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# A SEARCH FOR THE ZEEMAN EFFECT IN THE X-RAY STAR CANDIDATES $\theta^2$ ORIONIS AND X PERSEI, THE X-RAY SOURCE CYGNUS X-1, AND THE B2 Ib STAR HD 31327

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## ABSTRACT

Observations of the circular polarization in the wings of the He I line λ6678 in the X-ray star candidates $\theta^2$ Orionis A and X Persei, the X-ray star HDE 226868 (Cygnus X-1), and the B2 Ib star HD 31327 do not show evidence of the longitudinal Zeeman effect.

*Subject headings:* polarization — X-ray sources — Zeeman effect

## I. INTRODUCTION

Some mechanisms for the production of X-rays in binary stars invoke strong magnetic fields (Forman, Jones, and Liller 1972; Bahcall, Rosenbluth, and Kulsrud 1973). There have also been reports (Kemp and Wolstencroft 1973*a*, *b*) of the discovery of the Zeeman effect in some X-ray candidates. However, Angel, McGraw, and Stockman (1973) did not find evidence of the Zeeman effect in HD 77581, nor in HD 153919 for which Kemp and Wolstencroft report longitudinal fields of several thousand gauss. Angel *et al.* observed the circular polarization in the wings of Hα, while Kemp and Wolstencroft observed in Hβ. The fact that Hα has an emission component while Hβ is in absorption can, if not explain totally the discrepancy between the two sets of observations, at least give a reason for a lower Zeeman signal as the circular polarization in the Hα absorption component is diluted by unpolarized emission. Here we report observations of the circular polarization in the wings of the He I line at 6678 Å for two X-ray candidates, an X-ray star, and a B2 Ib star.

## II. THE OBSERVATIONS

The coudé polarimeter of the 100-inch (2.5 m) Mount Wilson telescope was used for the observations. The instrument has been briefly described by Borra and Landstreet (1973). A forthcoming publication (Borra and Vaughan 1975) will describe the instrument in more detail (see also Borra 1972), and will report on extensive observations of known magnetic stars. It is a rapid switching Pockels cell polarimeter used in conjunction with a two-tube high-resolution spectrum scanner. The starlight suffers only one oblique reflection before the analyzer. The phase shifts introduced by the reflection are a function of declination only and are eliminated with a Babinet-Soleil compensator.

Because of mechanical problems, only one tube of the scanner could be used (the movable one). No line profile could therefore be determined. The line used was He I λ6678. A helium emission lamp was observed at least twice throughout a night to calibrate possible wavelength drifts in the spectrograph. The drifts were always negligible. The location of the stellar line was found from the helium lamp, after taking into account the Doppler shifts introduced by the Earth motion and the radial velocity of the star. For Cyg X-1, because of the rapid orbital motion, it was necessary to change the location of the bandpass during the four hours of the run. The bandpass used for all the observations had 1 Å half-width.

The observation of an object lasted from 1 to 4 hours and consisted of sets of integrations of a few minutes' duration, alternating on the short- and long-wavelength wing of the spectral line. The longitudinal Zeeman effect will manifest itself as circular polarization changing handedness on the opposite wings of the line. The signal is superposed on the instrumental polarization, which is small (typically of the order of 0.1%) and changes very slowly with time. Thus for two observations on the opposite wings of the line, at a few minutes' interval, the instrumental polarization can be assumed to be constant.

The observations are listed in table 1. The table gives

TABLE 1

| Date (1974 UT) | $10^2\ q$ | $H_e$ (gauss) | Phase |
|---|---|---|---|
| | HDE 226868 | | |
| Oct 1.25...... | +0.220±0.40 | 350±640 | 0.79 |
| Oct 3.26...... | +0.060±0.33 | 95±520 | 0.15 |
| Oct 4.22...... | −0.08 ±0.25 | −130±400 | 0.33 |
| | HD 31327 | | |
| Oct 1.39...... | +0.02±0.18 | 40±290 | ... |
| | $\theta^2$ Orionis | | |
| Oct 1.49...... | +0.12±0.07 | 770±450 | ... |
| Oct 3.49...... | +0.02±0.07 | 140±450 | ... |
| Oct 4.50...... | +0.01±0.08 | 65±520 | ... |
| | X Persei | | |
| Oct 3.41...... | −0.06±0.18 | ⟨−2300±6900⟩ | ... |
| Oct 4.42...... | +0.32±0.20 | ⟨ 12300±7700⟩ | ... |

the date of the midpoint of the observation; the average circular polarization and its standard deviation; the longitudinal magnetic field in gauss and standard deviation; and the phase. The circular polarization is the mean for the nightly observation and the standard deviation is computed taking photon statistics as the only source of error. Previous experience with the instrument indicates that photon statistics is by far the dominant source of random error. For Cyg X-1 the dark counts and the sky are $\sim 10$ percent of the signal and have been removed and taken into account in computing the random error. The circular polarization is an average for the two wings and is taken to be positive when the polarization in the red and blue wings is such as to give a positive longitudinal magnetic field (vector toward the observer). The phases for HDE 226868 are computed from the ephemeris of Brucato and Zappala (1973). The longitudinal magnetic field *He* is obtained from the circular polarization with the formula

$$q = 4.67 \times 10^{-13}\, g\, He\, \lambda^2\, dI/d\lambda\, I^{-1}\,,$$

where $g$ is the Landé $g$ factor of the line, $I$ the intensity at the center of the bandpass (in units of the continuum), and $dI/d\lambda$ the slope of the wing of the line. The $g$ value used is 1.0. The profile $I(\lambda)$ includes the instrumental profile and rotational Doppler broadening. No stellar line profile was observed. The unbroadened intrinsic line profiles were taken from Auer and Mihalas (1972). The uncertainties in doing so will not be great, with the exception of X Per where the uncertainty is considerable. The lines in X Per are greatly broadened by rotation and mutilated by emission, and the radial velocity and $v \sin i$ of the star are uncertain. The radial velocity used is 17 km s$^{-1}$ as derived by Pearce. The conversion from polarization to longitudinal field for X Per is done assuming $v \sin i = 300$ km s$^{-1}$ and neglecting the emission. The most serious problem is the uncertainty in the radial velocity. If the radial velocity used is wrong, two consecutive measurements might not be on the opposite wings of the line, so the reduction procedure would be meaningless. For $\theta^2$ Ori, $v \sin i \leq 130$ km s$^{-1}$ and is essentially zero for HD 31327 (Slettebak 1956). A width $\sim 3$ Å is deduced from the spectra of HDE 226868.

## III. DISCUSSION

Longitudinal magnetic fields have not been detected in any of the stars observed. Neither is there evidence of fields in time scales of a few minutes (with of course lower accuracy). No longitudinal magnetic field is detected in $\theta^2$ Ori for which Kemp and Wolstencroft report the presence of a variable one. It is possible that the longitudinal component of the magnetic field happened to be small during the observations. However, we must point out that two out of four observations by Kemp and Wolstencroft show a field high enough to be detected with the accuracy of the present work.

The observations of HDE 226868 are especially interesting because of its established identification with Cyg X-1. Also, Bahcall *et al.* predict a polar field of the order of 30,000 gauss for this particular object. The longitudinal field observed will depend on the geometry of the magnetic field and its orientation with respect to the obse·ver. A pole-on dipolar field with a 30,000 gauss polar field would give a longitudinal field of $\sim 10{,}000$ gauss. The same dipole seen equator-on has a null longitudinal component. Preston (1970) tabulates the values of the longitudinal field seen from centered and decentered dipoles for various angles of inclination. Considering that HDE 226868 has been observed at three widely spaced points of the orbit, it seems unlikely that the orientation of a dipole-like field was always so unfavorable. For a given polar field, a complex geometry—e.g., a quadrupole or higher multipole—displays a much smaller longitudinal field than a dipole does. For example, a quadrupole of 30,000 gauss polar field shows a longitudinal component of only 1500 gauss in the most favorable orientation (with a typical limb darkening coefficient of 0.50). Such a complicated field cannot be excluded by the measurements of circular polarization.

A magnetic field will split a spectral line in several components, thus broadening it. The Zeeman broadening depends not on a component of the magnetic field alone, but rather on the strength of the magnetic field averaged over the surface of the star where the line is formed. Thus, one can, in principle, obtain an estimate of the field strength by examining the line profile. A quadrupolar or multipolar field could thus be seen. Unfortunately, early-type stars have only few, broad lines. We can thus hope to see only fairly strong fields. I have compared He I λ6678 in HDE 226868 with the same line seen in several other stars of similar spectral types. All those spectra were taken with the same instrument (Brucato and Zappala 1973) and were compared visually through a spectrum comparator. He I λ6678 does not appear exceptionally broad in HDE 226868. However, because of its intrinsic breadth, the line could possibly hide a surface magnetic field as high as 10,000 gauss. A much higher field (of a few tens of thousands) can, however, be excluded. A similar comparison could not be done with X Per and $\theta^2$ Ori because the lines are so broadened by rotation.

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