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The discovery of RE 1307 + 535: the shortest period AM Her system

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ABSTRACT

We report on a *ROSAT* Wide Field Camera EUV survey observation of RE 1307 + 535 which, together with optical spectroscopic and photometric observations, shows that this object is an AM Her system. These observations reveal that RE 1307 + 535 has an orbital period of 79.69 min, the shortest orbital period known for such a system. RE 1307 + 535 was observed by us in both high (V = 17–18) and low (V = 20–21) states, with evidence of cyclotron emission being seen in both cases. We use the high-state spectroscopy to show that the optical emission comes from a region with a magnetic field, $B \approx 30$–40 MG. We derive EUV temperature and luminosity limits. IRCAM infrared photometry is used to put a lower limit on the distance to RE 1307 + 535 of $d > 705$ pc. RE 1307 + 535 is thus one of the most distant AM Her systems known, and is the first that is at a measured distance of $z > 630$ pc above the Galactic plane.

Key words: binaries: close – stars: individual: RE 1307 + 535 – stars: magnetic fields – stars: variables: other – ultraviolet: stars.

1 INTRODUCTION

The *Einstein* and *EXOSAT* soft X-ray telescopes added significantly to the number of known magnetic cataclysmic variables (CVs). In particular, the AM Her systems, with their highly modulated, periodic soft X-ray flux, are especially easy to identify in soft X-ray data (Biermann et al. 1985; Beuermann et al. 1987; Morris et al. 1987; Osborne et al. 1988; Beuermann et al. 1989). The highly diagnostic soft X-ray characteristics of these systems are due to the synchronous rotation of a small binary system containing a strongly magnetic white dwarf with a small accretion-heated hotspot (Cropper 1990). The *Einstein* and *EXOSAT* observations did not cover more than a small fraction of the sky, however, and the *ROSAT* all-sky survey was expected to discover many more such systems.

The *ROSAT* EUV Wide Field Camera[1] (WFC, Sims et al. 1990) is co-aligned with the German X-ray telescope, and both telescopes made a survey of the sky in the interval 1990 July 30 to 1991 January 25. Pounds et al. (1993) have published a Bright Source Catalogue containing 384 EUV sources detected by the WFC with high confidence during this all-sky survey. In addition to six previously known AM Her systems in the catalogue, another six new sources (including RE 1307 + 535) have been identified as AM Her systems (Watson 1993).

RE 1307 + 535 is one of the relatively faint unidentified sources in the catalogue. It was observed as part of a programme to identify optically a sample of WFC EUV sources (Mason et al. 1991), and discovered to be a blue, variable, emission-line star. Subsequent examination of the EUV light curve shows a clear modulation at an apparent period of 7.78 h, possibly due to an intrinsic period of 79.7 or 120.9 min beating with the satellite orbital period. Optical CCD photometry selects the shorter of these two periods as

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the true modulation period of the star and, together with the optical spectroscopic properties and EUV light curve, strongly suggests that RE 1307+535 is a new AM Her system. Furthermore, it has the shortest orbital period, 79.7 min, among the AM Her stars.

In this paper, we present the WFC data on RE 1307+535, together with details of its optical identification and the subsequent CCD photometric study.

2 THE DATA

2.1 *ROSAT* EUV survey data

The *ROSAT* EUV Wide Field Camera consists of a set of three nested gold-coated Wolter–Schwarzschild type 1 mirrors mounted in front of a curved microchannel plate detector with a resistive readout. Filters restrict the sensitive energy range to S1: 90–206 eV (60–140 Å) and S2: 62–110 eV (110–200 Å). The WFC has a 5°-diameter circular field of view, in which the angular resolution varies between 1 and 3 arcmin from the centre to the edge. Between 1990 July 30 and 1991 January 25 the WFC surveyed almost the entire sky by scanning great circles perpendicular to the ecliptic plane as the satellite orbited the Earth. The scan path advanced by ~1° per day, keeping the telescope axis at ~90° from the Sun (Pounds et al. 1993). Individual sources were scanned once per satellite orbit ($P_{ROSAT}=96$ min) for an interval of at least 5 d (increasing to continuous viewing at the ecliptic poles). Away from the poles, source exposure in individual scans increased from zero to a maximum of 80 s, before decreasing to zero again as the field of view was daily advanced in ecliptic longitude. The S1 and S2 filters were inserted into the beam on alternate days during the survey.

RE 1307+535 was in the WFC field of view between 1990 November 23 and December 1. Total integration times were 2253 s in S1 and 2020 s in S2, yielding mean count rates of 0.042 ± 0.006 and 0.021 ± 0.006 count s^{-1}, respectively. The position of RE 1307+535, determined by maximum-likelihood fitting of the average PSF to the combined data from both filters, is

$$\mathrm{RA}\,(2000)=13^{\mathrm{h}}\,07^{\mathrm{m}}\,56\overset{\mathrm{s}}{.}4,$$
$$\mathrm{Dec.}\,(2000)=+53^\circ\,51'\,37'',$$

with a 90 per cent confidence error radius of 46 arcsec.

Data were extracted using optimized accumulation radii of 4 and 2.8 arcmin for the S1 and S2 bands, respectively. The background was determined by accumulating counts from a strip of sky along the same scan path as the source, thus using the same region of the detector. The light curve of the S1 filter data, background-subtracted and exposure-corrected, is shown in Fig. 1.

It is clear from Fig. 1 that RE 1307+535 is not a constant EUV source. A period search was carried out based on folding the data into five phase bins at all possible independent periods and testing against constancy using the χ^2 statistic. The results are plotted in Fig. 2, and show the presence of a period at $28\,050\pm150$ s at >95 per cent confidence. The times of the minima of this period are indicated by arrows in Fig. 1. Because the WFC light curves contain only small numbers of counts, the significance of the χ^2 values was determined by simulations. 1000 simulated light curves of a constant source were constructed, assuming Poisson noise, with the same mean count rate and exposure profile as the source light curve and with the same corrections applied. Significance levels were determined by subjecting these light curves to the same period search as the source light curve to give the maximum χ^2 value for each folded simulation. The distribution of these maximum χ^2 values, from which the significance levels were drawn, is plotted against the *y*-axis of the periodogram in Fig. 2. The significance of the detected period was confirmed with period searches using three and seven phase bins.

The low sampling frequency of the EUV data (less than 80 s every 96 min) allows the possibility that the true period of RE 1307+535 is considerably less than the detected (alias) period. Potential periods are $P=(P_{ROSAT}^{-1}\pm P_{\mathrm{obs}}^{-1})^{-1}=79.7\pm0.1$ and 120.9 ± 0.2 min.

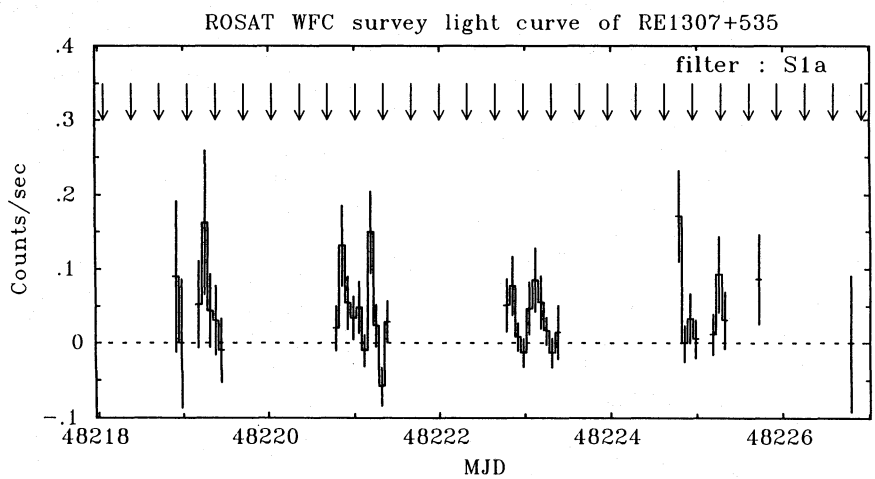

Figure 1. The *ROSAT* EUV Wide Field Camera survey light curve of RE 1307+535 in the S1 band (90–206 eV) obtained in 1990 November. One point is plotted per *ROSAT* orbit, although the exposure varies from zero to a maximum of 80 s per orbit and back to zero again as time progresses. Data gaps occur every other day, when the S2 filter was in use and during spacecraft passages through regions of high particle density. The arrows show the times of the 7.78-h minima.

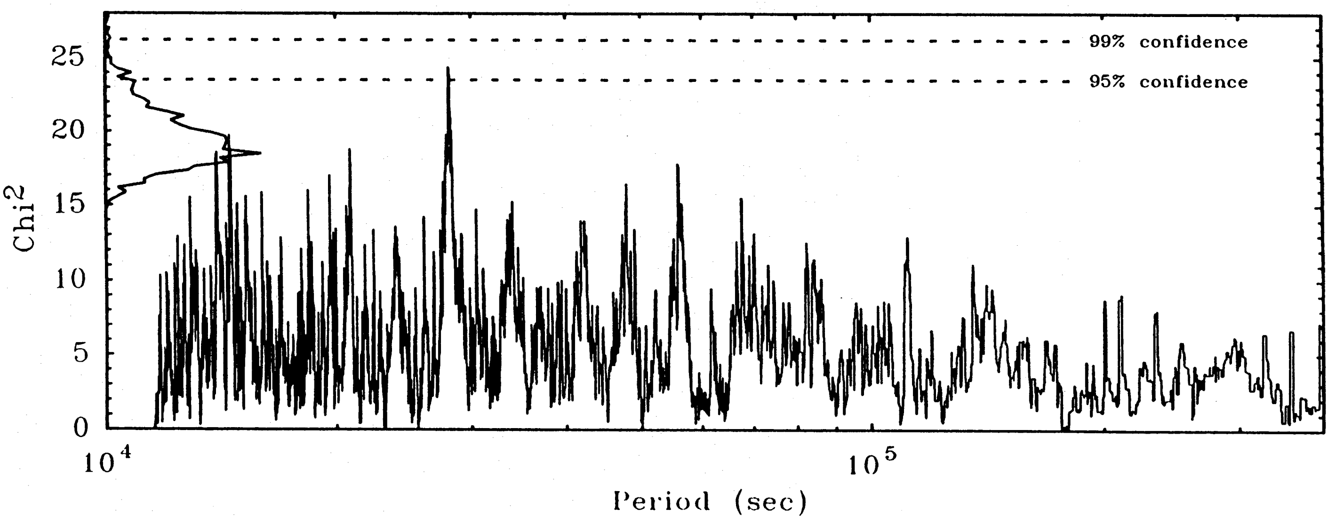

Figure 2. χ^2 for a hypothesis of constant flux as a function of trial period for the WFC data folded into 5 phase bins. On the left is a histogram representation of the maximum χ^2 values found in 1000 folded, simulated WFC light curves. The 95 and 99 per cent confidence levels are derived from this histogram.

2.2 Optical identification spectroscopy

The RE 1307+535 field was examined on 1991 May 11, using the 2.5-m Isaac Newton Telescope (INT) on La Palma. The EUV error circle is superposed on the optical field in Fig. 3. The latter was derived from a digitized scan of the blue (O) first-epoch POSS plate, made with the APM at RGO, Cambridge.

Attention was immediately drawn to the star labelled 1, which appeared much brighter on the INT TV finder than it is on the finding chart; star 1 is close to the plate limit on the O plate ($O \approx 21.7$), and is not recorded at all on the red (E) plate. Two spectra of star 1 were obtained using the Faint Object Spectrograph (FOS). Details of the FOS observations can be found in Table 1.

The FOS spectra were reduced using standard techniques, the overall flux scale being established in comparison with spectrophotometric standards observed throughout the night, and atmospheric absorption in the red being removed by reference to the spectrum of a bright, late F star observed immediately after the target and close to it on the sky. The resulting calibrated spectra are plotted in Fig. 4, and they show star 1 to be a blue object with strong emission lines of hydrogen, He I and He II. Furthermore, the star is obviously variable, the continuum flux at 5500 Å changing by almost 1 mag between the two exposures, which were centred approximately 20 min apart. The change in the line flux between the spectra is less dramatic. The (continuum) magnitudes of star 1, as measured through the spectrograph slit, are tabulated in Table 1, and these confirm our impression that this star was substantially brighter at the time of our observations than recorded on the POSS.

The position of star 1, measured on the POSS to an accuracy of 1 arcsec, is

RA (2000) = $13^h\ 07^m\ 53^s.85$,
Dec. (2000) = $+53°\ 51'\ 30''$.

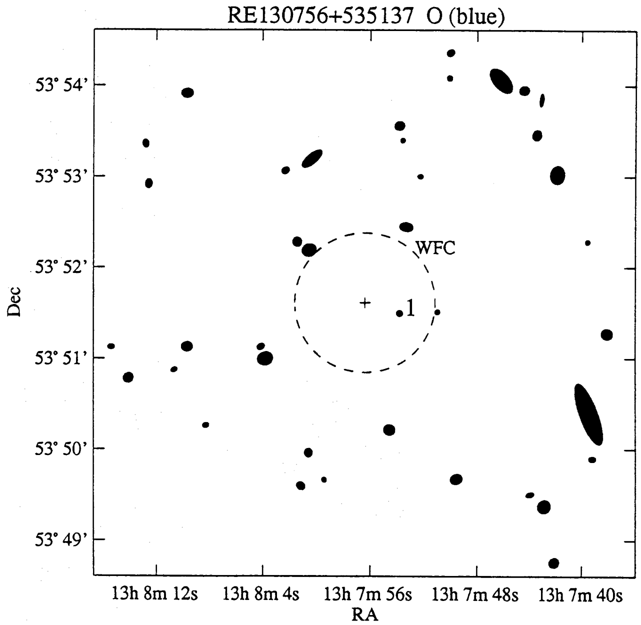

Figure 3. Finding chart derived from an APM scan of the blue (O) first-epoch POSS plate. The WFC error circle is superposed. The star to the east of the label '1' is the cataclysmic variable. Its coordinates are RA(2000) = $13^h\ 07^m\ 53^s.85$ Dec.(2000) = $+53°\ 51'\ 30''$.

Table 1. INT FOS observation log.

Start (UT)	Exposure (seconds)	Monochromatic magnitude B	V	R
11/5/91 02:08:07	500	17.2	17.1	17.2
11/5/91 02:23:16	1000	18.6	18.0	17.7

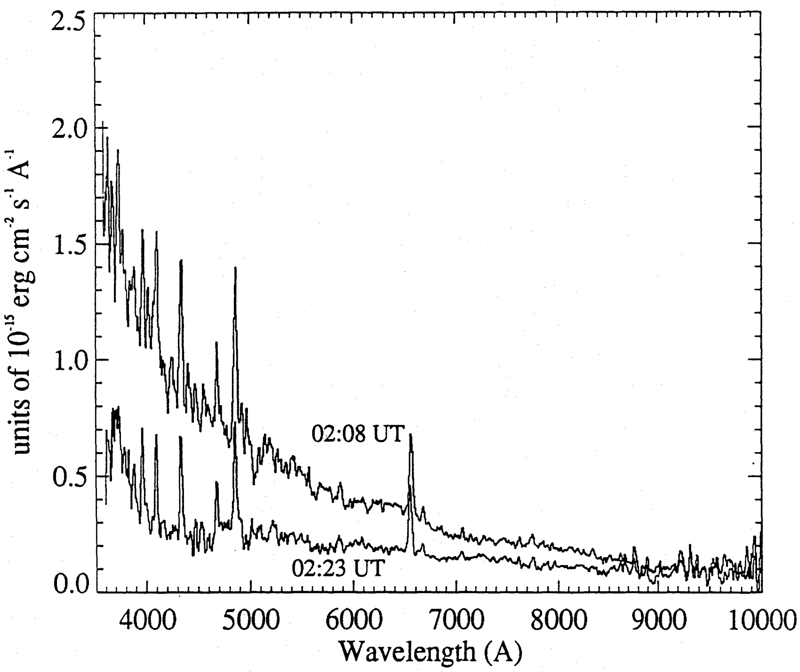

Figure 4. Optical spectra of RE 1307+535 star 1 taken with the FOS on the INT (see Table 1). The two spectra are from two successive observations, and are distinguished by their UT start times. A three-point running mean filter has been applied to the data to reduce point-to-point noise.

2.3 JKT CCD photometry

CCD photometry of the RE 1307+535 field was obtained with the 1.0-m Jacobus Kapteyn Telescope (JKT) on La Palma on the nights of 1992 March 26–28. The data were taken with a coated GEC CCD (580 × 390 0.3-arcsec pixels) at the $f/15$ Cassegrain focus. Because the source was faint, 10-min white-light (3200 – 9800 Å) exposures were made on the nights of March 26 and 27, and 10-min R-band exposures were made on the night of March 28. Two single V-band images were also obtained (see Table 2 for an observation log). Standard stars were observed to calibrate the R- and V-band data. The images were debiased, and flat-fielded using exposures of the twilight sky.

To allow for the effects of seeing and extinction, the sky-subtracted counts from RE 1307+535 were taken relative to those of a bright comparison also in the CCD frames (~70 arcsec NE, $R = 15.93$). A star about twice as bright as RE 1307+535 and ~20 arcsec to the north, but not shown on the finding chart, was used to check this process, indicating that photometric errors are less than 5 per cent. We note that the star ~24 arcsec west of RE 1307+535, and of similar brightness to it, is a variable with ~20 per cent peak–peak modulation in white light on a time-scale of 3.6 h.

The JKT CCD light curves of RE 1307+535 are shown in Fig. 5. A clear 60 per cent peak–peak modulation at a period of ~80 min is present in both the white-light and R-band data.

Table 2. JKT CCD observation log.

Start (UT)	Number of 10 min exposures	Filter	Magnitude
26/3/92 23:26:44	36	none	
28/3/92 01:27:42	1	V	20.84±0.11
28/3/92 01:51:31	20	none	
29/3/92 00:42:27	1	V	20.51±0.08
29/3/92 00:55:06	18	R	19.7 – 20.6

[NB High cirrus appeared after approximately 04:00 (UT) on the 29th.]

2.4 NOT CCD photometry

RE 1307+535 was observed on the nights of 1992 May 22, 24 and 29, using the CCD on the 2.56-m Nordic Optical Telescope (NOT) on La Palma. The CCD camera contains a front-illuminated, LN_2-cooled Tektronix CCD with 512 × 512 0.2-arcsec pixels. The camera is used in a position close to the $f/11$ Cassegrain focus, involving the reflection of the central field on to the CCD by a flat mirror.

The observations of RE 1307+535 consist of 300- and 500-s exposures using the R filter. The first exposures taken were of 300-s duration; later exposures were longer in order to improve photometric accuracy (see Table 3). The brightness of RE 1307+535 was measured against the star used as a photometric check ($R = 19.35$) in the previous section. The images were bias-subtracted and flat-fielded using dome flats.

The NOT CCD data are shown in Fig. 6. The R magnitude and magnitude range of RE 1307+535 are the same as in the JKT observation made two months earlier. The 80-min period found previously is also very clear in these observations. However, a strong secondary minimum has

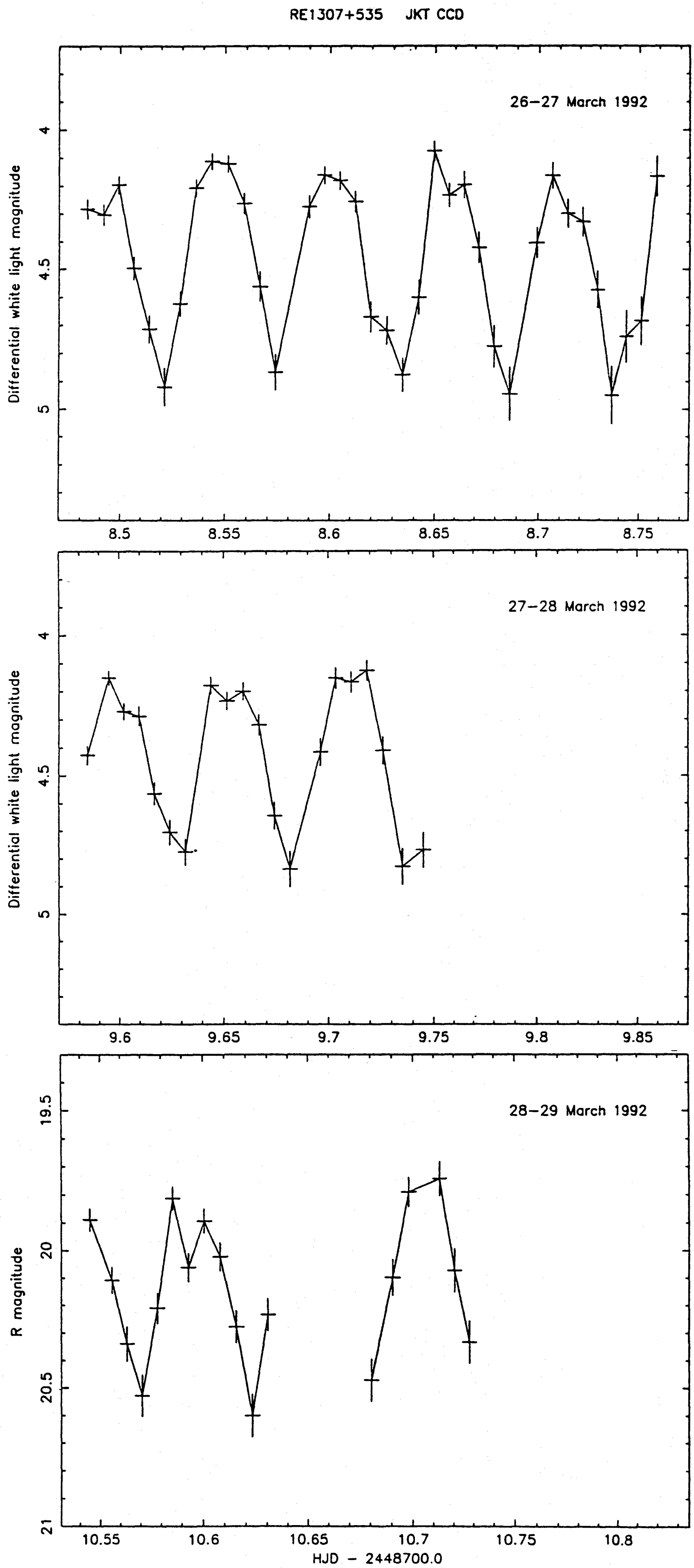

Figure 5. Three nights of CCD photometry of RE 1307 + 535 obtained using the 1.0-m JKT on La Palma.

Table 3. NOT CCD observation log.

Start (UT)	Number of exposures	Filter	Exposure time (seconds)
22/5/92 21:41:45	12	R	300
22/5/92 23:01:15	6	R	500
24/5/92 22:05:45	15	R	500
29/5/92 23:21:00	13	R	500
15/4/93 20:49:11	21	none	300

developed, whereas there was previously only a hint of it in the JKT *R*-band light curve.

A further observation spanning 1.5 cycles was made on 1993 April 15, using the same instrumental setup, but without the *R* filter. RE 1307+535 showed a similar modulation to that seen in the JKT data.

2.5 UKIRT infrared camera photometry

The Infrared Camera (IRCAM) on the United Kingdom Infrared Telescope was used to image the RE 1307+535 field in the *K* band on 1992 July 16. The IRCAM is a LN_2-cooled InSb array of 62×58 pixels, which was operated in direct imaging mode with 0.62-arcsec pixels during this service observation. A total of 168 30-s exposures of the RE 1307+535 field were made over 90 min in a 9-point 4×4 arcsec^2 raster. Images of a nearby star were taken before and after the RE 1307+535 sequence for photometric and positional calibration. Images were also made of the intrinsic IRCAM background. The standard star HD 129653 ($K=6.92$) was observed to provide absolute calibration.

The data were reduced, using the IRCAM software, to a single sky image by subtracting the intrinsic background, flat-fielding using the normalized median of all the rastered images, removing bad pixels from individual images, subtracting the median sky background from each image, and finally forming a mosaic of the resulting images. RE 1307+535 was visible as a faint source in this summed image. The other two faint stars referred to in Section 2.3 were also visible. By accumulating data in a 7-pixel diameter circle for both RE 1307+535 and the standard star, and taking the mean of seven different background regions, the *K* magnitude of RE 1307+535 was found to be, after a negligible airmass correction, $K=19.3 \pm 0.2$.

3 THE PHOTOMETRIC EPHEMERIS

We have fitted a function, consisting of a sine with a Gaussian subtracted at the peak, to the individual intensity pulses seen in the CCD light curves in an attempt to derive unbiased estimates of the times of the pulse centres. Typically seven intensity points were fitted at a time for the JKT data, whereas the NOT data were fitted in one-night groups. The resulting heliocentric pulse centre times are listed in Table 4.

Initially using the times of the JKT white-light pulse centres only, we searched for periods by evaluating χ^2_ν ($=\chi^2/\nu$, where ν is the number of degrees of freedom) of the 'observed minus computed' (O − C) values as a function of trial period and epoch, ensuring that the χ^2_ν behaviour was fully resolved. Inspection of the CCD light curves shows that any period must be between 0.04 and 0.07 d, and the search was restricted to periods in this range. Minimum χ^2_ν ($\chi^2_\nu=1.4$) occurred at a period of 79.8 min. No other period was found to give an acceptably low value of χ^2_ν. Following the value of χ^2_ν as a function of period and epoch around the best values, we derived confidence intervals for the two interesting parameters. These period, epoch and error estimates were confirmed by a linear least-squares fit to the (O − C) values.

The times of the pulse centres seen in the JKT red data are consistent with the ephemeris derived from the white light only. This justifies the use of all of the data from the JKT and NOT in order to find an improved ephemeris. Repeating the process described above, we found that the best period was 79.69 min, with a $\chi^2_\nu=0.97$. Again, no other formally acceptable period was found. The next best periods (with one less and one more cycle between the JKT and 1992 NOT data) are 79.77 min ($\chi^2_\nu=4.6$) and 79.62 min ($\chi^2_\nu=5.5$).

The ephemeris for the times of pulse centre derived from the white- and red-light data is

$$T_{\rm centre} = {\rm HJD}\ 244\,8749.4421(5) + 0.055\,338\,38(26)\,E, \qquad (1)$$

where the 68 per cent joint confidence error in the last digits is given in parentheses. Fig. 7 shows the CCD and WFC data folded on the 79.69-min period.

4 DISCUSSION

4.1 The classification of RE 1307+535

RE 1307+535 is almost certainly an AM Her system, i.e. a synchronously rotating, highly magnetic white dwarf accreting from a Roche-lobe-filling secondary star. The evidence in favour of this conclusion includes: periodic EUV emission; an optical spectrum typical of high-excitation cataclysmic variables; the sudden disappearance of the blue continuum in the second optical spectrum characteristic of eclipse of the accretion region by the body of the white dwarf; the decrease in optical brightness from $V=17$–18 to $V=20.5$–20.8 typical of a high–low state transition in AM Her systems; a photometric period identical to one of the candidate EUV periods and characteristic of AM Her cataclysmic variables; and a deep modulation of the optical light curve typical of AM Her systems.

Definitive classification will come with the detection of polarization modulated at the 79.7-min period. However, apart from the AM Her systems, no known class of astronomical object has the characteristics described above for RE 1307+535.

4.2 Implications of the orbital period

With a period of 79.7 min, RE 1307+535 is the shortest period AM Her system known. The well-studied system EF Eri previously held this record, having a period of 81.0 min; however, there are several non-magnetic CVs known with shorter orbital periods (Ritter 1990). These mostly have helium-rich secondary stars.

The significance of the discovery of a new short-period CV derives from our understanding of the evolution of CVs. From a binary period $P \approx 2$ h, at the edge of the period gap, CVs are expected to evolve to shorter periods under the influence of gravitational radiation. Eventually, the effect of mass transfer dominates that of gravitational radiation,

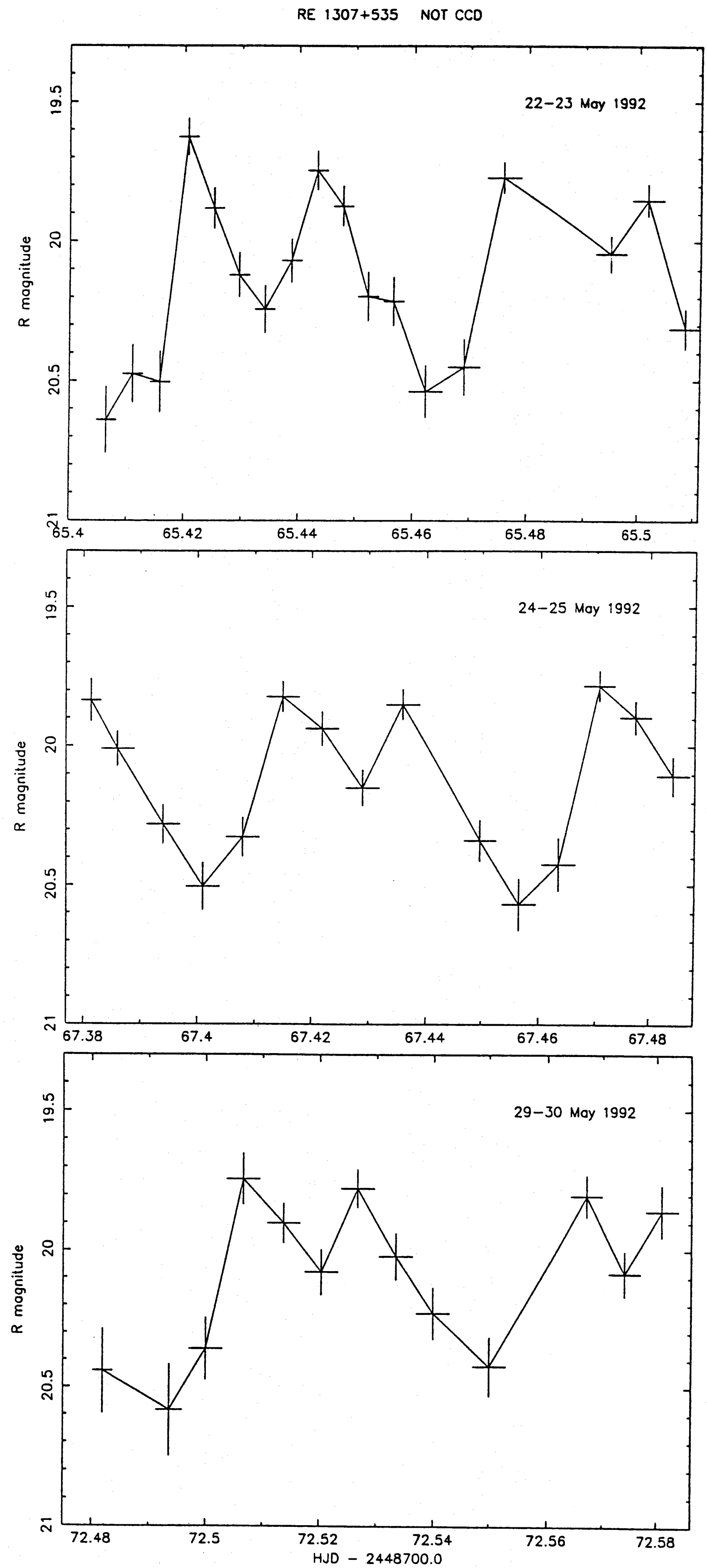

Figure 6. Three nights of *R*-band CCD photometry of RE 1307 + 535 obtained using the 2.56-m NOT on La Palma.

Table 4. Heliocentric Julian dates of the fitted times of the intensity pulses, together with the colour system used. The times have an estimated error of 100 s. Also given are the cycle counts and the observed minus calculated times of phase zero according to the ephemeris of Section 3.

Telescope	Colour	HJD	E	(O–C) (seconds)
JKT	white	2448708.4928	−740	95
JKT	white	2448708.5472	−739	14
JKT	white	2448708.6007	−738	−145
JKT	white	2448708.6578	−737	−7
JKT	white	2448708.7115	−736	−134
JKT	white	2448709.5979	−720	−49
JKT	white	2448709.6539	−719	8
JKT	white	2448709.7107	−718	135
JKT	R	2448710.5955	−702	82
JKT	R	2448710.7063	−700	92
NOT	R	2448765.4344	289	−43
NOT	R	2448767.4279	325	71
NOT	R	2448772.5185	417	26
NOT	white	2449093.4253	6216	−15

causing the binary system to expand and the period to increase. Accretion can continue at a low level in spite of this increase in separation, because the mass of the secondary star has been reduced to the point where nuclear burning ceases and the core becomes degenerate. Further mass loss then causes the star to expand, so it continues to fill its Roche lobe. There is thus a minimum orbital period in the life of a CV, which Rappaport, Joss & Webbink (1982) find to be $P_{\rm min} = 61.5$–74.5 min, well below that found for RE 1307+535. The high-state magnitude of $V = 17$–18 observed during the spectroscopic observation suggests that RE 1307+535 has episodes of high accretion rate, and so has not yet reached its minimum period. The existence of this stationary point in the period evolution of CVs suggests that we will eventually see a spike in the period distribution at the minimum period, similar to that seen at the short-period edge of the period gap (Hameury, King & Lasota 1990).

As the orbital period decreases from ~2 h towards $P_{\rm min}$, the secondary star is expected to become increasingly oversized for its mass with respect to the main sequence. Nevertheless, Patterson (1984) gives an *empirical* mass–radius relationship which, together with Kepler's law and an expression for the size of the secondary (Paczyński 1971), allows some basic parameters of the binary system to be derived. For a binary period of 79.7 min, we find that the secondary will have a mass $M_{\rm sec} = 0.10\ {\rm M}_\odot$ and a radius $R_{\rm sec} = 0.13\ {\rm R}_\odot$. This low mass is close to, but not below, the minimum mass required for main-sequence hydrogen-burning (Burrows & Liebert 1993, who also confirm the mass–radius relationship for such very low-mass M dwarfs). The binary separation will be $a = 0.54\ {\rm R}_\odot$. Patterson (1984) also gives an expression for the mass-transfer rate as a function of orbital period in CVs, which suggests that, for RE 1307+535, $\dot{M} \approx 2 \times 10^{-11}\ {\rm M}_\odot\ {\rm yr}^{-1}$ on average.

4.3 Distance of RE 1307+535, its location and history

Bailey (1981) originally provided a method of determining the distances to CVs that is based on knowledge of the K-band surface flux from M star photospheres. More recent work has led to improved colour–magnitude and mass–magnitude relationships for very low-mass field stars (Leggett 1992; Henry 1991, illustrated in Burrows & Liebert 1993). These can be combined with a new measurement of the K-band surface flux of late M stars as a function of $(V-K)$ colour by Ramseyer (1994), together with the mass, radius and K-band flux estimates of Sections 4.2 and 2.5, to yield an estimate of the distance to RE 1307+535. Such an estimate is a lower limit, because there is an unquantified contribution to the K-band flux from the cyclotron emission region.

Using the mass–magnitude relationship of Henry (1991), we obtain a magnitude $M_K = 9.40 \pm 0.36$ (taking the errors from Henry & McCarthy 1990). Comparing this to the observed K magnitude, $K = 19.3 \pm 0.2$, we find a lower limit to the distance of $d > 960 \pm 160$ pc. Making use of this derived magnitude in Leggett's colour–magnitude relationships, together with Ramseyer's surface flux calibration for the reddest dwarfs (and propagating all known uncertainties), we find that $d > 705 \pm 150$ pc if the secondary has the colours of a young disc object, and $d > 920 \pm 160$ pc if it has the colours of a halo object.

RE 1307+535 is at a galactic latitude of $b = +63°$. This means that it is at a height above the Galactic plane of $z > 630$ pc, and, as such, is the first CV located in the Galactic halo by infrared distance measurement. (See Howell & Szkody 1990 for a review of other halo-candidate CVs.)

The possible position of RE 1307+535 in the halo raises some interesting questions about its evolution to the present state, if it is believed that all stars in the halo were formed essentially along with the Galaxy. In particular, CVs are thought to spend no more than $\simeq 5 \times 10^9$ yr evolving to the minimum period ~80 min from any initial period (Rappaport, Joss & Webbink 1982; King 1988), whereas the Galactic age is $\sim 1.5 \times 10^{10}$ yr (Iben & Renzini 1984). There appear to be three possible ways of filling in the $t_{\rm disc} \sim 1 \times 10^{10}$ yr discrepancy between these two figures, of which two seem plausible.

(1) The system was born along with the Galaxy, evolved down to its present period in $\sim 5 \times 10^9$ yr, and has been near its present period for the intervening time $\sim t_{\rm disc}$. This has some appeal, in that period evolution near $P_{\rm min}$ is extremely slow. However, it is slow precisely because the mass-transfer rate there is very low, i.e. $< 10^{-11}\ {\rm M}_\odot\ {\rm yr}^{-1}$ (cf. fig. 6 of King 1988). This is hard to reconcile with the high intrinsic luminosity implied by the distance estimate; we would require the mass-transfer rate to have fluctuated by more than an order of magnitude above the evolutionary mean.

(2) The system spent $t_{\rm disc}$ as a pair of main-sequence stars, before the primary became a giant and then a white dwarf, followed by common-envelope evolution leading to CV formation. This route corresponds to the normal one for the formation of CVs in the Galactic plane, but is rather unlikely here, as the primary has to have had a main-sequence lifetime $\sim t_{\rm disc}$ and thus a mass $\lesssim 1\ {\rm M}_\odot$: this would imply a low white dwarf mass $M_1 \lesssim 0.55\ {\rm M}_\odot$ (Weidemann 1987). A low-mass white dwarf is only compatible with mass-transfer

stability if the secondary star was even less massive initially, in which case the discrepancy can probably be explained without any restriction on the white dwarf mass [see (3) below].

(3) The system finished common-envelope evolution with a secondary mass $M_2 \lesssim 0.3\ M_\odot$ and a period $\gtrsim 10$ h. The low secondary mass means that only gravitational radiation (rather than say magnetic braking) is available to reduce the period to the value $\lesssim 3$ h required to start mass transfer. The gravitational radiation time-scale to reduce the period from the initial value P_0 to $\lesssim 3$ h is then of order 1.5×10^{10} yr, and accounts for $t_{\rm disc}$. The system thus spent the major part of its life as a detached 'pre-cataclysmic' binary, finally reaching contact at a period within or below the 2–3 h period gap. Pre-cataclysmic systems destined to do this eventually are known (Ritter 1986).

It is also possible that RE 1307+535 is a member of the more recently recognized thick-disc population of intermediate-metallicity stars, which has a scaleheight of $\langle z \rangle \approx 1.0$ kpc (Freeman 1987). In this case, $t_{\rm disc}$ may be somewhat smaller.

4.4 Light curve and accretion geometry

The CCD light curve shown in Fig. 7 is characteristic of an accreting AM Her system, yet the system was some 3.3 mag fainter when it was obtained than when the spectra were taken. Could the observed modulation be due to the ellipsoidal variation of the secondary? This is most unlikely; the colour of RE 1307+535 [$(V-R)=0.4$–0.5], the large modulation depth and the changes in shape of the CCD light curves rule out this possibility. Similarly, the shape of the R-band light curves excludes the possibility that we have seen photospheric emission from a heated part of the white dwarf surface (cf. V834 Cen, Ferrario et al. 1992). We thus conclude that cyclotron emission from an accreting magnetic white dwarf dominates the CCD light curves, even though the peak V-band brightness of RE 1307+535 has fallen to only 5 per cent of its high-state level.

This conclusion is supported by the similarity of the optical light curves of RE 1307+535 to those of V834 Cen, QQ Vul, MR Ser and AM Her in their high states (Priedhorsky et al. 1978; Cropper, Menzies & Tapia 1986; Osborne et al. 1987a; Schwope et al. 1991). These systems all have their main optically emitting pole in the same hemisphere as the observer. The similarity with the well-studied system V384 Cen is particularly striking, as both RE 1307+535 and V834 Cen show a variable secondary minimum (e.g. Osborne, Cropper & Cristiani 1987b). Cropper (1989) has modelled these poorly understood light curves, and finds that the deep optical minimum occurs when the accreting pole is closest to face-on, being a consequence of the low optical depth of a cyclotron-emitting plasma along lines of sight aligned with the magnetic field (i.e. cyclotron beaming, Wickramasinghe & Meggitt 1985). Cropper gives a number of possible reasons for the secondary minimum, all related to the arc-like shape of the emission region. Ferrario & Wickramasinghe (1990), while generally agreeing with Cropper, ascribe the secondary minimum to a projected area effect.

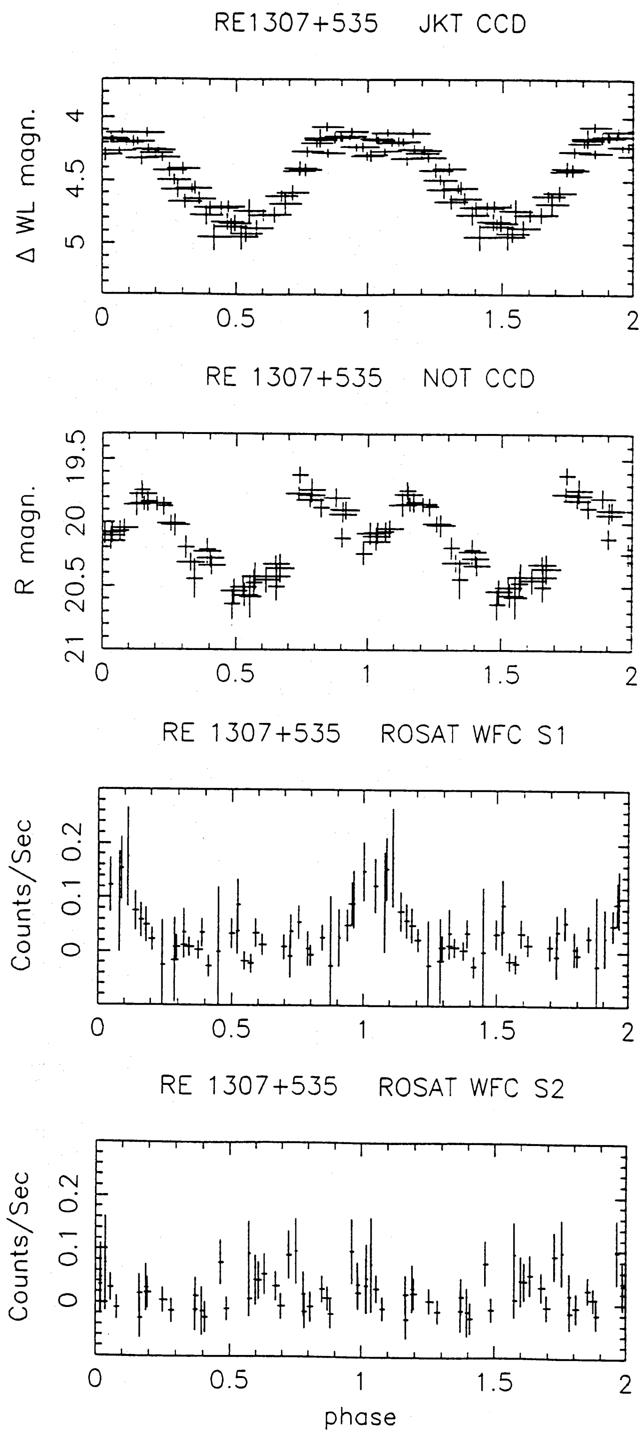

Figure 7. RE 1307+535 light curves, folded on the pulse centre ephemeris given in this paper. The data are shown twice for clarity. From top to bottom: 1992 March JKT unfiltered CCD photometry; 1992 May NOT R-band CCD photometry; *ROSAT* WFC sky survey data from 1990 November, S1 filter (90–206 eV); *ROSAT* WFC sky survey data from 1990 November, S2 filter (62–110 eV).

This orientation of the white dwarf successfully explains the remarkably similar V magnitude and simple/normal mode soft X-ray light curves of V834 Cen, QQ Vul, MR Ser and AM Her. In all these cases, the deep V-band minimum close to linear polarization phase 0.5 coincides with what would be the soft X-ray maximum, but for the usually total eclipse due to the distant accretion stream rising out of the orbital plane as it is captured by the magnetic field of the white dwarf. (AM Her itself is seen at low inclination, so the soft X-ray eclipse due to the accretion stream does not occur.) A soft X-ray maximum is expected when the accretion region is closest to face-on, as this emission is from the optically thick, heated photosphere of the white dwarf. In the complex/reversed mode soft X-ray light curves, the pole previously bright in both soft X-rays and optical light becomes fainter in soft X-rays, while a second emitting pole dominates the soft X-ray light curve in the phase range 0.7 to 0.2.

We are now in a position to interpret the light curve of RE 1307+535. As in the AM Her systems mentioned above, we expect that the optical maximum occurs when the accretion region is closest to the limb. Thus, if a linear polarization spike is found, it can be expected at phase zero of the ephemeris of Section 3. The deep optical minimum is due to cyclotron beaming, and occurs when the accretion region is closest to face-on. The origin of the variable minimum at phase zero predominantly seen in red light has a number of possible explanations, including perhaps partial occultation. It is variable because the location and extent of the accreting mass stream are variable. Taking i as the system inclination and β as the colatitude of the optical emission region, RE 1307+535 has $\beta>0°$, $(i+\beta)<90°$ and probably $|i-\beta|\leq 40°$.

An independent constraint can be put on the system inclination, as there is no clear eclipse due to the secondary star. The photometric errors in the light curve are of order 5 per cent, so a 10 per cent dip would be seen if one were present. A total eclipse of 1 min would cause such a dip in the 10-min bin JKT light curve. As no such dip is seen, the maximum duration of a total eclipse is 1 min. For a 0.6-$M_\odot$ white dwarf, this restricts the inclination of the system to $i<76°$, consistent with the constraints derived above.

The *ROSAT* WFC EUV light curves in the two filter bands are also shown folded in Fig. 7. The ephemeris error is negligible. In the harder S1 band we see a maximum centred on phase 0.05, and essentially zero flux elsewhere. The S2 light curve is of lower statistical quality, but appears also to show a maximum centred on phase 0.65. If RE 1307+535 were in a simple mode, we would expect to see a single maximum of the soft X-ray/EUV flux at phase 0.5 (unless there was an eclipse by the accretion stream, in which case we would expect two maxima centred on phase zero and separated by up to $0.5\,P_{\mathrm{orb}}$). On the other hand, if RE 1307+535 were in a complex/reversed mode, we would expect to see emission from two regions separated by $0.5\,P_{\mathrm{orb}}$, perhaps with the one spanning phase zero being longer and brighter than the other (cf. QQ Vul, V834 Cen), and perhaps with the two maxima having different spectral distributions (cf. AM Her). The *ROSAT* WFC EUV light curve of RE 1307+535 appears more like the complex, rather than the simple, soft X-ray light curves of QQ Vul and V834 Cen, and the phasing of this light curve is also consistent within the errors. This interpretation implies that the maxima seen in the S1 and S2 light curves are due to different emission regions, with the S2 region (around phase 0.65) being close to the source of the optical light.

It is interesting to compare the high-state results of 1991 May with the results from 1992 March to May when RE 1307+535 was so much fainter. The monochromatic magnitudes listed in Table 1 were taken at phase 0.2 ($V=17.1$) and phase 0.4 ($V=18.0$). Comparison with the V and R magnitudes of 1992 shows that RE 1307+535 was brighter close to phase zero when in its high state, just as it was in its fainter state in 1992. This suggests that the accretion geometry had not changed substantially, in spite of the large change in brightness.

4.5 EUV temperature and luminosity

We have folded blackbody spectra absorbed by cold gas (Morrison & McCammon 1983) through the response of the WFC in order to predict S1:S2 count rate ratios. These have been compared with the observed count rate ratio, after correction for the differential decline in WFC efficiency and inclusion of 10 and 15 per cent systematic efficiency errors added in quadrature for the S1 and S2 filters, respectively. The corrected count rate ratios that we have determined are from the phases of the two peaks seen in the folded WFC light curve; they are 3.56 ± 1.6 (for the $\phi=0.05$ peak) in the phase range 0.9 to 0.2, and 0.52 ± 0.23 (for the $\phi=0.65$ peak) in the phase range 0.5 to 0.77. These two peaks in the WFC light curve evidently have different spectra. Fig. 8 shows the blackbody temperature–absorption–luminosity regions implied by the observed count rate ratios for an assumed distance of 1200 pc.

Before discussing the limits due to the WFC data, we note that a theoretical limit exists. The temperature must be small enough that the observed luminosity is less than the Eddington luminosity for the implied emitting area (i.e. the surface flux must not be super-Eddington). Taking the expression for the radius of a white dwarf of mean molecular weight 2 as a function of its mass from Nauenberg (1972), this limit can be expressed as

$$T<(L_{\mathrm{Edd}}/4\pi R^2\sigma)^{1/4},$$

$$kT<63.7[M/(1.283M^{-2/3}-0.779M^{2/3})]^{1/4}\ \mathrm{eV}. \tag{2}$$

This limit is shown in Fig. 8 for a white dwarf mass of $M=0.6\ M_\odot$, together with the 68 and 95 per cent confidence limits from the WFC filter ratio, and the total Galactic hydrogen column density in that direction ($N_{\mathrm{H}}=1.6\times10^{20}$ cm^{-2}, Stark et al. 1984). Also shown are the luminosities implied by the spectral parameter values and the S1 count rate. Luminosities are calculated as $L=\pi d^2 f_{\mathrm{bol}}$.

It appears that, if the two emission regions suffer the same absorption, then the $\phi=0.05$ peak has a temperature at least twice that of the $\phi=0.65$ peak. The spectral limits and a reasonable luminosity limit suggest temperatures of $kT=22$–53 eV and $kT=10$–22 eV for the two peaks, respectively.

The allowed EUV luminosities are $\geq10^{32}$ erg s^{-1}. The lower end of this range is consistent with that expected for the orbital period of RE 1307+535 (Patterson 1984), and can be compared to the optical luminosity (taken from the bright spectrum in Fig. 4), which is $L_{3600-9000\,\mathrm{Å}}=2.3\times10^{32}$ erg s^{-1}. However, it is possible that a white dwarf atmosphere significantly modifies the intrinsic blackbody spectrum, thus distorting the implied EUV temperatures and

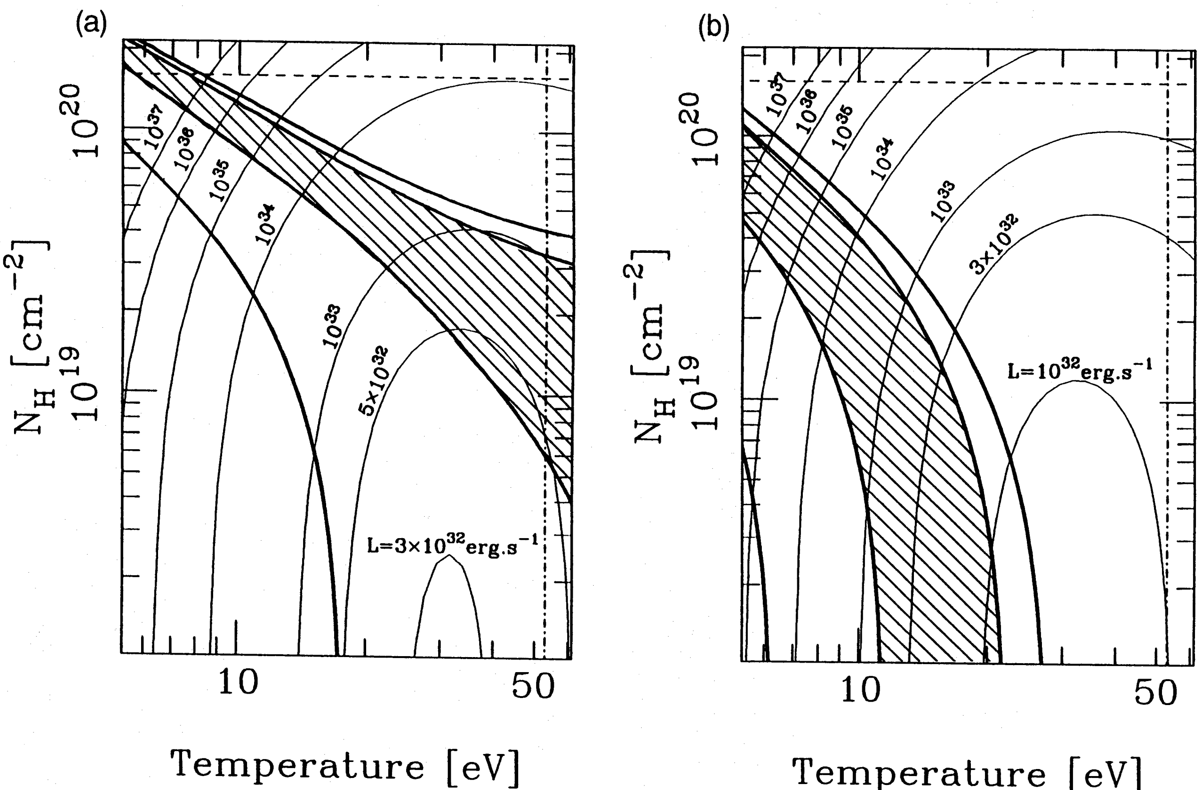

Figure 8. (a) The spectral parameters of the EUV light in the $\phi = 0.05$ peak derived from the S1:S2 count rate ratio assuming a blackbody emission spectrum. Also shown are contours of constant luminosity, based on the S1 count rate, for a distance of 1200 pc. The horizontal dashed line is the Galactic H I column density; the vertical dot-dashed line is the Eddington temperature limit for a 0.6-$M_\odot$ white dwarf. (b) As (a), but for the $\phi = 0.65$ peak.

luminosities. The lack of an intersection of the WFC curves with a sensible luminosity at the Galactic column density indeed suggests that the blackbody model is not appropriate.

4.6 Magnetic field strength

The INT FOS spectra show evidence of broad humps in the continuum which are characteristics of optically thin cyclotron radiation. Such humps are commonly seen in AM Her stars (e.g. Cropper et al. 1989, 1990; Wickramasinghe et al. 1991). To examine these in more detail, we have followed a procedure similar to that described by Cropper et al. (1989). The narrow spectral lines have been parametrized as Gaussians superimposed on a local continuum (which includes any cyclotron humps) and subtracted from the spectrum. The remaining continuum is then fitted by a low-order function, and the residuals plotted against frequency in Figs 9(a) and (b), which show the data from the two different FOS spectra, respectively.

There are clear humps in the red part of the spectrum, particularly in the first data set, where the source was brightest. The humps are less distinct in the second spectrum, and appear to be displaced towards higher frequency. Overall, the first RE 1307+535 spectrum is remarkably similar in appearance to that of the star DP Leo shown by Cropper et al. (1989) (see also Cropper et al. 1990), but with poorer signal-to-noise ratio.

Our data are too noisy, particularly in the blue, to permit a secure estimate of the magnetic field strength, B; with only two distinct humps in the best of our spectra, we have insufficient information to attempt to distinguish the temperature and orientation of the cyclotron emission region, which enter into the determination of B. However, if we assume a likely median temperature of 10 keV, and that we are viewing the emission region side-on to the field lines ($\theta = 90°$), we can estimate the likely field, making use of the table in Wickramasinghe (1989). The two prominent peaks in the first (brighter) RE 1307+535 spectrum are measured to be at 1.27×10^4 and 1.56×10^4 cm^{-1}, respectively (by fitting Gaussian profiles). Their separation suggests that they are either harmonics 4 and 5, in which case $B \sim 37$ MG, or harmonics 5 and 6, in which case $B \sim 30$ MG.

A formal fit to the humps in the second (fainter) RE 1307+535 spectrum yields peak positions of 1.37×10^4 and 1.61×10^4 cm^{-1}, but with large uncertainties. If $kT = 10$ keV and $\theta = 90°$, these imply a field strength $B \sim 32$–40 MG. These humps may be shifted to higher frequencies with respect to the first spectrum, because the magnetic axis of the emission region is at a lower angle to the line of sight, as expected from the discussion in Section 4.4 (cf. Wickramasinghe et al. 1991). Alternatively, we might be seeing a second emission region that has a genuinely higher field. Resolution of these questions must await a more detailed study of the star.

4.7 Final comments

It is ironic that one of the most distant AM Her systems has been discovered on the basis of its EUV emission, given the expected high opacity of the interstellar medium at this

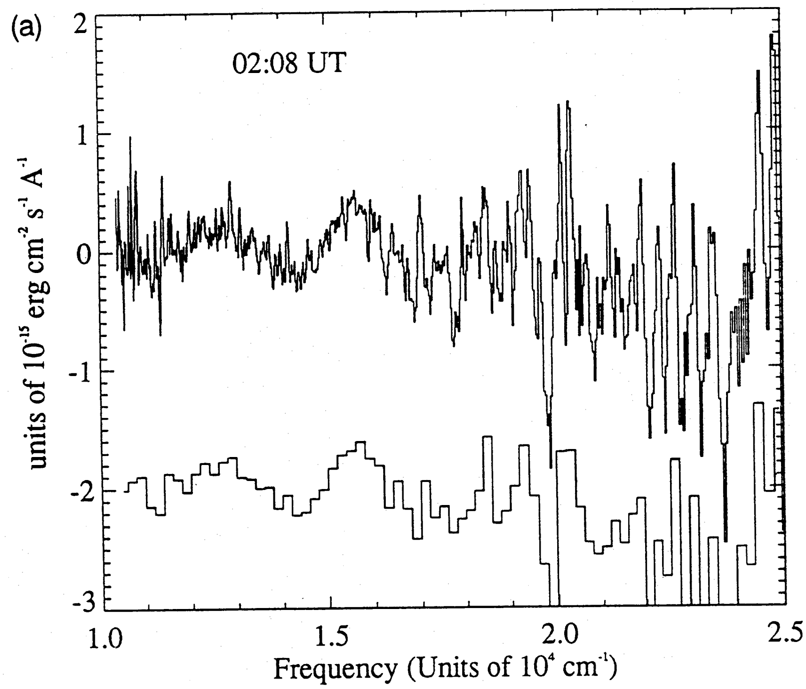

Figure 9. Residuals of the FOS spectra with respect to a low-order continuum after removal of prominent narrow emission lines. The data are plotted against frequency, because cyclotron humps are more nearly equally spaced in these units. Prominent humps can be seen, particularly in Fig. 9(a) centred on 1.27×10^4 and 1.56×10^4 cm^{-1}.

energy. In fact, RE 1307+535 is located in a region of high WFC source density. In a study of the WFC source statistics, Warwick et al. (1993) conclude that RE 1307+535 lies in a direction of an unusually long column of low-density gas ($d_{\rm bubble} \geq 120$ pc, compared to an average value of 80 pc, where the densities inside and outside the bubble are $n_{\rm i} \sim 0.05$ atom cm^{-3} and $n_{\rm o} \sim 0.50$ atom cm^{-3}, respectively).

The large distance to RE 1307+535 might at first glance suggest that it has a much larger luminosity than the other AM Her systems. However, RE 1307+535 is amongst the optically faintest of the AM Her systems and, as shown in Section 4.5, RE 1307+535 may have an EUV blackbody luminosity as low as 3×10^{32} erg s^{-1}, an unexceptional value. Finally, the distances to many AM Her systems are uncertain, at least four (and probably five) systems have distances $d > 400$ pc (Cropper 1990; Clayton & Osborne 1994).

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