Peculiar Versus Normal Phenomena in A-Type and Related Stars
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SEARCH FOR MAGNETIC FIELDS IN VEGA, GAMMA GEMINORUM, AND SIRIUS

MASAHIDE TAKADA-HIDAI and JUN JUGAKU
Research Institute of Civilization, Tokai University
1117 Kitakaname, Hiratsuka, Kanagawa, 259-12 Japan
E-mail(Internet): BHIDAIX@C1.MTK.NAO.AC.JP
BJUGAKU@C1.MTK.NAO.AC.JP

ABSTRACT Magnetic fields in Vega, γ Geminorum, and Sirius are searched by using empirical and theoretical relations of magnetic-field strength to the relative differences between the equivalent widths of each pair of the two Fe II lines near 6150 and 4400 Å. We estimated the possible strengths of their magnetic fields as follows: 0.0 kG or 2.5 – 3.5 kG for Vega, 0 – 2 kG or 2.8 – 3.0 kG for γ Gem, and 0.0 kG or $\sim$ 2(?) – 2.5 kG for Sirius. The empirical relation yields the former value in each star, which is consistent with those determined through polarization measurements, while the theoretical relation the latter with systematically large values.

INTRODUCTON

Mathys (1990) proposed a new simple method to determine stellar magnetic fields with the help of an empirical correlation of magnetic-field strength (H) with the ratio of $\Delta W_\lambda/\bar{W}_\lambda$, where ΔW_λ is defined as $\Delta W_\lambda \equiv W_\lambda(6147) - W_\lambda(6149)$, i.e., the difference of the equivalent widths (W_λ) of the two Fe II lines at 6147.74 Å and 6149.24 Å (hereinafter, denoted as *red* pair) and $\bar{W}_\lambda$ is their average value. Mathys and Lanz (1990) applied this method to the hot metallic-line A (Am) star o Peg and found that o Peg has a magnetic field of $\sim$ 2 kG with a complex structure, which cannot be detected through usual polarization measurements. Very recently, Mathys and Lanz (1992) analyzed high-resolution spectroscopic data of Ap stars with resolved magnetically split lines and found a more improved empirical correlation of H with $\Delta W_\lambda/\bar{W}_\lambda$, which is valid for a range of $3 \leq H \leq 5$ kG.

On the other hand, Takeda (1991) theoretically investigated the relations of H vs. $\Delta W_\lambda/\bar{W}_\lambda$ for the red pair of Fe II lines near 6150 Å and a pair of the two Fe II lines at 4385.4 Å and 4416.8 Å (hereinafter, denoted as *blue* pair), based on a model atmosphere with $T_{\rm eff}$ = 9500 K and log g = 3.5. Using the theoretical relations, he estimated the magnetic field in o Peg at $H \sim 2 - 3$ kG which agrees well with the result of Mathys and Lanz (1990). This successful agreement suggests that the relation of H vs. $\Delta W_\lambda/\bar{W}_\lambda$ is a credible, powerful tool for detecting magnetic fields which have a complex structure and cannot be detected by polarization measurements.

In this paper, we analyze the above-mentioned red and blue pairs of Fe II lines observed in two so-called normal A stars, Vega (spectral type A0V) and γ Gem (A0IV), and an Am star, Sirius (A1V), to search for their magnetic fields with the help of the empirical and theoretical relations of H vs. $\Delta W_\lambda/\bar{W}_\lambda$ derived by Mathys and Lanz (1990, 1992) and Takeda (1991), respectively.

OBSERVATIONS AND REDUCTIONS

Data of the red pair of Fe II lines are based on our observations carried out on 1991 March 9, 12, and 13 UT with the coudé feed telescope of the Kitt Peak National Observatory (KPNO), National Optical Astronomy Observatories (NOAO). The detector used is a Texas Instruments CCD TI3 with an 800×800 array of pixels with 15-μm size. We obtained high-resolution spectra of the red pair in Vega, γ Gem, and Sirius with a reciprocal dispersion of 2.1 Å mm^{-1} and resolution of $\simeq 8.5 \times 10^4$.

The observed raw spectral data were processed with the reduction program SPECRED at KPNO. Further reductions and measurements of these processed data were carried out at the National Astronomical Observatory of Japan (NAOJ) using the Image Reduction and Analysis Facility (IRAF) which is distributed by NOAO (cf. Tody 1986). Wavelength calibration, coaddition, and normalization of spectra were executed following the same procedure as adopted by Takada-Hidai and Jugaku (1992) who analysed the spectra of the red pair in the HgMn star μ Lep observed during the same period of the observations of the present sample stars. In Figure 1,

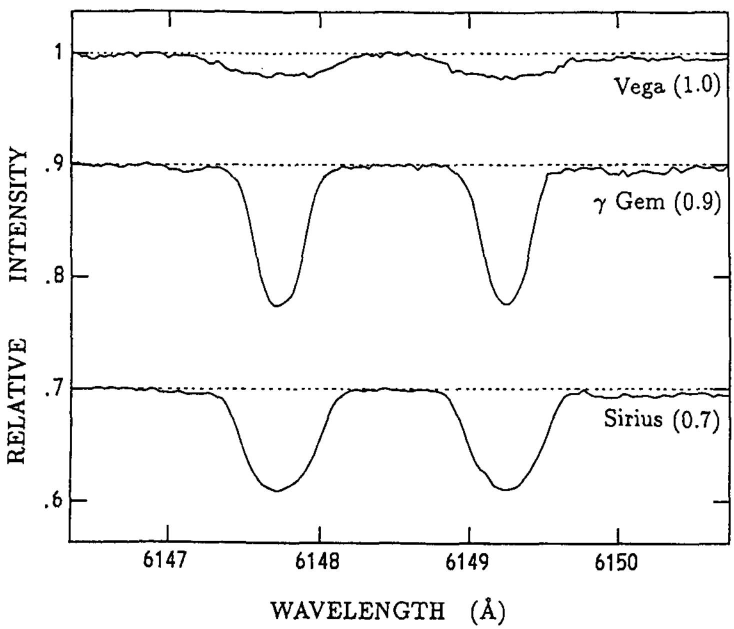

Fig. 1. Normalized spectra of the red pair of the Fe II lines at 6147.7 and 6149.2 Å observed in the sample stars. The continuum level of each star's spectrum is shifted according to the value given in parentheses beside its name.

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we show the resulting spectra of the red pair observed in the sample stars. Measurements of the W_λ of the two Fe II lines were made by direct integration on normalized spectra. Resulting values of W_λ and their rms errors are given in rows 2 and 3 of the red-pair panel in Table I with the average signal-to-noise ratios (S/N) measured for each star.

As concerns data of the blue pair of Fe II lines, we adopted them from the previous works cited in the last row of the blue-pair panel in Table I. The W_λ of the blue pair are given in rows 3 and 4 with both entries of the detector used and the S/N measured in each work, as far as data are available.

TABLE I. Equivalent Widths (mÅ) of the Red and Blue Pairs of Fe II Lines

data	Vega	γ Gem	Sirius
	red pair		
S/N	850	1120	1290
$W_\lambda(6147)$	15.0 ± 0.05	46.6 ± 0.04	46.7 ± 0.05
$W_\lambda(6149)$	14.8 ± 0.05	45.0 ± 0.04	46.2 ± 0.02
	blue pair		
Detector	reticon	photograph	photograph
S/N	1000	——	——
$W_\lambda(4417)$	41	76.8	80
$W_\lambda(4385)$	39	78.0	90
Reference	AG	SK	KO

Ref.: AG=Adelman and Gulliver 1990, SK=Savanov and Khalilov 1985, KO=Kohl 1964.

ESTIMATION OF H

First, we estimated the magnetic-field strengths (H) of the sample stars from the values of $\Delta W_\lambda/\bar{W}_\lambda$ for the red pair. These $\Delta W_\lambda/\bar{W}_\lambda$ were calculated from the W_λ given in Table I and are shown in Table II. The values of H (in kG) derived from the empirical relation of Mathys and Lanz (1990, 1992) are denoted as $H_{\rm ML}$ and given in the second row of the red-pair panel. When we estimated the $H_{\rm ML}$ for γ Gem, we took account of the case of o Peg with its $H_{\rm ML} \sim 2$ kG and $\Delta W_\lambda/\bar{W}_\lambda = 0.052$ (Mathys and Lanz 1990). Since the $\Delta W_\lambda/\bar{W}_\lambda = 0.035$ of γ Gem lies between those of stars with $H_{\rm ML} = 0.0$ kG and that of o Peg, the possible range of the $H_{\rm ML}$ was estimated at $0 < H_{\rm ML} < 2$ kG.

On the other hand, the values of H derived from Takeda's (1991) theoretical relation are denoted as $H_{\rm TK}$ and given in the third row of the red-pair panel in Table II. Estimatin of $H_{\rm TK}$ is based on the relation calculated for the case of a microturbulent magnetic field (referred to as MT) with a microturbulence $\xi = 0$ km s^{-1}, because the microturbulent magnetic field may correspond to a magnetic field which has a complex structure and is just such a field as we search for in this study. Error bars for $H_{\rm TK}$ come from those for $\Delta W_\lambda/\bar{W}_\lambda$.

Next, we estimated the H from the $\Delta W_\lambda/\bar{W}_\lambda$ for the blue pair by using Takeda's (1991) relation for the case of MT with $\xi = 0$ km s^{-1}. The $\Delta W_\lambda/\bar{W}_\lambda$ were calculated from the W_λ given in Table I, where $\Delta W_\lambda \equiv W_\lambda(4417) - W_\lambda(4385)$, and are given in the blue-pair panel in Table II together with the estimated $H_{\rm TK}$. The $H_{\rm TK}$ of Sirius is a rougher estimate because it is inferred from the behavior that the $\Delta W_\lambda/\bar{W}_\lambda$ becomes a minimum at $H \sim 2$ kG in the H vs. $\Delta W_\lambda/\bar{W}_\lambda$ relation, although there is no solution for the $\Delta W_\lambda/\bar{W}_\lambda = -0.118$.

In the lower panel of Table II, we give the possible values or ranges of both $H_{\rm ML}$ and $H_{\rm TK}$. The possible range of $H_{\rm TK}$ for γ Gem is determined by taking the $H_{\rm TK}$ in the blue pair consistent with that in the red pair.

TABLE II. Magnetic-Field Strengths Estimated from the Red and Blue Pairs of Fe II Lines

quantity	Vega	γ Gem	Sirius
		red pair	
$\Delta W_\lambda/\bar{W}_\lambda$	0.013 ± 0.007	0.035 ± 0.002	$0.011 \pm ^{0.001}_{0.002}$
$H_{\rm ML}$(kG)	0.0	0 – 2	0.0
$H_{\rm TK}$(kG):MT	2.50 ± 0.08	2.78 ± 0.07	2.46 ± 0.04
		blue pair	
$\Delta W_\lambda/\bar{W}_\lambda$	0.050	−0.016	−0.118
$H_{\rm TK}$(kG):MT	3.53	0.48, 3.00	~ 2(?)
		possible values or ranges	
$H_{\rm ML}$(kG)	0.0	0 – 2	0.0
$H_{\rm TK}$(kG):MT	2.5 – 3.5	2.8 – 3.0	~ 2(?) – 2.5

TABLE III. Magnetic-Field Strengths Determined Through Polarization Measurements

star	H (kG)	reference
Vega	$(+0.30, -0.015) \pm 0.015$	Severny (1970)
	$(+0.100, -0.060) \pm 0.010$	Severny, Kuvshinov, and Nikulin (1974)
	-0.009 ± 0.019	Landstreet (1982)
γ Gem	-0.165 ± 0.120	Landstreet (1982)
Sirius	$+0.038 \pm 0.012$	Severny (1970)
	$(+0.056, -0.024) \pm 0.005$	Severny, Kuvshinov, and Nikulin (1974)
	$+0.020 \pm 0.020$	Borra, Landstreet, and Vaughan (1973)

CONCLUSIONS

To compare our derived values of H with those determined through polarization measurements, we summarized the previous works in Table III. From Tables II and III, we may conclude as follows: (1) The empirical values of H_{ML} are consistent with the values of H measured through polarization, while the theoretical values of H_{TK} are systematically larger than the H_{ML} and the H measured through polarization. (2) That γ Gem has the strongest magnetic field in our sample stars may be consistently inferred from the results of H_{ML}, H_{TK}, and H measured through polarization.

The reasons for disagreement between H_{ML} and H_{TK} should be left open for the present. To discuss the disagreement and to search for magnetic fields in so-called non-magnetic stars by using the empirical and theoretical relations of H vs. $\Delta W_\lambda/\bar{W}_\lambda$, very high-quality, high-resolution observations are needed for the red and blue pairs of Fe II lines. It is also neccessary to establish the H vs. $\Delta W_\lambda/\bar{W}_\lambda$ relation in the range $0 \leq H \leq 3$ kG for the red pair as well as in the range $0 \leq H \leq 5$ kG for the blue pair.

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