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THE ABUNDANCE OF Mg IN THE INTERSTELLAR MEDIUM[1,2]

Edward L. Fitzpatrick
Princeton University Observatory, Peyton Hall, Princeton, NJ 08544-1001
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ABSTRACT

An empirical determination of the *f*-values of the far-UV Mg II λλ1239, 1240 lines is reported. The strong near-UV Mg II λλ2796, 2803 lines are generally highly saturated along most interstellar sight lines outside the local interstellar medium (ISM) and usually yield extremely uncertain estimates of Mg^+ column densities in interstellar gas. Since Mg^+ is the dominant form of Mg in the neutral ISM, and since Mg is expected to be a significant constituent of interstellar dust grains, the far-UV lines are critical for assessing the role of this important element in the ISM. This study consists of complete component analyses of the absorption along the lines of sight toward HD 93521 in the Galactic halo and ξ Persei and ζ Ophiuchi in the Galactic disk, including all four UV Mg^+ lines and numerous other transitions. The three analyses yield consistent determinations of the λλ1239, 1240 *f*-values, with weighted means of $(6.4 \pm 0.4) \times 10^{-4}$ and $(3.2 \pm 0.2) \times 10^{-4}$, respectively. These results are a factor of ∼2.4 larger than a commonly used theoretical estimate, and a factor of ∼2 smaller than a recently suggested empirical revision. The effects of this result on gas- and dust-phase abundance measurements of Mg are discussed.

Subject headings: atomic processes — dust, extinction — ISM: abundances — ISM: clouds — ultraviolet: ISM

1. BACKGROUND

The combination of high spectral resolution, photometric precision, and sensitivity provided by the Goddard High-Resolution Spectrograph (GHRS) has transformed the study of UV interstellar absorption lines, enabling a detailed examination of individual absorbing regions in the interstellar medium (ISM). The potential precision of these measurements has also triggered new interest in the determination of the atomic constants, particularly the oscillator strengths (*f*-values), required to convert measured line strengths into gas-phase column densities. Recent improvements in the available body of astrophysically interesting *f*-values have come from empirical studies using interstellar absorption lines, new laboratory measurements, and theoretical calculations (see Table 2 of Savage & Sembach 1996a).

One important species for which the *f*-values remain an impediment to determining accurate column densities is Mg^+, the dominant form of Mg in H I gas. Along most interstellar sight lines—with the exception of those that pass only through the local ISM (e.g., Linsky & Wood 1996)—the near-UV Mg II λλ2796, 2803 lines are strongly saturated and yield limited column density information. The natural source of accurate Mg^+ column densities is thus the only other pair of observationally accessible Mg^+ lines, the intrinsically much weaker λλ1239, 1240 doublet. The usefulness of these lines has been compromised, however, by uncertainty in the *f*-values. In recent years, the theoretical calculations from Hibbert et al. (1983) have been used by many investigators. However, Sofia, Cardelli, & Savage (1994) suggested that these values are a factor of ∼4.6 too small, based on an empirical investigation of absorption toward the star ξ Persei. These two results, listed in the first two rows of Table 1, are mutually inconsistent, given their quoted uncertainties, and imply Mg^+ column densities that differ by nearly a factor of 5. To our knowledge, no laboratory measurements of the λλ1239, 1240 *f*-values have been made, nor do other theoretical calculations shed light on the issue, since they span an even wider range than do the first two entries in Table 1 (Butler, Mendoza, & Zeippen 1984).

Magnesium is one of the most abundant metals and, because it readily condenses into the solid form, is also likely to be one of the main constituents of interstellar dust. In addition, Mg provides a diagnostic of electron density in the gas phase of the ISM, through the ionization ratio Mg^0/Mg^+. An accurate assessment of the importance of Mg in both the gas and the dust clearly must start with accurate column densities. Until laboratory measurements are made, a more definitive empirical determination of the *f*-values of these important features seems the only way to clarify the role of Mg in the ISM and to exploit its diagnostic potential. In this Letter, we report the result of such an empirical determination, based on absorption component analyses of the lines of sight toward the stars ξ Persei (HD 24912), ζ Ophiuchi (HD 149757), and HD 93521. The new analyses and the resultant *f*-values are described in § 2. In § 3, the implications of the revised Mg^+ column densities for interstellar gas and dust studies are discussed.

2. NEW ANALYSIS AND RESULTS

The analysis used here is the "component method," where complex interstellar profiles are assumed to result from the superposition of the absorption from a number of distinct interstellar clouds. The goal of the component method is to determine the set of velocity centroids, velocity widths, and individual atomic column densities that characterize each cloud along a line of sight. This analysis has been applied by us to a number of different sight lines, combining GHRS UV data

[1] Based on observations with the NASA/ESA *Hubble Space Telescope*, obtained at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, under NASA contract NAS5-2655.

[2] This Letter is dedicated to the memory of Professor Lyman Spitzer Jr. He was a great guy.

TABLE 1

OSCILLATOR STRENGTHS FOR Mg II λλ1239, 1240

Source (1)	$f(\lambda1239.9)$ $(\times10^{-4})$ (2)	$f(\lambda1240.4)$ $(\times10^{-4})$ (3)
Hibbert et al. 1983[a]	2.7 ± 0.7	1.3 ± 0.3
Sofia et al. 1994[b]	$12.5^{+7.8}_{-3.8}$	$6.25^{+3.85}_{-1.92}$
This Letter:		
HD 93521	5.65 ± 1.09	2.82 ± 0.55
ξ Per	6.86 ± 0.61	3.43 ± 0.30
ζ Oph	6.10 ± 0.60	3.05 ± 0.30
Weighted mean	6.4 ± 0.4	3.2 ± 0.2

[a] Theoretical calculation.
[b] Empirical result, based on ξ Per data.

with ground-based optical data and, sometimes, 21 cm data. The most recent results are described by Fitzpatrick & Spitzer (1997, hereafter Paper IV) for the star HD 215733 (see that paper and the references cited for a complete description of the process). The analysis in this Letter is the same as in the previous studies, except that the Mg II λλ1239, 1240 f-values are taken as free parameters to be determined from the fit to the data but constrained such that $f(\lambda1240) = \frac{1}{2}f(\lambda1239)$. The basic data processing was also carried out as described in the earlier papers, including the normalization of the interstellar absorption profiles using Legendre polynomials.

For this study, we applied the component analysis to the data for three sight lines, toward the stars ζ Oph, ξ Per, and HD 93521. The final model for ζ Oph is based on 14 UV transitions from seven species (including O^0, Mg^+, Si^+, Cr^+, Mn^+, Fe^+, and Zn^+); for ξ Per, on 18 UV transitions from nine species (including Mg^0, Mg^+, Si^+, S^0, S^+, Cr^+, Mn^+, Fe^+, and Zn^+); and for HD 93521, on 20 UV and optical transitions from nine species (including C^{+*}, Na^0, Mg^0, Mg^+, Si^+, S^+, Ca^+, Mn^+, and Fe^+). All four UV Mg^+ lines (λλ1239, 1240, 2796, and 2803) were included in each of the three analyses. The UV data for ζ Oph and ξ Per were taken from the *Hubble Space Telescope* archives and, with one exception, consist of GHRS echelle observations (Ech-A and Ech-B) obtained with the stars centered in the small science aperture (SSA). The exception is the Mg II λλ2796, 2803 observation toward ζ Oph, which was performed using the G270M intermediate-resolution grating and the SSA. Previous analyses of these data can be found in Savage, Cardelli, & Sofia (1992), Savage et al. (1991), and Cardelli et al. (1991). The data for HD 93521 consist of new cycle 5 GHRS observations obtained in 1996 November for this study, our own earlier GHRS data that were analyzed by Spitzer & Fitzpatrick (1993, hereafter Paper I), and new high-resolution ground-based observations of Ca II λ3933 and Na I λλ5890, 5896. All the GHRS observations of HD 93521 were made using the echelle modes and the SSA.

The component models for ζ Oph and ξ Per were based initially on the Ca II models of Welty, Morton, & Hobbs (1996), then iterated to find the best fits to the UV data. The HD 93521 model was based on our earlier results in Paper I. The details of these new models will be discussed in future papers (Fitzpatrick & Spitzer 1997b). Here we present only the results that pertain to the Mg^+ f-value determination. The normalized line profiles of the four UV Mg^+ lines are shown for each of the three stars in Figure 1 (*filled circles*). Note that the vertical scale is expanded for the HD 93521 λλ1239, 1240 lines and that the HD 93521 data were obtained at a higher

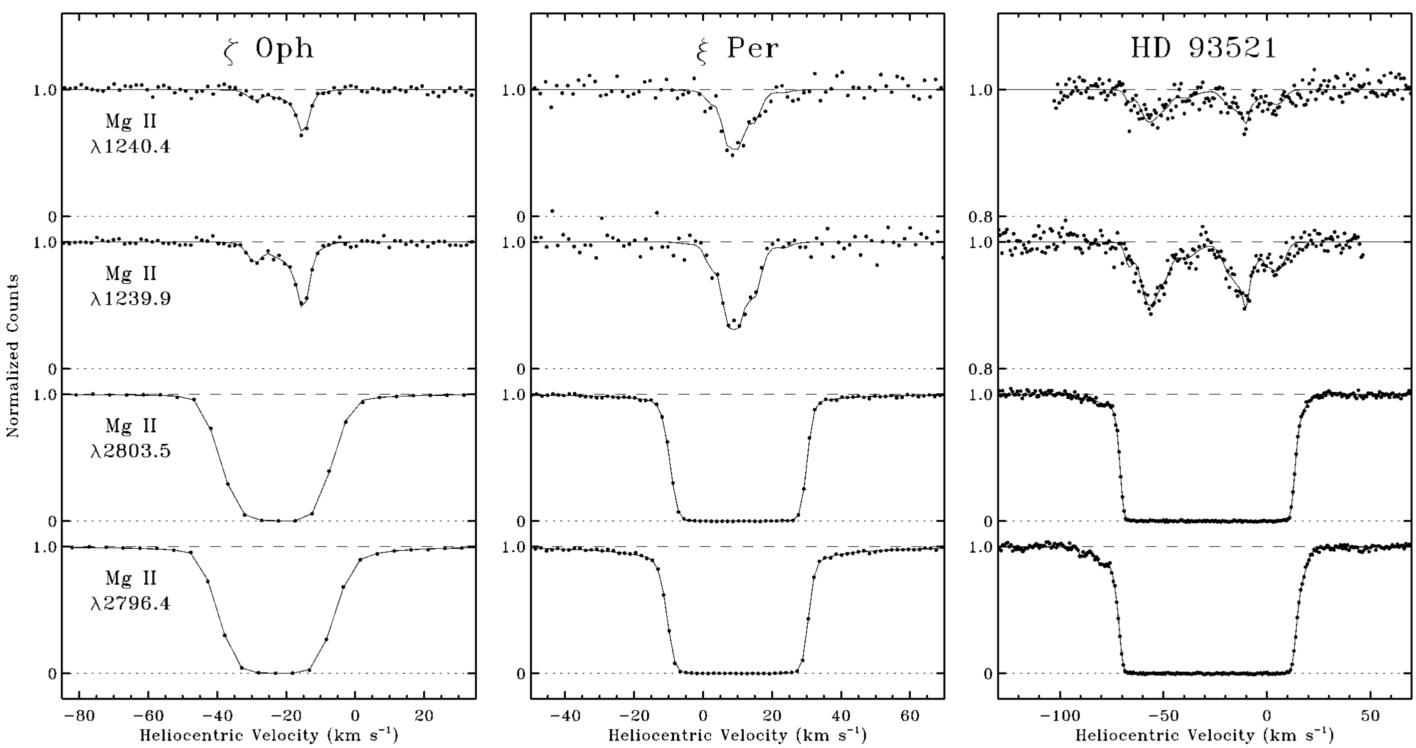

FIG. 1.—Normalized line profiles of the interstellar Mg II λλ1239, 1240, 2796, and 2803 lines are shown for the three stars ζ Oph, ξ Per, and HD 93521 (*filled circles*). All data were obtained with the GHRS using the SSA and the echelle modes, except the λλ2796, 2803 observations for ζ Oph, which were made with the G270M intermediate-resolution grating. The data for HD 93521 have a sampling frequency of 4 data points per GHRS diode, compared with 2 points per diode for the other stars. The solid curves through the data points are the theoretical profiles resulting from the component analyses. Note that the velocity scales are different for the three stars and that the λλ1239, 1240 lines for HD 93521 are shown with an expanded vertical scale.

sampling frequency (4 data points per diode) than those for ζ Oph and ξ Per (2 points per diode). The theoretical profiles resulting from the three component analyses are shown as the solid curves in Figure 1. The $\lambda\lambda$1239, 1240 f-values derived from these analyses are listed in Table 1. These results—as can be seen from the associated 1 σ errors, which incorporate uncertainties in the component models, in the continuum level determinations and from random noise in the data—are all mutually consistent at the 1 σ level and yield final weighted mean values as given in the last row of Table 1.

The fitting procedure that produced the results in Figure 1 and Table 1 is a complex, nonlinear process for determining many variables simultaneously. However, the solution for the f-values can be viewed in simplified form as follows: the *relative* column densities for the various absorption components of Mg^+ are determined from the weak $\lambda\lambda$1239, 1240 lines, which show the component structure clearly; the *total* Mg^+ column density and, hence, the $\lambda\lambda$1239, 1240 f-values are then found by scaling the relative column densities to fit the profiles of the strong $\lambda\lambda$2796, 2803 lines. The agreement of the results from the analyses of three very different sight lines is satisfying, and we believe the weighted means in Table 1 are the best currently available estimates of the $\lambda\lambda$1239, 1240 f-values.

3. DISCUSSION

The new f-values in Table 1 require a revision of all published Mg^+ column densities derived from the $\lambda\lambda$1239, 1240 lines. For those results based on the Hibbert et al. (1983) f-values (e.g., Paper IV and earlier papers in that series), $N(Mg^+)$ should be scaled *downward* by a factor of $\sim$2.4; for those based on the Sofia et al. (1994) results (e.g., Sembach & Savage 1996), $N(Mg^+)$ should be scaled *upward* by a factor of $\sim$2.0. These changes in $N(Mg^+)$ affect two distinct analyses: the determination of n_e in the ISM based on the Mg^0/Mg^+ ratio and the composition of interstellar dust grains. In this section, we briefly consider these two areas.

Evidence was presented in Paper IV showing that very different values of n_e can be obtained for the same interstellar cloud, depending on which n_e diagnostic is employed. In particular, values of n_e derived from ionization equilibrium involving a neutral species (e.g., C^0/C^+, Mg^0/Mg^+, and S^0/S^+) were found to be systematically larger (by 0.4–1.0 dex) than values derived from Ca^+/Ca^{++} ionization equilibrium or from collisional excitation of fine-structure levels in C^+. (These latter two diagnostics appear to be in accord.) The revised f-values presented here have the effect of increasing the values of n_e derived in Paper IV from Mg^0/Mg^+ by $\sim$0.4 dex. From Figure 6 of that paper, it can be seen that this enhances the discrepancy between these values and the Ca^+ results—but also decreases the scatter among the neutral species. N_e values from the neutrals now appear consistent with each other to within $\sim$0.2 dex but are systematically greater than those from other diagnostics by a factor of 0.8–1.0 dex. The cause of this discrepancy is not known, although it seems likely that unaccounted for processes are involved in the recombination of at least some singly ionized species.

Measurements of $N(Mg^+)$ in H I gas, when coupled with an assumed intrinsic abundance of Mg, indicate how much Mg is condensed into interstellar dust grains. Paper I showed, using the Hibbert et al. (1983) f-values and assuming solar system composition, that the total numbers of Mg + Fe atoms

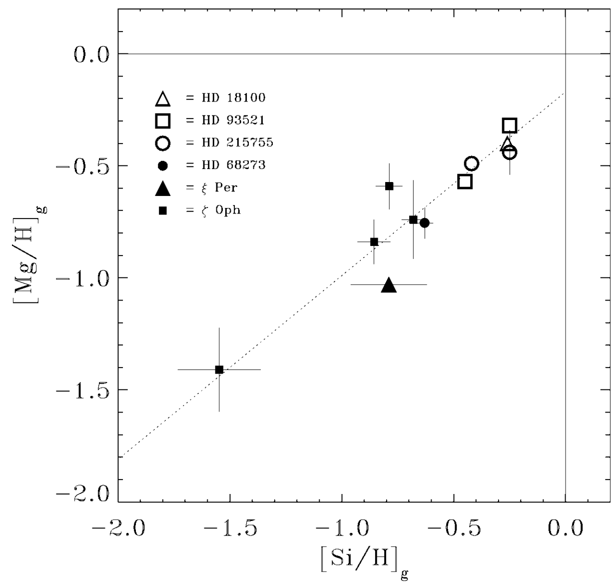

FIG. 2.—Relative gas-phase abundances (or "depletions") of Mg plotted against those of Si for the lines of sight toward the halo stars HD 18100, HD 93521, and HD 215733 and toward the disk stars HD 68273, ξ Per, and ζ Oph (see eq. [1] of Paper IV). Results shown for HD 68273 and ζ Oph are for individual components; for the other sight lines, integrations over multiple components are shown, as detailed below. The dotted line shows a linear fit to the data, with a slope and intercept of 0.82 and -0.17, respectively. The gas-phase abundances for HD 18100, HD 68273, HD 93521, and HD 215733 were normalized using the observed S^+ column densities, for ξ Per by the total H column density ($H^0 + H_2$), and for ζ Oph by the observed Zn^+ column densities, assuming that $[Zn/H]_g = -0.29$ for all the components. Column density errors in the normalization species (which are probably less than 0.1 dex) move the data points along a line of slope = 1, introducing negligible scatter in the observed relation. Results for HD 18100 and ξ Per are integrated over all absorption components; for HD 93521, the results are shown for integrations over the velocity ranges $v < -30$ km s^{-1} and $v > 0$ km s^{-1}; and for HD 215733, $v < -40$ km s^{-1} and $v > -40$ km s^{-1}. Data for HD 93521, ξ Per, and ζ Oph are from this Letter; for HD 18100, from Savage & Sembach 1996b; for HD 68273, from Fitzpatrick & Spitzer 1994; and for HD 215733, from Paper IV.

incorporated into dust at any general depletion level is about twice the number of Si atoms in the dust. This would be consistent with—but does not require—the hypothesis that all of the depleted Fe, Mg, and Si are located in silicate grains. In contrast, Sofia et al. (1994) found, using their much larger estimate of the $\lambda\lambda$1239, 1240 f-values, that the ratio of Mg + Fe atoms to Si atoms in dust grain "cores" is much greater than can arise from silicate grains, indicating that the equivalent of 50% or more of *both* the depleted Fe and Mg atoms must reside in another dust grain population, perhaps oxides. The new $\lambda\lambda$1239, 1240 f-values allow these contrasting conclusions about dust grain composition to be reconciled.

Figure 2 compares the "relative gas-phase abundances" (or "depletions"; see eq. [1] in Paper IV) of Mg and Si for those sight lines with the most secure Mg^+ column densities. The key to the symbols is shown on the figure, and the sources of the data are given in the legend. Unless otherwise indicated, uncertainties are comparable to or less than the symbol sizes. The dotted line shows a linear fit to the data, and has a slope of 0.82 and an intercept of -0.17 dex. Future results may show such a simple linear relation to be inadequate, but at the current time it represents the trend in the data reasonably well. Along this line, from $[Si/H] = -0.2$ to $[Si/H] = -1.5$, the ratio of Mg atoms to Si atoms in the gas varies relatively little, only over the range 0.8–1.3.

The results in Figure 2, combined with comparable data for Fe (shown in Fig. 2 of Fitzpatrick 1996), yield limits on the incorporation of Mg and Fe in silicate grains. In this particular case, and in many others, the strongest constraints on dust grain composition come from the sight lines with the smallest measured amounts of depletion. Along such sight lines, we have [Si/H] $\simeq -0.2$, [Mg/H] $\simeq -0.35$, and [Fe/H] $\simeq -0.55$, which imply 37%, 55%, and 72% of the Si, Mg, and Fe in dust grains, respectively, using the solar system composition as the abundance reference. These yield total dust-phase ratios of Mg/Si = 1.6 and Fe/Si = 1.8. We thus conclude, in qualitative agreement with Sofia et al. (1994), that the total ratio of Fe + Mg atoms to Si atoms in the dust (3.4:1) is greater than the maximum ratio that can be accounted for by silicate grains alone (i.e., 2:1). If the solar system composition is appropriate for the ISM, then these results imply that at least 50% of the total available Mg (i.e., gas + dust) *or* 50% of the total Fe (or some comparable combination, such as 25% of each) must reside in some grain population other than silicates. Alternatively, the Mg, Fe, and Si depletions would be completely consistent with silicates grains if the intrinsic interstellar abundances of Mg or Fe, or both, were reduced relative to Si by these same amounts.

As noted by Fitzpatrick (1996), the gas-phase abundances of some elements, notably Fe, always appear to be subsolar, even along the most lightly depleted sight lines. This result can be interpreted as evidence either for a population of extremely hardy dust grains or for intrinsically subsolar ISM abundances for these elements. Even with this ambiguity in interpretation, however, the observations of the smallest depletions still serve to provide lower limits to the ISM abundances. Magnesium, like Fe and Si, has not yet been detected reliably with a depletion approaching zero. The smallest well-measured Mg depletions are ~ -0.3 dex (see Fig. 2) and indicate that the ISM abundance of Mg is at least 50% of the solar system value. We note that Jenkins & Wallerstein (1996) find essentially zero depletion for Si and Mg toward the halo star HD 120086, but the column densities for Mg^+, Si^+, and the normalizing species S^+ have uncertainties of several tenths of a dex. Follow-up observations of this sight line could be important for discriminating between the two interpretations of the minimum depletions.

In summary, we have presented new, precise empirical measurements of the f-values of the important Mg II λλ1239, 1240 lines based on component modeling of absorption along three lines of sight. These new values require factor of 2 changes (both increases and decreases) in published Mg^+ column densities, which affect the measurements of interstellar electron densities and the determinations of the composition of interstellar gas and dust. The data confirm that not all the Fe and Mg atoms "missing" from the gas phase of the ISM can be incorporated in silicate grains. With the completion of this analysis, the set of f-values available for the most important diagnostic species in the diffuse, neutral ISM (e.g., Mg^+, Si^+, S^+, Fe^+, and Zn^+) appears to be extremely well determined, and finally justifies the common practice of ignoring f-value uncertainties when quoting column density uncertainties!

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