

DISCOVERY OF A MAGNETIC DZ WHITE DWARF WITH ZEEMAN-SPLIT LINES OF HEAVY ELEMENTS¹

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ABSTRACT

A spectroscopic survey of unstudied Luyten half-second proper-motion stars has resulted in the discovery of an unusual new magnetic white dwarf. LHS 2534 proves to be the first magnetic DZ, showing Zeeman-split Na I and Mg I components, as well as Ca I and Ca II lines for which Zeeman components are blended. The Na I splittings result in a mean surface field strength estimate of 1.92 MG. Apart from the magnetic field, LHS 2534 is one of the most heavily blanketed and coolest DZ white dwarfs at $T_{\text{eff}} \sim 6000$ K.

Subject headings: stars: magnetic fields — white dwarfs

1. INTRODUCTION

Magnetic white dwarfs comprise $\sim 5\%$ of all white dwarfs and have surface field strengths in the range $\sim 3 \times 10^4$ to 10^9 G. The 65 isolated (noninteracting binary) cases known at the time of the review of Wickramasinghe & Ferrario (2000) cover most of the white dwarf spectral types (e.g., DA, DB, DQ, DC) but have up to now not included any DZ stars, which show lines of heavy elements like Ca, Mg, Na, and Fe. This has restricted their use as astrophysical laboratories of the effects of strong magnetic fields on the light elements hydrogen, helium, and molecular carbon. The subject of this paper is the discovery of the first magnetic DZ object, identified in the course of routine spectral classification of cool stars from the Luyten half-second (LHS; Luyten 1979) proper-motion catalog. We present in § 2 the spectrum of this object, LHS 2534 (WD 1221–023, using the notation of McCook & Sion 1999). This dwarf offers the first empirical data in an astrophysical setting of the Zeeman effect on neutral Na, Mg, and both ionized and neutral Ca.

2. THE LHS 2534 SPECTRUM

The spectra of the new magnetic white dwarf was obtained on 1998 February 8 using the Low Resolution Imaging Spectrograph (LRIS; Oke et al. 1995) at the 10 m W. M. Keck Observatory (Keck-II) on Mauna Kea, Hawaii. These observations were made as part of a service observing request. The 300 g mm⁻¹ grating blazed at 5000 Å was used with a 1" slit to obtain spectra of 6 Å resolution covering 3800–7600 Å. A single 900 s exposure was obtained, and the data are plotted in Figure 1.

In addition to being magnetic, LHS 2534 is one of the most heavily blanketed of the known cool DZ white dwarfs. The temperature is evidently not too different from that of the Sun, as the strongest features—Ca II $\lambda\lambda 3933, 3968$, Ca I $\lambda 4226$, Mg I $\lambda 5175$, and Na I $\lambda 5892$ —are also among the strongest in the optical spectrum of the Sun. Hydrogen, especially H α , is not detected, so one may conclude that the star has a helium-dominated atmosphere, like most DZ stars.

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Monochromatic magnitudes for many cool white dwarfs were measured using the Palomar Multichannel Spectrophotometer colors and published by Oke (1974) and Greenstein (1976); the colors b (4255 Å), g (4717 Å), v (5405 Å), r (6944 Å), and i (8000 Å) overlap the wavelength range of these spectra. Synthetic colors from the pure helium atmosphere models of Bergeron, Wesemael, & Beauchamp (1995) may be compared. The $v-i$ slope is probably least affected by metallic absorption. The measured value of +0.24 from our spectrum compares with +0.266 for a 6000 K $\log g = 8$ atmosphere and +0.152 at 6500 K. From this we may conclude that LHS 2534 has a T_{eff} near 6000 K. The star is clearly warmer than the heavily blanketed LP 701-29 (Dahn et al. 1978) for which Kapranidis & Liebert (1986) estimated $T_{\text{eff}} = 4500$ K. The $v-i$ measurement of Greenstein (1984) suggests ~ 4800 K from the pure-helium models. Both $g-r$ and especially $b-v$ are substantially redder than the pure-He models predict. Likewise, LHS 2534 is cooler than the heavily blanketed DZ star G165-7, for which Wehrse & Liebert (1980) estimated 7500 K and the $v-i$ color (Greenstein 1984) suggests 7100 K. Perhaps the most similar of the well-known DZ stars is van Maanen 2, at $g-r = +0.26$ and $v-i = +0.13$. Bergeron, Ruiz, & Leggett (1997) estimate 6770 K from fitting a multicolor energy distribution of this star.

2.1. The Sodium Triplet and the Magnetic Field Strength

The Zeeman effect on neutral sodium is a classic problem (Zeeman 1897) that is encountered here for the first time in regard to white dwarfs. Thus, we briefly summarize the situation. Sodium is isoelectronic with hydrogen, so magnetic effects involve only the single valence electron. The D_1 ($\lambda 5895.9$) and D_2 ($\lambda 5890.0$) lines comprise a resonance doublet that couples the $^2S_{1/2}$ term with $^2P_{1/2}$ and $^2P_{3/2}$, respectively. The feature is also seen in G165-7 (Hintzen & Strittmatter 1974; Wehrse & Liebert 1980), where the doublet splitting cannot be resolved because of pressure broadening.

In a weak magnetic field ($B \lesssim 10^5$ G), the $J = \frac{1}{2}$ levels are each split into two sublevels, and the $J = 3/2$ level splits into five according to M_j , and the magnitude of the splitting is computed according to LS coupling. Ten distinct components result. This is the regime normally encountered in solar observations (e.g., Beckers 1969; Caccin, Gomez, & Severino 1993). The spin and orbit decouple when the splitting due to

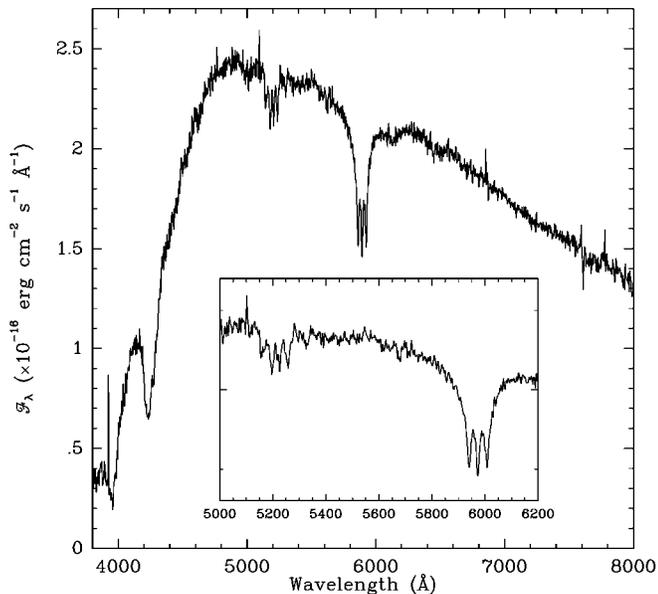


FIG. 1.—Keck II/LRIS spectrum of LHS 2534 showing strong Ca II, Ca I, Mg I, and Na I lines. The clear Zeeman splitting of the latter two features is examined in the inset.

the external magnetic field overwhelms that due to the fine-structure effect. In Figure 1, the Na I feature appears as a strong triplet at 5862, 5892, and 5924 Å. The observed splitting is not only considerably larger than the 6 Å fine-structure effect, but the pattern is centered near the mean wavelength of the nonmagnetic doublet. Hence, we conclude that the Paschen-Back approximation is appropriate, and we analyze the feature as an ordinary linear Zeeman triplet with an insignificant quadratic component. The displacements of the σ components are then $\Delta(1/\lambda) = +87$ and -92 cm^{-1} for $\lambda 5862$ and $\lambda 5924$, respectively. (It is customary in atomic spectroscopy to use wave-number units.) From the linear Zeeman effect, the mean surface field (cf. Garstang 1977) is computed according to

$$B(G) = \frac{\Delta(1/\lambda)(\text{cm}^{-1})}{4.6686 \times 10^{-5}}, \quad (1)$$

which yields an average value for the two components of $B = 1.92 \times 10^6$ G = 1.92 MG. There are, in fact, direct laboratory measurements of the Na I D lines that overlap this field strength and corroborate the accuracy of the linear approximation. Garn et al. (1966) reported splittings between the σ components that range from 30 Å for a longitudinal field of 0.94 MG up to 163 Å at 5.1 MG.

Our measurement of 1.92 MG is the mean surface field strength. Detailed modeling of the line profile, preferably supported with spectropolarimetric observations, is necessary to draw conclusions about the field geometry. A dipolar geometry

is usually an adequate approximation, though the pattern is often offset significantly from the center of the star. Time-dependent observations might determine whether the star rotates and allow the modeling of periodic changes in the geometric view. Both σ components and, to a lesser extent, the π component should be circularly polarized, while linear polarization and polarization of the continuum should be small.

2.2. Magnesium and Calcium

The subordinate Mg I triplet connects levels 3S_1 with $^3P_{0,1,2}$ for $\lambda\lambda 5167.3, 5172.7, 5183.6$, respectively. In LHS 2534 the region shows four principal components at wavelengths of $\sim 5149, 5180, 5205$, and 5235 Å. Modeling each component of the parent triplet as a simple Zeeman triplet in a field of $B = 1.92$ MG indeed produces a complex with only four lines because of overlapping of some of the nine components. The short-wavelength edge matches that of the data, but the splitting between lines is somewhat less than observed, and thus the feature does not extend sufficiently far to the red. We take this as evidence that the linear Zeeman approximation has broken down for this ion, where the fine-structure effect is comparable to the magnetic interaction. We are aware of no computations of the behavior of Mg I in this intermediate regime.

The Ca II ion is isoelectronic with Na I but has spin-orbit splitting that even exceeds that of the Mg I features and results in the well-known “H” (3933 Å) and “K” (3968 Å) doublet components being well resolved even at low spectral resolution in zero field. Since the linear magnetic term in the Hamiltonian is thus comparable to the spin-orbit term, the splitting at such a low field is more complicated still. Calculations have been published by Kemic (1975). At a field strength of 1.9 MG, the 10 Zeeman components of the doublet group themselves into three features centered around 3925, 3954, and 3987 Å and comprised primarily of transitions from upper levels $^2P_{3/2} \Delta M = -1$, $^2P_{3/2} \Delta M = 0$, and $^2P_{1/2} \Delta M = 0$. These are heavily blended for the observed line widths and together result in the broad depression centered near 3957 Å. Strong absorption features due to Fe I and many other heavy elements are prominent in the spectra of late-type stars shortward of 4000 Å and may also contribute in LHS 2534. Finally, the strong neutral calcium resonance line at 4226 Å shows a complex structure, and any magnetic components are severely blended.

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REFERENCES

- Beckers, J. 1969, A Table of Zeeman Multiplets (AFCRL-69-0115) (Hanscom AFB, MA: Air Force Cambridge Res. Lab.)
- Bergeron, P., Ruiz, M. T., & Leggett, S. K. 1997, *ApJS*, 108, 339
- Bergeron, P., Wesemael, F., & Beauchamp, A. 1995, *PASP*, 107, 1047
- Caccin, B., Gomez, M. T., & Severino, G. 1993, *A&A*, 276, 219
- Dahn, C. C., Hintzen, P. M., Liebert, J. W., Stockman, H. S., & Spinrad, H. 1978, *ApJ*, 219, 979
- Garn, W. B., Caird, R. S., Thompson, D. B., & Fowler, C. M. 1966, *Rev. Sci. Instrum.*, 28, 949
- Garstang, R. H. 1977, *Rep. Prog. Phys.*, 40, 105
- Greenstein, J. L. 1976, *AJ*, 81, 323
- . 1984, *ApJ*, 276, 602
- Hintzen, P. M., & Strittmatter, P. A. 1974, *ApJ*, 193, L111
- Kapranidis, S., & Liebert, J. 1986, *ApJ*, 305, 863

Kemic, S. B. 1975, *Ap&SS*, 36, 459

Luyten, W. J. 1979, *The Luyten Half-Second Catalog* (Minneapolis: Univ. Minnesota Press)

McCook, G. P., & Sion, E. M. 1999, *ApJS*, 121, 1

Oke, J. B. 1974, *ApJS*, 27, 21

Oke, J. B., et al. 1995, *PASP*, 107, 375

Wehrse, R., & Liebert, J. 1980, *A&A*, 86, 139

Wickramasinghe, D. T., & Ferrario, L. 2000, *PASP*, 112, 873

Zeeman, P. 1897, *ApJ*, 5, 332