The magnetic fields of EF Eridani and BL Hydri

Lilia Ferrario,1 Jeremy Bailey2 and Dayal Wickramasinghe1

1 The Australian National University Astrophysical Theory Centre, School of Mathematical Sciences, Canberra, ACT 0200, Australia
2 Anglo-Australian Observatory, PO Box 296, Epping, NSW 2121, Australia

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ABSTRACT
We present near-infrared spectroscopic observations of the AM Herculis systems EF Eridani and BL Hydri over the wavelength range 0.9 to 2.5 μm. During these observations, broad and resolvable cyclotron emission harmonics were visible near 1.05, 1.30, 1.70 and 2.20 μm in EF Eridani, and near 1.25, 1.60 and 2.20 μm in BL Hydri. We interpret these features as arising from cyclotron emission regions located near the polar caps of the white dwarf of magnetic field strength \( B = 23 \) MG in BL Hydri, and from two separate cyclotron emission regions of field strengths \( B = 16.5 \) and 21 MG in EF Eridani.

Key words: binaries: close – stars: individual: EF Eridani – stars: individual: BL Hydri – stars: magnetic fields – novae, cataclysmic variables – white dwarfs.

1 INTRODUCTION
The AM Herculis systems form a subclass of cataclysmic variables where the white dwarf primary has a strong enough magnetic field to affect the dynamics of the accretion flow close to its surface. They are the only systems known in nature to exhibit strongly circularly polarized radiation and resolvable cyclotron lines in the optical and/or near-infrared bands, indicating the presence of fields of \( \approx 10-70 \) MG at the surface of the white dwarf. The light intensity and polarization observed in AM Herculis variables all vary at a period that is equal to or very close to the binary period. All these observations have been explained by a model in which the magnetic white dwarf is locked into near-synchronous rotation with the orbital period. In this model the cyclotron radiation arises from accretion shocks at the base of accretion columns where the material flowing from the companion star impacts on to the white dwarf surface.

In AM Herculis systems, the fundamental cyclotron frequencies are in the infrared in the range between \( \sim 10 \) and 2 μm, and the cyclotron radiation that is observed in optical wavebands consists of harmonics of the fundamental cyclotron frequency. Cyclotron harmonic features in the optical spectra of AM Herculis systems are often washed away by field, temperature and density structure across an extended emission region (Wickramasinghe & Ferrario 1988). At longer wavelengths, cyclotron features are more easily resolvable, so that observations in the near infrared have proved to be crucial for the determination of the magnetic field strength at the emission region, together with physical parameters such as density, temperature and optical depth.

Following our successful detection of cyclotron harmonics in the infrared spectra of AM Herculis itself (Bailey, Ferrario & Wickramasinghe 1991) and ST LMi (Ferrario, Bailey & Wickramasinghe 1993), we have extended our search in the near-infrared region to another two AM Herculis systems: EF Eri and BL Hya. In this paper, we present new spectroscopic observations of these systems which also show the presence of strong cyclotron emission features in their spectra.

2 OBSERVATIONS
Observations were made on 1992 October 5 using the IRIS instrument (Allen et al. 1993) on the 3.9-m Anglo-Australian Telescope (AAT). Observations were made in the echelle mode of the instrument, in which a cross-dispersed transmission echelle produces spectra over a wide wavelength range with a resolution of about 400. The IJ echelle covers the range 0.9 to 1.5 μm, while the HK echelle covers 1.4 to 2.5 μm. Spectra of EF Eri and BL Hya were obtained using both echelles, with one or more orbital cycles of coverage at each setting. Standard stars close to the object were observed frequently, in order to correct for atmospheric absorption and to flux-calibrate the spectra. A journal of observations is given in Table 1.

Observations consisted of pairs of 300-s integrations, taken with the object at two slit positions.
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Table 1. Journal of observations.

<table>
<thead>
<tr>
<th>Source</th>
<th>Wavelengths (μm)</th>
<th>Date (UT)</th>
<th>Run start (UT)</th>
<th>Run end (UT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BL Hyi</td>
<td>1.4 – 2.5</td>
<td>5 Oct. 1992</td>
<td>09:01:22</td>
<td>11:00:42</td>
</tr>
<tr>
<td></td>
<td>0.9 – 1.5</td>
<td>11:23:21</td>
<td>13:22:12</td>
<td></td>
</tr>
<tr>
<td>EF Eri</td>
<td>0.9 – 1.5</td>
<td>5 Oct. 1992</td>
<td>13:54:31</td>
<td>15:56:55</td>
</tr>
<tr>
<td></td>
<td>1.4 – 2.5</td>
<td>16:11:22</td>
<td>18:58:47</td>
<td></td>
</tr>
</tbody>
</table>

Figure 1. AAT spectrum of EF Eri obtained on 1992 October 5, with our best model fits to the data superimposed. The solid and dashed lines correspond, respectively, to fields of 16.5 and 21 Mg. The data near 1.4 and 1.9 μm have been removed because of the increased noise caused by atmospheric absorption.

MODELLING AND DISCUSSION

The broad cyclotron emission features peak near 1.05, 1.30, 1.70 and 2.20 μm in EF Eri, and near 1.25, 1.60 and 2.20 μm in BL Hyi. This is the first time that cyclotron features have been detected in these systems.

From the spacing between successive cyclotron humps, it is possible to obtain a good estimate of the magnetic field strength at the emission region. The following equation gives the position of the nth harmonic for a magnetic field $B$ and a viewing angle $\theta = 90°$, provided that we consider low electron temperatures $T_e$ and point-source emission regions:

$$\lambda_n = \frac{10^{7.10}}{n} \left(\frac{10^8}{B}\right) \text{Å}.$$  

On the other hand, we know that cyclotron emission regions are usually quite extended over the stellar surface (Ferrario & Wickramasinghe 1990), so that the position of the harmonics will depend crucially on the extension of the regions and also on their electron temperature $T_e$, optical depth parameter $\Lambda$ and viewing angle to the magnetic field. In order to fit the present set of data, we have adopted the models developed by Ferrario & Wickramasinghe (1990), based on the assumption that the magnetic field structure is that of a centred dipole, and that the emission regions are in the form of linearly extended ribbons. The magnetic lon-
The calculations are carried out by dividing the emission arc into elementary areas over which the magnetic field strength and the angle between field direction and line of sight can be taken as constant. The transfer equations are solved for each of these elementary areas, and the Stokes parameters are rotated to a standard coordinate system to allow for variations in the field direction. An additional assumption is that the height of the shock is very much smaller than the white dwarf radius, and thus we neglect geometrical effects caused by the extension of the shock above the stellar surface. Finally, the total cyclotron emission output is obtained by adding the emission from point sources which are homogeneously distributed along the arcs and whose contributions are weighted with their elementary surface area projected on to the plane of the sky.

To carry out our modelling, we assume that the basic model parameters of EF Eri and BL Hyi, such as orbital inclination $i$, and colatitude of the magnetic axis $\theta_\alpha$, are consistent with previous studies of these systems that employed the phase dependence of the linear and/or circular polarization curves. We use the cyclotron spectrum to constrain the dipole field strength, electron temperature and optical depth parameters, assuming that the emission region is homogeneous. Then, the position and extension of the cyclotron emission arcs are modified until the theoretical curves match the observed spectra.

3.1 EF Eridani

The model adopted to fit our data has an orbital inclination $i=55^\circ$ and a dipole inclination $\theta_\alpha=150^\circ$ with respect to the spin axis. These values are consistent with those found by Piirola, Reiz & Coyne (1987a) and Meggitt & Wickramasinghe (1989) for the secondary emission region. The emission region is located below the orbital plane between magnetic colatitudes $\theta_1=9^\circ$ and $\theta_2=11^\circ$. To fit the present observations of EF Eri, we found that the models based on the assumption of a uniform emission region could not reproduce the observed spectral slope and the profiles of the cyclotron emission lines. To fit the data, we have introduced inhomogeneities by having two regions with the same geometrical extent, but with different temperatures and opacities along the emitting arc. The same kind of modelling was required to fit the cyclotron features detected in the infrared spectrum of ST LMi (Ferrario et al. 1993). A low-density, low-temperature region, which is responsible for the formation of the cyclotron features, extends from $\psi_1=120^\circ$ to $\psi=180^\circ$, and has $T_e=6$ keV and $\Lambda=2.8 \times 10^7$. A second, higher density region, which is responsible for the spectral slope, extends from $\psi=180^\circ$ to $\psi_2=240^\circ$, and has...
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1.2 1.4 1.6 1.8 2 2.2 2.4
Wavelength microns

Figure 3. AAT faint-phase spectrum of BL Hyi obtained on 1992 October 5. The cyclotron features present in this spectrum are probably caused by some residual contamination from the bright phase. The increased noise in the data near 1.4 and 1.9 μm is caused by atmospheric absorption.

Te = 10 kev and Λ = 2.8 × 10^6. The polar magnetic field strength is B_p = 16.5 MG. The fit of the model to our data for EF Eri is shown in Fig. 1. It is immediately apparent from our modelling that the cyclotron harmonic feature near 1.05 μm is not well reproduced. More specifically, the observed feature is much broader than that calculated. We have tried to achieve a better agreement with the data by changing the magnetic field strength at the pole. By doing so, we have found that a magnetic field of 21 MG can match the observed spectrum blueward of 1.60 μm, but with the result that the spacing between the cyclotron humps becomes so large that the reddest calculated harmonic falls well beyond the observed wavelength range, thus failing to reproduce the cyclotron emission feature near 2.2 μm (this model is also included in Fig. 1). It is therefore clear from our analysis that it is not possible to interpret the present set of data with a single cyclotron spectrum. The most likely explanation is that what we are observing is the overlapping of two different sets of cyclotron harmonics which originate from two separate emission regions.

The magnetic field strength found by us for EF Eri has to be compared with the polar field value of 15 ± 2 MG previously deduced for this system by Achilles, Wickramasinghe & Wu (1992). The magnetic field strength estimate by Achilles et al. was based on the study of Zeeman absorption features that are sometimes observed in the spectra of this system. In the data analysed by this group, the Zeeman features were not present during the faint phase of the orbital cycle (i.e., when the cyclotron funnel was hidden by the body of the white dwarf itself), but only during the bright, cyclotron-dominated phase. Consequently, the features could not have been of photospheric origin, and were thus interpreted as arising from a cool halo of unshocked material that surrounds the shock where the X-rays and the cyclotron emission are produced. In this case, we are able to compare directly our magnetic field strength determination with that of Achilles et al., since both field determinations are pertinent to the accreting region of the white dwarf. This is unusual, since Zeeman studies of the magnetic fields of white dwarfs always give photospheric values that are averaged over the whole visible hemisphere of the star. If we assume that the two magnetic field strengths found by us correspond to the magnetic fields at the two polar caps, then this implies that the dipole is offset by about 5 per cent from the centre of the star along the magnetic axis itself, and that the Zeeman features analysed by Achilles et al. were originating from the accretion region near the lower field polar cap.

3.2 BL Hydri

We assume that the basic model parameters are as deduced by Piirola, Reiz & Coyne (1987b) from the phase dependence of the linear polarization curves, namely i = 70° and...
\(\theta = 150^\circ\). The emission region is located below the orbital plane between magnetic colatitudes \(\theta_1 = 15^\circ\) and \(\theta_2 = 17^\circ\), and extends in magnetic longitude from \(\psi_1 = 175^\circ\) to \(\psi_2 = 185^\circ\). The electron temperature of the shock is \(T_e = 20\) keV, and the cyclotron emission is characterized by an optical depth parameter \(\Lambda = 7.9\) perpendicular to the stellar surface (see Wickramasinghe 1989 for a definition of \(\Lambda\) for extended emission regions). The magnetic field strength at the pole is \(B_p = 23.0\) MG. The model fit to the bright-phase spectrum of BL Hyi is shown in Fig. 2. We note that some evidence for cyclotron features is also present in the faint-phase spectrum of BL Hyi. Since these features look much weaker than those seen in the bright-phase spectrum and they have not moved in wavelength, we conclude that they are caused by some residual contamination from the bright phase.

Previous estimates of the magnetic field strength of BL Hyi were based on observations of Zeeman absorption features arising from the white dwarf surface during a low state of this system (Wickramasinghe, Visvanathan & Tuohy 1984). Wickramasinghe et al. modelled their spectrophotometric observations with a centred dipole field distribution of polar field strength \(B_p = 30\) MG. This value differs somewhat from the value found to fit the present data, thus suggesting that for this system, as for most AM Herculis systems, the dipolar field is not centred, and that the pole with the weaker field is located on the hemisphere that faces the companion star and accretes more strongly.

### 4 CONCLUSIONS

Our observations of the AM Herculis systems EF Eri and BL Hyi have shown the presence of prominent cyclotron harmonic features in their infrared spectra. Our detailed modelling of these spectra has shown that the harmonics are generated in cyclotron emission regions located near the polar caps of the white dwarf.

Our study of EF Eri points to the presence of two separate cyclotron emission regions of field strengths \(B = 16.5\) and 21 MG. We have assumed that the two values found by us correspond to the magnetic fields near the two polar caps, thus implying that the dipole is offset by about 5 per cent from the centre of the white dwarf along the magnetic axis. We have compared our field determination with the value of \(15 \pm 2\) MG deduced by Achilleos et al. (1992) from a halo Zeeman study of EF Eri, and we have argued that, given the above field structure, the Zeeman features analysed by Achilleos et al. were probably arising from a region located in the vicinity of the lower magnetic field polar cap.

The modelling of BL Hyi indicates a polar field strength of 23 MG. This value is significantly lower than the value of 30 MG deduced by Wickramasinghe et al. (1984) from a Zeeman study of this system during a low state of accretion. We have interpreted this discrepancy as an indication that the field structure of BL Hyi is probably that of an offset dipole, with the weaker field located on the hemisphere that faces the companion star and accretes more strongly.

### ACKNOWLEDGMENTS

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### REFERENCES