cool circumstellar envelopes.

Clearly, observations of the intercombination multiplet of C II have added considerably to our understanding of the outer atmospheres of late-type giant stars.

III. PUBLICATION OF RESULTS

The chief results from this work have been published under grant NSG 5368 to the Ohio State University and grants NAG 5-82 and NAS 5-23274 to the University of Colorado.

The following paper has been published under the subject grant NAG 5-266:

> "Density Sensitive C II Lines in Cool Giant Stars", by Robert E. Stencel and Kenneth G. Carpenter, in Advances in Ultraviolet Astronomy: Four Years of IUE Research, ed. Y. Kondo, J. M. Mead, and R. D. Chapman, NASA CP-2238, 1982; pp. 243-246.

Reprints of the above paper are submitted herewith.

IV. PROJECT EXPENDITURES

The project budget of $5000. was spent entirely for the salary of a graduate research assistant, and for the associated fee waivers and indirect costs. The student worked half-time for 4.5 months and was primarily involved with the reduction and measurement of the IUE spectra.

from Advances in Ultraviolet Astronomy: Four Years of IUE Research, ed. Y. Kondo, J. M. Mead, and R. D. Chapman, NASA CP-2238 (1982), p. 243.

DENSITY SENSITIVE C II LINES IN COOL GIANT STARS

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ABSTRACT

The density sensitivity of the emission lines within the UV 0.01 multiplet of C II near 2325 Å has been examined in additional late type giants and supergiants with deep LWR high dispersion exposures. The new data support the original contention based on these lines that noncoronal red giants possess geometrically extended chromospheres.

INTRODUCTION

Given the complexity of the spectra of late type post main sequence stars, it is crucial that spectroscopic methods be established which can unambiguously determine basic atmospheric parameters, such as the electron density. One such density diagnostic involves the mid-UV intercombination lines of C II, multiplet UV 0.01 near 2325 Å (Stencel et al. 1981). By iterating between three observed line ratios within the multiplet and atomic theory, a self-consistent set of atomic parameters which fit the observations was derived. These lines exhibit a density sensitivity between 10^7-10^9 cm^{-3}. In that study, except for the solar chromosphere which provided the high density limit, all of the stars considered were late K and M giants and supergiants which are inferred to lack solar-like corona on the basis of their low upper limits of soft X-ray emission (Ayres et al. 1981a).

We have endeavored during the fourth year of IUE operations to extend the observational sample across the cool half of the H-R diagram, particularly to explore the so-called Linsky and Haisch (1979) division between giant stars with and without transition regions (TR) and coronae. To this end, we have observed three coronal type stars: Beta Dra (G2 Ib-II), Beta Gem (K0 III) and 56 Peg (K0 IIp + wd). The latter is an interacting binary and must be cautiously compared with single stars (cf. Schindler et al. 1982). In addition, we have observed Epsilon Gem (G8 Ib) and Epsilon Peg (K2 Ib) to extend the survey of C II] in the spectra of noncoronal stars.

OBSERVATIONS

Figure 1 displays the 2320-2330 Å region of spectrum in the five new observations, plus a comparison with the previously observed, high signal-to-noise (S/N), strong C II lines in Alpha Ori (M2 Iab). The figure also indicates the exposure times used for these LWR echelle mode observations during 1981. The wavelength scales are those provided by the IUESIPS, and given the small range of THDA (13±1°C), suggest real velocity shifts. The primary member of the multiplet, near 2325.4 Å appears to have been detected in each case, except perhaps in Beta Dra where a strong continuum has swamped much of the emission. The ratio of 2325.4 Å/2328.1 Å (R_1) theoretically decreases with increasing electron density, while the ratios 2325.4 Å/2326.9 Å (R_2) and 2324.7 Å/2326.9 Å (R_3) both increase with increasing electron density. On this basis we can derive some preliminary density estimates, limited largely by the low S/N:

Star	Spectral Type	Radial Velocity	C II] Ratios R_1	R_2	R_3	Log $\bar{N}_e$
β Dra	G2 Ib-II	-20 km s^{-1}	1.8	2.3	1.5	8.3 ± 1.0
β Gem	K0 III	+3	2.2	4.8	2.0	8.7 ± 0.3
56 Peg	K0 IIp+wd	-24	3.0	2.5	1.3	8.0 ± 0.5
ε Gem	G8 Ib	+11	3.2	2.3	0.9	7.8 ± 0.6
ε Peg	K2 Ib	+5	2.5	2.7	1.2	8.0 ± 0.8

Improvements in the use of the C II ratios for accurate density determinations must await more accurate atomic parameters for C II, as well as higher S/N observations which will become possible with the High Resolution Spectrograph on the Space Telescope in the mid-1980s.

INFERENCES

The ratios of the 1335 Å resonance lines of C II to the intercombination lines is sensitive to T_{exc}. Among coronal type giants like Beta Dra and Beta Gem, the lines of C II near 1335 Å are clearly present. Among the noncoronal giants, the resonance lines of C II are much weaker and often blended with fluoresced CO emission (Ayres et al. 1981b). These resonance lines are computed to form in the lower TR in the Sun ($\lesssim$20,000 K), but our calculations for giant stars suggest significant contribution to the line flux from the chromospheres. We are typically finding upper limits to the T_{exc} for noncoronal giant stars, of 5000-7000 K. Physically, the emission measure suggests that in order to obtain significant flux from the intercombination lines when the resonance lines are weak or absent (low T_{exc}), formation in an extended chromosphere is required. Solving for the line emissivity of C II UV 0.01 requires an accurate ionization equilibrium, which is difficult to compute in the turbulent and partially-ionized chromospheres of red giants. However, because the C II UV 0.01 lines are not self-reversed, we can adopt an optically thin approximation, and the emitting layer thickness (cm) can be expressed as a function of the observed flux, distance factors and the ionization-excitation populations which involve an exponential of inverse T_{exc}. Thus, coronal type giants like Beta Dra and Beta Gem which have solar like T_{exc} are deduced to have thin C II emitting layers ($r \ll R_*$). The noncoronal giants with low T_{exc} are deduced to have very large C II emitting layers ($r > R_*$). Although the calculations require improvements and generalization, it is encouraging that this evidence concurs with parallel data from radio and narrow band speckle interferometry observations which also point to extended chromospheres among noncoronal giants and supergiants (cf. Stencel 1982). The evidence for a discontinuous change in chromospheric extent between coronal and noncoronal giants must be a crucial clue to the mechanism of rapid mass loss (cf. Mullan and Stencel — this volume).

LINES OF Si II UV 0.01

Multiplet UV 0.01 of Si II which occurs between 2330-2350 Å also appears in emission in the spectra of our observed stars. We have examined line ratios in this multiplet to look for any correlation they may exhibit against the C II derived densities, and find little evidence for such. Presumably chromospheres can easily populate the upper level of UV multiplet 1 of Si II (which is only 1.5 eV above the upper level of UV 0.01), in contrast to populating the upper levels of UV 1 of C II, which are 4.0 eV above UV 0.01.

ACKNOWLEDGMENTS

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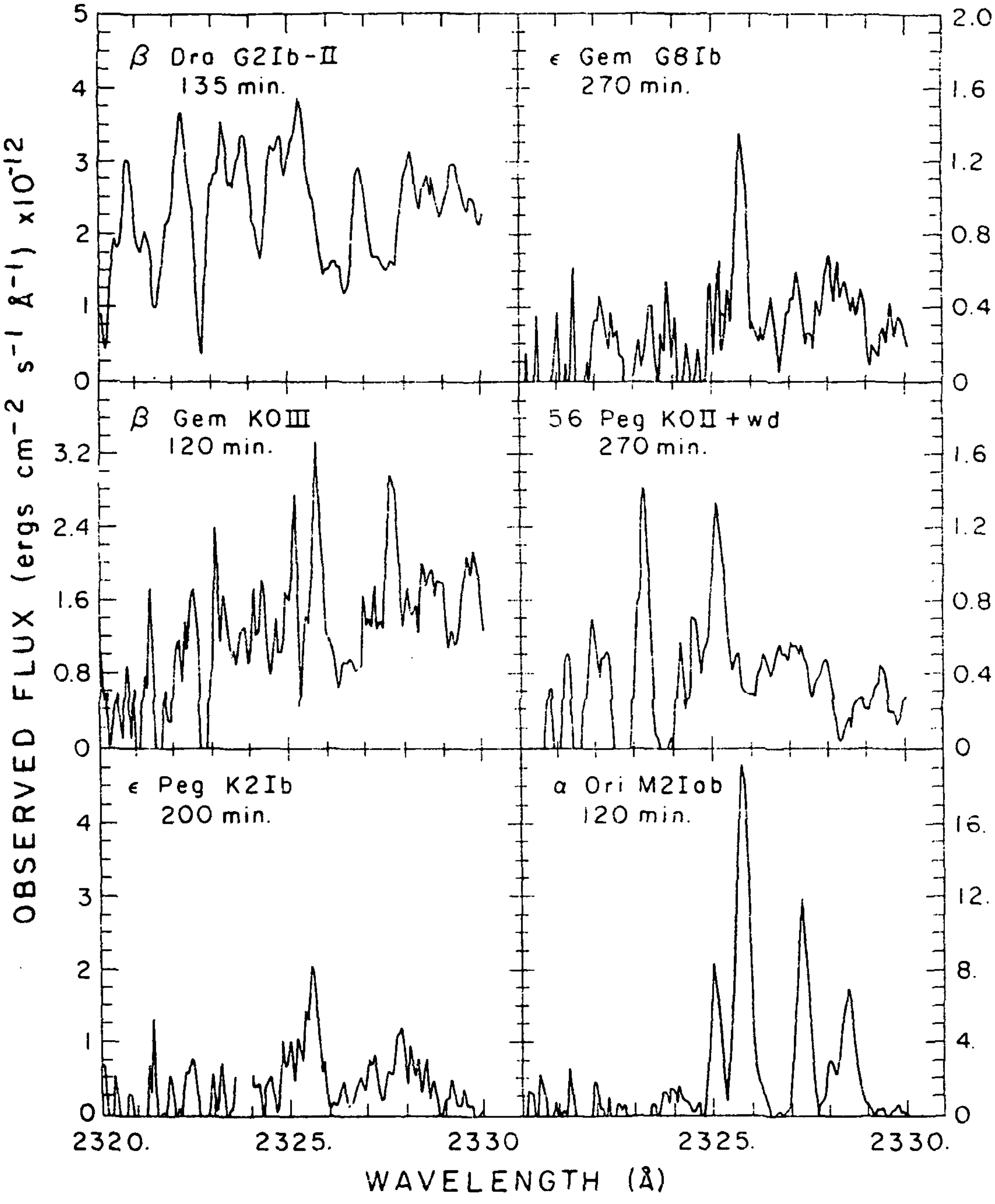

Figure 1. The C II intersystem lines in several late-type stars.