Discovery of four white dwarfs with strong magnetic fields by the Hamburg/ESO Survey

D. Reimers\textsuperscript{1}, S. Jordan\textsuperscript{2}, D. Koester\textsuperscript{2}, N. Bade\textsuperscript{1}, Th. Köhler\textsuperscript{1}, L. Wisotzki\textsuperscript{1}

\textsuperscript{1} Hamburger Sternwarte, Gojenbergweg 112, D-21029 Hamburg, Germany
\textsuperscript{2} Institut für Astronomie und Astrophysik der Universität, D-24098 Kiel, Germany

INTERNET (SJ): jordan@astrophysik.uni-kiel.d400.de

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Abstract. Four magnetic white dwarfs have been found in the course of the Hamburg/ESO Survey for bright QSOs. The objects have been selected as QSO candidate on the basis of its blue continuum and the apparent absence of strong hydrogen or helium lines. One star, HE 1211-1707, shows a rather fast spectral variability: both the strength and the position of the shallow absorption features change on a time scale of 20 minutes. We interpret this variability as being due to a magnetic field on the surface of a rotating white dwarf, having a relatively uniform magnetic field on one hemisphere and a much larger spread of field strengths visible during other phases of the rotational period. All attempts to determine the magnetic field structure in detail with the help of synthetic spectra have failed so far because the star must have a rather complicated field geometry. However, both the optical and the UV spectra indicate that a significant part of the surface is dominated by a magnetic field strength of about 80 MG.

The spectrum of HE 0127-3110 is also rotationally modulated. This star (approximate range of magnetic fields: 85-345 MG) as well as HE 2201-2250 (a spectroscopic twin of HE 0127-3110) and HE 0000-3430 (43-118 MG) could be reasonably well reproduced with the help of theoretical spectra calculated assuming magnetic dipoles which are offset by 0.1 and 0.2 stellar radii along the magnetic axis. This result is in agreement with the assumption that Ap stars, also showing significant deviations from a centered dipole, are the progenitors of magnetic white dwarfs.

Key words: stars: white dwarfs – stars: magnetic fields – stars: individual: HE 1211-1707 – stars: individual: HE 0127-3110 – stars: individual: HE 2201-2250 – stars: individual: HE 0000-3430

1. Introduction

Degenerate stars with strong magnetic fields have been studied intensively in recent years (see Chanmugam 1992 for a review), ever since Greenstein et al. (1985) could show that in Grw+70\degree 8247, whose peculiar absorption bands (Minkowski, 1938) resisted for decades a successful identification, these bands are due to hydrogen in magnetic fields of several hundred MG. In the meantime, there has been considerable progress in numerical quantum mechanical calculations of the hydrogen levels in strong magnetic fields (Rösner et al. 1984; Forster et al. 1984; Henry & O’Connell, 1984; Wunner et al., 1985), in applying these results to stellar atmospheres and line spectrum synthesis calculations (Achilleos and Wickramasinghe 1989, Putney and Jordan 1995 and references therein) and in discovering more single degenerate stars field strengths of several hundred Megagauss, cf. Table 2 in Schmidt & Smith (1995). Several of these stars like PG 1031+234 (Schmidt et al. 1986, Latter et. al. 1987) or PG 1015+014 (Wickramasinghe & Cropper 1988) in addition exhibit strong rotational modulation of their spectral lines with periods as short as 1.65 hours. As relics of stellar cores, the study of magnetic fields in white dwarfs should shed important light on the role such fields play in stellar formation and main sequence evolution. In this paper we present spectra of four newly discovered magnetic white dwarfs. Three of the objects have been successfully modelled with offset dipole configurations. We also present time resolved
spectra of HE 1211-1707, probably one of the fastest rotating white dwarfs with a rather complicated magnetic field configuration.

![Finding charts for HE 1211-1707 and HE0127-3110 produced with the help of the Digitized Sky Survey](image)

**Fig. 1.** Finding charts for HE 1211-1707 and HE0127-3110 produced with the help of the Digitized Sky Survey

### 2. Observations

The four new magnetic degenerates have been discovered within the Hamburg/ESO Survey for bright QSOs. The project is briefly described by Reimers (1990) and Wisotzki et al. (1995). The objects have been selected as QSO candidates on the basis of their blue continuum and the apparent absence of Balmer H or He lines. Coordi-
Table 1. Coordinates and approximate magnitudes

| Object      | R.A. (1950) | Decl. (1950) | V magnitude |
|-------------|-------------|--------------|-------------|
| HE 1211-1707| 12°11'33"5 | -17°07'58"  | 16°9±0°05   |
| HE 0127-3110| 01°27'37"8 | -31°10'34"  | 16°1±0°50   |
| HE 2201-2250| 22°01'57"7 | -22°50'51"  | 16°2±0°50   |
| HE 0000-3430| 00°00'06"3 | -34°30'07"  | 15°0±0°50   |

Table 2. Log of observations

| Object          | Date in UT | Instrument   | Resol. | Exp.  |
|-----------------|------------|--------------|--------|-------|
| HE 1211-1707    | 22.3.93, 7:28 | 1.5 m+B&C | 6 Å   | 60min |
|                 | 12.1.94, 7:42 | 3.6 m+EFOSC | 20 Å | 30min |
|                 | 12.1.94, 8:02 | 3.6 m+EFOSC | 20 Å | 15min |
|                 | 12.1.94, 8:21 | 3.6 m+EFOSC | 20 Å | 30min |
|                 | 23.2.94, 1:54 | 2.2 m+B&C  | 12 Å  | 60min |
|                 | 01.3.95, 7:49 | 3.6 m+EFOSC | 16 Å  | 10min |
|                 | 01.3.95, 8:11 | 3.6 m+EFOSC | 16 Å  | 10min |
|                 | 02.3.95, 7:29 | 3.6 m+EFOSC | 16 Å  | 10min |
|                 | 02.3.95, 7:51 | 3.6 m+EFOSC | 16 Å  | 10min |
|                 | 02.3.95, 8:12 | 3.6 m+EFOSC | 16 Å  | 10min |
|                 | 28.4.95     | IUE SWP (LA) | 7 Å   | 390min |
|                 | 29.4.95     | IUE SWP (LA) | 7 Å   | 390min |
| HE 0127-3110    | 24.09.94 | 1.5 m+B&C | 6 Å   | 10min |
|                 | 25.09.94 | 1.5 m+B&C | 6 Å   | 30min |
|                 | 23.11.94 | 1.5 m+B&C | 20 Å  | 90min |
| HE 2201-2250    | 23.11.94 | 1.5 m+B&C | 20 Å  | 15min |
| HE 0000-3430    | 20.11.94 | 1.5 m+B&C | 20 Å  | 5min  |

behaviour was also confirmed by EFOSC observations performed in March 1995 (see Fig. 3 and Fig. 4). Three of the spectra (12.1.94, 8:21UT; 01.3.95, 8:11UT; 02.3.95, 7:29UT) are extremely similar and are obviously taken during the phase where the features are strongest. In the other spectra the absorption bands are shallower and at different positions. The lower three spectra taken within one hour show a time sequence where the strong depression at 5700 Å becomes weaker, whereas a shallower absorption gradually becomes stronger at 5000 Å; this feature is also visible in two other spectra taken on January 12, 1994. A further spectrum that covers in particular the red spectral range up to 8200 Å has been taken in February 1994 at the Calar Alto 2.2 m telescope with the aim to detect possibly present σ components of Hα. The spectrum is, however, much too noisy to identify additional absorption bands. In the blue the spectrum resembles those taken during the “strong feature” phase.

Fig. 5 shows two UV spectra taken with the SWP camera of the IUE satellite on April 28 and 29, 1995. The signal-to-noise ratio is about 3 making the interpretation rather problematic. The strong and broad emission line at 1485 Å is probably an artifact since it is only present in one exposure of the exposures.
HE 0127-3110: two spectroscopic observations have
been made in September 1994 using the B & C spectro-
graph at the ESO 1.5 m telescope. Its spectrogramm is
characterized by broad bands around 4000, 4300, 4700,
and 5100 Å and a much sharper feature at ≈ 5850 Å
(Fig. 7). A new spectrum with higher S/N has been taken
on Nov. 13, 1994 with the 1.5 m telescope. The absorption
features appear weaker than in the Sept. 94 spectra.

HE 2201-2250 has been observed in November 1994
also at the ESO 1.5 m telescope. It is virtually a twin to
HE 0127-3310 both in its spectral energy distribution and
absorption lines.

Fig. 4. Same spectra as in Fig. 3, but in order to discern the
weak features more clearly, the flux is “normalized” by multi-
plcation of $f_\lambda$ by $\lambda^{3.4}\times$const.

Fig. 5. Two very low S/N ($\approx$ 3) UV spectra of HE1211-1707,
taken with the IUE satellite and smoothed with a boxcar of
10 Å. The strong and broad emission line at 1485 Å is prob-
ably spurious since it only occurs in one exposure. The IUE
spectrum and the optical flux (the latter is calculated from the
$V$ magnitude) is compared with a 80 MG dipole model with
$T_{\text{eff}} = 23000$ K. For clarity the optical flux is multiplied by a
factor of ten

Fig. 6. Spectrum of HE 0000-3430, taken with the ESO 1.5 m
telescope, compared to a synthetic spectrum for a magnetic
dipole with polar field strength of 86 MG, offset by -0.1 stellar
radii toward the southern magnetic pole. The magnetic axis
of the model is inclined at $-45^\circ$ to the line of sight, the ef-
fective temperature is of the model is 7000 K. The red part
of the spectrum is strongly blended by telluric lines. For com-
parison a spectrum from Stevenson (1994) is shown where the
atmospheric bands are identified.
Fig. 7. Three spectra of HE 0127-3110 taken with the ESO 1.5 m telescope. The zero point corresponds to the high S/N spectrum taken on November 23, 1994; for clarity the other spectra are shifted upwards. Note that the upper two spectra are smoothed with a boxcar of 10 Å width and were taken under non-photometric conditions. The lower spectrum is compared to an offset-dipole model (-0.2 stellar radii) with a polar field strength of 176 MG. The inclination of the dipole axis is $-50^\circ$ and $T_{\text{eff}} = 18000$ K. Note that the strength of the H$\beta$ absorption at 4650 Å is somewhat stronger in the September 1994 spectra, probably due to rotational modulation.

Fig. 8. The spectrum of HE 2201-2250, taken with the ESO 1.5 m telescope, is compared to the same model as its “twin” HE 0127-3110 (November 23, 1994, observation). Within the noise level no significant differences can be found.

Fig. 9. Distribution of the magnetic field strength vs. latitude for the best-fit models used in Fig. 6.

HE 0000-3430: the slope of the spectrum taken with the ESO 1.5 m telescope is much smaller compared to the spectra of the other three objects. This indicates a much lower effective temperature. The most prominent feature is an absorption band at about 4650 Å.

3. Interpretation and Discussion

A large grid of about 800 theoretical spectra for different effective temperatures and magnetic field configurations have been calculated with a program developed in Kiel (see Jordan 1992 and Putney & Jordan 1995 for a detailed description). For this analysis the magnetic field configuration is described by dipoles shifted by 0., 0.1, 0.2 or 0.3 stellar radii along the magnetic axis. The viewing angle $\alpha$ is defined such that $+90^\circ$ and $-90^\circ$ means that the observer is directly looking at the north and south magnetic pole, respectively, and $0^\circ$ corresponds to an equator-on view. The third free parameter is the magnetic field strength at the pole $B_p$ of the unshifted dipole.

Zero field model atmospheres (see Koester et al. 1979) were used to determine the temperature and pressure structure of the white dwarf’s outer layers; convection has been suppressed since the magnetic field substantially decreases the convective efficiency. The gravitational acceleration at the surface was assumed to be $10^8$ cm sec$^{-2}$. The four equations of radiative transfer were solved for the Stokes parameters $I$, $Q$, $V$, and $U$ on a large number of surface elements (about 5000) with a procedure similar to the semi-analytical algorithm described by Wickramasinghe & Martin (1979), and subsequently combined in order to obtain the result from the whole visible hemisphere of the star. We considered line absorption by all Balmer components up to H$_\alpha$ (Forster et al. 1984, Rösnner et al. 1984, and additional data from the Tübingen group). The magnetooptical parameters were treated according to Jor-
3.1. HE1211-1707

This object is by far the most interesting of the four objects due to its exceptionally fast variation of the spectral features. In general white dwarfs have turned out to be slow rotators (e.g. Koester and Herrero 1988) and there are several magnetic white dwarfs like Grw+70°8247 whose spectropolarimetry is constant on time scales up to at least 10 years (Schmidt & Norsworthy 1991). Within about 20 minutes the clearly visible absorption features apparently disappear almost completely.

The most probable explanation for this behaviour is that HE1211-1707 is a magnetic white dwarf. Although the faintness of this object (V = 16.9) did not allow a measurement of the polarization, the spectral variations are similar to that of a few other magnetic objects, e.g. in PG1031+234, the white dwarf with the highest known field strength. For this star Schmidt et al. (1986), and Latter et. al. (1987) found a rotational period of 3.4 hours; they concluded that in addition to a global dipole field with a polar field strength of 500 MG a region (spot?) must exist with a field up to 1 GG.

Recently, Barstow, Jordan et al. (1995) discovered that the hottest (50kK) known magnetic white dwarf REJ0317-853 has a rotational period of 725 seconds, and a rather inhomogeneous magnetic field varying from about 170 MG to almost 660 MG (B_p=340 MG, offset offset by 0.2 stellar radii toward the southern magnetic pole). The rotational period of REJ0317-853 could be measured with the help of high speed optical photometry; it turned out that the amplitude is = 10^{-1}. Photometric measurements of HE 1211-1707 have been performed by Darragh O’Donoghue. However, no significant optical variation has been found. From the speed of the spectral variation we can only estimate the rotational period to lie between that of PG1015+014 (98.7 minutes; Wickramasinghe & Cropper 1988) and REJ0317-853.

In order to understand the spectra of HE1211-1707 we have calculated a large grid of high-temperature magnetic white dwarf model atmospheres. However, we have not yet been able to identify the visible features unambiguously. The absorption features between 4000 and 5000 Å, visible during the “strong feature” phase (see Fig. 4) have a strong similarity with theoretical profiles of Hβ and Hγ at about 80 MG. The same is true for the absorption at 5700 Å, which at these field strengths would be caused by blue shifted Hα components. There is, however, no possibility to explain the absorption at λ ≈ 5300 Å at such a low field, a feature which is present in the same spectra. Therefore we are not sure if there are indeed regions on the surface of the star, with a field as low a 80 MG.

Although we believe that this is true it is also possible that similar features may occur at field strengths larger than 1000 MG, hitherto the limit of our model calculations (currently the line data sets for the model atmospheres are completed to account for magnetic fields extending 1 GG). One possibility is a global dipole-like field of about 80 MG plus regions on the star with a considerably larger magnetic field strengths. This would mean that the field is at least as complicated as PG1031+234. Another alternative is that the star belongs to the group of highly magnetic white dwarfs with unidentified absorption features most probably containing helium in their atmospheres (e.g. GD229, Greenstein et al. 1974). However, Engelhard & Bues (1995) have proposed that the hitherto unexplained features in GD229 are not due to helium but quasi-Landau resonances at extremely high fields (> 10^9 G). It would be interesting to test this hypothesis for the case of HE1211-1707 as well.

UV observations have turned out to be rather helpful to determine the magnetic field strength, because this spectral region shows one or two of the three Lyman α components. The presence of these absorptions would prove that hydrogen is the dominating absorber in HE1211-1707. The position of the red shifted Lyman α σ component would directly tell us the dominating field strength, as has been shown by Barstow et al. (1995) for REJ0317-853.

Unfortunately, the star is much too faint for the IUE spectrum (Fig. 5; S/N= 3) to answer this question unambiguously. We believe, however, that the UV spectrum confirms our speculation that a part of the surface is dominated by a field strength of about 80 MG: the absorption trough close to the geocoronal Lyman α emission is so broad, that it cannot be explained by the Lyman α component only (see Fig. 5). Therefore it is probably blended by the red shifted σ component meaning that the magnetic field responsible for this width must be lower than about 100 MG. A UV spectrum taken with HST is necessary to test if this is really the case and would also help to find additional absorption features produced by the Lyman σ component at other field strengths.

Since the slope of the optical spectra varies strongly from observation to observation due to non-photometric weather conditions it is difficult to determine an effective temperature. Using the V magnitude of 16th and the the flux level of the IUE spectra we could, however, constrain the effective temperature to about 20000 K and 25000 K (see Fig. refHE1211lill) so that HE1211-1707 is one of the hottest magnetic white dwarfs known.
3.2. **HE 0127-3110**

The spectrum shown in Fig. (Fig.?) is characterized by broad absorption features around 4000, 4300, 4650 and 5080 Å respectively and a narrow feature at ≈ 5870 Å.

At first glance one might tentatively identify the 5870 Å line with He I 5875 Å and the two longest wavelength features with Swan bands of C₂ as in DO stars. However, there is no 4471 Å He I line, no 5500 Å band (one of the Swan bands), and the two bands near 4000 Å and 4300 Å remain unidentified. A more convincing identification of the 5870 Å feature - a similar line is seen in PG 1031+234 - is that of a stationary 2s0 → 3p0 Hα component at magnetic field strengths of about 230 MG.

We have compared the November 1994 spectrum to theoretical spectra assuming a centered magnetic dipole. None of the models was able to reproduce the observed spectrum in detail. All absorption features are shallower than observed and also in some cases at the wrong positions. This indicates that the variation of the magnetic field is larger than in the case of a centered dipole, where the range of field strength covers a factor of two. The next attempt was to assume dipoles offset by 0.2 stellar radii toward the southern magnetic pole. The best solution was found for a polar field strength of 176 MG seen and a viewing angle of α = −50° (see Fig.?). For such a model the field strength varies between 85 and 345 MG (see Fig.?). Both the slope of the continuum of the November 1994 spectrum and the line strength are compatible with an effective temperature of $T_{\text{eff}} = 18000 ± 1000$K.

The two spectra of HE 0127-3110 taken in September have a rather low signal-to-noise ratio. Therefore we were not able to perform a detailed analysis with synthetic spectra. If smoothed with a boxcar of 10 Å one can see that the absorption features, especially at 4650 Å are somewhat stronger than in the November 1994 observation. This is probably also due to rotation: probably the field looks somewhat more homogeneous during the September 1994 observations (corresponding to a larger viewing angle α) compared to the spectrum taken in November, 1995. In the future we hope that time resolved spectra will enable us to determine the overall magnetic field configuration in some more detail.

3.3. **HE 2201-2250**

It is very surprising that the spectrum of HE 2201-2250 looks almost identical to that of HE 0127-3110, especially since no simple dipole configuration can explain the observations in detail. The similarity is so large that we could not find any significant differences within the observational uncertainties: In Fig. we compared the spectrum of HE 2201-2250 to same model spectrum that has been used to explain the observation of HE 0127-3110. Therefore we conclude that the effective temperature and the approximate field distribution over the visible hemisphere must be about the same. Only time resolve spectroscopy and polarimetry can prove if this also the case for the detailed field structure. Note that the description of the field by a dipole offset along the magnetic axis is only one way to account for the observations with a minimum number of free parameters. This offset provides a reasonable description of the field variation (either smaller or larger than in the case of a centered dipole). It can, however, not be excluded that the stars have offsets perpendicular to the magnetic axis or even more complicated field geometries (e.g. global dipole-like structures plus a magnetic spot). Putney & Jordan (1995) have shown that one flux spectrum of a magnetic white dwarf can be described by several slightly different model geometries (offset dipoles or dipole-quadrupole combinations) while a measurement of the polarization strongly constraints the possible field parameters. This means that despite the similarity of the flux spectra of HE 2201-2250 and HE 0127-3110, the star may still have different field configurations in detail.

3.4. **HE 0000-3430**

From the continuum slope we have estimated an effective temperature of 7000 K. Although the error may be relatively large due to observational uncertainties, the star is certainly the coolest white dwarf discovered by the Hamburg/ESO survey. The reason is that due to the Zeeman splitting of the Balmer lines is strongly reduced compared to the situation without a magnetic field. Therefore magnetic white dwarfs have a bluer continuum and are easier found by the selection criteria of the Hamburg/ESO survey. The next hotter white dwarf found by the HE survey is also magnetic (HE1045-0908, Reimers et al. 1994) while the coolest non-magnetic DAs have temperatures above about 11000K.

The strongest feature in the spectrum of HE 0000-3430 looks very similar to the complex of Hβ components in magnetic white dwarfs of moderate field strengths (≈100 MG). However, strong absorption by Hα is seen in the spectrum, and especially the blue shifted σ component of Hα is rather shallow. This, again, can only be explained if a spread of the field strength larger than a factor of two is assumed: the observed spectrum is best reproduced by a dipole offset by -0.1 stellar radii toward the southern magnetic pole and a viewing angle α of −45°. The corresponding range of magnetic fields is 43 MG to 118 MG (see Fig.?). For such a field the Hα π components are shifted to about 6500 Å and while the σ components are indeed rather shallow. Several components of Hβ are also well reproduced by the synthetic spectrum. Note, that the spectrum is strongly blended by telluric lines at wavelengths above 6000 Å. For an easy identification of the atmospheric O₂ and H₂O bands the average continuum-normalized spectrum of two metal-poor giant stars, HD 195636 and BD−09°5831, taken from Stevenson (1994), has been plotted in Fig. for comparison.
4. Conclusions

Beside quasars, the Hamburg/ESO Survey has turned out to be a rich source of interesting blue stars. Together with HE1045-0908 the survey has enlarged the number of magnetic white dwarfs with field strengths above 10 MG by 25% (Schmidt & Smith 1995).

With HE 1211-1707 we have discovered one of the hottest magnetic white dwarfs showing a rather fast rotational modulation of the spectrum. Most likely, the star has a rather complicated structure of the magnetic field. The hemisphere that is seen during the rotational phase where the absorption features are strongest is probably dominated by a magnetic field of about 80 MG, while much higher field strengths are present on the rest of the star. Without better time resolved spectra (which are also necessary to determine the rotational period) and high S/N UV spectroscopy an unambiguous identification of the absorption features remains impossible at the moment.

Recently, Muslimov et al. (1995) performed theoretical calculations demonstrating that non-dipole components can survive much longer on the white dwarf cooling sequence than previously believed. This is confirmed by our result that all four stars have a spread of magnetic field strengths larger than in the case of a centered dipole-field.

The spectra of HE0127-3110, HE 2201-2250, and HE 0000-3430 have been successfully modelled with the help of synthetic spectra in the framework of offset dipoles geometries. Putney & Jordan (1995) have also considered dipole-quadrupole combinations as a more physical model. However, for a detailed analysis which can distinguish between both these geometries it would be necessary to obtain measurements of the polarization first. The flux spectrum alone can be reproduced by several slightly different offset-dipole models or dipole-quadrupole combinations.

The fact that the spectra of many magnetic white dwarf show evidence for non-centered magnetic dipoles strengthens the connection to Ap stars as their precursors since these objects also exhibit large deviations from the centered dipole structure.

Time resolved observations of the rotating white dwarfs HE 1211-1707 and possibly HE 0127-3110 will allow to determine the field geometry over a large portion of the stellar surface. This will provide a rather important test for theoretical calculations of the magnetic field structure.

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