

AN EMPIRICAL TEST OF THE Mg II λ 1240 DOUBLET BRANCHING RATIO AND OSCILLATOR STRENGTH¹

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ABSTRACT

We empirically confirm the theoretical branching ratio and oscillator strength for the weak Mg II $3s-4p$ doublet at 1240 Å as determined by Theodosiou & Federman. We use the independent methods of apparent optical depth analysis for the sight lines toward μ Col, γ Ara, and ρ Leo and profile component fitting for the sight line toward μ Col in order to determine the branching ratio. We find $f_{1239}/f_{1240} = 1.74 \pm 0.06$, in agreement with the theoretical value of 1.78 ± 0.03 . Profile fitting for the line of sight toward μ Col gives an f -value for the doublet of $9.71 \pm 0.32 \times 10^{-4}$, which agrees with both the theoretical value of Theodosiou & Federman and the empirical value of Fitzpatrick.

Subject headings: atomic data — ISM: abundances — ultraviolet: ISM

1. INTRODUCTION

Magnesium is an important element to study in the interstellar medium (ISM) because it is both abundant and reactive. These characteristics make Mg a substantial component of interstellar dust—specifically silicate and oxide grains (Ossenkopf, Henning, & Mathis 1992; Fadeyev 1988; Spitzer & Fitzpatrick 1993; Sofia, Cardelli, & Savage 1994; Savage & Sembach 1996). Magnesium is also a useful diagnostic for the electron density, n_e , through the ionization ratio of Mg^0/Mg^+ (Fitzpatrick & Spitzer 1997; Fitzpatrick 1997, hereafter F97). A testament to the importance of Mg is the recent work that has gone into refining the f -values of the transitions used to determine its abundances in the interstellar medium (Cardelli et al. 1991; Sofia et al. 1994; F97; Fleming et al. 1998; Theodosiou & Federman 1999, hereafter TF99).

The dominant ion of magnesium in the neutral ISM is Mg^+ (the ionization potentials of Mg^0 and Mg^+ are 7.65 and 15.03 eV, respectively). The λ 1240 ($3s-4p$) doublet of Mg II is the primary absorption used for determining the interstellar abundance of Mg in these regions because the other observable lines at 2800 Å are usually severely saturated. The oscillator strength for the λ 1240 doublet is difficult to measure experimentally because the lifetimes for the transitions are not controlled by de-excitations to the ground state (Hibbert et al. 1983). The theoretical determination of the f -value is also difficult because of substantial cancellation in the radial overlap integral (Hibbert et al. 1983). For this reason the theoretical values for this doublet varied greatly over time (Butler, Mendoza, & Zeippen 1984; F97).

Until recently, the oscillator strength most commonly adopted for the λ 1240 doublet was a theoretical value determined by Hibbert et al. (1983). The resolution and high signal-to-noise capabilities of the Goddard High Resolution Spectrograph (GHRS) aboard the *Hubble Space Telescope* allowed this f -value to be empirically tested by comparing the column densities obtained from the λ 1240 transitions and the damping wings of the λ 2800 absorption features. Cardelli et al. (1991) found a large discrepancy between the column densities determined from each of the doublets. Sofia et al. (1994) suggested that the Hibbert et al. value was too small by a factor of about 4.6, based on a simple analysis of the damping wings of the λ 2800 transitions toward ζ Per. A more detailed component-fitting analysis of both doublets by F97 in three lines of sight (ζ Oph, ξ Per, and HD 93521) lowered the f -value by ~ 2 with respect to those of Sofia et al. (1994). Most recently, TF99 presented a theoretical oscillator strength for the λ 1240 doublet that agrees with F97 to within the errors. A difference between the two results is that F97 constrained the profile fit so that the ratio of the f -values in the weak doublet was $f_{1240} = \frac{1}{2}f_{1239}$, as would be expected from LS coupling. TF99, however, find that the branching ratio for the doublet is 1.78 rather than 2.

Since the F97 and TF99 λ 1240 doublet f -values agree within the errors, the main goal of this paper is to empirically test the f -value branching ratio found by TF99. They list four components necessary to accurately test their f -value and branching ratio empirically: (1) high-quality data, (2) a sight line with simple component structure, (3) comparison with only those species likely to coexist with Mg II, and (4) allowing the branching fraction of the weak lines to be a free parameter in the fitting procedure. Here we perform such an analysis on the line of sight toward μ Columbae. We also use apparent optical depth analysis on three sight lines (toward μ Col, γ Ara, and ρ Leo) as an independent test of the Mg II λ 1240 branching ratio. We

¹ Based on observations obtained with the NASA/ESA *Hubble Space Telescope* through the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NASA-26555.

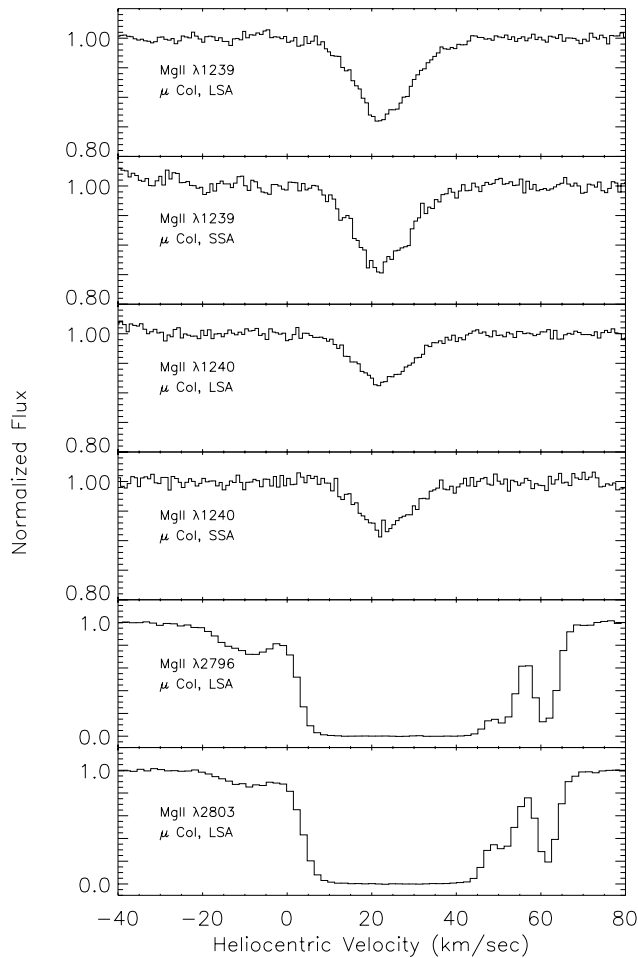


FIG. 1a

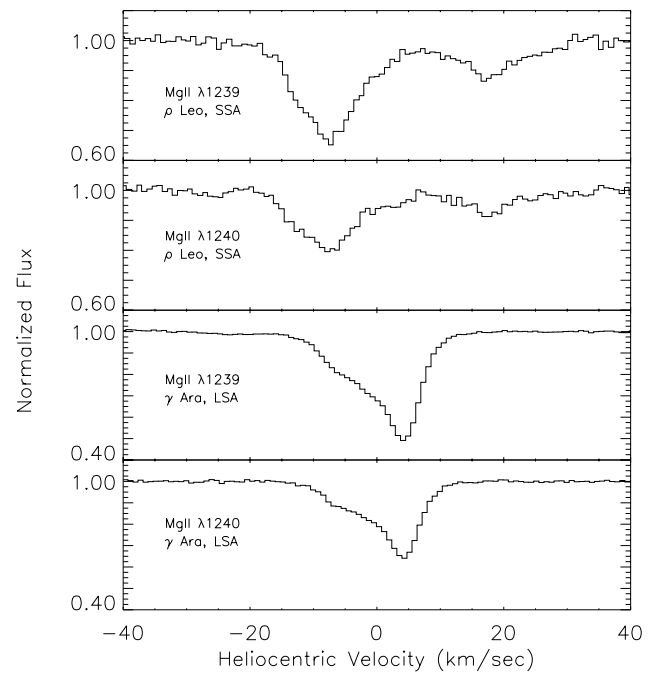


FIG. 1b

FIG. 1.—Normalized flux vs. heliocentric velocity for the Mg II lines in our sample. (a) Mg II absorption toward μ Col; (b) features toward ρ Leo and γ Ara. There are two sets of the weak λ 1240 transition lines toward μ Col because one was taken through the large and one through the small science aperture of the GHRS. The coarser spacing of the λ 2800 data toward μ Col results from those data being obtained at two substeps per diode compared with the four substeps per diode for the other observations.

discuss in § 2 the data and their calibration. We present our analysis in § 3 and discuss our results in § 4.

2. OBSERVATIONS AND CALIBRATIONS

All of the data used for this study were observed with the *Hubble Space Telescope's* (HST) Goddard High Resolution Spectrograph in the echelle mode ($\sim 3.5 \text{ km s}^{-1}$ resolution) after the installation of Corrective Optics Space Telescope Axial Replacement (COSTAR). The observations for two of the sight lines were obtained from the HST archive (μ Col and ρ Leo), and one object was from our program to study the Mg II f -values (γ Ara). The sight line toward μ Col was chosen for the high signal-to-noise ratio (S/N) quality of its observations and because the component structure of the neutral ISM toward the star has recently been studied by two of us (Howk, Savage, & Fabian 1999). The sight line toward ρ Leo was selected for its data quality and the relatively broad absorption region with no saturation in the weak Mg II λ 1240 lines. The sight line toward γ Ara was observed for the Mg II study because of the simplicity of its absorption component structure and because it is bright enough to produce high S/N data with a short exposure time.

Our analysis makes use of the interstellar Mg II λ 1240 doublet absorption toward all three of the stars and the λ 2800 doublet toward only μ Col. The μ Col and γ Ara data were obtained through the GHRS Large Science Aperture (LSA) with the exception of the λ 1240 doublet toward μ Col, for which we have both LSA and Small Science Aperture (SSA) data. The ρ Leo data were all observed through the SSA. The GHRS team's interactive data language (IDL) software package, CALHRS, was used to calibrate the spectra (space telescope optimum-reference-file calibrations do not differ significantly from the team CALHRS package). Sophisticated flat-fielding algorithms were employed to further reduce the effects of fixed pattern noise (FPN), beyond the reduction afforded by the FP-SPLIT observing strategy. These algorithms are described in Spitzer & Fitzpatrick (1993), Cardelli & Ebbets (1994), and Cardelli (1995). Once the FPN was removed, the FP-SPLIT data for a given observation were co-added, aligning the spectra by centroiding on absorption features when possible and otherwise using the nominal GHRS carousel-grating positions.

The standard GHRS echelle scattered-light background coefficients (Cardelli, Ebbets, & Savage 1993) were used for

the calibrations. These corrections are accurate to within 1% of the continuum flux level (Cardelli et al. 1993). The backgrounds for the spectra containing the strong ($\lambda 2800$) absorption were adjusted, if needed, so that the bottoms of the absorption profiles reached zero intensity.

The final extracted spectra have S/N values of approximately 330, 75, 130, 185, and 120 for the γ Ara $\lambda 1240$, ρ Leo $\lambda 1240$, μ Col $\lambda 1240$ small aperture, μ Col $\lambda 1240$ large aperture, and μ Col $\lambda 2800$ lines, respectively. These S/N values are per pixel and were determined from the scatter about the continuum adjacent to the absorption features. The spectra were normalized to a continuum level of 1.0 by fitting low-order (≤ 5) polynomials to the regions of spectra that are adjacent to the absorption and are free of other interstellar features. The continua of the stars are well behaved in the regions of the Mg II absorption, so the fitting procedure was not difficult. The final normalized profiles are shown in Figure 1.

3. ANALYSIS

We use two independent methods to determine the Mg II $\lambda 1240$ doublet-branching ratio. The first is the apparent optical depth method, which we applied to all three lines of sight. This analysis eliminates the need to rely on sight lines that have simple component structure, because the method makes no assumptions about the distribution of absorbing material along a sight line. Optical depth analysis will give only the branching ratio for the doublet; i.e., it does not give values for the oscillator strengths. The most important factors for accurate optical depth analysis are high S/N data and a lack of unresolved saturated structure in the observed profile (see § 3.1). The second method for determining the branching ratio is profile-fitting analysis. We use this method only toward μ Col because it is necessary to have a well-defined component structure for the line of sight that has been determined by elements that exist in similar environments. The component structure toward μ Col was recently characterized by Howk et al. (1999). Component fitting produces not only the branching ratio, but also the oscillator strengths.

3.1. Optical Depth Analysis

The apparent optical depth method for interpreting abundances has been discussed in great detail by Savage & Sembach (1991) and Jenkins (1996). The apparent optical depth, an instrumentally blurred version of the true optical depth, as a function of velocity is given by

$$\tau_a(v) = \ln \left[\frac{I_0}{I(v)} \right], \quad (1)$$

where I_0 is the continuum intensity level, and $I(v)$ is the observed intensity of the absorption line as a function of velocity. Where absorption is weak, or where the instrument has fully resolved the velocity structure of the profile, we can find the column density per unit velocity as a function of velocity through

$$N_a(v) = 3.768 \times 10^{14} \frac{\tau_a(v)}{f\lambda} \text{ cm}^{-2} (\text{km s}^{-1})^{-1}, \quad (2)$$

where f is the transition's f -value and λ is expressed in angstroms. If narrow, saturated components exist in the absorption profile, then $N_a(v)$ will underestimate the true column density per unit velocity, $N(v)$. For regions of the absorption

where $N_a(v)$ represents $N(v)$ well,

$$\tau_a(v) \propto f\lambda N(v). \quad (3)$$

If one compares two absorption features from the same species, then their apparent optical depths in regions without unresolved saturation should be in the ratio of their $f\lambda$ values. In the case of the weak Mg II doublet, the wavelengths of the two transitions are so close (1239.9253 and 1240.3947 Å; Morton 1991) that we can safely ignore them and simply assume $\tau_a(v) \propto f$.

Figure 2 shows the apparent optical depth profiles of the Mg II $\lambda 1240$ doublet features toward γ Ara with their $\pm 1 \sigma$ error bars. For the optical depth analysis, we want to isolate the regions of the profiles where we believe that $N_a(v)$ accurately represents $N(v)$, i.e., the weakest portions of the profiles; strong absorption may contain some unresolved saturation even at the resolution of the GHRs. We believe that the $\lambda 1240$ doublet profiles toward μ Col and ρ Leo are free from unresolved saturation, since they have the small peak apparent optical depths of 0.17 and 0.43, respectively. The absorption toward γ Ara, however, has a peak value of $\tau_a = 0.71$ and likely does have unresolved saturation in its profile. We therefore exclude any data points from our optical depth analysis toward γ Ara that are closer to the peak absorption than $\pm 3.5 \text{ km s}^{-1}$ (the approximate resolution of the data). The analysis also requires optical depths that are large enough to give useful comparisons between the two lines of the doublet (i.e., that give us leverage in the fitting procedure). Therefore, we exclude any data in the three sight lines where the stronger line of the doublet ($\lambda 1239$) has an apparent optical depth $\tau_a < 0.05$.

To determine the branching ratio for the weak lines, we multiply the τ_a profile from the weaker ($\lambda 1240$) transition by an f -value ratio, f_{1239}/f_{1240} , and compare that with the τ_a from the stronger ($\lambda 1239$) transition using a χ^2 test. We vary the multiplication factor to find the best fit and the 1σ errors. The best fits for the branching ratios are shown in the bottom panels of Figures 3, 4, and 5 for γ Ara, μ Col, and ρ Leo, respectively.

3.2. Profile Fitting

The component structure of neutral ISM absorption in the sight line toward μ Col has been well determined

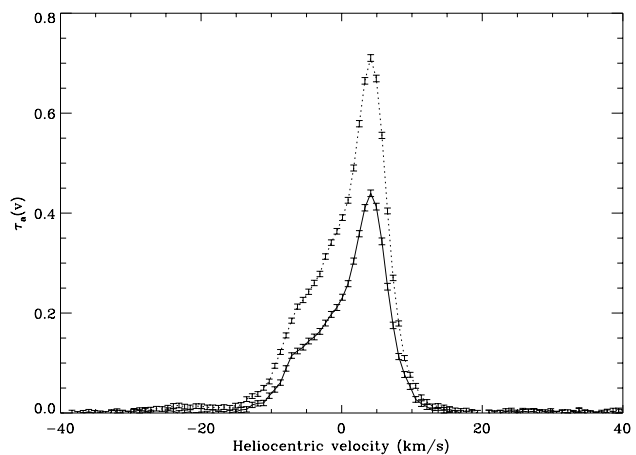


FIG. 2.—Apparent optical depths of the $\lambda 1240$ doublet toward γ Ara. The stronger profile (dotted line) is from the 1239.9253 Å transition, and the weaker profile (solid line) is from the 1240.3947 Å transition. The error bars show the 1σ uncertainties in each of the points.

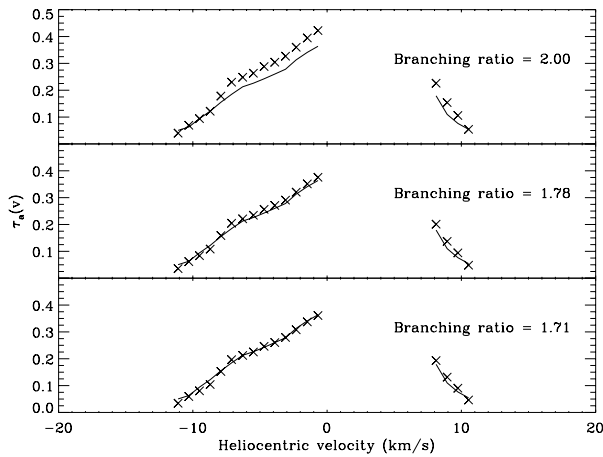


FIG. 3.—Comparisons between the weak Mg II doublet lines toward γ Ara with branching ratios of 1.71 (the best fit for the data), 1.78 (the theoretical value from TF99), and 2.00 (the previously assumed branching ratio). The solid line is the optical depth of the stronger transition, and the crosses are the weaker transition optical depths multiplied by the branching ratio. The gap in the data represents a region that we believe to be contaminated by unresolved saturated structure.

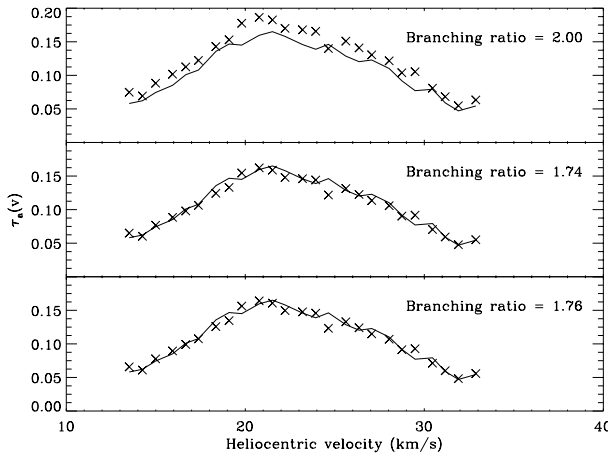


FIG. 4.—Comparisons between the weak Mg II doublet lines toward μ Col with branching ratios of 1.76 (the best fit for the data), 1.74 (the mean value determined from this paper), and 2.00 (the previously assumed branching ratio). The solid line is the optical depth of the stronger transition, and the crosses are the weaker transition optical depths multiplied by the branching ratio.

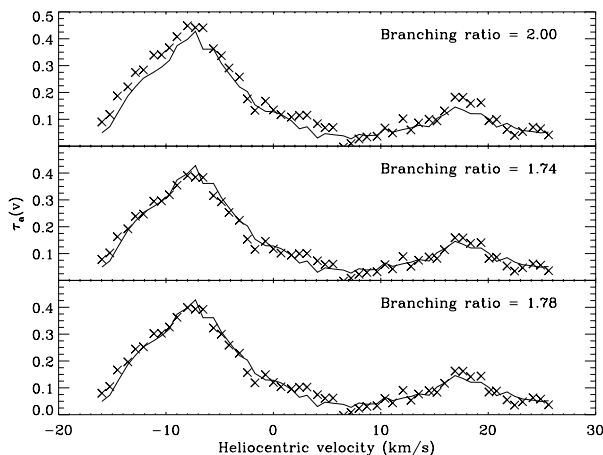


FIG. 5.—Same as Fig. 4, but for the sight line toward ρ Leo. The best fit shown in the bottom panel is for a branching ratio of 1.78.

through the analysis of nearly 50 lines of 14 species that are dominant in the neutral ISM (Howk et al. 1999). We make use of this well-defined structure in order to simultaneously fit the absorption profiles from the weak ($\lambda 1240$) and strong ($\lambda 2800$) doublets of Mg II.

We use the component-fitting software originally written by E. Fitzpatrick and described in detail by Spitzer & Fitzpatrick (1993) and Fitzpatrick & Spitzer (1997). The software was updated by one of us (J. C. H.) in order to account for large-aperture observations (see Appendix A of Howk et al. 1999). We refer the reader to the previous articles describing the specifics of the fitting software.

We started the fitting procedure with the TF99 f -values and the Howk et al. (1999) component structure. We allowed the software to refine the fit for the Mg II lines by varying the seven absorption components in velocity (position), column density, and Doppler spread parameter (b). We chose to use the TF99 f -values to refine the component structure for Mg II because of the agreement in value between TF99 and F97 and because our optical depth analysis indicated that the TF99 branching ratio was reasonable (see § 4). Once the basic component structure was defined, we fitted the six lines again, this time allowing only the column densities and $\lambda\lambda 1240, 1239$ f -values to vary. The Mg II $\lambda 2800$ atomic constants are well determined, so these lines serve as an anchor point for the fitting. The best fit to the six individual profiles is shown in Figure 6.

4. RESULTS

Profile fitting of the μ Col sight line finds a best fit to the data with f -values of $6.17 \pm 0.27 \times 10^{-4}$ and $3.54 \pm 0.17 \times 10^{-4}$ for the $\lambda 1239$ and $\lambda 1240$ transitions, respectively. These values are a weighted average of the small-aperture and large-aperture data results. The doublet value for the oscillator strength of $9.71 \pm 0.32 \times 10^{-4}$ agrees well with both the theoretical value of TF99 ($9.88 \pm 0.07 \times 10^{-4}$) and the empirical value of F97 ($9.6 \pm 0.6 \times 10^{-4}$). This is further confirmation that the Mg II $3s-4p$ doublet oscillator strength is well determined.

Since the theoretical doublet oscillator strength of TF99 had previously been confirmed, our main goal for this study was to test the theoretical branching ratio empirically. Table 1 shows that our four determinations of the Mg II $\lambda 1240$ branching ratio produced by the two different methods are all consistent within their errors. Our results are 1.71 ± 0.10 , 1.76 ± 0.13 , and 1.78 ± 0.23 for the γ Ara, μ Col, and ρ Leo optical depth analyses, respectively. There is only one value for μ Col because we combined the small and large-aperture data in the optical depth analysis for a S/N of approximately 200. The large decrease in error with

TABLE 1

MG II $\lambda 1240$ DOUBLET-BRANCHING RATIO		
Sight Line	Method ^a	f_{1239}/f_{1240}
γ Ara	$N_a(v)$	1.71 ± 0.10
ρ Leo	$N_a(v)$	1.78 ± 0.23
μ Col	$N_a(v)$	1.76 ± 0.13
μ Col	CF	1.74 ± 0.11
Weighted mean		1.74 ± 0.06

^a The method used for determining the branching fraction: $N_a(v)$ —apparent optical depth method; CF—component fitting.

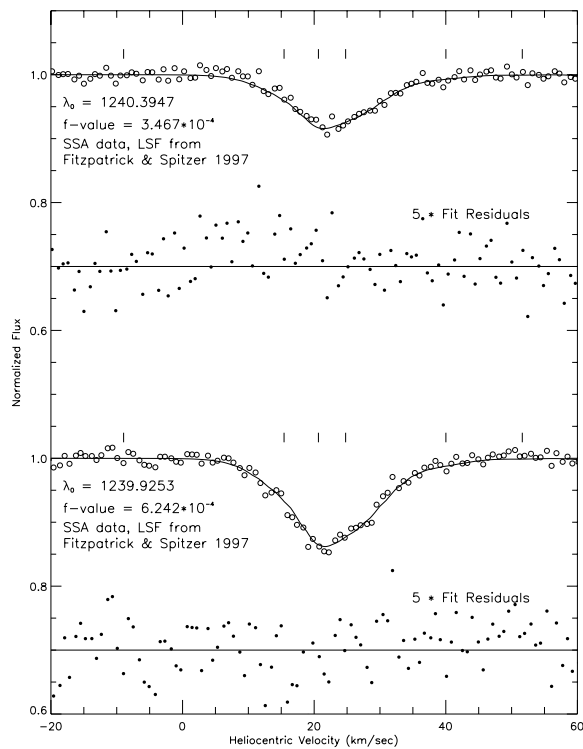


FIG. 6a

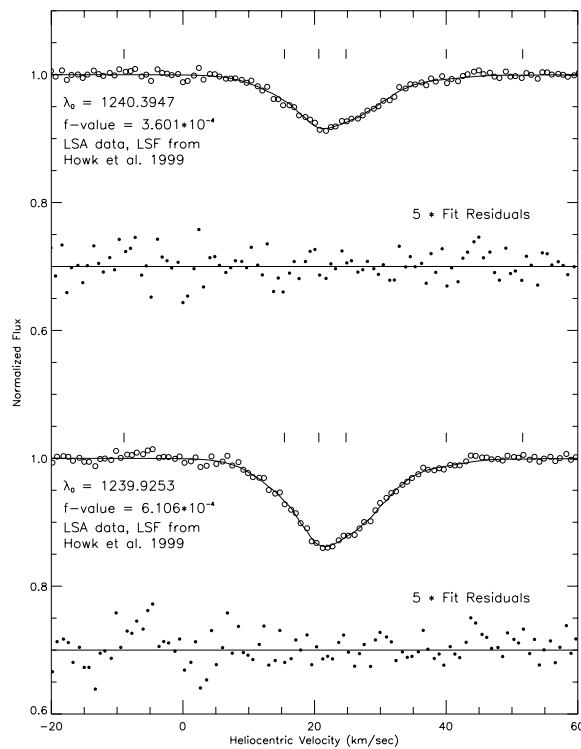


FIG. 6b

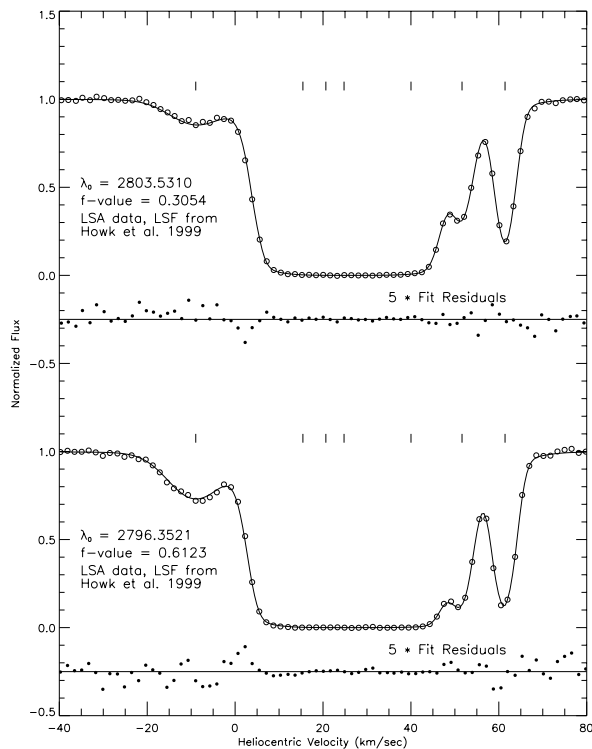


FIG. 6c

FIG. 6.—Best fit to the μ Col Mg II absorption profiles. The observed data are shown as open circles and the fitted absorption is shown as a solid line. The short vertical lines over the profiles show the velocities of the absorbing components. The residuals are multiplied by a factor of 5 in order to show more detail. (a) The weak transition ($\lambda 1240$) small-aperture data; (b) the weak transition large-aperture data; and (c) the strong transition ($\lambda 2800$) large-aperture data.

increased S/N shows the need for high-quality data for this type of analysis. The μ Col component-fitting procedure produced a branching ratio of 1.74 ± 0.11 . A weighted average of all of the values gives the branching ratio

1.74 ± 0.06 . Within the errors, this ratio agrees with the theoretical value of 1.78 ± 0.03 determined by TF99. This agreement can also be seen quite clearly from Figures 3, 4, and 5. The center panel of Figure 3 shows the optical depth

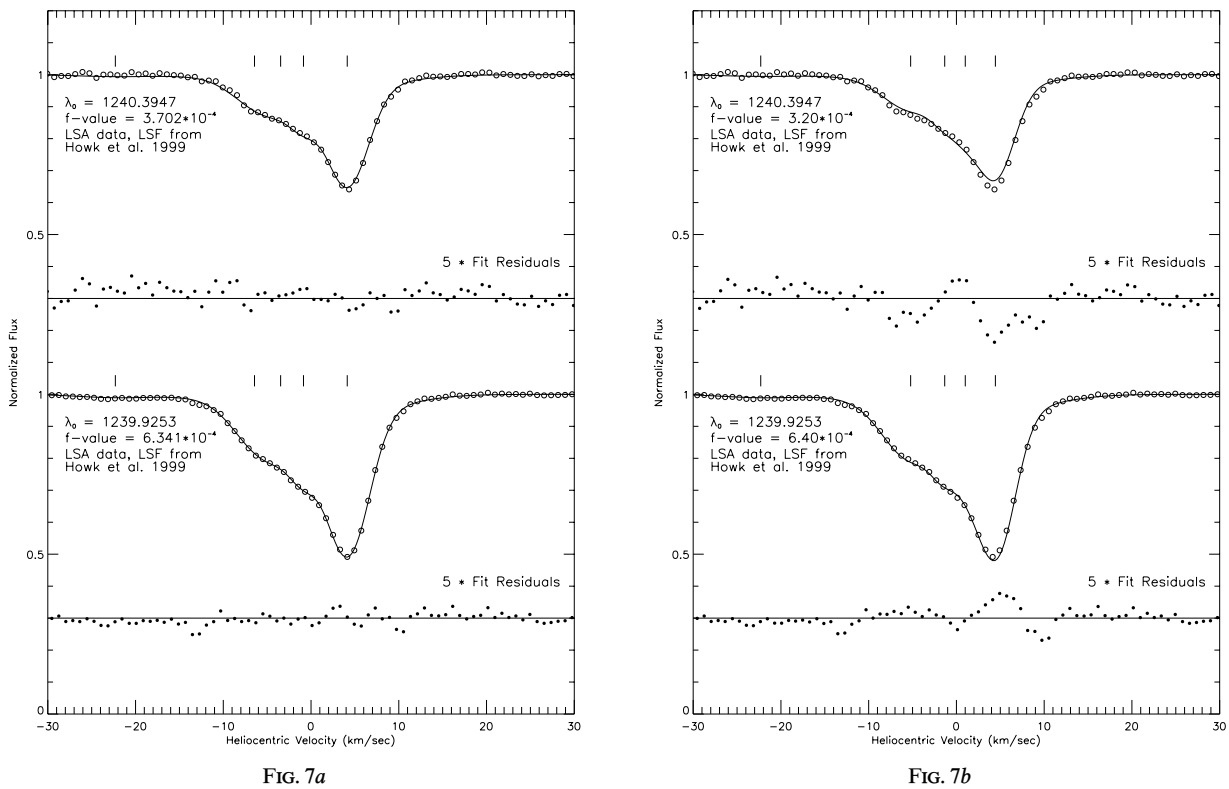


FIG. 7.—Fit to the weak Mg II doublet toward γ Ara. (a) The best fit with a branching ratio of 1.71; and (b) the best fit that we could get with a branching ratio of 2.00. The data are shown as open circles and the fits are shown as solid lines. The residuals shown below the spectrum are multiplied by 5 in order to show detail.

fit using TF99’s branching ratio of 1.78. Although the 1.71 branching ratio obviously is a better fit to the data, the 1.78 value looks like a plausible fit and is within the 1σ errors. The center panels of Figures 4 and 5 show the fit for the μ Col and ρ Leo Mg II $\lambda 1240$ optical depth profiles, respectively, using the mean branching ratio from this paper (1.74). These fits are not significantly worse than the best-fit values for the data shown in the bottom panels of the figures (just as one would expect from the branching ratio fit uncertainties).

The data presented here show not only that the TF99 branching ratio is valid, but also that the previously assumed branching ratio of 2.00 is unreasonable. The top panels of Figures 3, 4, and 5 show the optical depth fits for a branching ratio of 2.00 toward γ Ara, μ Col, and ρ Leo. The fits are unacceptable for the γ Ara and μ Col data. Even the fit to the lower quality ρ Leo data starts to become implaus-

sible. Profile fitting also illustrates the need for a branching ratio below 2.00. Figure 7 shows a profile fitted to our highest quality (γ Ara) Mg II data. We fitted the $\lambda 1240$ lines by starting with the component structure of Welsh et al. (1997). Since the weakest components in the sight line are not well defined, we could not do the full analysis (with the $\lambda 2800$ doublet) that we did with μ Col. We did, however, find a best fit to the $\lambda 1240$ doublet with a branching ratio of 1.71 (the fit is shown in Fig. 7a), the same value found from the optical depth analysis. We do not include this determination of the branching ratio in our mean value, because we believe the fit may not be constrained enough by the $\lambda 1240$ doublet alone. Figure 7b shows the best fit to the data that we could achieve using a branching ratio of 2.00. It is quite apparent that a branching ratio of 2.00 cannot properly fit the data (the poor fit is significant even if the data are not constrained enough to give a reliable branching ratio).

TABLE 2
Mg II $\lambda 1240$ DOUBLET f -VALUES AND BRANCHING RATIOS

Source	f_{tot} ($\times 10^{-4}$)	f_{1239}/f_{1240}	Method
Fitzpatrick 1997	9.6 ± 0.6	2 ^a	GHRS
Fitzpatrick 1999 ^b	9.5 ± 0.6	1.82 ± 0.08	GHRS
Fleming et al. 1998	8.3	2 ^a	Theory
Theodosiou & Federman 1999.....	9.88 ± 0.07	1.78 ± 0.03	Theory
This work	9.71 ± 0.32	1.74 ± 0.06	GHRS

^a A branching fraction of 2.0 was assumed.

^b Fitzpatrick’s reanalysis of the F97 data set as reported in TF99.

It is clear from the high S/N data presented here that a branching ratio of 2.00 is not reasonable for the Mg II doublet. The data used in the F97 analysis of the Mg II had lower S/N or lower spectral resolution than those used here. For those reasons, it was not obvious that a lower branching ratio was needed (i.e., the fits in Fig. 1 of F97 look quite reasonable). Fitzpatrick, however, does get a better fit when a smaller branching ratio is used for the F97 sample (TF99).

Table 2 shows that the f -value for the Mg II $\lambda 1240$ doublet has become much more reliable recently. Including the results from this paper, there are now three recent independent f -value determinations that all agree within their errors. The branching ratio for the doublet is also reliably known. We have clearly shown that the previously assumed branching ratio of 2.00 is inappropriate for the Mg II $\lambda 1240$ ($3s-4p$) doublet. We have further shown that the theoretical branching ratio of TF99 is valid to within our measurement

errors. This result also agrees with Fitzpatrick's reanalysis of the F97 data set as reported in TF99. TF99 point out that the revised branching ratio does not have a great affect on previous results. We have shown, however, that the quality of spectra now available is high enough that they can readily discriminate between branching ratios of 1.78 and 2.00. The TF99 oscillator strengths will help to produce more precise abundances for this important element than were previously possible.

We thank Ed Fitzpatrick for sharing his original software with us. We also thank C. Theodosiou and S. Federman for sharing their results before publication. U. J. S. acknowledges support from the *HST* grant GO-06686.01 and the NASA LTSARP grant NAG5-8249 through Whitman College.

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Note added in proof.—After this paper was accepted, we became aware of the article by Godefroid & Fischer (1999, *J. Phys. B*, 32, 4467) that reports theoretical atomic constants for the Mg II $\lambda 1240$ doublet. These authors find an f -value of 7.42×10^{-4} and the first published branching ratio different than 2.00 with $f_{1239}/f_{1240} = 2.53$. Our results do not support these values.