MAGNESIUM EMISSION VARIABILITY AMONG LATE-TYPE GIANT STARS

D. J. Mullan
Bartol Research Foundation of The Franklin Institute, University of Delaware

AND

R. E. Stencel
Joint Institute for Laboratory Astrophysics, University of Colorado, and National Bureau of Standards

Received 1981 April 27; accepted 1981 August 20

ABSTRACT

We have investigated the variability of the emission cores in the h and k lines of Mg II in a sample of 21 late-type giants. We have used high resolution line profiles obtained by IUE to determine not only the total emission intensity, but also the ratio of the intensities of the shortward and longward components of the doubly-reversed emission. We argue that variations in the total emission intensity are indicative of variations in chromospheric heating, while variations in the ratio can be interpreted in terms of variations in structures in the corona and outer atmosphere.

Subject headings: stars: chromospheres — stars: emission-line — stars: late-type — ultraviolet: spectra

I. INTRODUCTION

a) General

Most of the previous variability studies of late-type stars have used emission lines of Ca II. Wilson (1978) has obtained measurements of the total K emission intensity in dwarf stars over baselines of up to 10 years, in order to test for cyclic behavior. On shorter time scales, the total intensity of Ca K emission has been monitored by Baliunas et al. (1981) in a sample of stars containing one dwarf, one subgiant, and one giant: In the giant, intensity variations were detected at a level of a few percent. These results suggest that good photometric precision is a prerequisite for a variability study in giants as we envision here. The advantages of obtaining high spectral resolution (as well as good photometric precision) have been demonstrated in recent work by Gray (1980), who obtained high resolution line profiles of the Ca II K line in a Boo. Gray's resolution was high enough to allow him to follow the variations in the short wavelength emission peak separately from variations in the long wavelength peak. Data of a similar kind, although with lower photometric precision, had been obtained for the same star by Chiu et al. (1977), and the earlier data also showed that the short and long emission peaks do not necessarily always vary in phase with each other.

The aim of the present work is to obtain data on the Mg II h and k lines in a representative sample of late-type giants with sufficient photometric precision to detect variations in the total emission intensity, and sufficient spectral resolution to detect variations in the short and long wavelength emission peaks separately. The only star which has previously been investigated for magnesium variability is Arcturus (McClintock et al. 1978). In this star, upper limits of ±20% were set on variations in the intensity of Mg emission. We refer to the intensities of the short and long wavelength peaks as S and L respectively. (In the case of Ca II K emission, these are traditionally referred to as V and R; cf. Stencel 1978; Gray 1980.) In the present paper, we search for variations in S+L, and variations in S/L.

The S/L ratio serves as a (nonunique) diagnostic of the velocity field in the stellar atmosphere (cf. Stencel et al. 1980). Thus, S/L < 1 is consistent with a large rate of mass loss. Variations in S/L may be interpreted as evidence for variations in the velocity field.

In solar-like chromospheres, the lines which we study here are expected to be formed at somewhat higher level than the levels of formation of the Ca II H and K lines, because of differences in abundances and ionizations. In support of this expectation, we may cite the following empirical evidence. Certain stars in our sample (56 Peg, θ Cen, α Ser, ι Cet, ε Sco, 51 And, and ε Gem) have S/L asymmetries which are in the opposite sense for the Mg and Ca emission. (By the term "sense of the asymmetry," we mean whether S/L [or equivalently V/R] exceeds unity or is less than unity.) In all cases, the sense of discrepancy is such that the Mg lines have S/L < 1 (i.e., consistent with rapid mass loss), while the Ca lines have V/R > 1. This discrepancy is consistent (again, nonuniquely) with mass flux conservation: in the upper layers, the velocity of the mass...
outflow may be large enough to be detectable, while in the lower, denser, layers, the flow is so slow as to appear essentially static (cf. Mullan 1978). It is true that if a counterexample could be discovered (i.e., \( S/L > 1 \) for Mg, but \( V/R < 1 \) for Ca), this would challenge our basic interpretation of the asymmetries; however, to the best of our knowledge, no such counterexample is known, among the \( \sim 100 \) late-type stars which have been analyzed to date. In a similar vein, it is worth remarking that, within the Mg \( h \) and \( k \) doublet itself, we have found certain stars (e.g., \( \delta \) Crt, \( \alpha \) UMa, \( \alpha \) Phe, \( \gamma \) Leo, \( \iota \) Cet, and \( \iota \) Hya) in which the sense of the asymmetry in the \( k \) line is opposite to that of the \( h \) line. Again, in these cases, the sense of the discrepancy is in all cases that the stronger line (i.e., the line formed higher up in the atmosphere, the \( k \) line) shows evidence for mass outflow (\( S/L < 1 \)), whereas the deeper-lying line does not. However, the asymmetry of the \( h \) line in IUE spectra is strongly affected by the echelle blaze, and so these data are secondary to the comparison of the asymmetries of the Mg \( k \) line with Ca K line data (see below). The point we wish to make is that our study is based on a spectral feature which is formed high enough up in the atmosphere to be potentially sensitive to mass loss processes in the outer atmosphere.

**b) Rationale for the Present Program**

The essence of our program is to use a chromospheric line to provide information on conditions in both the chromosphere and the corona (or outer atmosphere, where the mass loss process is rapid). We expect that variations in the rate of mechanical energy deposition in the chromosphere will lead to variations in the total intensity of chromospheric radiation. To the extent, therefore, that the total intensity of the emission in Mg \( II \ h \) and \( k \) is proportional to the total chromospheric energy losses, variations in the total intensity (i.e., \( S + L \)) can be considered as an indication of variations in chromospheric heating. On the other hand, the ratio \( S/L \) is here interpreted as evidence for rapid mass loss if \( S/L < 1 \): In such a case, it appears that the radiative losses from the corona/outer atmosphere are small (Ayres et al. 1981). Hence, in such stars, the major sink of energy in the outer atmosphere is the stellar wind. Therefore, by monitoring variations in the wind (as evidenced by variations in \( S/L \)), we are essentially monitoring variations in the rate of mechanical energy deposition in the corona/outer atmosphere.

Our claim that measurements of a chromospheric emission feature contains information on conditions in the corona/outer atmosphere is based on several recent surveys of the giant region of the H-R diagram. Thus, Stencel and Mullan (1980a, b) found that there is a boundary in the H-R diagram along which \( S/L \) changes from \( S/L < 1 \) to \( S/L > 1 \). This boundary agrees remarkably well with a "temperature boundary" along which hot material is observed to disappear from the atmospheres (Linsky and Haisch 1979; Ayres et al. 1981).

An additional motivation for our work is to develop quantitative diagnostics for mass loss among stars which do not show evidence for circumstellar lines in their spectra. An example of how this might be achieved has been given by Chiu et al. (1977) in connection with \( V/R \) variations in the Ca \( II \) K line in \( \iota \) Boo.

In the immediate vicinity of the "mass loss boundary" in the H-R diagram (i.e., where \( S/L \) changes from \( <1 \) to \( >1 \)), there is no significant jump in the intensity of the chromospheric emission (i.e., \( S + L \)) (Stencel et al. 1980). Hence, along this boundary, there seems to be no alteration in the rate of mechanical energy deposition in the chromosphere. It is possible that the rate of mechanical energy deposition in the corona also remains unchanged as stars cross the mass loss boundary: only the distribution of energy losses might be different. For example, on the side where mass loss rates are low, energy sinks in the corona/outer atmosphere might be mostly radiative and conductive; whereas when mass loss rates are high, it seems likely that the major sink will be wind losses. The change in the distribution of energy losses may be associated with a change in the magnetic structures which can exist in the corona/outer atmosphere (Mullan 1981, 1982): On the low mass side of the boundary, closed loops of magnetic field can exist in static equilibrium, whereas on the other side of the boundary, static loops may not exist, and the magnetic field in the atmosphere may find itself in a state of constant magnetic upheaval.

**II. OBSERVATIONS**

The stars listed in Table 1 were observed with the high resolution spectrograph on board the International Ultraviolet Explorer satellite (Boggess et al. 1978). Sample profiles are shown in Figures 1–3, where we have used a calibration factor for Mg \( II \) of \( 0.57 \times 10^{-14} \) ergs cm\(^{-2}\) s\(^{-1}\) \( \AA^{-1} \) (FN/min)\(^{-1}\) (Ake and Holm, 1980). Backgrounds were recorrected from the time of earlier reduction (Stencel et al. 1980) to ensure uniformity, and an "active echelle ripple correction" procedure devised by T. Ayres (1980, private communication) has been applied. Exposure times were chosen to optimize the signal/noise ratio (10–20) at the Mg emission peaks.

There are several sources of difficulty encountered by our program, because peak fluxes in the Mg emission features can be distorted by several factors. These include pixel-to-pixel nonuniformities, particle and microphonics data "hits," saturation and near-saturation effects on the image transfer function (ITF), and differences in focus, camera temperature, guiding, background subtraction, and echelle blaze (ripple) correction. In order to address these difficulties, we have examined the observing log, photowrites, and the data tapes to...
TABLE 1

MG II DATA OBSERVATION LOG

<table>
<thead>
<tr>
<th>Star</th>
<th>HD</th>
<th>Sp. Type</th>
<th>$V-R$</th>
<th>LWR</th>
<th>Exp. (min)</th>
<th>Date</th>
<th>Var.*</th>
<th>Class</th>
<th>SWP</th>
<th>$V_r$ (km s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>γ Cep</td>
<td>222404</td>
<td>K1 IV</td>
<td>0.77</td>
<td>4430</td>
<td>25</td>
<td>1979 May 1</td>
<td>D</td>
<td>+2.7</td>
<td>-41</td>
<td></td>
</tr>
<tr>
<td>δ Crt</td>
<td>098430</td>
<td>G8 III–IV</td>
<td>0.83</td>
<td>4706</td>
<td>60</td>
<td>1979 Jun 6</td>
<td>(A)?</td>
<td>+0.5</td>
<td>-05</td>
<td></td>
</tr>
<tr>
<td>ε Sco</td>
<td>151680</td>
<td>K2 III–IV</td>
<td>0.86</td>
<td>4444</td>
<td>15</td>
<td>1979 May 2</td>
<td>D</td>
<td>+0.7</td>
<td>-02</td>
<td></td>
</tr>
<tr>
<td>α Cas</td>
<td>003712</td>
<td>K0 III + A?</td>
<td>0.79</td>
<td>4712</td>
<td>19</td>
<td>1979 Jun 6</td>
<td>A</td>
<td>-1.0</td>
<td>-04</td>
<td></td>
</tr>
<tr>
<td>α Phe</td>
<td>002261</td>
<td>K0 III</td>
<td>0.81</td>
<td>4441</td>
<td>20</td>
<td>1979 May 2</td>
<td>(A)</td>
<td>+1.0</td>
<td>+75</td>
<td></td>
</tr>
<tr>
<td>α Ser</td>
<td>140573</td>
<td>K2 III</td>
<td>0.81</td>
<td>4719</td>
<td>28</td>
<td>1979 Jun 8</td>
<td>D</td>
<td>+1.1</td>
<td>+05</td>
<td></td>
</tr>
<tr>
<td>β Oph</td>
<td>161096</td>
<td>K2 III</td>
<td>0.81</td>
<td>4721</td>
<td>38</td>
<td>1979 Jun 8</td>
<td>A</td>
<td>+0.2</td>
<td>-11</td>
<td></td>
</tr>
<tr>
<td>κ Oph</td>
<td>153210</td>
<td>K0 III</td>
<td>0.83</td>
<td>4720</td>
<td>47</td>
<td>1979 Jun 6</td>
<td>D</td>
<td>+0.5</td>
<td>-56</td>
<td></td>
</tr>
<tr>
<td>α Ari</td>
<td>012929</td>
<td>K2 III</td>
<td>0.84</td>
<td>5019</td>
<td>15</td>
<td>1979 Jul 12</td>
<td>D</td>
<td>+0.0</td>
<td>-14</td>
<td></td>
</tr>
<tr>
<td>α Tel</td>
<td>211416</td>
<td>K3 III+?</td>
<td>0.9</td>
<td>4418</td>
<td>45</td>
<td>1979 Apr 30</td>
<td>(B)</td>
<td>+0.0</td>
<td>+40</td>
<td></td>
</tr>
<tr>
<td>β UMi</td>
<td>131873</td>
<td>K4 III</td>
<td>1.10</td>
<td>4431</td>
<td>7</td>
<td>1979 May 1</td>
<td>(C)</td>
<td>-0.3</td>
<td>+16</td>
<td></td>
</tr>
<tr>
<td>α Tau</td>
<td>029139</td>
<td>K5 III</td>
<td>1.22</td>
<td>8580</td>
<td>5</td>
<td>1980 Aug 22</td>
<td>(D)</td>
<td>+0.0</td>
<td>+55</td>
<td></td>
</tr>
<tr>
<td>ζ Cyg</td>
<td>202109</td>
<td>G8 II b</td>
<td>0.70</td>
<td>4722</td>
<td>45</td>
<td>1979 Jun 8</td>
<td>D</td>
<td>+0.8</td>
<td>+17</td>
<td></td>
</tr>
<tr>
<td>ζ Hya</td>
<td>076294</td>
<td>G8 II (+)</td>
<td>0.72</td>
<td>4415</td>
<td>40</td>
<td>1980 Apr 21</td>
<td>(A)</td>
<td>+0.5</td>
<td>+23</td>
<td></td>
</tr>
<tr>
<td>θ Lyr</td>
<td>180809</td>
<td>K0 II +?</td>
<td>0.87</td>
<td>4428</td>
<td>105</td>
<td>1979 May 1</td>
<td>C</td>
<td>-2.5</td>
<td>-31</td>
<td></td>
</tr>
<tr>
<td>α Hya</td>
<td>081797</td>
<td>K2 II</td>
<td>1.04</td>
<td>4414</td>
<td>25</td>
<td>1979 Apr 30</td>
<td>C</td>
<td>-1.6</td>
<td>-13</td>
<td></td>
</tr>
<tr>
<td>β Aqr</td>
<td>204867</td>
<td>G0 Ib</td>
<td>0.60</td>
<td>4442</td>
<td>11</td>
<td>1979 May 2</td>
<td>(B)</td>
<td>...</td>
<td>-4.6</td>
<td>+06</td>
</tr>
<tr>
<td>α Aqr</td>
<td>209750</td>
<td>G2 Ib</td>
<td>0.66</td>
<td>4443</td>
<td>10</td>
<td>1979 May 2</td>
<td>B, (C)</td>
<td>-4.6</td>
<td>+06</td>
<td></td>
</tr>
<tr>
<td>β Dra</td>
<td>159181</td>
<td>G2 II a</td>
<td>0.68</td>
<td>4700</td>
<td>8</td>
<td>1979 Jun 5</td>
<td>D</td>
<td>-3.3</td>
<td>-20</td>
<td></td>
</tr>
<tr>
<td>9 Peg</td>
<td>206589</td>
<td>G5 Ib</td>
<td>0.80</td>
<td>4429</td>
<td>82</td>
<td>1980 Apr 20</td>
<td>B</td>
<td>-3.9</td>
<td>-22</td>
<td></td>
</tr>
<tr>
<td>56 Peg</td>
<td>218356</td>
<td>K0 II p</td>
<td>0.97</td>
<td>4699</td>
<td>50</td>
<td>1979 Jun 5</td>
<td>A, C</td>
<td>5447</td>
<td>9547</td>
<td></td>
</tr>
</tbody>
</table>

*aVariation types: A—S/L Var.; B—CS Var; C—Flux Var.; D—"Non-Var." See text, § III.
*bFrom Stencel and Mullan 1980 a.
*cHeliocentric radial velocity, from Abt and Biggs 1972.
search for "hits," saturations, and guiding errors, and we have rechecked background and ripple corrections. We estimate that residual errors in the monochromatic fluxes of the Mg II emission lines are approximately 5% (see § IIIc below). Further, the redundancy in the Mg doublet itself, and in the repeat of the Mg h line in subsequent echelle order, provides additional analog mode advantage for pattern recognition. In the following sections, we will describe the nature of the changes in the Mg II asymmetry observed in the course of this investigation.

III. VARIATIONS IN THE SPECTRA

We group the variations which we have detected into four classes: (a) radical S/L variables; (b) circumstellar variables; (c) flux variables; and (d) "non-variables."

a) Radical S/L Variables

In this class, we place the stars 56 Peg, β Oph, α Cas, and possibly ζ Hya and α Phe. For these stars, the S/L ratio altered by more than 5% over the observation intervals (i.e., ~10⁴ to ~10⁷ s). The archetype for this class is the remarkable object 56 Peg (K0 IIp) which has shown a large change in S/L and Δλ₄³ since 1979 (Figs. 1a and 1b). Among the other peculiarities of this object are the following: (1) The asymmetry of the Ca K emission core is in the sense V/R > 1, and this remains unchanged during the great change in S/L for the Mg lines; (2) Wilson-Bappu magnitudes derived from Ca K and Mg k disagree strongly, by some 4 mag; (3) the spectrum contains "hot" lines due to C IV and N V, despite its location far above the Linsky-Haisch temperature boundary. This peculiar object is discussed in detail by Schindler et al. (1981).

Of the other stars in this class, α Cas and β Oph also showed a fundamental change in S/L. (By "fundamental change," we mean that the sense of the asymmetry changes, i.e. from S/L < 1 to S/L > 1 or vice versa.) The changes in these stars were less dramatic than in 56 Peg. However, there was one feature in common: the change in the asymmetry occurred in the same sense in all three, i.e., from S/L < 1 at the first epoch to S/L > 1 at the second epoch.

In the cases of ζ Hya and α Phe, S/L decreased by less than 10% between first and second epochs. Thus our sample contains three stars (56 Peg, β Oph, and α Cas) for which we would claim a real detection of a fundamental alteration in atmospheric structure.

The stars in this class lie in and near a peculiar region of the H-R diagram in terms of the S/L asymmetry in Mg and Ca. Thus, stars in this class include objects in which S/L < 1 for the Mg lines, but V/R > 1 for the Ca K line. (We refer to these as "discrepant asymmetries.") It is difficult to simulate such discrepant asymmetries in the context of a standard one-dimensional model chromosphere without invoking extreme velocity gradients between the formation levels of the Mg and Ca lines.
Fig. 2.—(a) Observed Mg II profiles of α Aqr, showing the increased strength of the circumstellar component near 2794.5 Å. (b) Observed Mg II profiles of 9 Peg, showing changes in the strength of the circumstellar component near 2795 Å.

Ca lines. B. Lites (1980, private communication) has argued that discrepant asymmetries could be produced in an upward moving layer which is optically thick in the Mg line but optically thin in Ca (or inversely in a downward-moving layer). Thus, the absorption feature would be blueshifted in the Mg line, while in the Ca line, the blue shifted feature would add to the emission. This suggests the presence of large-scale inhomogeneities in this kind of cool giant star (cf. Heasley et al. 1978, who argue for inhomogeneities in α Boo, an archetypal “discrepant asymmetry” star (McClintock et al. 1978)). We hypothesize that magnetic structures analogous to solar prominences are involved, for the following reasons. First, a discrepancy between optical depths in Ca and Mg lines has been observed in solar prominences (Vial et al. 1979; Vial, Martres, and Salm-Platzer, 1981). Second, K. Harvey (1981, private communication) has pointed out that in spectroheliograms taken in the 10830 Å line of He I, rather small eruptive filaments and active prominences are capable of causing spatially large-scale
absorptions in 10830 Å, and these would be detectable in total flux if the sun were viewed as a star. Among stars, the most active 10830 Å variables are in fact cool giants for which S/L = 1 (O'Brien 1980). We note that the latter objects lie in the region of the H-R diagram which is occupied by the “discrepant asymmetry” stars.

Third, recent studies of UV emission measures (Stencel et al. 1981) and speckle interferometry in a chromospheric line (A. K. Hege 1981, private communication) have shown that red giants possess geometrically extended chromospheres. These chromospheres (which extend outwards to several times the photospheric radius) can hardly be supported by hydrostatic forces alone.

Stencel et al. (1980) pointed out that as the wavelength of the central absorption shifts to the red, S/L increases. This is consistent with our interpretation of S/L terms of the atmospheric velocity field. Similar behavior has been reported for the emission core of calcium in cool stars (Linsky et al. 1979). Are the variations which we have detected in S/L related to the shift in central absorption? A definitive answer cannot be

Fig. 3.—(a) Observed Mg II profiles α Hya, showing evidence for decreased flux between the given epochs. Note constancy of monochromatic fluxes between λλ2788–2794 Å. (b) Observed Mg II profiles in κ Oph, showing apparent lack of changes in flux or asymmetry between the given epochs. (c) Observed Mg II profiles in θ Lyr, showing evidence for increased flux between the given epochs.
given at present, because the observed shifts in central absorption (see Table 2) can barely be resolved by IUE, except for one star (possibly two). In the case of 56 Peg, the measured S/L values agree with the values which would be "predicted" from $\Delta \lambda_{k_3}$ (on the basis of the empirical relationship derived by Stencel et al. 1980). In $\alpha$ Hya, at first sight, it appears that the observed alteration in S/L is not consistent with the observed alteration in $\Delta \lambda_{k_3}$. However, close examination of the line profile in this star reveals that the $k_3$ absorption contains two components, one located at the position expected of interstellar gas which is at rest in the local galactic standard of rest (see Fig. 3a above). The interstellar component obscures the chromospheric S/L ratio. Interstellar effects on the observed S/L values have been discussed by Stencel and Mullan 1980b, where the stellar radial velocity can be used to select against strong interstellar features near line center. The other stars in Table 2 fall within the IUE measurement errors.

**TABLE 2**

<table>
<thead>
<tr>
<th>Star</th>
<th>Sp.Type</th>
<th>LWR</th>
<th>$\Delta \lambda_{k_3}$</th>
<th>$S/L_{\text{obs}}$</th>
<th>$S/L_{\text{pred}}$</th>
<th>$f_k$</th>
<th>$f_S$</th>
<th>$f_kS$</th>
</tr>
</thead>
<tbody>
<tr>
<td>56 Peg</td>
<td>K0 IIp</td>
<td>4699</td>
<td>-0.30 Å</td>
<td>0.39</td>
<td>0.40</td>
<td>1.9 (—11)s</td>
<td>1.2 (—11)</td>
<td>3.1 (—11)</td>
</tr>
<tr>
<td>4724</td>
<td>-0.21</td>
<td>0.41</td>
<td>0.58</td>
<td>1.7 (—11)</td>
<td>1.2 (—11)</td>
<td>2.9 (—11)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8298</td>
<td>+0.26</td>
<td>sat.</td>
<td>1.52</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td></td>
</tr>
<tr>
<td>8324</td>
<td>+0.22</td>
<td>1.04</td>
<td>1.44</td>
<td>3.1 (—11)</td>
<td>2.5 (—11)</td>
<td>5.6 (—11)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8578</td>
<td>+0.17</td>
<td>1.40</td>
<td>1.34</td>
<td>2.2 (—11)</td>
<td>1.6 (—11)</td>
<td>3.8 (—11)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9573</td>
<td>+0.15</td>
<td>1.04</td>
<td>1.30</td>
<td>2.3 (—11)</td>
<td>1.8 (—11)</td>
<td>4.1 (—11)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\alpha$ Phe</td>
<td>K0 III</td>
<td>4441</td>
<td>-0.02, -0.08</td>
<td>(0.61)</td>
<td>0.90</td>
<td>2.0 (—11)</td>
<td>1.6 (—11)</td>
<td>3.6 (—11)</td>
</tr>
<tr>
<td>7579</td>
<td>-0.04</td>
<td>0.99</td>
<td>0.92</td>
<td>2.2 (—11)</td>
<td>1.8 (—12)</td>
<td>4.0 (—11)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7580</td>
<td>-0.03</td>
<td>1.03</td>
<td>0.94</td>
<td>2.2 (—11)</td>
<td>1.9 (—11)</td>
<td>4.1 (—11)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\beta$ Oph</td>
<td>K2 III</td>
<td>4721</td>
<td>-0.11</td>
<td>0.85</td>
<td>0.78</td>
<td>1.1 (—11)</td>
<td>1.7 (—12)</td>
<td>1.9 (—11)</td>
</tr>
<tr>
<td>9029</td>
<td>-0.12</td>
<td>1.01</td>
<td>0.76</td>
<td>1.1 (—11)</td>
<td>7.2 (—12)</td>
<td>1.8 (—11)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\alpha$ Cas</td>
<td>K0 III+?A</td>
<td>4712</td>
<td>-0.01</td>
<td>1.03</td>
<td>0.98</td>
<td>2.1 (—11)</td>
<td>1.4 (—11)</td>
<td>3.5 (—11)</td>
</tr>
<tr>
<td>9027</td>
<td>+0.04</td>
<td>1.03</td>
<td>1.08</td>
<td>1.9 (—11)</td>
<td>1.5 (—11)</td>
<td>3.4 (—11)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\kappa$ Oph</td>
<td>K2 III</td>
<td>4720</td>
<td>+0.17</td>
<td>1.62</td>
<td>1.34</td>
<td>7.6 (—12)</td>
<td>6.4 (—12)</td>
<td>1.4 (—11)</td>
</tr>
<tr>
<td>9028</td>
<td>+0.11, +0.35</td>
<td>1.65</td>
<td>1.38</td>
<td>7.2 (—12)</td>
<td>5.1 (—12)</td>
<td>1.2 (—11)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\alpha$ Hya</td>
<td>K2 II</td>
<td>4414</td>
<td>-0.16, +0.08</td>
<td>0.57</td>
<td>0.68</td>
<td>3.2 (—11)</td>
<td>2.0 (—11)</td>
<td>5.2 (—11)</td>
</tr>
<tr>
<td>9025</td>
<td>-0.16, -0.04</td>
<td>0.54</td>
<td>0.68</td>
<td>2.2 (—11)</td>
<td>1.7 (—11)</td>
<td>3.9 (—11)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\xi$ Hya</td>
<td>G8 II</td>
<td>4415</td>
<td>+0.02</td>
<td>0.95</td>
<td>1.04</td>
<td>8.6 (—12)</td>
<td>6.2 (—12)</td>
<td>1.5 (—11)</td>
</tr>
<tr>
<td>7582</td>
<td>-0.04</td>
<td>1.05</td>
<td>0.92</td>
<td>8.1 (—12)</td>
<td>5.9 (—12)</td>
<td>1.4 (—11)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Superscripts:
- $a$ Uncertainty in $\Delta \lambda_{k_3}$ is ±0.6 Å.
- $b$ $S/L_{\text{pred}}$ = $2\Delta \lambda_{k_3}$ + 1.0 (cf. Stencel et al. 1980).
- $c$ Uncertainty in fluxes ±10%. Calibration factor used was 0.57×10$^{-14}$ ergs cm$^{-2}$ s$^{-1}$ Å$^{-1}$ (FN/min)$^{-1}$.

**b) Circumstellar (CS) Variables**

Stars that lie very close to the V/R asymmetry division (Stencel 1978), namely the G supergiants and late K giants, exhibit shortward shifted (≈100 km/s$^{-1}$) absorption features which can be associated with circumstellar (CS) material and rapid mass loss (Stencel et al. 1980; Carpenter and Wing 1979). Our sample includes $\alpha$ Aqr, $\beta$ Aqr, 9 Peg, $\alpha$ Tra, $\alpha$ Tuc, and $\alpha$ Tau which exhibit such CS features in Mg II. Dupree and Baliunas (1979) discovered significant changes in the strength of the CS component in $\alpha$ Aqr. We report here continued changes in $\alpha$ Aqr and evidence for similar CS variations in other stars.

In $\alpha$ Aqr (G2 Ib), our observations bracket and extend beyond those reported by Dupree and Baliunas. The sense of the variation is that of changes in the equivalent width of the CS absorption, which also affects the emission peak nearer line center (see Fig. 2a). The behavior of the equivalent width suggests a discrete mass loss event occurring over a multimonth period, but whether this is isolated or rotationally modulated remains to be determined. An event of comparable magnitude was observed in 9 Peg (G5 Ib), where the CS feature also increased in strength (Fig. 2b). In $\beta$ Aqr (G0 Ib), we have some evidence for small increases in the depth of the −60 km s$^{-1}$ CS component and perhaps a weakening of a notch near −140 km s$^{-1}$ from line center. Among the K giants, $\alpha$ Tra (K4 III) shows a slight weakening of the central absorption feature, while $\alpha$ Tuc (K3 III+) shows possible strengthening of a CS-like notch near −40 km s$^{-1}$. No changes were found in $\alpha$ Tau at two epochs, although Liller (1968), Reimers (1977), and Baliunas et al. (1981) report striking Ca K line changes. Four other K giants recently have been shown to have substantial CS features in Mg II (Simon, Stencel, and Linsky 1981), namely, $\theta$ Her (K1 III), $\iota$ Aur (K3 III), $\gamma$ Aql (K3 II), and $\gamma$ Dra (K5 III). These are currently being monitored for CS variations.

The variations in circumstellar strength indicate that the mass loss process in these stars is essentially time-dependent. The stars $\alpha$ Aqr and $\beta$ Aqr lie near the
boundary line in the H-R diagram along which the velocity structure of stellar atmospheres should show significant alteration (Mullan 1978). These stars are also of interest because they may have hot material in their atmosphere, despite their strong mass loss (Hartman, Dupree, and Raymond 1980). The relation between time variations in the emission measure of hot material and variations in the rate of mass loss from the star has yet to be established.

c) Flux Variables

In this class we place stars in which the total emission flux in Mg II changed by more than 5–10% between exposures. To date, this includes α Hya, β UMi, θ Lyr, and 56 Peg. Our ability to evaluate the changes in flux is influenced by (1) differing background levels and their removal, (2) differences in ripple corrections, and (3) sensitivity variations. The sensitivity variations are reported to be significantly less than 5% between 1979 and 1980, while the ripple correction procedure (2) which we have used reduces errors to less than 5% as well. Information on the background level was considered in this analysis, and an estimated noise level (near 2799 Å) determined. A pair of consecutive LWR exposures on α Phe (LWR 7579 and 7580) were examined for systematic differences due to short term observation and processing differences, and the agreement in all respects is better than 5%.

Our best example for flux variation, other than 56 Peg (Fig. 1b), is α Hya (K2 II) which showed a 25% decrease in monochromatic peak fluxes between exposures of comparable background levels made in 1979 April and 1980 October (Fig. 3a). By way of contrast, κ Oph, observed at similar times, remained constant to 2% (Fig. 3b). The flux change in β UMi (K4 III) was marginally significant, showing a 10–15% decrease in monochromatic flux over a 16 month interval. θ Lyr (K0 II +?) showed no significant monochromatic flux change to 10%, but it did exhibit a peculiar total flux increase in the form of a 30% increase in width of the shortward emission component (Fig. 3c). It is noteworthy that of the present sample of stars, the bright giants appear to be the most likely flux variables.

The detection of changes in flux from low gravity stars implies high luminosity events occurring on the surface of these objects. Considering the surface Mg II fluxes for θ Lyr and α Hya (Stencel et al. 1980), and their likely radii (30–40 R⊙), the 1.1–15% integrated flux changes seen translate into luminosity changes of roughly 10^{30} ergs s^{-1} in Mg II. If the radiative losses in Mg II are roughly 10% of the total measured power in a solar-like flare event (Canfield et al. 1980), the total power of such events are orders of magnitude above the most energetic solar flares. Similar conclusions were reached by Baliunas et al. (1981) who monitored the Ca II K emission cores in three late-type stars and determined that “flarelike” events with total radiative energy output of 10^{30} ergs s^{-1} occurred. Their Fourier analysis of lengthy synoptic observations revealed the presence of significant power at specific frequencies which suggested that a small number of coherent emitting regions dominated the chromospheric emission. Although we lack the extensive sampling available to ground-based observers, we believe our results are qualitatively in agreement with the findings of Baliunas et al. (1981). Further, we strongly agree that the contrast of photospheric flux for different effective temperatures is important in defining the impression of flare activity which can lead to underestimating the ubiquitous nature of flarelike phenomena among stars warmer than the M types.

Further assessment of the reality of the flux variations reported here is in progress, as well as further data acquisition and recalibration of various effects which may influence the signal.

d) “Non-variables”

Of the 21 stars listed in Table 1, about one-third showed no detectable variations over the time scales investigated here (≈10^4 − 10^7 s). The locations of these nonvariable objects in the H-R diagram are shown in Figure 4. Also shown in Figure 4 are the mass loss boundary (labeled k, as derived by Stencel and Mullan (1980a,b) from Mg k data) and the hot material boundary (labeled X, from the X-ray survey of Ayres et al. 1981). (As noted above, these boundaries are essentially coincident.) The mass loss boundary derived from V/R asymmetries in the Ca K line is labeled K.
This boundary also serves (roughly) to separate stars in line is nonvariable (O'Brien 1980). in absorption and emission from stars in which the He i which the He i 10830 Å line exhibits extreme variations (from Stencel 1978 and Stencel and Mullan 1980a).

We plan to expand the sample and to continue monitor-ing these stars for variability on other time scales. The rapid mass loss are found to be variable in some respect. Of course, the small number of our targets and limited sampling frequency could make this division fortuitous.

... (from Stencel 1978 and Stencel and Mullan 1980a). This boundary also serves (roughly) to separate stars in which the He i 10830 Å line exhibits extreme variations in absorption and emission from stars in which the He i line is nonvariable (O'Brien 1980).

We note that our "nonvariable" stars show a ten-dency to lie in the part of the H-R diagram where hot corona exist, while stars which exhibit some sign of rapid mass loss are found to be variable in some respect. Of course, the small number of our targets and limited sampling frequency could make this division fortuitous. We plan to expand the sample and to continue monitor-ing these stars for variability on other time scales. The fact that our sample seems to bifurcate between variables and nonvariables in a manner which is quite similar to the bifurcation found by O'Brien from his He i data encourages us to believe that studies of variability can be realistically attempted with the IUE system, at least down to the 5–10% limit suggested above.

Short exposures of the target spectrum at short wave-lengths (1100–2000 Å) can be acquired by the IUE spectrograph without loss of Mg ii observing efficiency, and we adopted this mode of operation in order to search for possible variations in the emission measure of hot material in conjunction with variations in Mg ii. Unfortunately, the SWP spectra were usually too under-exposed to warrant detailed examination, except for α Tuc, θ Lyr, δ Hya, and α Cas, where evidence for a warm (F-type) companion was deduced from the strength of the continuum near 2000 Å. Integrated strengths of various features are given in Table 3.

### IV. DISCUSSION

We have obtained profiles of the Mg ii h and k emission features in the spectra of 21 late-type giant stars. The spectral resolution is high enough (~0.2 Å) to enable us to measure the emission strengths separately in the shortward (S) and longward (L) emission components. Variations in the total emission intensity (i.e., S+L) can be interpreted as evidence for variations in the rate of mechanical energy deposition in the chromosphere. On the other hand, mass loss processes in the corona/outer atmosphere may be strong enough to affect the ratio of S/L: thus, rapid mass loss causes S/L to be less than unity. In the case of rapid mass loss, it is highly likely that mechanical energy deposited in the corona/outer atmosphere is disposed of mainly by the stellar wind. In such a case, variations in the S/L ratio are a measure of variations in the rate of mechanical energy deposition in the corona/outer atmosphere.

For each star in our sample, we have obtained at least two spectra, separated by time intervals of ~10<sup>2</sup> to
MAGNESIUM EMISSION VARIABILITY

No. 2, 1982

Historically been applied only to lower main-sequence stars. Stars belonging to class (d) have not yet been found to be variable, but we cannot exclude the possibility of variability on time scales outside the range which we have sampled.

In the solar atmosphere, there is a well established correlation between the intensity of chromospheric emission and the magnetic flux (Skumanich, Smythe, and Frazier 1975). It is customary to interpret stellar observations in terms of a solar analogy as a first approximation, despite the fact that the solar analogy may not be valid in other stars (cf. Vaiana and Rosner 1978). In the spirit of this first approximation, however, we presume that the variability which we have detected in our Mg λ h and k data is due to magnetic activity on the stellar surface. Direct observational evidence for magnetic fields on the surfaces of giant stars is rather scarce at present. Borra et al. (1980) have reported fields of 10–30 gauss on three supergiants. Wilson (1973) has provided an indirect argument for the existence of surface magnetic flux in giants (arguing from the solar analogy). Very recently, Boice et al. (1981) have reported a possible radio flare on the M2 giant α Cet. If events of this nature could be confirmed, and especially if evidence for circular polarization could be obtained during such events, the evidence for magnetic fields in giants would become more compelling. Among subgiants evidence of this type already exists for members of the RS CVn class: however, these are close binaries, where tidal effects apparently help to generate strong magnetic fields (cf. Mullan 1975). In the present paper, the stars in our sample are not known to be members of close binaries, and so they are not expected to exhibit magnetic activity on the grand scale shown by the RS CVn systems. The stars in our sample are expected to show variability of a more modest kind. This is a further reason for us to use variability probes which are as sensitive as possible to changes in the state of the atmosphere. The S/L ratio, which has played a central role in our investigation, is such a probe.

This work has been supported by NASA contract NAS5-26595 to Bartol Research Foundation. We thank Paul Buster for help in data reduction and acknowledge helpful comments from an anonymous referee.

REFERENCES

Ake, T., and Holm, A. 1980, Bull. AAS 12, 816.
Carpenter, K. and Wing, R. 1979, Bull. AAS 11, 419.

© American Astronomical Society • Provided by the NASA Astrophysics Data System

D. J. MULLAN: Bartol Research Foundation, University of Delaware, Newark, DE 19711

R. E. STENCHEL: Joint Institute for Laboratory Astrophysics, University of Colorado, Boulder, CO 80309