

THE LORENTZ FORCE IN ATMOSPHERES OF CP STARS: Θ AUR

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ABSTRACT

The slow evolution of global magnetic fields and other dynamical processes in atmospheres of CP magnetic stars lead to the development of induced electric currents in all conductive atmospheric layers. The Lorentz force, which results from the interaction between a magnetic field and the induced currents, may modify the atmospheric structure and provide insight into the formation and evolution of stellar magnetic fields. This modification of the pressure-temperature structure influences the formation of absorption spectral features producing characteristic rotational variability of some spectral lines, especially the Balmer lines (Valyavin et al., 2004 and references therein). In order to study these theoretical predictions we began systematic spectroscopic survey of Balmer line variability in spectra of brightest CP magnetic stars. Here we present the first results of the program. A0p star Θ Aur revealed significant variability of the Balmer profiles during the star's rotation. Character of this variability corresponds to that classified by Kroll (1989) as a result of an impact of significant Lorentz force. From the obtained data we estimate that amplitudes of the variation at H_α , H_β , H_γ and H_δ profiles reach up to 2.4% during full rotation cycle of the star. Using computation of our model atmospheres (Valyavin et al., 2004) we interpret these data within the framework of the simplest model of the evolution of global magnetic fields in chemically peculiar stars. Assuming that the field is represented by a dipole, we estimate the characteristic e.m.f. induced by the field decay electric current (and the Lorentz force as the result) on the order of $E \sim 10^{-11}$ cgs units, which may indicate very fast ($\ll 10^{10}$ years) evolution rate of the field. This result strongly contradicts the theoretical point of view that global stellar magnetic fields of CP stars are fossil and their the characteristic decay time of about 10^{10} yr. Alternatively, we briefly discuss concurring effects (like the ambipolar diffusion) which may also lead to significant atmospheric currents producing the observable Lorentz force.

Key words : stars: chemically peculiar – stars: magnetic fields – stars: atmospheres

I. INTRODUCTION

Magnetic chemically peculiar (CP) stars comprise 10–15% of the main sequence B–F stars. Statistical properties of the fields in these stars and results of detailed modelling of field geometries in individual objects are generally consistent with the picture of smooth, roughly dipolar (e.g., Landstreet, 2001) or quadrupolar magnetic field (Bagnulo et al., 2002), inclined with respect to the stellar axis of rotation. It is currently believed, that in a contrast to solar-type stars having dynamo-generated complicated fields, magnetic fields of convective-free CP stars are fossil remnants of the galaxy magnetic field. The conventional model of such fields suggests them to be slowly decaying with the

characteristic decay time of about 10^{10} yr (Moss, 1984). If so, then the fields are nearly force-free (i.e., the Lorentz force is close to zero) and do not significantly change the hydrostatic structure of stellar atmospheres (Landstreet, 1987). It should be noted however, such a long time scale of the field evolution has been obtained under very simplified assumptions. The life time of A-B stars on the order of 10^8 yr suggests that significant transformation of a star during evolution across the HR diagram reduces the field evolution rate toward much shorter times. In this case the quick field evolution may be revealed and described through the significant magnetic force term in atmospheres of magnetic CP stars (Valyavin et al., 2004). This implies that a study of the Lorentz force in atmospheres of CP stars is of fundamental importance for understanding the origin and evolution of global stellar magnetic fields.

The Lorentz force in atmospheres of CP stars appears as a result of the interaction between their mag-

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netic fields and is induced by the field evolution electric currents. If the field evolutionary rate is significant ($\ll 10^{10}$ years), the Lorentz force may affect the atmospheric structure and produce characteristic variability of spectral lines during a star's rotation (especially hydrogen Balmer lines, Valyavin et al., 2004). Additionally, consideration of any global magnetic field topology gives a large collection of other possibilities for consideration of the non force-free fields in atmospheres of CP stars (for instance Landstreet, 1987; Stępień, 1978; Madej, 1983a, 1983b; Carpenter, 1985; Peterson & Theys, 1981; LeBlanc et al., 1994). Some of these studies suggested that magnetic forces may lead to significant differences between the atmospheric structures of magnetic and non-magnetic stars. This conclusion was supported by photometric studies (Madej et al., 1984; Musielok & Madej, 1988). Spectroscopy of hydrogen lines also points to this direction. Kroll (1989) found variability with amplitudes more than 1% of the Balmer lines in a number magnetic stars. He showed that at least part of this variability can be attributed to the presence of non-zero Lorentz force in the atmospheres of magnetic stars.

Unfortunately, apart from the study by Kroll, who presented low-resolution spectroscopic observations of rotational modulation of Balmer lines in only a few CP stars, there have been no other systematic spectroscopic surveys of Balmer line variability. Such a situation has probably been formed by the following obvious fact: the observational aspect of the problem is too complex, and comprehensive answers to the most important questions can be obtained only within the framework of high-precision, high-resolution spectroscopic observations. Very weak variations in the Balmer profiles (for the majority of the stars are expected to be less than 2% of value) need for reconstruction of strongly broadened spectral features with an accuracy on the order of about 0.1 % of value. Such a level could not be reached by high resolution spectroscopy up to recent. Presently, however, the situation has been significantly improved with the development of high stable fiber-fed spectrographs having outstanding possibilities for study of the fine profile variations.

With this series of papers we begin publication of systematic survey of rotation phase-resolved high-resolution spectra of a sample of bright CP stars. Here we present the first preliminary result on one of the most bright, weak-field magnetic stars, Θ Aur.

II. OBSERVATIONS

The survey was carried out with the BOES echelle spectrograph of the 1.8 m telescope of the Korean Astronomy Observatory. The spectrograph and observational technique are described by Kim (2000). The instrument is a moderate-beam, fiber-fed high-resolution spectrograph which incorporates 3 STU Polymicro fibers of 300, 200 and 80 μm core (the spectral resolution is $R = 30000; 45000; 90000$, respectively). Working wave-

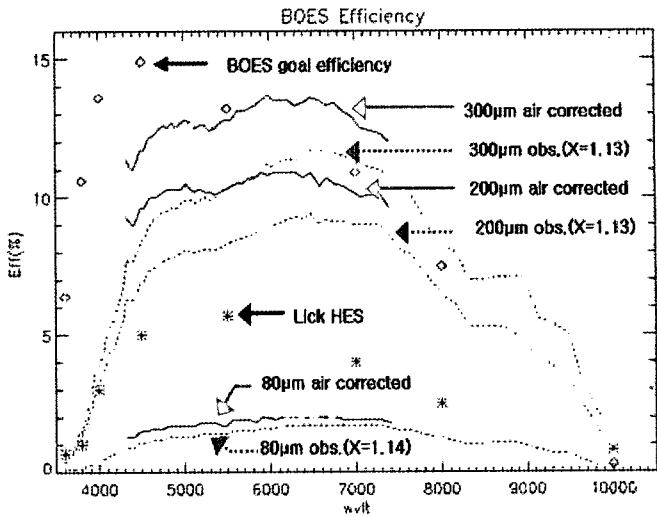


Fig. 1.— Total efficiency of BOES for different fiber types (the measurement on Nov.3,2003).

length range is from 3500 \AA to 10000 \AA . The throughput of the instrument is presented in Fig. 1.

The quite high throughput of the spectrograph at 4100–8000 \AA wavelength range, such as its high stability make it possible to obtain high quality spectra to analyze basic Balmer line profiles with an accuracy of about 0.2-0.3 % (see below).

TABLE 1.
THE OBSERVATIONS OF Θ AUR

DATE	JD	ROTATION PHASE
2004.01.10	2453015.0215	0.70
2004.01.11	2453015.9937	0.95
2004.01.15	2453020.0125	0.05
2004.02.02	2453038.089	0.05
2004.02.03	2453039.1756	0.35
2004.02.04	2453039.9194	0.55
2004.02.05	2453040.9131	0.85
2004.02.07	2453042.9284	0.40
2004.02.10	2453046.0284	0.25

The first star in our list, Θ Aur, is a broad-lined A0p star with a comparatively weak dipolar magnetic field (Wade et al., 2000). We start our survey with this star for the following reasons: during the rotation, the star shows equatorial regions of its magnetosphere (phases 0.2, 0.85, see Wade et al., 2000) as well as the polar areas (phases 0.0, 0.5). As it follows from the above studies, the maximum atmospheric perturbation by the Lorentz force is expected to be at the equatorial plane and it is nearly zero at the polar regions that makes it possible to estimate the magnetic force term from the analysis of the difference between the Balmer line profiles obtained at these two points. In addition, the

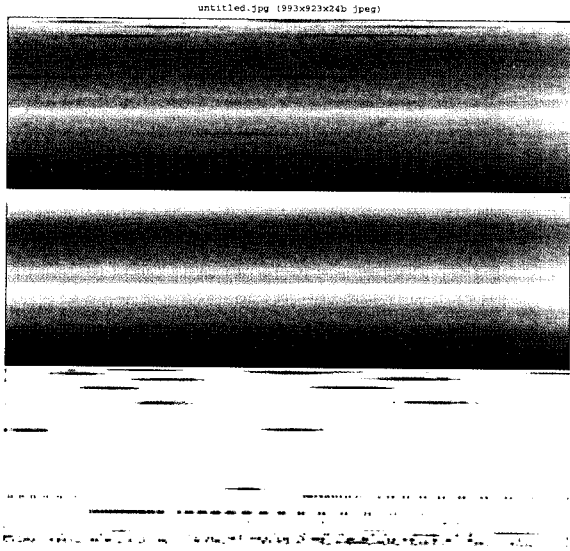


Fig. 2.— An example (from top to bottom) of initial composed image, its 2-D continuum and normalized image.

star is fairly bright and its magnetic field is represented by a dominating dipolar component, which essentially simplifies our first consideration.

Observations of ΘAur were carried out in a course of nine observing nights in the period from January 10, 2004 to February 10. We used the $200 \mu m$ ($R = 45000$) fiber. Table 1 gives an overview of the observations. (In the table: **Date** is the date of an observation; **JD** is corresponding Julian date; **Rotation phase** is a star rotation phase taken from ephemeris presented by Wade et al. (2000)).

The reductions were carried out using the image processing program DECH (Galazutdinov, 2004) and MIDAS package. The general steps are standard, involving the following steps: cosmic ray hits removal, electronic bias and scatter light subtraction, extraction of spectral orders, division by the flat-field spectrum, normalization to the continuum and wavelength calibration. Normalization to the continuum deserves some additional comments.

In order to obtain uniformly reconstructed continuum in all the observed spectra, we apply the following technique. After flat-fielding, all extracted spectral orders of individual frames were merged into new 2D (4000×75) composed fits-images where the orders (75 orders in all) were placed consequently as image rows. Then, filtering by median and Gaussian filters we remove all narrow spectral features in all the spectral orders. Finally, ignoring the Balmer line regions we fit all the images using 2-D cubic spline function forming the 2-D continuum images. Normalized spectra are a result of the normalization of the initial composed images on their 2-D continuum images. Examples of initial image, its 2-D continuum and result of the normalization are

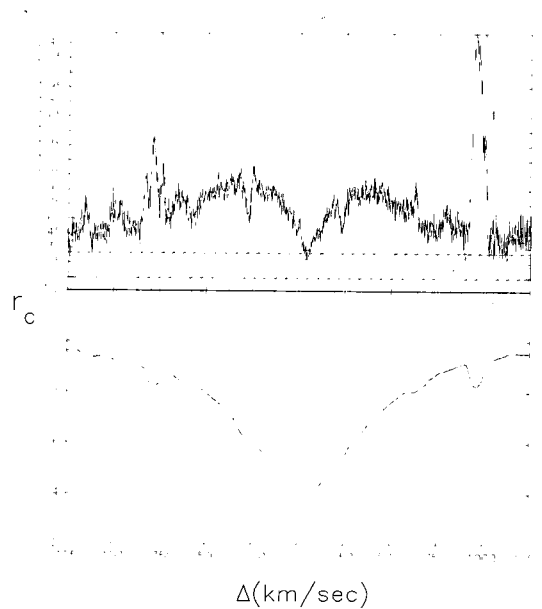


Fig. 3.— Standard deviation $\sigma(\%)$ (the upper plot) and mean H_β profile in km/sec units relative to the line core (the lower plot).

presented in Fig. 2. Our analysis showed that such a technique makes it possible to reach very high accuracy of the continuum reconstruction in the Balmer profiles. In our study the accuracy is as good as 0.2 % of value.

III. RESULTS

For the search of the star's Balmer profile variation we used the normalized spectra at H_α , H_β , H_γ and H_δ regions. In each of the regions we examined the standard deviation $\sigma(\%)$ of individual profiles from the mean profile, averaged over the full rotation cycle. The most clear and significant result were obtained at H_β . The standard deviation at the H_β profile is presented in Fig. 3. Analyzing the other spectral regions in the spectrum of this star (also other stars of the program) we found that the standard deviation by the natural noise or by inaccuracies in spectra processing lies below 0.3% (the dashed area in the upper plot of Fig. 3). Any deviation from this value reflects the presence of significant physical variability.

The standard deviation we have obtained at the H_β line seems to have a characteristic fingerprint: peaks in the wings of the line and a drop at the line center (see the broad-band behaviour of $\sigma(\%)$). Such a shape of the variability in terms of the standard deviation may be understood only as evidence of the presence of non force-free magnetic field in the star (see Stępień, (1978); Kroll, 1989; LeBlanc et al., 1994; Valyavin et al., 2004). The narrow features at the upper plot of the figure are other spectral lines' influence on the Balmer pro-

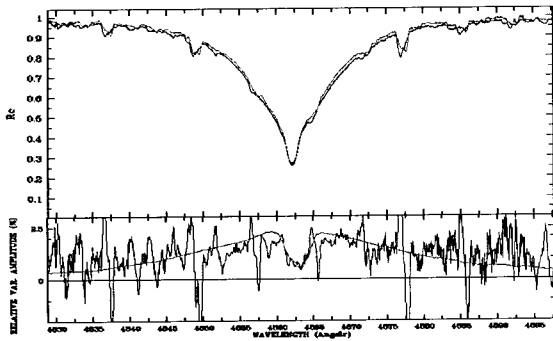


Fig. 4.— H_{β} profiles (the upper plot) of θ Aur obtained at rotation phase $\phi \approx 0.2$ (the black line) and at $\phi \approx 0.5$ (the red line), and their difference (the lower plot).

file. These lines indicate the presence of other chemical compositions which are strongly peculiar and variable during the star's rotation. Their contribution makes the picture noisy, but the predicted behaviour of the Balmer profile variation is clearly seen.

The next figure (Fig. 4) demonstrates the direct difference between the profiles at two specific phase points when the observer look at the magnetic equator (the black lines). The red lines are averaged data obtained with the other spectral lines extracted from the Balmer profile wings. As one can see, the difference is up to $2.2 \pm 0.2\%$ at H_{β} . This result and the shape of the difference over wavelengths suggest the presence of significant Lorentz force which is inward-directed at the equatorial plane of θ Aur magnetosphere. Using our atmosphere model we estimated that H_{β} Stark profile variability with an amplitude of about 2% is produced by induced e.m.f. on the order of about 10^{-11} cgs that exceeds the theoretical value for the fossil field more than 2 orders of value (Valyavin et al., 2004).

IV. CONCLUSION

It is known from theoretical studies, if the magnetic field of a typical CP star is a fossil and approximately dipolar, its characteristic decay time must be about 10^{10} years (Moss, 1984). Such a slow evolution of the global field has negligible effect on the atmospheric structure and cannot produce observable variations of the Balmer line profiles (Landstreet, 1987). However, our present study revealed very strong evidence for the presence of significant Lorentz force in atmosphere of at least one of all known chemically peculiar magnetic stars. Thus, if observations of the strong electric currents in all atmospheres of CP stars are confirmed, we may conclude that the general concept of a slow decay of fossil fields in magnetic CP stars is invalid. The large amplitude of the induced electric currents may indicate

that the dipolar geometry, dominating at the surface, becomes significantly distorted inside a magnetic star. Such a distortion is very likely to occur due to the existence of a convective zone or other dynamical processes in subphotospheric stellar layers.

Alternatively, even in the absence of processes of the dipolar field distortion inside a magnetic CP star, motions of stellar plasma induced by stellar rotation or large-scale diffusion currents (for instance LeBlanc et al., 1994) may also lead to significant surface Lorentz force. In any case, we hope that our survey for more complete sample of stars will stimulate new attempts of MHD modelling of CP stars with alternative boundary conditions. By taking into account *observed* strength of the induced surface electric field as an additional boundary condition, estimates of the decay time and the characteristic strength and configuration of the interior magnetic field can be put on a more sound basis.

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