THE ASTROPHYSICAL JOURNAL, Vol. 154, October 1968

ISOTOPES OF MAGNESIUM IN STELLAR ATMOSPHERES*

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Received February 19, 1968

ABSTRACT

High-dispersion coudé spectrograms (3–4 Å mm^{-1}) of ten late-type stars of all luminosity classes have been taken to determine the isotopic abundances of Mg^{25} and Mg^{26} relative to Mg^{24} from the (0,0)-band of MgH near 5211 Å A computer program has been used that determines line profiles from a simple exponential radiative-transfer model and includes the blending effects of nearby lines and both Doppler and instrumental broadening. Profiles were computed for several different isotope ratios and were compared with direct-intensity microphotometer tracings of the spectrograms. It is found that Mg^{25} and Mg^{26} are certainly present in these stars and may be slightly enhanced over their terrestrial abundances.

I. INTRODUCTION

The study of isotopic abundances in stellar atmospheres is limited to a few elements. Information about the isotopes of hydrogen, helium, and lithium can be obtained from their atomic spectra; for a few other elements the molecular spectra can yield estimates or upper limits for the isotope abundances. Of interest in problems of stellar structure and evolution is the varying C^{12}/C^{13} ratio, which can be determined from the C_2 and CN bands (e.g., Wyller 1966). Other isotopes that have been studied from their molecular spectra are those of Ti in TiO by Herbig (1948), N in CN by McKellar (1949), Si in SiH by Schadee (Babcock 1966), and Zr and O in ZrO by Schadee and Davis (1968).

The abundance of the isotopes of magnesium can be studied through the spectrum of the MgH molecule. This has been done in the laboratory spectra of the (0,0)-band by Watson and Rudnick (1926). The two less abundant isotopes, Mg^{25} and Mg^{26}, each compose about 10 per cent of the terrestrial samples; the same ratio in late-type stars would produce observable effects on high-dispersion spectrograms.

According to current theories of nucleosynthesis, Mg^{24} is produced by the α-process or carbon burning. The other two isotopes probably are results of a modified, light-element *s*-process. Thus it is interesting to examine whether the terrestrial isotope ratio is universal or whether there are variations from star to star.

II. MgH SPECTRUM

The calculated and laboratory information regarding the $A\ ^2\Pi$–$X\ ^2\Sigma^+$ transition of MgH has been taken from many sources. The classification of the (0,0) vibrational band (band head at 5211 Å) has been done by Watson and Rudnick (1927). Other vibrational bands have been classified by Guntsch (1939). Laboratory wavelengths were originally listed by Fowler (1909) from 4372 to 5622 Å on the scale of Rowland's *Preliminary Table of Solar Spectrum Wavelengths* but can be reconverted to the absolute scale on which they were measured. These reconverted wavelength measures are in good agreement (all within 0.035 Å) with the later measurements of Watson and Rudnick (1927), with a mean difference for the MgH lines used in the present analysis of $\lambda_F - \lambda_{WR} = +0.02$ Å. Either scale agrees well with the known wavelengths of the stellar atomic lines. Although Fowler's wavelengths were used here, the choice of scale is not crucial: the im-

* This research was supported by the United States Air Force under grant AFOSR 68-1401, monitored by the Air Force Office of Scientific Research of the Office of Aerospace Research.

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portant quantities are the isotope shift and the blending effects of other molecular and atomic lines.

The Franck-Condon factors are known from the work of Ortenberg (1960). The formulations of the line strengths have been collected and refined by Schadee (1967). The wavelength shifts for $Mg^{25}H$ and $Mg^{26}H$ in the lines of the (0,0)-band and the (1,0)-band have been calculated by Schadee (1966). The terrestrial abundances of the magnesium isotopes are Mg^{24}, 78.60 per cent; Mg^{25}, 10.11 per cent; and Mg^{26}, 11.29 per cent (White and Cameron 1948). The molecular constants derived are based on the terrestrial mixture.

III. OBSERVATIONAL MATERIAL

The molecule MgH has long been known to be present in the spectra of late-type stars (e.g., Joy 1926; Öhman 1936; Davis 1937). The (0,0)-band, which begins at 5211 Å and degrades to the violet, is particularly prominent in late K dwarfs but also appears in giants. The (1,0)-band at 4845 Å and the (0,1)-band at 5621 Å are also present but considerably weaker than the (0,0)-band.

Since the spectra of such late-type stars are very crowded with atomic and molecular lines and, since the wavelength shifts for $Mg^{25}H$ and $Mg^{26}H$ are a few tenths of an Ångstrom for the (0,0)-band, high-resolution spectrograms are required to determine the isotope aboundances. The initial spectrograms for this program were taken of 61 Cyg B, a K7 dwarf with very strong lines of MgH. A spectrogram of dispersion 4 Å mm^{-1} on 103aD emulsion, centered at 5000 Å, was kindly secured by Dr. George W. Preston using the 80-inch coudé camera of the 120-inch reflector. In addition, two spectrograms of this same star were kindly taken by Dr. Jesse L. Greenstein at 4.5 Å mm^{-1} in the blue and at 6.8 Å mm^{-1} in the yellow with the coudé spectrograph of the 200-inch telescope. Subsequent spectrograms of nine late-type giants were obtained by the writer using the 73-inch coudé camera of the 100-inch telescope; these spectrograms are of 3 Å mm^{-1} dispersion widened to 0.7 mm, and centered at 5000 Å to include both the (0,0)- and the (1,0)-bands. The stars observed and the details of the spectrograms are given in Table 1.

Direct-intensity microphotometer tracings were made of all the spectrograms at a magnification of 136. Identifications of atomic and molecular features were made on these tracings with the help of the identification list for β Peg (Davis 1947), the MgH list by Fowler (1909), and the MIT wavelength tables.

After each spectrogram was traced on the microphotometer, intensity traces were made with the same slit settings along three or four calibration strips covering a sizable range in intensity, in order to estimate the amount of grain noise at different intensities. The tracing of the stellar spectrogram was then smoothed out using these strip tracings as a guide to the fluctuations due to emulsion grain.

IV. ANALYSIS

Although the calculated isotope shifts for the (1,0)-band are about twice as large as those for the (0,0)-band, the (1,0)-band was not used in any more than a confirmatory manner, for several reasons. First, the $Mg^{24}H$ lines of the (1,0)-band are much weaker than those of the (0,0)-band and in some stars cannot be firmly identified. Second, there is much overlying TiO in that spectral region. Also, the isotope shift for $Mg^{25}H$ is often nearly the same magnitude as the doublet splitting, making accurate measurement difficult.

Three wavelength regions, including fourteen MgH lines of the (0,0)-band, in which the MgH lines are fairly free from blends, were chosen to be analyzed in the following manner. A computer program that computes and plots the molecular band has been developed by Dr. A. Schadee in connection with work on isotopes of the ZrO spectrum; the method is described in some detail by Schadee and Davis (1968). This program was somewhat modified for application to the magnesium-isotope problem. The input data included wavelengths and calculated relative line strengths for $Mg^{24}H$, wavelength shifts and abundance ratios for the magnesium isotopes, wavelengths and measured intensities for the atomic lines, a Doppler half-width, and an instrumental half-width.

The atomic and molecular lines are broadened by a Gaussian function, given the Doppler half-width, and residual intensities are determined from a simple exponential relation, including the blending effects of adjacent lines. The theoretical profiles are then broadened by the instrumental Gaussian function. The computer plots a continuous curve, giving the predicted residual line intensities over the desired wavelength interval at a dispersion matching that of the microphotometer tracings. The Doppler half-widths for these stars are typically 0.13–0.15 Å (about 8 km sec^{-1}), while the instrumental half-width for the Mount Wilson plates (dispersion 3 Å mm^{-1}) is 0.03–0.04 Å (about 2 km sec^{-1}). Table 2 lists the MgH lines used in the analysis. Successive columns give the line identification, the wavelength given by Fowler converted back to the absolute scale as discussed by him (1909), the isotope shifts for $Mg^{25}H$ and $Mg^{26}H$, and the relative intensities calculated for 3500° and 3900° K. In general, the values for 3900° were used for the K stars, and those for 3500° for the M stars. When normalized to the continuum, the two sets of values differ very little. The wavelength intervals that were plotted are 5087–5092, 5115–5123, and 5133–5136 Å. These intervals include many

TABLE 1

OBSERVATIONS

Star	Spectral Type	Disp. (Å mm^{-1})	Emulsion	Star	Spectral Type	Disp (Å mm^{-1})	Emulsion
β And	M0 III	3	Baked IIaD	π Her	K3 II	3	Baked IIaD
γ Eri	M1 III	3	Baked IIaD	β Oph .	K2 III	3	Baked IIaD
α Hya	K4 III	3	Baked IIaD			4	103aD
ϵ Crv	K3 III	3	Baked IIaD	61 Cyg B	K7 V	6 8	IIaD
δ Vir	M3 III	3	Baked IIaD			4 5	Baked IIaO
δ Oph	M1 III	3	Baked IIaD	ϵ Peg	K2 Ib	3	Baked IIaD

TABLE 2

MgH LINES USED

IDENTIFICATION	λ (FOWLER)	Δλ $Mg^{25}H$	Δλ $Mg^{26}H$	RELATIVE INTENSITIES	
				3500° K	3900° K
$R_2(19)$	5088 72	+0 18	+0 34	2 09	2 29
$R_1(19)$.	5089 21	18	34	2 20	2 40
$Q_2(32)$	5090 38	19	36	1 32	1 77
$Q_1(32)$.	5090 74	19	36	1 37	1 71
$Q_2(27)$.	5116 16	.13	.26	2 27	2 82
$Q_1(27)$.	5116 47	13	26	2 36	2 72
$R_2(14)$	5118 34	12	23	2 35	2 48
$R_1(14)$.	5118 80	12	23	2 52	2 65
$Q_2(26)$	5120 88	12	24	2 48	3 06
$Q_1(26)$	5121 23	12	24	2 58	2 94
$Q_2(23)$	5134 22	10	19	3 13	3 72
$Q_1(23)$	5134 58	10	19	3 26	3 57
$R_2(11)$	5134 58	09	18	2 28	2 35
$R_1(11)$	5135 09	+0 09	+0 18	2 48	2.56

atomic lines, and from these the correctness of the Doppler half-widths, the effects of blending, and an estimate of the accuracy of the method can be evaluated. The five different isotopic abundance mixtures tried are defined in Table 3.

V. RESULTS

The observed and computed tracings were compared, and the Doppler width and the isotope mixture that gave the best fit were determined. Figure 1 compares a section of the observed tracings with the profiles computed with the terrestrial mixture and the computed "20 per cent" mixture (mix V) for two stars in part of the first wavelength region (5087–5092 Å). Figure 2 shows a region in the third wavelength interval for two other stars; here the isotope shift is too small to separate the isotopic lines, but the effect on the line profile is still apparent. Figure 3 shows both a part of the first and a part of

TABLE 3

ISOTOPIC MIXTURES (PER CENT)

Mix	Mg^{24}	Mg^{25}	Mg^{26}
I. Terrestrial	78 6	10 1	11 3
II. Only Mg^{24} .	100 0	0 0	0 0
III Mg^{26} enhanced	69 9	10 1	20 0
IV. No Mg^{26} . . .	89 9	10 1	0.0
V. Mg^{25} and Mg^{26} enhanced	60 0	20 0	20 0

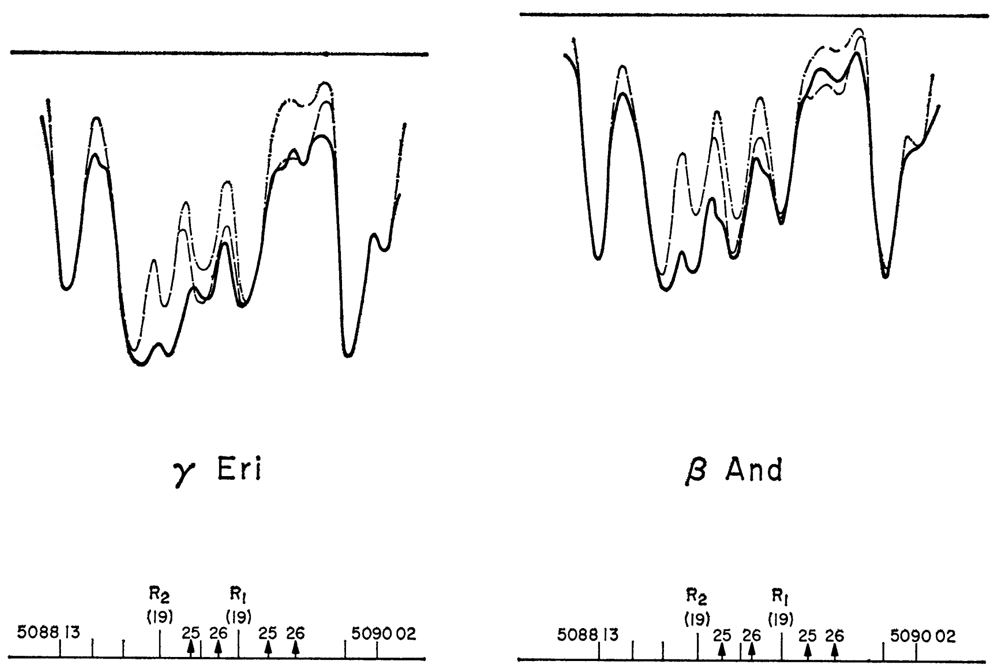

FIG 1.—Observed and computed tracings of part of the first wavelength region (5087–5092 Å) for γ Eri and β And *Heavy solid line:* observed profile; *dashed-dotted line:* profile computed with the terrestrial isotope mixture (mix I); *dashed line:* profile computed with mix V—Mg^{25} and Mg^{26} both enhanced (only the dashed line is shown in regions where the two computed profiles agree); *upper horizontal line:* position of the continuum The centers of the atomic and molecular lines used in calculating the profiles are marked on the lower horizontal line (= clear plate) There is probably an unidentified line blending with $R_2(19)$

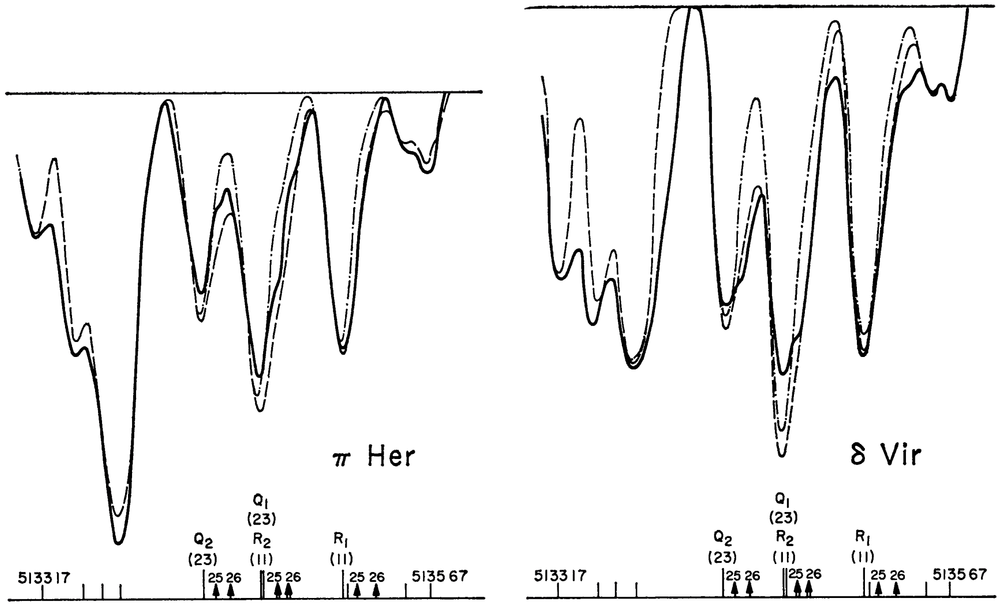

FIG. 2.—Observed and computed tracings of the third wavelength region (5133–5236 Å) for π Her and δ Vir. The line symbols are the same as for Fig 1.

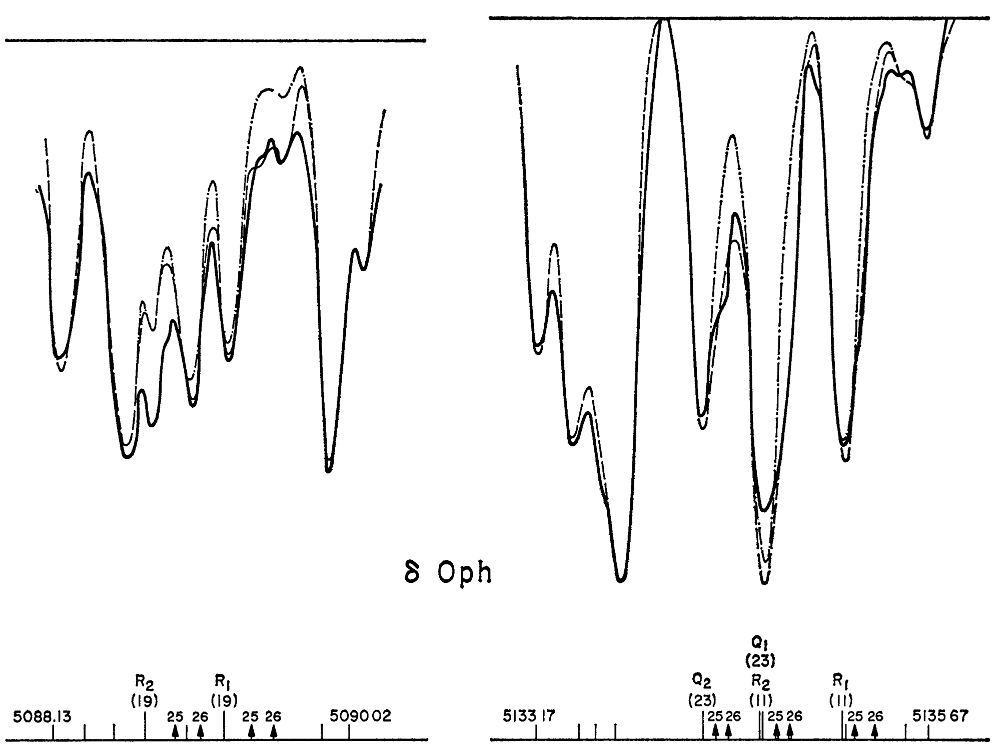

FIG. 3.—Observed and computed tracings in both the first and the third wavelength regions for δ Oph. The line symbols are the same as for Fig. 1.

the third wavelength region for another of the stars. These figures imply that the observations agree better with the 20 per cent mixture than with the terrestrial. This may be due to effects of saturation, as discussed below.

The MgH line in the clearest region is $R_1(19)$. For these stars the optical depth in the center of this line is, typically, 0.40. If the dependence of residual intensity on optical depth varies as $1/(1 + \tau)$, rather than the exponential form used here, the corresponding optical depth for $R_1(19)$ is, typically, 0.50. With either relation, the optical thickness at the centers of the isotope lines is 0.035 for the terrestrial mixture and 0.07 for the 20 per cent mixture. The measured equivalent width of the $R_1(19)$ line for $Mg^{24}H$ ranges from about 25 mÅ for ϵ Peg to almost 120 mÅ for 61 Cyg B; the majority of the stars studied here have equivalent widths near 60–70 mÅ ($\log W/\lambda \simeq -4.90$). If lines in these stars start to become saturated near $\log W/\lambda = -5.00$ ($W_\lambda = 51$ mÅ), then we must consider slight saturation effects. The direction of this effect would be to overestimate the number of isotopic molecules necessary to match the observed profiles. The stars in which the equivalent width of $R_1(19)$ is <50 mÅ (β And, π Her, ϵ Crv, ϵ Peg) seem to fit a mixture intermediate between the terrestrial and the 20 per cent mixture (cf. Fig. 1 for β And).

On the basis of this analysis we may conclude that Mg^{25} and Mg^{26} are certainly present in stars with an abundance ratio relative to Mg^{24} not radically different from the terrestrial ratio, and there may even be an enhancement over the terrestrial values of both isotopes by a small factor, as shown. It is not possible to distinguish any star-to-star variations from this analysis.

I wish to thank Dr. George H. Herbig for suggesting this work, and Dr. Jesse L. Greenstein and the Mount Wilson and Palomar Observatories for their hospitality. I am especially indebted to Dr. Aert Schadee for modifying his computer program for application to this research, for the use of his unpublished isotope shifts for the (0,0)-band, and for several helpful discussions on molecular spectroscopy.

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