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# CHROMOSPHERES OF METAL-DEFICIENT FIELD GIANTS

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## ABSTRACT

Observations of the $\lambda$2800 Mg II line have been obtained with *IUE* for a sample of 10 metal-deficient field giant stars to search for chromospheric emission and signatures of mass loss, as well as to establish the level of chromospheric radiative energy losses from these stars. Mg II emission is probably present in all stars. High-resolution spectra of three of the brightest giants show asymmetric Mg II profiles which indicate a differentially expanding atmosphere signaling the presence of outward mass motions. Surprisingly, the stellar surface fluxes in the Mg II lines are commensurate with the values found for disk giant stars (Population I) of similar color. In spite of substantially depleted magnesium abundances in the target stars (by factors of $\sim$10–100 relative to the solar abundance), the radiative losses implied by the Mg II fluxes, and possibly the chromospheric heating mechanism, appear to be reasonably independent of metallicity and age. Whereas decay of magnetic activity is generally invoked to explain chromospheric evolution in main-sequence stars with solar abundances, a different mechanism may be present here. These old stars and the M67 giants observed by Smith and Janes, taken together, appear to increase in Mg II surface flux as they evolve up the red-giant branch. Our observations and the H$\alpha$ profile measurements of Smith and Dupree suggest that the chromospheric emission may be enhanced by pulsation and resultant shock dissipation in addition to a component of magnetic activity. Chromospheres of evolved stars may represent a pure form of hydrodynamic atmosphere.

*Subject headings:* stars: abundances — stars: chromospheres — stars: late-type — stars: mass loss — stars: Population II — ultraviolet: spectra

## I. INTRODUCTION

The study of stellar chromospheres through ultraviolet spectroscopy has generally been confined to Population I stars in the Galaxy with ages comparable to or younger than the Sun. In this paper, we report observations made with the *International Ultraviolet Explorer* (*IUE*) satellite of metal-deficient galactic-halo field giants, which constitute part of the oldest population of stars in the Galaxy. In addition to investigating the properties of chromospheric activity, the presence of mass outflows from old red giants can be sought; this being a necessary, but unknown, input quantity to the calculation of the evolution of globular cluster stars.

Chromospheres, transition regions, and coronae of dwarf stars generally decay with age. Following Wilson's (1963) pioneering observations of the Ca II H and K lines, many studies have demonstrated these effects from a variety of atmospheric tracers (Herbig 1985; Caillault and Helfand 1985; Simon, Herbig, and Boesgaard 1985). Chromospheric emission is believed to reflect the level of magnetic activity on a stellar surface which results from a dynamo mechanism. The decay of this activity is attributed to the effects of spin-down of a star caused by the torque of a stellar wind (see discussion in Hartmann and Noyes 1987). In current theories, the strength of the magnetic field depends on the interaction between the differential rotation of the star and the convection zone. Strong correlations exist between the rotation period of a star and the level of radiative energy losses in line emission from the outer atmosphere, suggesting that the decay of emission for old low-mass dwarfs results from angular momentum loss and the slowing down of the rotation rate.

Giant stars have not been studied as intensively as the dwarfs with respect to the evolution of their chromospheric properties. It has been appreciated that the surface fluxes per unit area of chromospheric and transition region lines are lower in single giants than in dwarf stars (Ayres, Marstad, and Linsky 1981; Hartmann, Dupree, and Raymond 1982). In moving redward across the giant region of the H-R diagram, after an initial rise in surface flux (presumably due to the growth of the convection zone), a rapid decay of C IV transition region emission occurs, possibly resulting from weakening of the dynamo due to spin-down of the star (Simon 1984). Whitney (1988) has demonstrated that rotational periods of giant stars increase as they evolve to lower effective temperature (for values of $B-V \sim 0.6$–1.0), and that the Ca II H and K strength as measured by the *S*-index also decreases (see also Baliunas *et al.* 1983). In even cooler giants, Smith and Janes (1988) measured the Mg II emission lines of seven red stars along the upper giant branch in M67 (having colors of $B-V \sim 1.4$–1.7) and found no decrease in Mg II surface flux, although the stellar radii increased by a factor of $\sim$3. The M67 giants are believed to have ages of $\sim$5 Gyr (VandenBerg 1985).

This paper presents *IUE* observations of the $\lambda$2800 Mg II resonance line for a sample of even older giant stars. Our targets, the metal-deficient field giants, are of interest for

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several reasons. Their spatial distribution within the Galaxy as well as their dynamical properties are similar to those of the globular clusters, and they exhibit metal deficiencies comparable to those of the clusters (Carney 1988; Zinn 1988), although the precise form of the metallicity distribution may differ (Laird *et al.* 1988). Thus, they are assumed to be similar to the globular clusters in age. Most of our target stars have metallicities of [Fe/H] $\sim -2$. Because the abundances of metals in our target stars are substantially less than solar values, it is possible that metal-poor stars would possess atmospheric characteristics that are distinctly different from those stars with solar abundances. Studies of the color-magnitude diagrams of the metal-poor globular clusters M15 (Fahlman, Richer, and VandenBerg 1985), M68 (McClure *et al.* 1987), and M92 (Stetson and Harris 1988), which have very similar metallicities to our target stars, indicate ages in the range $\sim$14–16 Gyr. Consequently, we will adopt an age of 15 Gyr for the metal-poor field giants in our study. These stars greatly extend the age and metallicity range over which the chromospheric properties of red giants can be studied and enable us to address the evolution of chromospheric activity up the red giant branch. This represents an extension in age by a factor of 3 beyond the M67 giants.

## II. OBSERVATIONS AND REDUCTION

### *a) The Spectra*

The *IUE* was used to obtain long-wavelength spectra of eight bright metal-deficient field giants. Additional spectra of three stars were obtained from the *IUE* archive: HD 84903, HD 184711 (Spite, Caloi, and Spite 1981), and HD 122563 (Bohm-Vitense 1982). Low-dispersion spectra were taken through the large aperture in order to search for emission in the Mg II multiplet: $\lambda$2795.5 and $\lambda$2802.7. Four stars were sufficiently bright to attempt high-dispersion spectroscopy through the large aperture. The physical parameters of the stars and the sequence of *IUE* images are given in Tables 1 and 2. Each *IUE* image was carefully inspected for flaws, hot pixels, and "hits" which were removed. The spectra were extracted from the line-by-line files, and the standard *IUE* calibration was applied.

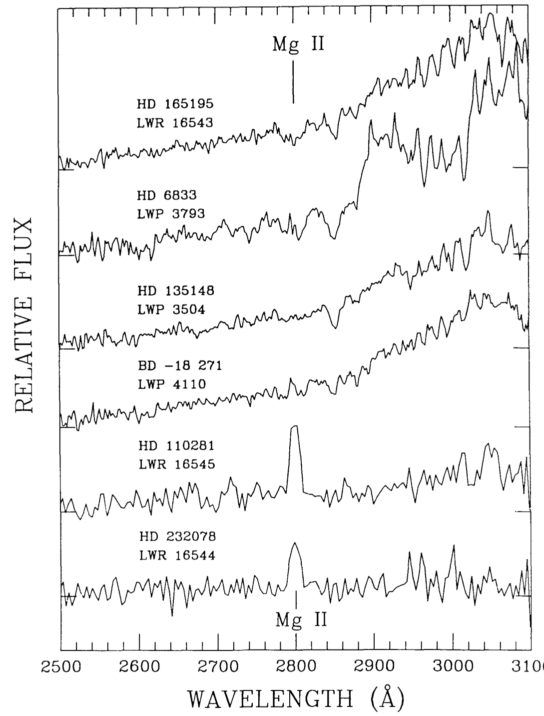


FIG. 1.—Low-resolution *IUE* spectra of six metal-deficient field giants, arranged in approximate order of decreasing temperature (top to bottom). Reseaux and "hits" on the spectra have been removed from the line-by-line files for each image.

Low-resolution spectra (Fig. 1) demonstrate the increasing contrast of the Mg II transition with decreasing stellar effective temperature. In the hottest stars, an absorption feature is

TABLE 1

*IUE* OBSERVATIONS OF METAL-DEFICIENT FIELD GIANTS

| Star | Image Number[a] | Date | Dispersion (High or Low) | Exposure Time (minutes) |
|---|---|---|---|---|
| HD 6268 .............. | LWP 6677 | 1985 Aug 16 | H | 333 |
| HD 6833 .............. | LWP 3792 | 1984 Jul 18 | H | 340 |
| | LWP 3793 | 1984 Jul 18 | L | 12 |
| | LWP 3794 | 1984 Jul 18 | L | 20 |
| | LWP 4486 | 1984 Oct 2 | H | 429 |
| BD −18 271 .......... | LWP 4110 | 1984 Aug 30 | L | 350 |
| HD 84903 ............. | LWR 5232[b] | 1979 Aug 2 | L | 90 |
| HD 110281 ............ | LWR 16545 | 1983 Aug 7 | L | 135 |
| HD 122563 ............ | LWR 4356 | 1979 Apr 25 | H | 295 |
| | LWR 5314[c] | 1979 Aug 11 | H | 120 |
| | LWP 7677 | 1986 Feb 18 | H | 390 |
| HD 135148 ............ | LWP 3504 | 1984 Jun 6 | L | 355 |
| HD 165195 ............ | LWR 11703[d] | 1981 Oct 6 | L | 50 |
| | LWR 16543 | 1983 Aug 7 | L | 50 |
| | LWP 1909 | 1983 Jun 27 | L | 50 |
| | LWP 2870 | 1984 Mar 1 | H | 437 |
| HD 184711 ............ | LWR 8989[b] | 1980 Oct 9 | L | 90 |
| HDE 232078 .......... | LWR 16544 | 1983 Aug 7 | L | 120 |

[a] All images were obtained through the large aperture.
[b] Image obtained from NSSDC/Program VC158 (P.I. V. Caloi).
[c] Image obtained from NSSDC/Program CCBEB (P.I. E. Böhm-Vitense).
[d] Image obtained from NSSDC/Program FS592 (P.I. F. Spite).

TABLE 2

Parameters of Target Stars

| Star | $V^a$ | $(V-R)^b$ | $E(B-V)^c$ | $M_V{}^a$ | [Fe/H][a] | $V_0{}^d$ | $(V-R)_0{}^e$ | Velocity (km s$^{-1}$) | $T_{eff}{}^b$ |
|---|---|---|---|---|---|---|---|---|---|
| HD 6268 ........... | 8.11 | ... | 0.03 | −1.2 | −2.4 | 8.01 | 0.82 | +40.1 | 4580 |
| HD 6833 ........... | 6.75 | 0.947 | 0.06 | −0.9 | −1.6 | 6.55 | 0.90 | −245.0[a] | 4400 |
| BD −18°271 ....... | 9.8 | 1.030 | 0.03 | −2.5 | −2.4 | 9.7 | 1.0 | −209.3[f] | 4180 |
| HD 84903 .......... | 8.06 | 1.01 | 0.13 | −2.1 | −2.6 | 7.63 | 0.91 | +92.0[a] | 4500[h] |
| HD 110281[a] ........ | 9.34 | ... | 0.03: | −2.0: | ... | 9.24 | 1.4: | +141.6[f] | 3490 |
| HD 122563 ......... | 6.21 | 0.805 | 0.00 | −1.5 | −2.6 | 6.21 | 0.81 | −26.0[a] | 4600 |
| HD 135148 ......... | 9.49 | 0.987 | 0.04 | −1.4 | −1.4 | 9.36 | 0.96 | −91.9[f] | 4260 |
| HD 165195 ......... | 7.34 | 1.076 | 0.25 | −1.8 | −2.1 | 6.52 | 0.88 | −0.2[a] | 4440 |
| HD 184711 ......... | 8.00 | ... | 0.07 | −2.8 | −2.5 | 7.77 | 0.90 | +101.6[a] | 4400[h] |
| HDE 232078[i] ....... | 8.7v | 1.621 | 0.25: | −2.0 | −1.8 | 7.9 | 1.4 | −390.5[a] | 3490 |

[a] Bond 1980.

[b] Stone 1983, with the exception of HD 84903 (from Carney 1980) and HD 110281, where the color for the star BD +00°2970 was erroneously substituted for HD 110281 in Stone's Table I (Stone 1984). We assume the unreddened color of HD 110281 to be similar to that of HDE 232078 based on the appearance of the Hα spectrum.

[c] Color excesses taken from Bond 1980, with the exception of HD 122563 and 165195 (from Wallerstein *et al.* 1963).

[d] Assuming $A_V = 3.3E(B-V)$.

[e] Assuming $E(V-R)/E(B-V) = 0.80$. Unreddened colors for HD 6268 and HD 184711 obtained from $T_{eff}$ (Barbuy, Spite, and Spite 1985; Spite and Spite 1979), and Stone's (1983) relation between $(V-R)_0$ and $T_{eff}$.

[f] Carney and Latham 1986.

[g] Little-studied star with strong Hα emission (Dupree, Hartmann, and Smith 1984; Smith and Dupree 1988). Reddening from galactic position ($l$ = 297°4; $b$ = +62°1) following technique of Bond 1980. Assumed absolute magnitude similar to HDE 232078.

[h] Spite and Spite 1979.

[i] Reddening consistent with galactic position ($l$ = 53°2; $b$ = −2°3); Values of $E(B-V)$ in the literature vary from 0.0 (Jones and Dixon 1972) and 0.06 (Sandage 1969) to 0.9 (Christiansen 1978). $M_V$ taken to agree with values for globular cluster giants (Mallia and Pagel 1978). [Fe/H] ratio from Pagel 1966.

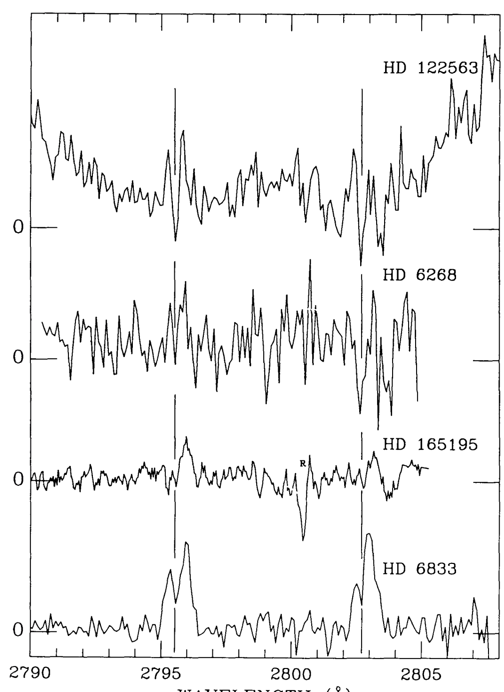


Fig. 2.—High-dispersion Mg II spectra of four stars: HD 122563 (LWP 7677), HD 6268 (LWP 6677), HD 165195 (LWP 2870), and HD 6833 (LWP 4486). Spectra have been corrected for the stellar radial velocities given in Table 2. Vertical lines denote the laboratory positions of the Mg II *h* and *k* lines. The horizontal line indicates the zero level of each spectrum. Both lines of the Mg II multiplet were taken from Order 83 of the *IUE* echelle spectrum. The spectra of HD 165195 and HD 6833 were binned into two-resolution elements.

present (HD 165195), and with increasing $T_{eff}$, the Mg II emission core begins to fill in the photospheric absorption profile; the coolest stars in the sample display strong Mg II emission above the level of the adjacent continuum (see also Spite, Caloi, and Spite 1981). Four stars, (HD 6268, HD 6833, HD 122563, and HD 165195), were observed at high dispersion, and the Mg II profiles are shown in Figure 2. One star, HD 165195, has been observed three times with *IUE* over a period of 2 years (see Fig. 3).

### *b) Flux Extraction*

The flux in a high-dispersion spectrum was measured by integration over the emission core of the *h* and *k* lines separately and calibrated by assuming a factor of 100 between high- and low-dispersion calibration constants at λ2800 (Cassatella, Ponz, and Selvelli 1981; Hartmann, Dupree, and Raymond 1982; Baliunas, Hartmann, and Dupree 1983). Böhm-Vitense (1982) derived a value of the Mg *k* flux for HD 122563, which exceeds ours by a factor of 2.5 due to her reduction technique. The line profile was assumed to be intrinsically symmetric and was constructed from the observed red emission wing. Because line asymmetries can arise naturally in a differentially expanding atmosphere (see, for instance, HD 6833 in Fig. 2), the Böhm-Vitense procedure may not be valid. We have simply measured the flux under the line profile since the cores of the strong photospheric absorption lines reach zero intensity (see Fig. 2).

The fluxes in the emission features were measured from the low-dispersion spectra in different ways depending upon the strength of the emission with respect to the continuum. For the coolest stars (HD 110281 and HDE 232078) with prominent Mg II emission, a local continuum was subtracted from the Mg II flux. For the hotter stars (BD −18°271 and HD 184711), both lower and upper limits are given. A local continuum was removed from the region near λ2800 to yield a lower limit to

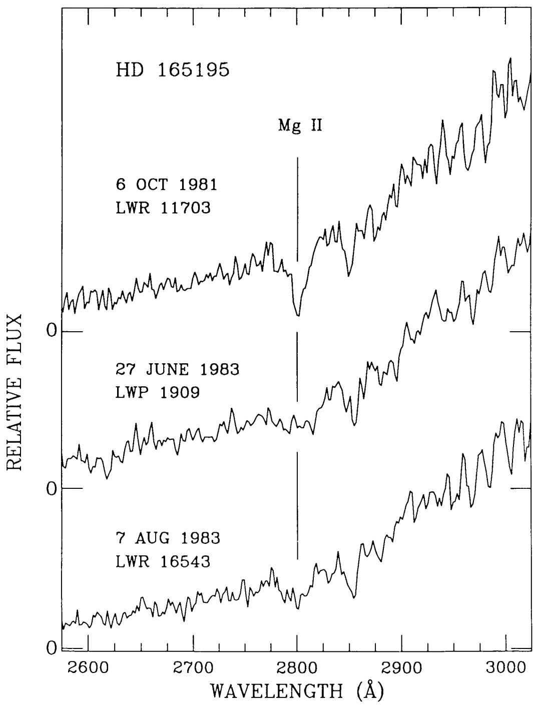


FIG. 3.—Long-wavelength *IUE* spectra of HD 165195 obtained over an interval of 2 years. The wavelength region centered on the Mg II feature shows a larger variation in flux (by a factor of 4) than other regions at shorter and longer wavelengths, suggesting that some variation is prsesent in the Mg II emission.

the Mg II flux. And an upper limit to the flux was obtained by integrating over the Mg II wavelength region without subtracting a background continuum. The Mg II emission in HD 135148 lies at the continuum level, so only an upper limit was obtained. One star, HD 84903, shows simply an absorption feature at $\lambda 2800$; an upper limit to the flux was obtained by integration over the core of the absorption.

The flux measured from low-dispersion spectra without removing the continuum overestimates the Mg II flux as compared to values obtained from high-dispersion spectra in which the line core can be clearly identified. For a warm star, such as HD 165195, in which the emission appears only as a "filling in" of the Mg II absorption, our upper limit from low-dispersion spectra (Dupree, Hartmann, and Smith 1984) exceeds that from a (noisy) high-dispersion spectrum by a factor of 3.8. A much cooler, luminous star, $\alpha$ Ori (M2 Iab) with prominent Mg II at low dispersion shows only a 16% discrepancy between values extracted from high- and low-dispersion spectra by this procedure. The effect of interstellar Mg II absorption on the line fluxes is minimized in these objects because seven out of 10 of the stars have radial velocities $\gtrsim |90|$ km s$^{-1}$, sufficiently high to move the stellar Mg II lines away from interstellar absorption features.

The observed Mg II fluxes are listed in Table 3. The uncertainty in the spectrophotometric accuracy of *IUE* spectra arises from numerous sources (see Grady and Imhoff 1985). A useful empirical estimate of the error in our Mg II fluxes derives from the repeatability of the measurements. Sonneborn and Garhart (1986) found that the reproducibility of individual spectra taken with the LWP camera amounted to $\sim 3.5\%$ (1 $\sigma$) over a 150 Å interval; the LWR camera has a slightly larger rms error for the repeatability of a single observation, namely, 4.2% (1 $\sigma$) over a 300 Å interval. To extract Mg II fluxes, however, a much smaller wavelength interval is considered, and here observations of other cool stars are helpful. The Mg II flux from the four giant stars in the Hyades was repeatable to $\sim 5\%$ in successive exposures (Baliunas, Hartmann, and Dupree 1983). Alpha Ori, a cool supergiant, exhibited a less than 2% change in Mg II flux extracted from two high-dispersion spectra taken within 8 hr (Dupree *et al.* 1987). A sequence of high-dispersion spectra obtained during a flare of $\lambda$ And (Baliunas, Guinan, and Dupree 1984) showed a standard deviation of only 2% of the value of the Mg II flux. Two stars in this study, for which we have been fortunate enough to obtain two high-dispersion spectra each, show only 3% and 7% difference between the extracted total Mg II fluxes in the two images. Two low-dispersion spectra for HD 6833 show a difference of 10% between two successive exposures. Thus, it seems conservative to adopt an uncertainty of $\pm 20\%$ ($\sim 2\,\sigma$) in our measurement of the Mg II fluxes from well-exposed spectra with low background. For weaker spectra, we have scaled the uncertainty as a function of the square root of the signal strength following the prescription of Hartmann, Dupree, and Raymond (1982). In Table 3, the quality index A denotes an error of $\leq \pm 20\%$, B $\leq \pm 30\%$, and C $\sim \pm 50\%$. Long-term changes in the camera sensitivity (Sonneborn and Garhart 1986) are low near $\lambda 2800$ (0.2% yr$^{-1}$ for the LWP or 1% yr$^{-1}$ for the LWR) and can be ignored over the 2–4 yr period when these spectra were accumulated.

Stellar surface fluxes have been obtained by correcting the observed flux for reddening (using the color excess given in Table 2 for each star) and by applying the relationship defined by Barnes, Evans, and Moffett (1978) between $V-R$ color and a visual surface brightness parameter $F_V = 4.2207 - 0.1 V_0 - 0.5 \log \phi$, where $V_0$ is the unreddened Johnson $V$ magnitude, and $\phi$ is the stellar angular diameter in milliarcseconds. The relationship, usually expressed in the form of an $F_V$–$(V-R)$ diagram, is widely used to obtain stellar surface brightnesses. It is based on measurements of the visual magnitude and angular diameter of Population I stars. Bell and Gustafsson (1980) demonstrated with model atmosphere calculations that the $F_V$–$(V-R)$ relation varies little with metal abundance, the Population I and M92 relations being essentially identical in the color range $0.6 \leq V-R \leq 1.1$. Calculations of $V-R$ colors with a different set of model atmospheres (Cohen, Frogel, and Persson 1978) also reveal little dependence of the $F_V$–$(V-R)$ locus on gravity or metal abundance, although their values are discordant with the Barnes-Evans-Moffett relation. For hotter Population II stars such as RR Lyraes, small but significant sensitivities to gravity and metal abundances may occur (Manduca and Bell 1981). However, for the majority of cool giants in our survey, the Barnes-Evans-Moffett relation appears to be satisfactory.

### c) *Interstellar* Mg II *Absorption*

Interstellar Mg II can create an absorption feature superposed on the stellar Mg II emission core if sufficient Mg II exists along the line of sight at a velocity coinciding with the stellar emission profile (Böhm-Vitense 1981). Depending on its strength, an interstellar absorption feature can change the appearance of the line profile and somewhat reduce the observed stellar line flux.

The majority of the metal-deficient stars in this survey have radial velocities sufficiently high ($\geq |90|$ km s$^{-1}$) that an inter-

TABLE 3

Mg II FLUXES FROM METAL-DEFICIENT FIELD GIANTS

| STAR | Mg II OBSERVED FLUX[a] | | | QUALITY | $\phi$[b] | $F_*$[c] | $F_*/F_\odot$[d] |
|---|---|---|---|---|---|---|---|
| | λ2802 | λ2795 | Total | | | | |
| HD 6268 .............. | 0.63 | 0.62 | 1.2 | C | 0.481 | 11. | 0.087 |
| HD 6833: | 2.3 | 3.2 | 5.5 | A | 1.060 | 12. | 0.093 |
| (LWP 4486) ........ | 2.6 | 2.7 | 5.3 | A | 1.060 | 11. | 0.089 |
| (LWP 3792) ........ | ... | ... | 7.8 | A | 1.060 | 16. | 0.13 |
| (LWP 3793) ........ | ... | ... | 8.6 | A | 1.060 | 18. | 0.15 |
| (LWP 3794) ........ | ... | ... | <0.60 | A | 0.288 | <14. | <0.12 |
| BD −18°271[e] ...... | ... | ... | (>0.16) | A | 0.288 | (>3.9) | (>0.03) |
| | ... | ... | <1.8 | B | 0.654 | <14.5 | <0.12 |
| HD 84903[f] ........... | ... | ... | 1.2 | B | 0.642 | 5.9 | 0.047 |
| HD 110281 ............ | | | | | | | |
| HD 122563: ........... | ... | 1.8 | ... | | ... | ... | ... |
| (LWR 4356)[g] ....... | 1.3 | 1.4 | 2.7 | B | 1.086 | 3.9 | 0.031 |
| (LWR 5314) ........ | 1.1 | 1.8 | 2.9 | B | 1.086 | 4.2 | 0.033 |
| (LWP 7677) ........ | ... | ... | <0.53 | C | 0.318 | <11. | <0.090 |
| HD 135148[h] ........... | 0.38 | 0.61 | 0.99 | C | 1.044 | 6.3 | 0.050 |
| HD 165195 ............ | ... | ... | <3.00 | A | 0.605 | <20. | <0.17 |
| HD 184711[e] ........... | ... | ... | (>0.94) | A | 0.605 | (>6.5) | (>0.054) |
| HDE 232078 .......... | ... | ... | 0.87 | C | 1.190 | 4.3 | 0.034 |

[a] Units of $10^{-13}$ ergs cm$^{-2}$ s$^{-1}$. High-dispersion spectra were used to obtain the flux at λ2802 and λ2795 separately from orders 82 and 83, respectively. The quality of the flux measurement is indicated by its uncertainty A, B, or C, where A ≤ ±20%, B ≤ 30%, C ≤ 50%.

[b] Stellar angular diameter (in units of $10^{-3}$ arcsec) from the Barnes, Evans, and Moffett 1978 relation.

[c] Stellar surface flux (in units of $10^4$ ergs cm$^{-2}$ s$^{-1}$) where $F_* = F_{obs}(d/R_*)^2 = F_{obs} \times 1.702 \times 10^{17}/\phi^2$. $F_*$ has been corrected for reddening where $A_{\lambda 2800} = 6.1\ E(B-V)$ from Seaton 1979. Reddenings are listed in Table 2.

[d] Solar flux in Mg II lines taken as $1.25 \times 10^6$ ergs cm$^{-2}$ s$^{-1}$.

[e] Upper limit derived by integration over line with no continuum subtracted. Lower limit (in parentheses) obtained by removing the local continuum.

[f] Absorption line present at low dispersion. Upper limit was derived by integrating over core of absorption feature. Spectrum illustrated in Spite, Caloi, and Spite 1981.

[g] The λ2802 transition in the LSR 4356 image was extremely noisy and weak, so its flux was not included.

[h] Mg II feature lies approximately at the level of the continuum, so only an upper limit could be obtained.

stellar Mg II feature will not modify the emission profile. (As an example, the profile of the Mg II *k* line in HD 6833 has a half-width of 85 km s$^{-1}$ at the base of the emission, so that a star with radial velocity in excess of this value should not be affected). Three stars, however, have the potential for velocity coincidences with interstellar material because their radial velocities are low: HD 6268 (40 km s$^{-1}$); HD 122563 (−26 km s$^{-1}$); and HD 165195 (−0.2 km s$^{-1}$). We can estimate the velocity where a feature from the local interstellar medium might occur, based on models (Crutcher 1982) that have been used to identify absorption features in the Mg II profiles of nearby giant stars (Molaro, Vladilo, and Beckman 1986). These local interstellar features might exist at the following velocities with respect to the stellar profile: −34 km s$^{-1}$ (HD 6268); 12 km s$^{-1}$ (HD 122563); −27 km s$^{-1}$ (HD 165195). In addition, there could be nonlocal components.

To predict the strength of the interstellar Mg II lines as a function of $E(B-V)$, we rely on surveys of these transitions in the spectra of hot stars (de Boer *et al.* 1986) and cool stars (Böhm-Vitense 1981; Molaro, Vladilo, and Beckman 1986). The data presented in these papers demonstrate that the equivalent width of the interstellar Mg II *k* line (λ2795) generally increases with increasing value of $E(B-V)$ (or distance), but variation in equivalent width of a factor of 3 or 4 at any one value of the color excess or distance occurs frequently.

Among the three stars with potential interstellar contamination, HD 165195 has the highest value of $E(B-V)$, namely 0.25 ± 0.05 (Wallerstein *et al.* 1963). The deBoer *et al.* (1986) results suggest that a value of 300 mÅ for the equivalent width of the interstellar Mg II line at λ2795 would not be unreasonable. To evaluate the effect of such an absorption on the measured *k*-line flux, we consider the profile in HD 6833 which is unaffected by interstellar magnesium absorption because of the stellar radial velocity of −245 km s$^{-1}$. If we assume that a 300 mÅ absorption feature were to occur on the short-wavelength side of the line, we can evaluate the amount by which observed flux is lowered. This procedure reduces the observed flux in HD 6833 by ~25% and suggests that if a similar line were present in the HD 165195 spectrum, the intrinsic stellar flux should be ~25% higher. Because the color excesses of the other stars, HD 6268 and HD 122563, are vanishingly small, 0.03 and 0.00, respectively, and the stars are at high galactic latitudes (−87°.3 and +65°.8, respectively; Bond 1980), we believe that the change in the stellar flux would be less than 25%. There is no systematic difference between the derived fluxes for the high- and low-velocity stars with similar color excesses, and this fact also suggests that interstellar Mg II absorption does not affect the fluxes in a substantive way.

The profile of the Mg II *h* line for HD 165195 shows long-wavelength emission extending ~0.8 Å from line center as defined by the photospheric rest wavelength (see Fig. 2). An interstellar absorption feature could contribute to the asymmetry of the line, but an exceptionally strong line is required (~800 mÅ) which must be precisely located in velocity to

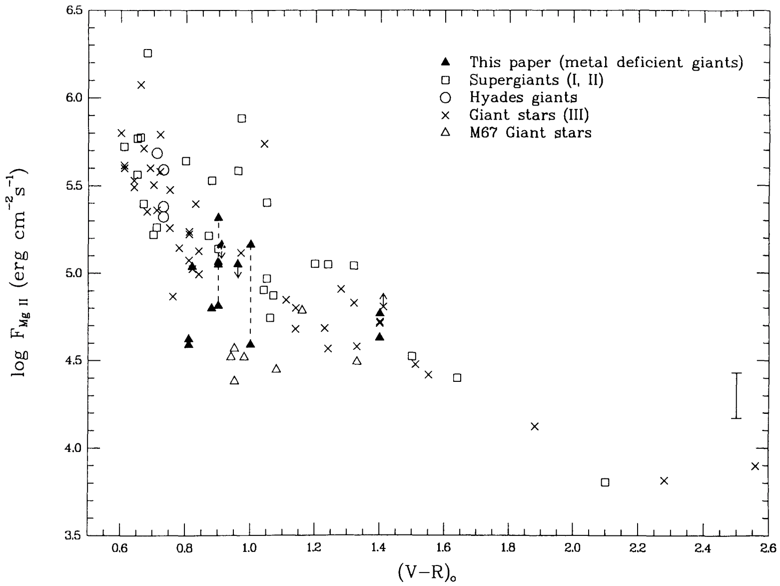


FIG. 4.—The Mg II surface flux for the sample of metal deficient giants as compared to other luminous stars. Values of the stellar fluxes are given in Tables 3, 4, 5, and 6, where the reduction procedures are noted. Upper and lower limits for the same star are joined by a broken line. For comparison, the solar flux (ergs cm$^{-2}$ s$^{-1}$) in Mg II has a typical value of 6.1 dex. An error bar corresponding to $\pm 30\%$ of the Mg II flux is shown.

eliminate any sign of emission. A more attractive explanation is the weakening of the short-wavelength side of the line due to the outward expansion of the atmosphere.

## III. DISCUSSION

### *a) The Surface Fluxes*

The Mg II surface fluxes for the metal-deficient giants are shown in Figure 4 as a function of $(V-R)_0$ as compared to the fluxes of other luminous stars. Values of the Mg II fluxes for a sample of comparison stars are given in Tables 4, 5, and 6. Surface fluxes have been calculated from published observed Mg II fluxes in a uniform fashion. The procedures are discussed in the footnotes to the tables. It is likely that no unique relationship exists between chromospheric flux and effective temperature for red giants due to variations in magnetic activity (either long- or short-term) and other physical parameters such as age and rotation. Particularly critical is the fact that stars in many different stages of evolution occupy the giant region of the color-magnitude diagram. Additional uncertainties in the derived fluxes exist which are due to reddening and calibration. For all these reasons, there is a scatter of surface fluxes, amounting to a factor of $\sim 10$ for stars of a given color. This far exceeds the uncertainty in the flux measurements themselves. In § III*d*, we examine aspects of the flux dependence for giants of known ages. Overall, however, there is a general decrease in the surface flux of Mg II toward cooler giants, which may be due in part to increasing stellar radius (for a constant energy input) or simply a decay of the chromospheric heating mechanism as the rotation period of the star increases with lower effective temperature. There is no sign of an abrupt decrease in flux at any color. For the specific case of the M67 giants, although the predicted stellar radii vary by a factor of $\sim 3$ among the sample, the surface flux remains approximately constant (Smith and Janes 1988).

It is striking that surface fluxes of the metal-deficient sample are comparable to the fluxes found in giants with near-solar abundances. To a first approximation, the Mg II surface fluxes among red giants of comparable color are not dependent on age or metal abundance. In absolute terms, however, the Mg II surface fluxes of all giant stars, including the metal-poor halo giants and the M67 giants, the latter of which are of solar-like age, are less than that of the Sun (see Fig. 4 and Tables 3 and 5). Radiative transfer calculations have shown that the lines of Mg II are effectively optically thin in cool giant stars (Judge 1990), and so for the purposes of this discussion, we assume that all the photons created in the line emerge from the star.

The level of the Mg II flux from a star depends on several factors: the abundance of magnesium, the structure of the atmosphere, and the structure of the interior, since that is likely to affect the atmospheric heating processes. Although the magnesium abundance in field halo giants as a group is enhanced by 0.3–0.5 dex over iron (Luck and Bond 1985; Carney 1988; Gratton and Sneden 1988), Mg is still depleted by factors of 10–100 with respect to its solar value over a range of [Fe/H] depletions of $-1.3$ dex to $-2.4$ dex. There is no systematic dependence of the Mg/Fe ratio on the [Fe/H] abundance (Spite and Spite 1985; Gratton and Sneden 1988). Since the surface fluxes of Mg II from the halo stars do not show a large discrepancy with respect to Population I stars, the halo stars must compensate in some way to produce comparable surface fluxes. Simply considering the magnesium abundance alone will require a factor of 10–100 enhancement in the Mg II emission rate over giants with solar abundances.

There are several ways this could happen. The atmosphere could include more high-temperature material, resulting in additional Mg II emission. The Mg II emission is produced at temperatures $\sim$6000–8000 K (see Fig. 2 in Dupree 1986), and a small increase in temperature would substantially affect the Boltzmann factor for the excitation of the line. It is plausible that these atmospheres are warmer than in stars with solar metal abundances due to the lower cooling rates forced by the low metal abundance. If the chromospheric heating processes are not metal dependent, the metal-deficient atmospheres might be warmer than those in stars with solar metals, leading to increased emission produced by ions at high temperatures.

TABLE 4

Mg II FLUXES IN GIANT AND SUPERGIANT STARS

| Star | HD | Sp Type | V[a] | V-R[a] | $\phi$[b] | Mg II[c] Obs. | $F_*$[d] | Notes |
|---|---|---|---|---|---|---|---|---|
| β Aqr | 204867 | G0 Ib | 2.87 | 0.61 | 3.11 | 3.00 E-11 | 5.28 E+5 | f |
| α Aqr | 209750 | G2 Ib | 2.93 | 0.66 | 3.44 | 4.15 E-11 | 5.97 E+5 | f |
| β Dra | 159181 | G2 Ib-IIa | 2.78 | 0.68 | 3.87 | 1.58 E-10 | 1.80 E+6 | g |
| ξ Pup | 63700 | G3 Ib | 3.35 | 0.88 | 4.49 | 4.0 E-11 | 3.38 E+5 | e |
| 9 Peg | 206859 | G5 Ib | 4.31 | 0.80 | 2.57 | 1.70 E-11 | 4.38 E+5 | g |
| ε Gem | 48329 | G8 Ib | 2.98 | 0.96 | 6.00 | 8.12 E-11 | 3.84 E+5 | g |
| 56 Peg | 218356 | K0 Ibp | 4.77 | 0.97 | 2.67 | 3.2 E-11 | 7.64 E+5 | e |
| ε Peg | 206778 | K2 Ib | 2.39 | 1.05 | 8.98 | 1.2 E-10 | 2.53 E+5 | e |
| λ Vel | 78647 | K5 Ib | 2.21 | 1.24 | 12.91 | 1.1 E-10 | 1.12 E+5 | g |
| ξ Cyg | 200905 | K5 Ib | 3.70 | 1.20 | 6.13 | 2.5 E-11 | 1.13 E+5 | e |
| σ CMa | 52877 | K7v Ib | 3.43 | 1.32 | 8.28 | 4.4 E-11: | 1.1 E+5 | e |
| α Ori | 39801 | M2 Iab | 0.37 | 1.64 | 54.3 | 4.3 E-10 | 2.5 E+4 | h |
| ε Leo | 84441 | G1 II | 2.98 | 0.65 | 3.27 | 3.7 E-11 | 5.89 E+5 | e |
| β Lep | 36079 | G5 II | 2.84 | 0.65 | 3.49 | 2.62 E-11 | 3.66 E+5 | g |
| δ Col | 44762 | G7 II | 3.85 | 0.67 | 2.31 | 1.4 E-11 | 2.5 E+5 | i |
| ζ Cyg | 202109 | G8 II | 3.20 | 0.70 | 3.36 | 1.10 E-11 | 1.66 E+5 | g |
| ζ Hya | 76294 | G8 II-III | 3.10 | 0.71 | 3.61 | 1.40 E-11 | 1.83 E+5 | g |
| θ Lyr | 180809 | K0 II | 4.37 | 0.87 | 2.77 | 7.40 E-12 | 1.64 E+5 | g |
| α Hya | 81797 | K2 II | 1.97 | 1.04 | 10.7 | 5.40 E-11 | 8.02 E+4 | e |
| γ Aql | 186791 | K3 II | 2.72 | 1.07 | 8.0 | 1.4 E-11 | 7.45 E+4 | j |
| ι Aur | 31398 | K3 II | 2.69 | 1.06 | 7.9 | 1.0 E-11 | 5.54 E+4 | j |
| θ Her | 163770 | K3 II | 3.87 | 0.90 | 3.7 | 5.6 E-12 | 1.38 E+5 | j |
| α TrA | 150798 | K4 II | 1.9 | 1.05 | 11.5 | 3.6 E-11 | 9.29 E+4 | j |
| β Peg | 217906 | M2 IIb | 2.42 | 1.50 | 17.2 | 5.8 E-11: | 3.34 E+4: | e |
| α Her | 156014 | M5 II | 3.06 | 2.1: | 31.0 | 3.6 E-11: | 6.4 E+3: | e |
| ε Hya | 74874 | G0 III | 3.38 | 0.60 | 2.40 | 2.14 E-11 | 6.32 E+5 | f |
| o UMa | 71369 | G5 III | 3.36 | 0.69 | 3.04 | 2.2 E-11 | 4.0 E+5 | i |
| μ Vel | 93497 | G5 III | 2.69 | 0.66 | 3.84 | 1.03 E-10 | 1.19 E+6 | g |
| η Psc | 9270 | G7 IIIa | 3.62 | 0.72 | 2.90 | 1.9 E-11 | 3.8 E+5 | i |
| β Crv | 109379 | G7 IIIa | 2.64 | 0.61 | 3.46 | 2.91 E-11 | 4.14 E+5 | g |
| β Her | 148856 | G7 IIIa | 2.77 | 0.64 | 3.51 | 2.26 E-11 | 3.12 E+5 | g |
| ι Cnc | 74739 | G7.5 IIIa | 4.02 | 0.75 | 2.61 | 1.2 E-11 | 3.0 E+5 | i |
| δ Crt | 98430 | G8 III-IV | 3.56 | 0.83 | 3.79 | 2.1 E-11 | 2.5 E+5 | i |
| η Dra | 148387 | G8 III | 2.74 | 0.61 | 3.30 | 2.56 E-11 | 4.00 E+5 | g |
| μ Peg | 216131 | G8 III | 3.48 | 0.68 | 2.81 | 1.05 E-11 | 2.26 E+5 | g |
| ε Vir | 113226 | G8 IIIb | 2.84 | 0.64 | 3.40 | 2.31 E-11 | 3.40 E+5 | g |
| η Her | 150997 | G8 IIIb | 3.50 | 0.67 | 2.71 | 2.23 E-11 | 5.17 E+5 | g |
| δ Dra | 180711 | G9 III | 3.07 | 0.70 | 3.57 | 2.4 E-11 | 3.2 E+5 | i |
| ε Tau | 28305 | G9.5 III | 3.54 | 0.73 | 3.10 | 1.19 E-11 | 2.11 E+5 | Hyades, k |
| α Phe | 2261 | K0 III | 2.40 | 0.81 | 6.28 | 4.00 E-11 | 1.73 E+5 | g |
| δ Tau | 27697 | K0 III | 3.76 | 0.73 | 2.80 | 1.11 E-11 | 2.41 E+5 | Hyades, k |
| α Cas | 3712 | K0 IIIa | 2.23 | 0.78 | 6.44 | 3.40 E-11 | 1.40 E+5 | g |
| ν Oph | 163917 | K0 IIIa | 3.34 | 0.71 | 3.23 | 1.4 E-11 | 2.3 E+5 | i |
| α UMa | 95689 | K0 IIIa | 1.79 | 0.81 | 8.31 | 6.80 E-11 | 1.68 E+5 | g |
| θ Cen | 123139 | K0 IIIb | 2.06 | 0.76 | 6.62 | 1.90 E-11 | 7.38 E+4 | g |
| θ'Tau | 28307 | K0 IIIb | 3.83 | 0.71 | 2.58 | 1.90 E-11 | 4.86 E+5 | Hyades, k |
| β Gem | 62509 | K0 IIIb | 1.14 | 0.75 | 9.86 | 1.04 E-10 | 1.82 E+5 | k |
| γ Tau | 27371 | K0- IIIab | 3.65 | 0.73 | 2.95 | 2.00 E-11 | 3.91 E+5 | Hyades, k |
| β Cet | 4128 | K1 III | 2.02 | 0.72 | 6.09 | 1.35 E-10 | 6.20 E+5 | g |
| α Boo | 124897 | K1+ IIIb | -0.05 | 0.97 | 24.56 | 4.66 E-10 | 1.31 E+5 | g |
| β Oph | 161096 | K2 III | 2.77 | 0.82 | 5.37 | 1.80 E-11 | 1.06 E+5 | g |
| κ Oph | 153210 | K2 III | 3.20 | 0.84 | 4.54 | 1.20 E-11 | 9.91 E+4 | g |
| α Ari | 12929 | K2 IIIab-b | 2.00 | 0.84 | 7.89 | 4.90 E-11 | 1.34 E+5 | g |
| α Ser | 140573 | K2 IIIb | 2.64 | 0.81 | 5.62 | 2.21 E-11 | 1.19 E+5 | g |
| α Tuc | 211416 | K3 III | 2.85 | 1.04: | 7.16 | 1.65 E-10 | 5.48 E+5 | g |
| β UMi | 131873 | K4 III | 2.08 | 1.11 | 11.32 | 5.30 E-11 | 7.04 E+4 | g |
| γ Dra | 164058 | K5 III | 2.22 | 1.14 | 11.09 | 3.47 E-11 | 4.80 E+4 | g |
| α Tau | 29139 | K5 III | 0.86 | 1.23 | 23.69 | 1.60 E-10 | 4.85 E+4 | g |
| β And | 6860 | M0 III | 2.05 | 1.24 | 13.90 | 4.20 E-11 | 3.70 E+4 | f |

[a] From Johnson *et al.* 1966.

[b] Stellar angular diameter in units of $10^{-3}$ arcsec. Obtained from $V$, $V-R$ (here generally assumed unreddened), and Barnes-Evans-Moffett relationship (1978).

[c] Units of ergs $cm^{-2}$ $s^{-1}$ in Mg *h* and *k* emission cores.

[d] Units of ergs $cm^{-2}$ $s^{-1}$ from stellar surface.

[e] Stencel *et al.* 1980.

[f] Hartmann, Dupree, and Raymond 1982.

[g] Simon, Linsky, and Stencel 1982.

[h] Dupree *et al.* 1987. The Mg II line in α Ori is variable with a total amplitude of about a factor of 2.

[i] Simon and Drake (1989) kindly provided observed fluxes in advance of publication.

[j] Hartmann *et al.* 1985. Observed flux in the Mg II *h* line only. Flux at stellar surface in Mg *h* has been multiplied by a factor of 2 in order to approximate the contribution of the Mg II *k* line in the Mg II doublet.

[k] Baliunas, Hartmann, and Dupree 1983.

TABLE 5

Mg II FLUX FROM M67 GIANT STARS

| Star | $V^a$ | $(V-R)_{KC}$[a] | $(V-R)_{J,0}$[b] | $\phi$[c] | Mg II[d] Observed | $F'$[e] | $F_*$[f] | $R_*$[g] |
|---|---|---|---|---|---|---|---|---|
| S-1553 ......... | 8.74 | 0.97 | 1.33 | 0.795 | 8.5 E-14 | 2.3 E4 | 3.1 E4 | 55 |
| IV-202 ......... | 8.86 | 0.85 | 1.16 | 0.583 | 8.5 E-14 | 4.3 E4 | 5.8 E4 | 46 |
| T-626 .......... | 9.37 | 0.79 | 1.08 | 0.412 | 1.7 E-14 | 1.7 E4 | 2.3 E4 | 31 |
| T-829 .......... | 9.53 | 0.70 | 0.95 | 0.317 | 1.6 E-14 | 2.7 E4 | 3.7 E4 | 24 |
| F-170 .......... | 9.69 | 0.70 | 0.95 | 0.295 | 9.0 E-15 | 1.8 E4 | 2.4 E4 | 22 |
| F-108 .......... | 9.72 | 0.72 | 0.98 | 0.301 | 1.2 E-14 | 2.3 E4 | 3.1 E4 | 22 |
| T-856 .......... | 9.84 | 0.69 | 0.94 | 0.268 | 1.3 E-14 | 3.1 E4 | 4.2 E4 | 20 |

[a] Janes and Smith 1984; $V-R$ colors on Kron-Cousins system.

[b] Unreddened colors on Johnson system. $V-R$ values observed on Kron-Cousins system were dereddened assuming $E(V-R)/E(B-V) = 0.69$ for K5 giant stars (Janes 1988), $E(B-V) = 0.056$ for M67 (Janes and Smith 1984), and the transformation between Kron-Cousins and Johnson $V-R$ colors was made using the equation proposed by Cousins (1976), viz.: $(V-R)_J = 1.40\,(V-R)_{KC} + 0.028$ for $(V-R)_{KC} < 1.0$.

[c] Angular diameter in units of $10^{-3}$ arcsec obtained from Barnes-Evans-Moffett relation (Barnes, Evans, and Moffett 1978).

[d] Observed at Earth; Units of ergs cm$^{-2}$ s$^{-1}$. From Smith and Janes 1988.

[e] Units of ergs cm$^{-2}$ s$^{-1}$ from stellar surface (no correction for reddening).

[f] Mg II stellar surface flux (ergs cm$^{-2}$ s$^{-1}$) corrected for reddening by assuming $A_{\lambda 2800} = 6.1\ E(B-V)$ from Seaton (1979), where $E(B-V) = 0.056$ (Janes and Smith 1984).

[g] In solar units ($R_{\odot}$). From Smith and Janes 1988.

With this hypothesis, the chromospheric heating rates among the metal-deficient giants need not necessarily be substantially higher than among Population I giants.

There are other ways in which the chromosphere could compensate for the abundance disparity. If the chromosphere is of higher density, or thicker, or both, a stronger line will result. It is well known that Hα profiles in metal-deficient giants differ from those in metal-rich stars by frequently exhibiting emission wings (Cohen 1976; Smith and Dupree 1988). This emission can be straightforwardly produced by increasing the amount of material at the temperature of formation of the Hα wings. Semiempirical atmospheric models for metal-deficient field giants (Dupree, Hartmann, and Avrett 1984) reproduce the Hα line profiles and predict Mg fluxes that are much stronger than observed here. Despite the overestimate of the Mg II emission flux by these models, they nonetheless demonstrate that it is reasonable to postulate a chromospheric origin for both the Hα and Mg II emissions.

### b) *The Line Profiles*

The profiles of the Mg II *k* emission core in three of the four giants for which high-dispersion spectra are available are similar in their asymmetry: the short-wavelength peak is weaker than the long-wavelength peak. (The spectra in Fig. 2 include the *h* line as recorded on Order 83 of the *IUE* LWP spectrograph where it frequently appears stronger than in Order 82. However, uncertainties in the blaze correction make the line profile less reliable.) The spectrum of the fourth star, HD 6268, is noisy, making it hard to define the relative strength of the components of the emission core. A part of the

TABLE 6

Mg II FLUXES FROM COOL GIANT STARS

| Star | HD | Spectral Type[a] | $V$ | $E_{V-K}$[a] | $(V-K)_0$[b] | $(V-R)_0$[c] | Mg II[d] Observed | $\phi$[e] | $F'$[f] | $F_*$[g] |
|---|---|---|---|---|---|---|---|---|---|---|
| 87 Leo ......... | 99998 | K4.5 III | 4.76 | 0. | 3.57 | 1.14 | 5.1 E-12 | 3.71 | 6.31 E4 | 6.31 E4 |
| 74 Gem ........ | 61338 | M0.0 III | 5.05 | 0. | 3.87 | 1.28 | 4.20 E-12 | 2.97 | 8.10 E4 | 8.10 E4 |
| | 29051 | M1.1 III | 7.1 | 1.18 | 3.94 | 1.32 | 3.4 E-13 | 3.01 | 6.39 E3 | 6.75 E4 |
| π Leo .......... | 86663 | M1.7 III | 4.70 | 0. | 4.11 | 1.40 | 5.70 E-12 | 4.88 | 4.07 E4 | 5.28 E4 |
| λ Aqr .......... | 216386 | M2.0 III | 3.79 | 0.36 | 4.06 | 1.40 | 1.00 E-11 | 8.21 | 2.52 E4 | 5.17 E4 |
| 82 Vir .......... | 119149 | M2.1 III | 5.01 | 0. | 3.98 | 1.33 | 4.20 E-12 | 4.34 | 3.80 E4 | 3.80 E4 |
| υ Cap .......... | 196777 | M2.1 III | 5.17 | 0.26 | 4.04 | 1.41 | >5.00 E-12 | 4.72 | >3.82 E4 | >6.42 E4 |
| WW Psc ....... | 5820 | M2.4 III | 6.11 | 0. | 4.54 | 1.55 | 1.54 E-12 | 3.16 | 2.62 E4 | 2.62 E4 |
| ψ Vir ........... | 112142 | M2.7 III | 4.80 | 0.26 | 4.32 | 1.51 | 3.60 E-12 | 5.85 | 1.79 E4 | 3.01 E4 |
| XZ Psc ........ | 224062 | M4.6 III | 5.61 | 0. | 5.49 | 1.88 | 3.12 E-12 | 6.30 | 1.33 E4 | 1.33 E4 |
| | 172816 | M5.2 III | 6.27 | 0.49 | 6.08 | 2.28 | 1.18 E-12 | 9.03 | 2.46 E3 | 6.55 E3 |
| RZ Ari ......... | 18191 | M5.9 III | 5.91 | 0. | 6.65 | 2.56 | 4.8 E-12 | 10.2 | 7.91 E3 | 7.91 E3 |

[a] Ridgway *et al.* 1980. When the difference between observed $V-K$ and Johnson's 1966 values of $V-K$ for the star's spectral type exceeded 0.2 mag, it was set equal to $E(V-K)$. Otherwise $E(V-K) = 0$.

[b] $(V-K)_{\rm observed}$ tabulated by Steiman-Cameron, Johnson, and Honeycutt 1985; the tabulated values were corrected by $E_{V-K}$ to obtain $(V-K)_0$.

[c] Measured by Barnes, Evans and Moffett 1978, or taken from relation between $(V-K)_0$ and $(V-R)_0$ tabulated by Johnson 1966.

[d] Flux in Mg II *h* and *k* lines observed with *IUE* (units of ergs cm$^{-2}$ s$^{-1}$). From Steiman-Cameron, Johnson, and Honeycutt 1985.

[e] Occultation angular diameter (Ridgway *et al.* 1980). Units of $10^{-3}$ arcsec.

[f] Stellar surface flux (ergs cm$^{-2}$ s$^{-1}$) in Mg II *h* and *k* lines with no correction for reddening. $F' = 1.702 \times 10^{17}\ F_{\rm obs}/\phi^2$.

[g] Unreddened stellar surface flux (units of ergs cm$^{-2}$ s$^{-1}$) using the relations $E_{B-V} = 0.355\ E_{V-K}$, $A_{\lambda 2800} = 6.1\ E_{B-V}$ (Seaton 1979), and thus $F_* = F'\,10^{0.868\,E_{V-K}}$.

asymmetry for HD 165195 might be attributed to interstellar absorption, since the radial velocity of the star ($-0.2$ km s$^{-1}$; Bond 1980) coincides with that characteristic of the interstellar medium. It would be fortuitous indeed for interstellar absorption to eliminate the short-wavelength side of the line because an exceptionally strong line ($\sim 800$ mÅ) is required which must be precisely located in velocity in order to eliminate any sign of emission. However, for HD 122563 and HD 6833 with radial velocities of $-26$ km s$^{-1}$ and $-245$ km s$^{-1}$, respectively, interstellar absorption would become evident on the long-wavelength wing (or lie entirely beyond the stellar line). Thus, there is intrinsic stellar asymmetry to the profiles indicative of a differentially expanding atmosphere. Mass loss most probably occurs in these stars, although the spectra do not give direct evidence for mass loss, since no absorption feature with velocity comparable to the escape velocity is found. The Mg II asymmetries in these metal-deficient stars are consistent with asymmetric Mg II line profiles observed in luminous Population I stars of similar colors (Stencel and Mullan 1980*b*).

The H$\alpha$ line has been surveyed among the metal-deficient giants by Smith and Dupree (1988), and the core is found to show a blue asymmetry for two of the stars in our sample: HD 165195 and HD 122563. However, the H$\alpha$ core is symmetric for HD 6833, which at $M_V = -0.9$ is significantly fainter than the two other stars, and it lies below the visual magnitude where core H$\alpha$ asymmetries generally are found (Smith and Dupree 1988). By contrast, the Mg II profile for HD 6833 is asymmetric. This observation illustrates the utility of the Mg II line as a sensitive probe of atmospheric mass motions. Due to its high opacity, the profile can be modified by the outermost parts of an atmosphere. Mg II can mark the presence of a stellar wind before motions are detectable in the deep chromosphere of a star as signaled by the H$\alpha$ profile.

The width of the Mg II emission core may be sensitive to the absolute visual magnitude of a star, much like Ca II K emission (Wilson 1976; Weiler and Oegerle 1979; Stencel and Mullan 1980*a*). The core emission in the high-resolution spectrum of HD 6833 shows a full width of 1.52 Å measured at the base of the Mg II line, a value that implies $M_V(k) = 1.42$ using the relationship between Mg II line width and absolute magnitude derived by Weiler and Oegerle (1979). This magnitude is substantially fainter than the value of $-0.9$ inferred from comparing the Strömgren colors of the star to the giant branch of a globular cluster with similar metallicity (Bond 1980). Because of the high radial velocity of HD 6833, $-245$ km s$^{-1}$, the profile should not be affected by interstellar Mg II absorption. Ayres (1979) conjectures that the base width of the Mg II emission should be proportional to abundance as ${A_{\rm Fe}}^{0.25}$; however, this scaling predicts a line width that is even more narrow, corresponding to about one-half the width that is observed.

A preferred explanation of the narrow emission core results from the effects of opacity in the stellar wind. The wind and circumstellar material can obscure part of the blue wing of the Mg II emission and cause the line profile to appear more narrow. An upper limit to the line width can be obtained by measuring the width from the wavelength corresponding to the stellar photospheric velocity to the long-wavelength extent of the profile and doubling that measurement. The value of 2.29 Å or 245 km s$^{-1}$ found in that way leads to a prediction of $M_V = -1.3$ as an upper limit to the magnitude using the Weiler and Oegerle (1979) relation; this upper limit is not inconsistent with Bond's (1980) determination of $M_V = -0.9$. The maximum wind velocity required, $\sim 120$ km s$^{-1}$, is in harmony with that found for luminous cool giants (Hartmann *et al.* 1985) and confirms that wind opacity may be important in modifying the observed line profile.

The question of a metallicity dependence of the absolute-magnitude calibration has been addressed for the Ca II (K) transition (Wilson 1970; Wilson, Olsen, and Kjaergaard 1972; Pagel 1972) and vigorously debated. It is interesting that four of our metal-deficient field giants (HD 6833, HD 122563, HD 165195, and HD 221170) were measured in the Ca K line by Wilson (1976), who derived absolute magnitudes, $M_V$(K), that are systematically fainter by values ranging from 1.7–3.1 mag than the Bond (1980) determination. However, there is scatter in the determination of the relationship itself, leading Wilson (1976) to argue that the line width is independent of metallicity. It will also be difficult to determine the intrinsic width of the chromospheric lines in luminous stars because of the effects of absorption in a stellar wind. Study of Mg II lines with *IUE* has revealed subtle variable features on the short-wavelength side of the profiles of giant stars (see Hartmann *et al.* 1985) that result from variations in the opacity of the wind. For one star, $\alpha$ TrA, the width determined from a high-quality *IUE* profile exceeds the width obtained from the *Copernicus* profile by a factor of 1.8; this factor corresponds to a difference of $\sim 4$ mag in the predicted absolute magnitude.

We can make a rough estimate of the mass-loss rate required to provide the observed asymmetry in the Mg II resonanace line profiles of HD 6833. The Sobolev optical depth for a linear velocity law is (Castor 1970):

$$\tau_s \sim \frac{\pi e^2}{mc} \lambda_0 f N_{\rm Mg} \frac{R}{V} ,$$

where we have taken the stellar radius as the characteristic length. Substituting for $N_{\rm Mg}$ into the mass-loss rate, $\dot{M} = 4\pi R^2 N_{\rm H} \mu_{\rm H} V$, where $N_{\rm Mg} = N_{\rm H} A$, we find

$$\dot{M} \sim 4.5 \times 10^{-11} \tau_s \left(\frac{R}{30 R_\odot}\right)\left(\frac{V}{50 \text{ km s}^{-1}}\right)^2 \times \left(\frac{A}{10^{-1.6}}\right)^{-1} M_\odot \text{ yr}^{-1} ,$$

where we have taken the characteristic radius of the star as $30 R_\odot$ and the velocity shift to be about 50 km s$^{-1}$ to explain the asymmetry, and we have assumed that the magnesium abundance, $A$, is depleted to the same level relative to hydrogen as is iron. For these values, and $\tau_s = 1$, the derived mass-loss rate of $4.5 \times 10^{-11}$ $M_\odot$ yr$^{-1}$ is less than the value $10^{-9}$ $M_\odot$ yr$^{-1}$ used by Dupree, Hartmann, and Avrett (1984) to explain the asymmetric H$\alpha$ profiles of metal-poor giants. HD 6833 did not have an asymmetric H$\alpha$ core (Smith and Dupree 1988), and so its mass-loss rate might be expected to be less. Although this estimate is obviously crude, it suggests that the present mass loss from HD 6833 is unlikely to have important evolutionary effects. Preliminary radiative transfer calculations along the lines of Dupree, Hartmann, and Avrett (1984) also suggest that the required Mg II asymmetry can be produced with mass-loss rates lower than $10^{-9}$ $M_\odot$ yr$^{-1}$.

### c) *Variability*

The most luminous metal-deficient field giants, including HD 165195, display photometric variability (Bond 1980) and spectroscopic variability in the H$\alpha$ profile (Smith and Dupree 1988). Both the appearance and the strength of emission wings in Hα can change in less than a year. Since the presence of these emission wings depends on the density and temperature structure in the chromosphere, the Mg II emission might be expected to change also. The region of the Mg II lines (20.6 Å centered on the λ2800 feature) shows a variation of 21% from the mean as compared to smaller variations of 5% or 6% of the mean for equivalent wavelength intervals at longer and shorter wavelengths. Thus, these spectra seem to suggest that the Mg II flux is variable (at the 4 $\sigma$ level), behavior that is consistent with variability in the Hα emission wings from HD 165195. Another star, HD 6833, was observed twice at high dispersion separated by an interval of 3 months, and the total Mg II fluxes are the same to within the uncertainties. Because the shorter exposure (LWP 3792) is noisy, the profiles of the line cores are not discernibly different from those in LWP 4486 obtained 3 months later. Thus, our spectra provide no evidence for variability of the Mg II lines in HD 6833, and marginal evidence for variability in HD 165195.

### *d*) *Evolution of Chromospheres*

A subset of the sample of giant stars in Figure 4 have well-defined ages and evolutionary states: the Hyades giants, the M67 giants, and the metal-deficient field giants. A color-magnitude diagram of these objects is shown in Figure 5, and the dependence of the Mg II surface flux on luminosity and age is displayed in Figures 6 and 7. These stars, with ages from 0.7–15 Gyr, do not show substantially less Mg II emission than other Population I red giants, but because their ages are known, the Mg II measurements have significant implications for chromospheric evolution.

A critical element in this assessment is the measured flux of the seven red giants in M67 and the possibility that the fluxes are underestimated due to interstellar absorption. These cluster stars have radial velocities ranging from 33.0 to 34.7 km $s^{-1}$ (Mathieu *et al.* 1986), which suggest that interstellar absorption by Mg II might affect the line fluxes. However, the cluster reddening is low, $E(B-V) = 0.056 \pm 0.006$ (Janes and Smith 1984), consistent with its position above the galactic plane ($b^{II} = 32°$) and suggests that the equivalent width of any

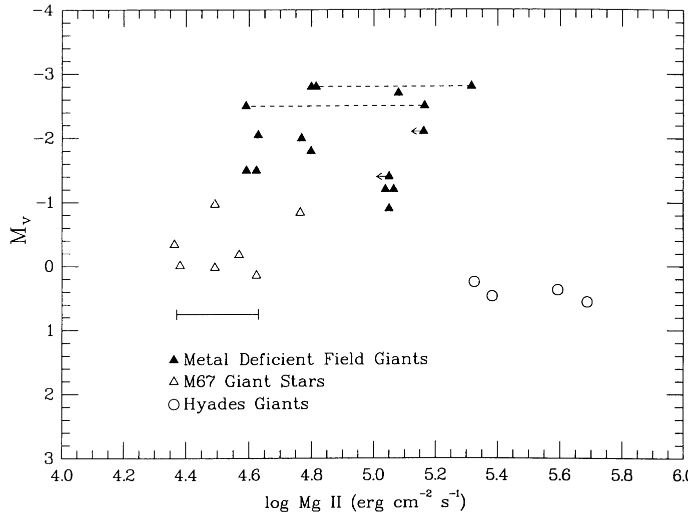


FIG. 6.—The relation between absolute visual magnitude and surface flux of the Mg II emission for stars with well-defined ages. Upper and lower limits for a single star are joined by a broken line. For the low-mass stars (M67 and metal deficient field giants), there appears to be an increasing Mg II surface flux with increasing absolute visual magnitude or evolution along the red giant branch. A typical error bar of $\pm 30\%$ of the Mg II flux is shown.

interstellar Mg line would be $\leqslant 300$ mÅ. As noted in § II*c*, the fluxes would be underestimated by less than 25%. Another test for a systematic effect of interstellar absorption on the observed fluxes derives from reddenings to the individual stars. Janes and Smith (1984) estimated $E(B-V)$ for six of the seven giants; these values range from $E(B-V) = 0.00$–$0.14$. There is no systematic dependence of the surface flux of the M67 giants with $E(B-V)$ value, reaffirming our conclusion that the effect of interstellar magnesium absorption does not significantly affect the fluxes.

It is useful to compare the results with the predictions of previous studies. To illustrate, we consider the "expected" behavior based on earlier studies of Population I stars. On the main sequence, chromospheric activity declines with age.

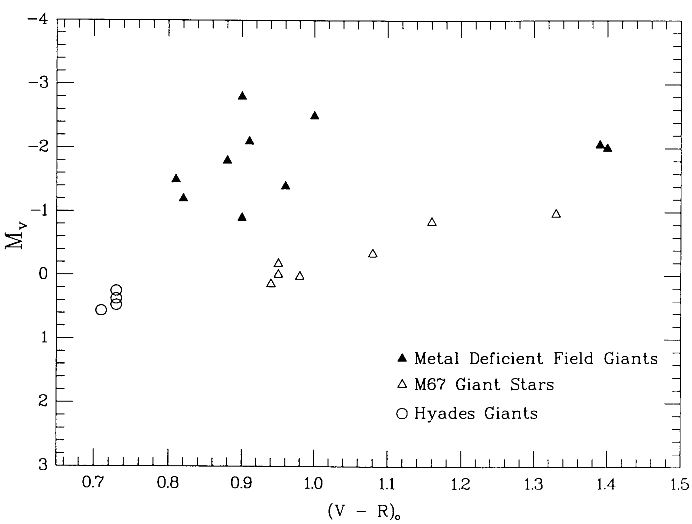


FIG. 5.—A color-magnitude diagram showing the position of cluster giants (Hyades and M67) with measured Mg II fluxes. The Hyades giants are the youngest (0.7 Gyr), with masses in the range 2.5–3 $M_{\odot}$. The other stars have lower mass $\leq 1$ $M_{\odot}$, with ages ranging from 5 Gyr (M67) to $\sim 15$ Gyr (metal-deficient field giants).

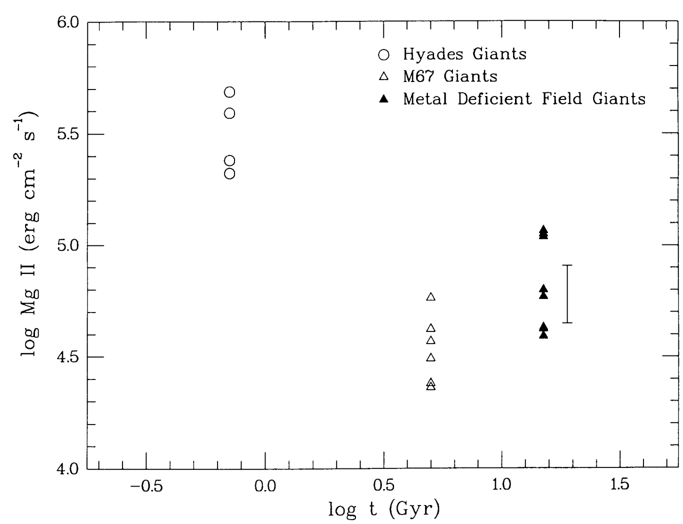


FIG. 7.—The Mg II surface flux as a function of age for the three groups of giants with known ages: Hyades giants (0.7 Gyr); M67 giants (5 Gyr); metal-deficient field giant stars (15 Gyr). A typical error bar is shown, corresponding to $\pm 30\%$ of the Mg II flux.

Simon, Herbig, and Boesgaard (1985) evaluated the decay of Mg II emission among F7-G2 dwarfs (masses $\sim 1\ M_\odot$) for which Li abundances were available and could be used to determine the stellar ages. The decline in Mg II flux with time was fitted with both an exponential decay law of the form $F_{\rm Mg\,II} \sim e^{-t/3.16}$ and a power law of the form $F_{\rm Mg\,II} \sim t^{-0.49}$, where $t$ is the age (Gyr) of a main-sequence star. According to the exponential law, the main-sequence progenitors of the M67 giants (age $\sim 5$ Gyr; VandenBerg 1985) would be expected to have a Mg II level which is reduced by a factor of $\sim 4$ relative to the progenitors of the Hyades giants[2] (age $\sim 0.7$ Gyr; Patenaude 1978, Hirshfeld, McClure, and Twarog 1978), whereas the power law would predict a factor of $\sim 2.7$ difference in $F_{\rm Mg\,II}$. The observations plotted in Figure 7 are more consistent with the larger $F_{\rm Mg\,II}$ difference predicted by the exponential law. In fact, the difference between the giants in these two clusters appears to be even larger, amounting to a factor of 10 in the Mg II line and suggesting a more rapid decay (at least $\sim e^{-t/0.85}$). The differences in Mg II surface flux between the Hyades giants and M67 giants found in Figure 7 may be consistent with an extension of the rapid decay of C IV found by Simon (1984) and Simon and Drake (1989), although their observations did not extend beyond stars with $B-V \sim 1$. The C IV decay rate cannot be applied because high-temperature plasma, including transition region lines such as C II and C IV, diminish more rapidly with age than chromospheric emission such as Mg II, if the dwarf stars are a reasonable guide (Dupree 1982; Simon, Herbig, and Boesgaard 1985).

Similar considerations for an exponential decay law would predict a difference of a factor of 24 in Mg II flux between the main-sequence progenitors of the 15 Gyr halo field giants and the progenitors of the 5 Gyr M67 giants. However, the *IUE* observations for these two groups of stars reveal little difference between the Mg II fluxes. In fact, the older halo giants have stronger Mg II fluxes than the M67 giants (see Fig. 7). If interpreted in terms of the properties of the main-sequence progenitors of these giants, the observations would seem to imply a much more gradual decay in activity among main-sequence stars older than 5 Gyr than is given by the exponential law. For example, a $t^{-1/2}$ decay law would predict a factor of 1.7 difference in Mg II flux between the M67 main-sequence turnoff stars and the halo field giant progenitors which is much less inconsistent with the data available for the giants.

These considerations do not take into account any change in chromospheric activity which may occur as stars evolve off the main sequence and up the red giant branch. Studies of giants (Rutten 1984; Rutten and Pylyser 1988; Whitney 1988) have revealed a decrease in Ca II flux with increasing color through the range $B-V = 0.4$ and 1.6; similarly, Simon (1984) and Simon and Drake (1989) have noted a rapid decay in high-temperature C IV emission in giants between $B-V = 0.3$ and 1.0. The metal-deficient halo field giants and the M67 giants observed by Smith and Janes (1988) are located on the upper giant branch of the color-magnitude diagram (see Fig. 5) and are much more advanced in evolution than are dwarfs and the early spectral-type giants. To determine how chromospheric activity of the type seen among dwarfs may behave as a star evolves up the giant branch, it is useful to consider the dynamo theory.

Measurements of the Ca II and Mg II fluxes in cool dwarf stars (Noyes *et al.* 1984; Hartmann *et al.* 1984) suggest that the level of chromospheric line flux can be correlated with the Rossby number, $R_0$: the ratio of the stellar rotational period to the convective overturn time ($R_0 \equiv P_{\rm rot}/\tau_c$). The line fluxes increase with decreasing Rossby number. This derives from the idea that the dynamo mechanism producing enhanced magnetic activity and hence enhanced chromospheric emission depends on the balance between convective efficiency (loosely related to the turnover time) and the rotation of the star. The convective zone depth or its overturn time relates to the dynamo regeneration of the magnetic field. Fast rotation of the star acts to amplify the magnetic dynamo. A star evolving to higher luminosities on the giant branch would be expected to decrease in rotation rate, at least in the envelope, due to the increase in radius, assuming that angular momentum is conserved and that there is no mass loss. Consequently, dynamo activity would be expected to decrease with increasing luminosity among giants. This is illustrated by the models of Gilliland (1985), which show that for stars of 1 and 1.6 $M_\odot$, the ratio of the convective turnover time to the moment of inertia (this ratio corresponds to the inverse of the Rossby number upon assuming evolution with angular momentum conservation and solid body rotation) decreases continuously with increasing luminosity on the giant branch.[3]

The group of M67 giants with measured Mg II fluxes (Smith and Janes 1988) increases in radius by a factor of $\sim 2.5$ with increasing luminosity. Larger stellar radii that accompany increasing luminosities imply longer rotation periods for the most luminous stars. According to the magnetic dynamo theory, as incorporated in the models of Gilliland (1985), the surface fluxes of Mg II would be expected to decline with increasing luminosity, having their lowest values in the largest and most luminous giants. However, this is not observed to happen among both the M67 giants and the metal-deficient field giants. As the data in Figure 6 demonstrate, there appears to be a dependence of the Mg II surface flux on luminosity in the sense that the metal-deficient stars as a group exhibit comparable or higher surface flux than the M67 giant stars.

Consideration of the main-sequence progenitors of these stars points up another anomaly. The metal-deficient field giants would be expected to be slower rotators than the M67 giants, since their greater age suggests they have evolved from less massive, more slowly rotating stars on the main sequence. Hartmann *et al.* (1984) have demonstrated that Mg II surface fluxes are lower for those main-sequence dwarf stars with longer rotation periods. This fact suggests that the Mg II fluxes of the main-sequence progenitors of the metal-deficient field giants would be lower than the progenitors of the M67 giants. Our current understanding leads to the expectation that the Mg II fluxes would decay with evolution away from the main sequence. Yet the Mg II fluxes of the metal-deficient field giants are certainly not less than those of the M67 giants, and as a group they may even be larger (see Fig. 7).

Evolutionary models of low-mass ($M_* \leq 3\ M_\odot$) red giants for both Population I (Maeder and Meynet 1989) and Population II abundances (Demarque and Mengel 1971) show that surface convective zones exist in our sample of giant stars, and with it, the potential for magnetic dynamo activity. Both calcu-

[2] The main-sequence progenitors of the Hyades giants were more massive ($\sim 2.5\ M_\odot$; Boesgaard, Heacox, and Conti 1977) than the M67 giants, and the relationship for chromospheric decay may not be strictly applicable.

[3] Although Gilliland (1985) predicts that magnetic activity should increase in the subgiant phase for stars with masses $\sim 1$–$1.6\ M_\odot$, such an increase does not appear to be present (Simon and Drake 1989).

lations demonstrate that the mass fraction of the star which is convective generally decreases with increasing stellar luminosity for stars as luminous as the M67 giants and the metal-deficient field giants. If the amount of convective material alone were the sole determinant of the level of chromospheric activity, then the field giants would display less Mg II emission than the M67 giants, when in fact just the opposite is found.

### e) *Possible Sources of Chromospheric Emissions*

Chromospheric emission in the Hyades giants is believed to result from magnetic dynamo activity, and the level of Mg II emission conforms to other Population I field giants (see Fig. 4; Baliunas, Hartmann, and Dupree 1983; Simon and Drake 1989). Moreover, the level of the chromospheric Ca II strength in the Hyades giants and the rotational velocities of these stars are consistent with gradual angular momentum loss and a weakened magnetic dynamo (Rutten and Pylyser 1988; Whitney 1988). However, the behavior of chromospheric emission among the M67 giants and the metal-deficient field giant stars, as a function of both luminosity and age, appears to be inconsistent with that expected from a magnetic dynamo mechanism. The model of a long-term decay of magnetic dynamo activity due to the spin-down of a star as its radius increases does not apply to these evolved giant stars.

The drop in the Mg II flux from the Hyades to M67 shown in Figure 7 could represent decay of magnetic dynamo-driven activity, but the decay could also proceed much more rapidly for giants older than 0.7 Gyr. With a rapid diminution of magnetic activity, the level of the M67 emission would represent a resurgence of stellar chromospheres. Although more observations are needed to define the behavior of Mg II emission, particularly in giants with ages between the Hyades and M67, the present data suggest that a revitalization of chromospheric activity occurs at some time between ages 0.7 and 14 Gyr.

The magnetic dynamo may become more vigorous with evolution on the giant branch, by some as yet unrecognized mechanism. Or possibly the strong chromospheric emission is being produced by another process, and the magnetic dynamo has become relatively inactive and dies out in evolved giant stars. An attractive explanation for the increase in Mg II flux with age and luminosity could be a different physical mechanism from the traditional magnetic dynamo interpretation. The Mg II emission could be enhanced by pulsation among the luminous red giants, creating a *hydrodynamic* chromosphere. A pulsation instability in the photosphere could produce increased densities in the chromosphere due to the passage of compression or shock waves. This explanation is particularly appealing, since various lines of evidence such as variability of Hα line profiles and some photometric variability indicate that pulsation is altering the properties of chromospheres of the metal-deficient red giants (see discussion in Smith and Dupree 1988). Evidence also exists for period radial velocity variations in the red giant α Bootis (Smith, McMillan, and Merline 1987; Cochran 1988; Irwin *et al.* 1989) and long-term velocity variations in several K giants and a K supergiant (Walker *et al.* 1989). Periodic chromospheric variability has been detected in the supergiant α Orionis (Dupree *et al.* 1987) as well as radial velocity variations corresponding to the chromospheric period (Patten, Smith, and Goldberg 1987). Pulsation could heat and extend the atmospheres of the luminous stars and also enhance the process of mass loss.

Further spectroscopic or photometric observations could reveal whether a periodic enhancement occurs in the atmospheres of these giants. Additional ultraviolet spectroscopy, particularly of giants in globular clusters, could define the state of the chromospheres in a well-understood sample of homogeneous stars. It may be that the fundamental mechanism producing chromospheric emission in dwarf stars and young giants changes with evolution of a star along the red giant branch.

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