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MAGNETIC OBSERVATIONS OF WHITE DWARFS*

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ABSTRACT

A search has been made among the brighter DA-type dwarfs for magnetic fields by using a new, highly sensitive photoelectric polarimeter. No magnetic fields have been detected in the nine stars so far observed, and upper limits of about 10^5 gauss can be placed on fields that may be present.

I. INTRODUCTION

It has recently been pointed out by Woltjer (1969) that one inference to be drawn from recent pulsar models is that many white dwarfs may be expected to have magnetic fields of the order of 10^6 gauss. The reasoning is that if a pulsar is indeed a neutron star with a magnetic field of the order of 10^{12} gauss (Pacini 1968; Gunn and Ostriker 1969), then this magnetic field is probably the result of compression of a field of the order of 10^2 gauss already possessed by the star when it was on the main sequence. The abundance of pulsars indicates that it must be fairly common for main-sequence stars to possess fields of this size. If a main-sequence star possessing a field of 10^2 gauss collapses to the white-dwarf state rather than to the neutron-star state, a general field of the order of 10^6 gauss will result if the flux is conserved, so one might expect many white dwarfs to possess fields of this magnitude. We have therefore undertaken an observational program to measure magnetic fields in white dwarfs, and we present in this paper a preliminary report of our results.

For two reasons, detection of the Zeeman effect in white dwarfs is not straightforward. First, about 75 percent of the known bright white dwarfs are type DA and exhibit only very broad Balmer lines in their spectra. These lines are generally between 20 and 50 Å wide at half-depth (Eggen and Greenstein 1965). Furthermore, observational upper limits may be placed on the fields which may be present in well-observed DA stars that are low enough to make detection of the Zeeman effect in the broad Balmer lines quite difficult. Preston (1970) has recently argued that the absence of displacements due to the quadratic Zeeman effect in the lines of DA stars measured for radial velocity by Greenstein and Trimble (1967) indicates that it is unlikely that DA stars have mean surface fields greater than about 5×10^5 gauss. We may also use the observed sharpness of the cores of the Balmer lines tabulated by Greenstein (1961) to place upper bounds on mean surface magnetic fields that may be present. The effect of a field too weak to split a Balmer line into resolved components is to blunt or round the core; this effect is weakest if the field is largely transverse and the π-component is large relative to the σ-components. If we assume that Hγ splits as a normal Zeeman triplet, which is valid for $H \lesssim 1 \times 10^6$ gauss (see Preston 1970), numerical experiments indicate that the observed sharpness of the line cores of DA stars tabulated by Greenstein (1961) allows us, even if the field is

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PLATE L2

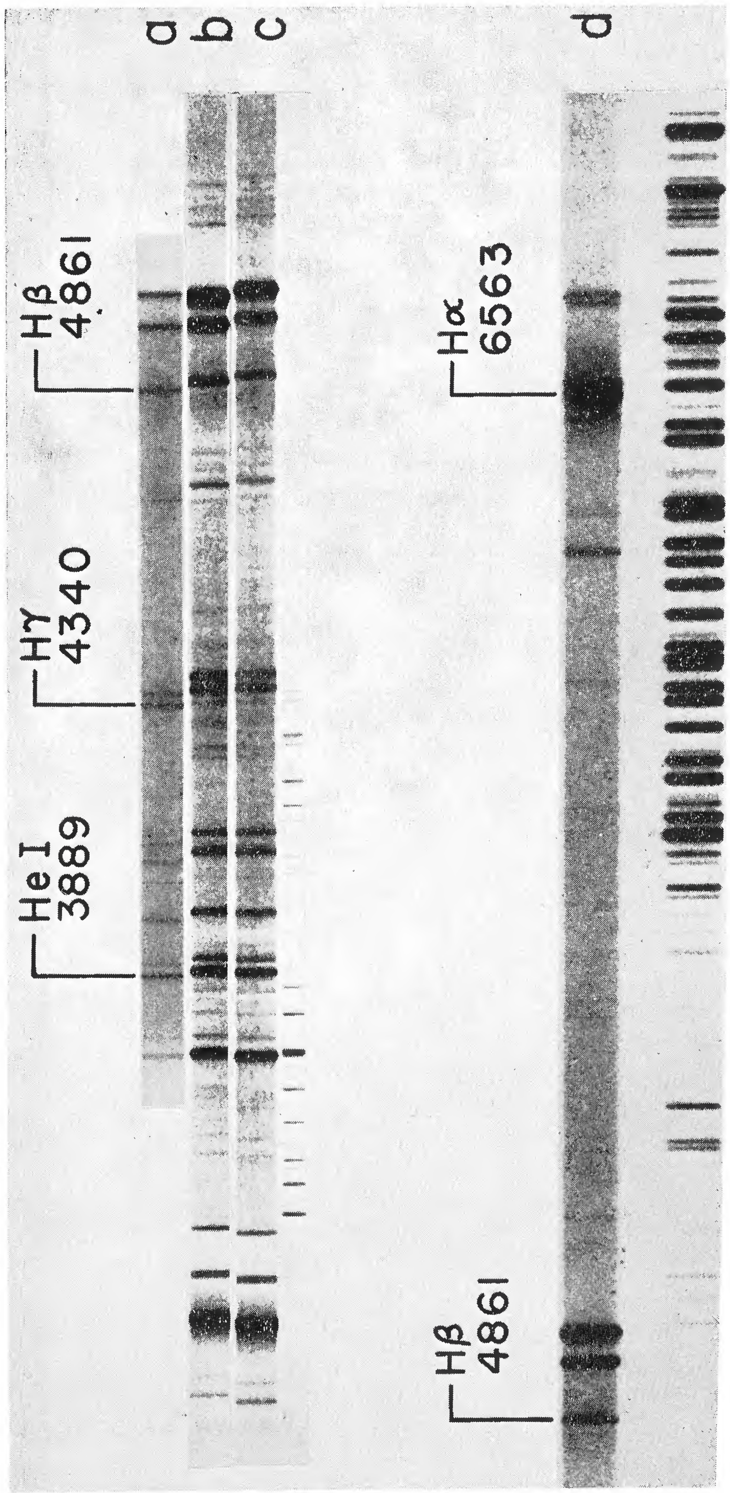

FIG. 1.—Spectrograms of the nucleus of NGC 4151. (*a*) Spectrum taken by Sargent in 1962. There is no evidence for Hβ absorption on this spectrum nor on any others we have seen taken prior to 1969. Spectrograms *b*, *c*, *d* were taken in late 1969 and early 1970 and show the Hβ absorption clearly.

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transverse, to set fairly conservative upper limits of about 3×10^5 gauss for fields present in twelve stars for which spectra at 18 or 38 Å mm^{-1} are given (Pd and Pe spectra). (The DA stars R627, HZ 43, and HZ 9 have unusual profiles; for these stars we set upper limits of 4×10^5, 5×10^5, and 10^6 gauss, respectively.) We note in passing that the observed sharpness of the line cores also allows us to set upper limits on the projected rotational velocities $v_e \sin i$ of these DA stars of about 250 km sec^{-1} for Pd or Pe spectra and about 750 km sec^{-1} for N spectra (180 Å mm^{-1}).

The second problem is that the field may be rapidly varying, so that a search should be made for periodic as well as steady Zeeman effects. A variable field could easily arise if the white dwarf is in rapid rotation, and if the axes of the magnetic field are generally inclined at fairly large angles to their rotation axes, as they seem to be in most known magnetic stars (Preston 1967; Landstreet 1970). Detection of a variable field would give the rotational period of the star, a quantity not known at present for any white dwarf. From the profiles of line cores, lower limits of between about 30 sec and a few minutes may be placed on the rotation periods of individual stars. A measurement of field strength made over a time long compared with the rotation period of the star would yield a substantially lower field strength than is actually present, and would make detection of a field correspondingly more difficult.

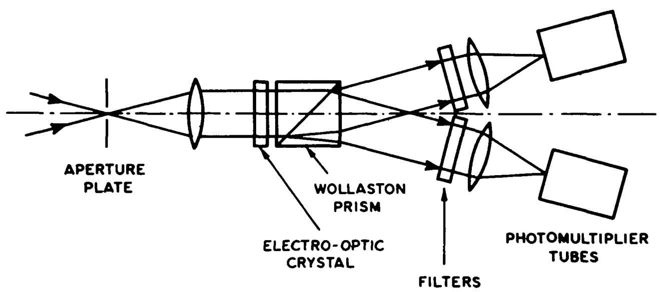

FIG. 1.—Schematic diagram of polarimeter

II. INSTRUMENTATION

With these considerations in mind, we have made a photoelectric polarimeter to search for the Zeeman effect by looking for slight circular polarization in the wings of the Balmer lines, shown in Figure 1. The instrument is mounted at the Cassegrain focus. Light passes through the aperture stop and a collimating lens, and is then analyzed for circular polarization by a Pockel cell used as a reversible quarter-wave plate, as in Babcock's (1953) solar magnetograph. The axis of the electro-optic crystal is set so that an electric field applied in one direction causes right-circularly polarized light to become linearly polarized along one axis of the following Wollaston prism; and reversing the field causes left-circularly polarized light to become linearly polarized along that axis of the Wollaston. The two diverging beams pass through separate interference filters which isolate the desired line wing and are focused onto two Bendix Channeltron photomultipliers with S-20 photocathodes, which were chosen for their high quantum efficiency and very low dark current (about 6 counts per min at dry-ice temperatures). The net polarization of the incoming light is determined separately in each of the two phototubes (whose filters may be set on the same or opposite line wings of one line, or on different lines) by the digital data-handling system. Each amplified pulse from one phototube passes through a gate which is open only after the voltage switch (lasting about 30 μsec) is complete. The pulses are counted by two scalers, one sensitive when a voltage is applied in one direction to the crystal, the other sensitive during reversed voltage. Thus each scaler measures the intensity of one circular component passed by the filter of that phototube, and polarization is detected as a change of counting rate in one tube when the crystal polarity is reversed rather than as a difference of counting rate between two tubes. This system results in systematic errors below 0.1 percent, and allows for a very long integration time. The crystal switching is timed by a crystal clock which switches polarity every 1 msec and ensures that both scalers fed by one tube are active for exactly the same amount of time. This fast rate ensures that variable seeing, atmospheric transmission, and tube sensitivity do not result in spurious signals. The second phototube merely increases the number of counts recorded per unit time. Incoming counts are usually scaled for 10 sec and then printed out with a dead time of 0.5 sec; thus later Fourier analysis of the data can detect periods down to about 21 sec.

III. OBSERVATIONS AND RESULTS

The polarimeter has been used for several nights on the 36-inch and 82-inch telescopes of the McDonald Observatory of the University of Texas, and on the 24-inch telescope of the Harriman Observatory of Columbia University. The nine white dwarfs observed to date are listed in Table 1. Their names are given in column (1), their number in the catalog of Eggen and Greenstein (1965) in column (2), and their visual magnitudes in column (3). In column (4) is given the total number of counts N (in thousands) obtained from each star.

Observations were usually made in both wings of Hγ, alternating from one to the other by changing the angle of tilt of the interference filters every few minutes. This provides a check on any suspected field as observed circular polarization due to Zeeman splitting must have opposite handedness and approximately equal magnitude in the two wings (as long as the magnitude of the field is less than about 5×10^5 gauss [Preston 1970]). The filters used for white-dwarf observations have a full width at half-height of 30 Å and were tilted so that maximum transmission occurred about 15 Å from the line core in each line wing. This was done by setting for half-maximum transmission of Hγ from a hydrogen lamp.

Some of the data were taken by using a single interference filter between the collimating lens and the Pockel cell, rather than the configuration shown in Figure 1. Examination of these data, together with laboratory tests, has shown that an interference filter in this position introduces a spurious circular polarization of a few tenths of a percent into the blue line wing. This effect was constant during any one run and consequently does not affect sensitivity to variable polarization, but it varies from run to run because the filter was often removed. In observations in which this effect was present, only data from the red line wing (which shows no detectable spurious effect) have been used to obtain the steady component of circular polarization P (in percent) listed in column (5) of Table 1. Where reliable results were obtained in the blue wing, the tabulated steady polarization uses data from both wings. Polarization is considered positive in the blue wing if the polarization is left-handed, and positive in the red wing if the polarization is right-handed; with this sign convention, positive polarization corresponds to a positive field in Babcock's (1958) notation. The errors given are the standard deviations due to counting statistics. It is seen that the steady polarization is not significantly different from zero, except in the case of 40 Eri B. Although the measured polarization for this star is 4 standard deviations from zero, the actual value is so small that we cannot rule out the possibility that systematic error occurred because no measurement of a comparison star was taken during that run. We intend to improve our data on 40 Eri B as soon as it becomes visible again.

The data were Fourier-analyzed for variable polarization with periods from twice the length of the run to twice the scaling period; the periods examined usually ranged from about 4 hours down to 21 sec. In every case the power spectrum is indistinguishable from a pure noise spectrum. In column (6) of Table 1 are given the apparent polarization

TABLE 1

OBSERVATIONS OF WHITE DWARFS

Star Name (1)	Eggen and Greenstein Number (2)	V (3)	Total Counts Recorded (thousands) (4)	Measured Steady Circular Polarization (percent) (5)	Circular-Polarization Equivalent of Highest-Power Spectrum Peak (percent) (6)	Equivalent Steady Magnetic Field (gauss) (7)	Equivalent Periodic Field (gauss) (8)
Feige 22........	19	12.65	80	$+0.57 \pm 0.50$	1.8	$(+7.4\pm6.0)\times10^4$	2.3×10^5
40 Eri B.......	33	9.52	9030	$+0.15 \pm 0.04$	0.23	$(+2.0\pm0.5)\times10^4$	3.0×10^4
Wolf 485A......	99	12.30	240	-0.36 ± 0.21	1.2	$(-4.7\pm2.7)\times10^4$	1.6×10^5
L770−3........	118	12.40	150	-0.80 ± 0.37	1.5	$(-1.0\pm0.5)\times10^5$	2.0×10^5
Wolf 1346......	139	11.54	2920	$-0.06 + 0.08$	0.5	$(-8 \pm10)\times10^3$	7×10^4
L711−10.......	141	12.0	290	-0.13 ± 0.26	1.0	$(-1.7\pm3.4)\times10^4$	1.3×10^5
Grw+73°8031..	144	12.88	350	-0.20 ± 0.26	1.1	$(-2.6\pm3.4)\times10^4$	1.4×10^5
Feige 108.......	157	12.90	340	$+0.34 \pm 0.24$	0.8	$(+4.4\pm3.1)\times10^4$	1.0×10^5
L1512−34B....	162	12.90	680	-0.11 ± 0.18	1.2	$(-1.4\pm2.3)\times10^4$	1.6×10^5

amplitudes P (in percent) of the highest peaks observed in the power spectra. The statistical origin of the peaks is demonstrated by their being proportional to $N^{-1/2}$.

Interpretation of these figures in terms of lower limits on detectable magnetic fields is somewhat uncertain since the observed Balmer lines are complicated mixtures of transitions split and mixed by the Stark effect. We may estimate, however, that the effective z-value (Babcock 1962) is of the order of 1, in which case a longitudinal field of 10^5 gauss results in a separation of the two circularly polarized components of Hγ by 1.76 Å. This would produce a net circular polarization of between 0.65 and 0.85 percent in the light transmitted by the 30 Å filter set in the wing of a typical white-dwarf absorption line, the variation being due to differences in line profile from one star to another. We may thus relate the degree of polarization and effective field by the approximate relation

$$H_e \text{ (gauss)} \simeq 1.3 \times 10^5 P \text{ (percent)} .$$

In columns (7) and (8) of Table 1 are given the magnetic fields which would result in the listed values of circular polarization. The upper limits for steady fields which could have escaped detection can be taken as 3 times the standard deviation (col. [7]), while the values in column (8) may be regarded as upper limits on periodic fields present. A periodic field with an amplitude 50 percent greater than that given in column (8) would result in a peak clearly distinguishable from the noise spectrum.

TABLE 2

POLARIZATION IN A STARS

Star	Polarization (percent)		
	Blue Hγ Wing	Red Hγ Wing	Net
HR 5332......	-0.035 ± 0.07	$+0.039\pm0.07$	$+0.002\pm0.05$
53 Cam.......	$+0.32\pm0.08$	$+0.33\pm0.08$	$+0.33\pm0.06$

We have been able to confirm that the instrument is operating properly by measuring the field of the magnetic Ap star 53 Cam at a time when the elements given by Preston and Stępień (1968) predicted a field of about +4000 gauss. The measurement was carried out in exactly the same way as for white dwarfs, except that a 5 Å filter at Hγ was used instead of a 30 Å filter because of the narrow absorption lines. In Table 2 we list the observed polarization for the two line wings of 53 Cam and that of a comparison A star having no field (HR 5332), observed immediately beforehand. The circular polarization of the magnetic star, although only 0.3 percent, is clearly visible, while that of the comparison star is essentially zero. The polarization calculated for this ephemeris from the profile of 53 Cam, if a z-value of 1 and an ideally tuned filter are assumed, is 0.65 percent. The lower observed value is probably because of a broadened response of the narrow filters caused by beam divergence, which does not affect observations made with the 30 Å filters.

It is apparent from our results for white dwarfs that any coherent fields which may exist at the surface of these stars are substantially weaker than those which we are led to expect by the arguments of § I. This may indicate either that the less massive stars which presumably evolve to the white-dwarf state have substantially smaller internal fields than the stars which evolve to neutron stars or that the magnetic field is lost during collapse or soon after. We are planning to extend our survey of white dwarfs and to obtain more data on some of those already observed to illuminate this question further. We shall report further observations and describe our instrument and techniques of analysis in more detail in a future paper.

It is a pleasure to acknowledge many useful discussions with Professor L. Woltjer, and to thank the Director of the McDonald Observatory for making available to us the 36-inch and 82-inch telescopes of the Observatory. Acknowledgment is also due Mr. Arthur Glassman for his help in building the polarimeter.

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