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THE DISCOVERY OF VARIABLE POLARIZATION OVER THE 13.9 MINUTE SPIN PERIOD OF THE INTERMEDIATE POLAR RE 0751+14

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ABSTRACT

The total (peak-to-peak) circular polarization variation over the 13.9 minute spin period of RE 0751+14 on 1992 October 26 was 4.2% ± 0.6% in the *I* band (830 nm) and 2.2% ± 0.3% in the *R* band (690 nm), with slightly stronger negative extremes and a faster transition from the negative to the positive values. The linear polarization reached about 2% in *I* and 0.8% in *R*. Our analysis suggests cyclotron emission from two extended regions near the opposite magnetic poles of the white dwarf, and a field strength $B > 5$ MG (1 MG = 10^6 G). Fitting the existing cyclotron models to the relative amplitudes of the polarization and intensity variations in *R* and *I* bands required field strengths in the range 8–18 MG, with the dimensionless plasma parameter of the emission region $\Lambda = 10^8$–10^5. Larger Λ values are needed at lower field strengths. The position angle variability could be tentatively explained with the inclination of the magnetic white dwarf spin axis $i = 45°$–$70°$ and the two cyclotron emission regions 35°–60° off from the rotational poles. The power spectra of the *I*- and *R*-band intensity modulation are dominated by the cyclotron-originated spin period peak at 13.9 minutes, but secondary maxima are seen at ~15 minutes. The *UBV* bands show maximum modulation at the period of 14.5 minutes, which could be the beat period in the system having a binary period of about 5 hr.

Subject headings: accretion, accretion disks — binaries: close — magnetic fields — polarization — stars: individual: RE 0751+14 — white dwarfs

1. INTRODUCTION

RE 0751+14 was discovered in the extreme-ultraviolet (70–200 Å) all-sky survey by the UK Wide Field Camera (WFC) on the *ROSAT* satellite (Mason et al. 1992, hereafter MWP). The optical counterpart, identified by the 2.5 m Isaac Newton telescope (INT) on La Palma, showed spectral features typical of cataclysmic variables (CVs). Follow-up observations (MWP) by other telescopes, and the *Ginga* X-ray satellite, revealed that the object belongs to the subclass of magnetic CVs called intermediate polars (IPs), or DQ Her stars. These objects have their magnetic white dwarf component rotating asynchronously (typically $P_{spin} \sim 15$–30 minutes, $P_{orb} \sim 4$–5 hr).

In this *Letter* we report the discovery of variable linear and circular polarization over the 13.9 minute spin period of RE 0715+14. This is the first time that spin-modulated polarization has been found in an IP and makes RE 0751+14 an important object for further studies.

2. OBSERVATIONS

Our observations were made on the night 1992 October 25/26 at the 2.56 m Nordic Optical Telescope (NOT) on La Palma, using the Double Image Chopping Polarimeter (Piirola 1973, 1988; Korhonen, Piirola, & Reiz 1984). The instrument is capable of simultaneous measurements in the *UBVRI* bands by using four dichroic filters, which split the light into the five spectral passbands.

The polarimeter was used in the simultaneous linear and circular polarization mode by rotating the superachromatic quarter-wave ($\lambda/4$) retarder in 22°.5 steps above the plane-parallel calcite plate polarizing beam splitter. For each orientation of the retarder, the two polarized beams were integrated with a 25 Hz chopping frequency for a 5 s total integration time each. With some dead time involved in the chopping procedure, the resulting time resolution is about 12 s for photometry. One complete polarization observation consists of eight integrations, and the time resolution is correspondingly about 1.6 minutes.

3. RESULTS AND DISCUSSION

3.1. *Polarization and Light Curves*

Figure 1*a* gives the circular polarization data obtained from our 2.7 hr monitoring of RE 0751+14 in the time interval HJD 2,448,921.646–2,448,921.758, grouped into 20 phase bins over the 13.9 minute spin period inferred by MWP. There is a clear modulation in the *I* band with the negative circular polarization peaking at ~−2.7% and the positive near 1.5%. The transition from the negative to the positive values near the phase 0.7 is faster than the opposite zero-crossover near the phase 0.3. In the *R* band, the amplitudes are smaller by a factor of about 2, but confirm the circular polarization variability in the *R* band, suggested by Rosen, Mittaz, & Hakala (1993). In the *V* band the modulation is only marginally visible.

The only other IP having circular polarization detected is BG CMi (Penning, Schmidt, & Liebert 1986). However, the measured polarization appears to be constant [$P_c(I) \sim -0.25\% \pm 0.06\%$, $P_c(J) \sim -1.74\% \pm 0.26\%$; West, Berriman, & Schmidt 1987], with no clear modulation at the white dwarf rotation period.

The simultaneous *UBVRI* light curves obtained during the polarization observations are given in Figure 1*b*, binned over the 13.9 minute period. In the *I* and *R* bands the curves are double peaked, and the total amplitudes are ~0.18 and ~0.11 mag, respectively. There is a sharp intensity maximum prior to the positive crossover of the circular polarization. In the *UBV*

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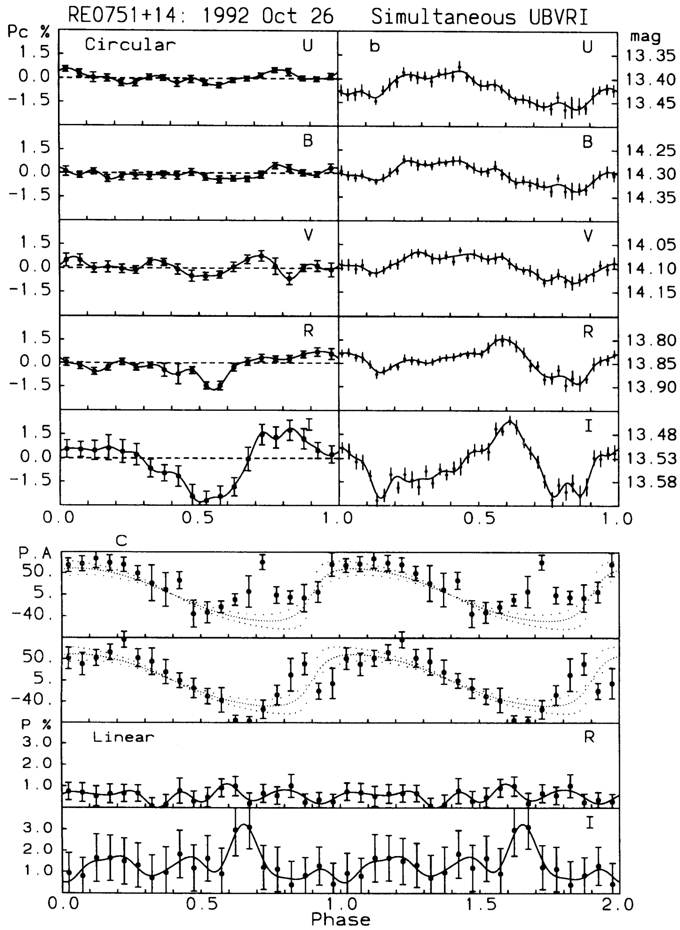

FIG. 1.—(*a*, marked Circular) Circular polarimetry of RE 0751+14 on 1992 October 26 plotted against the phase of the 13.9 minute spin period. The time of the zero phase (HJD 2,448,921.6390) is arbitrary. (*b*) Light curves obtained during the polarization observations in Fig. 1*a*. (*c*) The position angle of linear polarization in the *R* and *I* bands (*top*) and the corresponding degree of polarization in *R* and *I* (*bottom*), plotted against the 13.9 minute spin period. The dotted curves give a point-source model fit for $i = 60°$ and $\beta = 45°$. The coarse dotted lines give contours for $\beta = 55°$ (steeper slope) and $\beta = 35°$.

bands, the shapes of the light curves are almost sinusoidal, and the amplitude is decreased to about 0.07 mag.

The zero-points of the magnitude scales were determined from observations of two *UBVRI* standard stars from Landolt (1983). The star 9636 was observed just before the continuous monitoring of RE 0751+14, and the star 98185 immediately after. Both standards give results which agree within ~0.02–0.03 mag.

The linear polarization data are shown in Figure 1*c*. Due to the somewhat reduced efficiency (50%) of the linear polarization measurements in the simultaneous L&C mode, the data are noisier than for the circular polarization. However, the position angle values are not randomly scattered, and reveal a pattern of apparently continuous variations between about $-80°$ and $+90°$, both in *R* and *I*. This suggests that real linear polarization is present. A linear polarization pulse appears at phase 0.65, i.e., at the positive crossover of the circular polarization, as expected for polarization of cyclotron origin.

We also give the unfolded light curves in Figure 2*a* for the whole duration of our monitoring interval on 1992 October 25/26. The original 12 s time resolution data have been grouped into 100 independent successive average bins, resulting in time resolution of ~1.6 minutes, i.e., about the same as for the polarization data. The standard errors of the mean values were calculated from the scatter of the individual (about eight) integrations and are shown as $\pm\sigma$ error bars for each point. The statistical errors are very small in the *UBVR* bands and are visible practically only in the *I* light curve.

The light curves show gradually increasing amplitude of the short-period (~14 min) variations toward the middle of the monitoring interval (Fig. 2*a*) and a rather abrupt decay of the modulation toward the end of the run, particularly in the *UBVR* bands. The periodically changing amplitude may arise from the interference (beat) of two waves with slightly different period, as the waves shift alternatingly either in or out of phase. In a binary system other effects, e.g. visibility, can also contribute. The length of our run corresponds almost exactly to the half of the suggested orbital period of ~5.5 hr (MWP).

A sharp and well-defined peak occurs in the *I*-band power spectrum (Fig. 2*b*) at the suggested 13.9 minute spin period. Weaker side pulses are seen at ~15 minutes in *R* and *I*. In the *UBV* bands, the peaks are broader and centered at ~14.5 minutes. This would correspond to a beat (synodic) period in a binary system having an orbital period of 5.3 hr (see also Rosen et al. 1993).

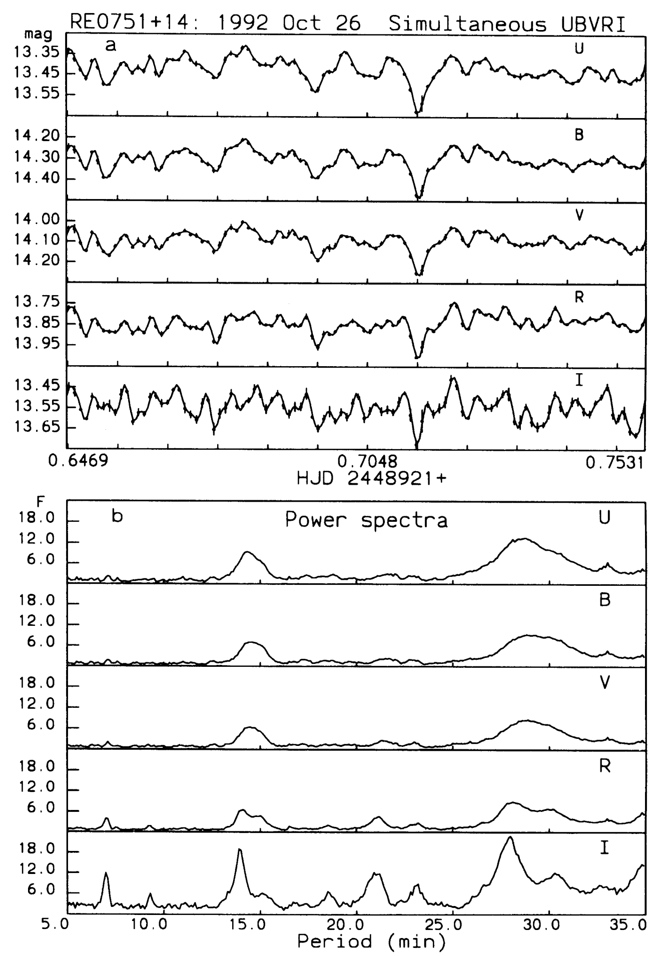

FIG. 2.—(*a*) Light curves of RE 0751+14 during our 2.7 hr monitoring on 1992 October 26. Tick marks give 13.9 minute intervals. (*b*) Power spectra of the intensity modulation in the *UBVRI* bands.

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The power spectra show strongest peaks near 28–30 minutes, i.e., double the assumed spin period. While strong aliases are expected at multiples of the true period, it is rather puzzling that in Figure 2*a* near the middle of the run every second of the light curve minima seem to be consistently deeper than the ones in between. This significant modulation power at the *first* harmonic of a 28–30 minute period would require an explanation, if present also in later observations. A beat process from two nearby frequencies (periods 14–15 minutes) cannot produce the alternatingly deep and weak successive minima in the light curves.

3.2. *Cyclotron Model Fittings*

The steep increase of the spin modulation amplitude from the *R* to the *I* band suggests that the 13.9 minute period variations are of cyclotron origin. Since the cyclotron flux is diluted by several practically unpolarized "background" components, including the stellar light, the accretion stream, the possible disk and hot spot, and reprocessed X-rays, the comparison of the observed degrees of polarization with the models is not quite straightforward. Hence, we have deduced also the polarized *fluxes*, which are independent of any unpolarized additional background. The observed polarized fluxes, $F_c = P_c F_{tot}$, can be compared with those given by the existing cyclotron models (e.g., Wickramasinghe & Meggitt 1985, hereafter WM).

Figure 3 gives the peak circularly polarized fluxes from our 1992 October 26 data in the *I*, *R*, and *V* bands. For the *B* and the *U* bands, there is no clear detection. The best fits to moderately low $\Lambda \sim 10^5$, $kT \sim 10$ keV, models are obtained with a field $B \sim 18$ MG. For lower field strengths, the models give too rapid a decrease of polarized flux from *I* to *R*, as the higher harmonics required for lower fields appear at the steeply descending part of the log F_c versus log (ω/ω_c) curve. Increasing the size parameter Λ and/or the temperature shifts the peak of the polarized flux toward higher harmonics, and similar fits are obtained for lower field strengths, e.g., $B \sim 10$ MG for the $kT = 20$ keV, $\Lambda = 10^6$ constant temperature model of WM (Piirola, Hakala, & Coyne 1993).

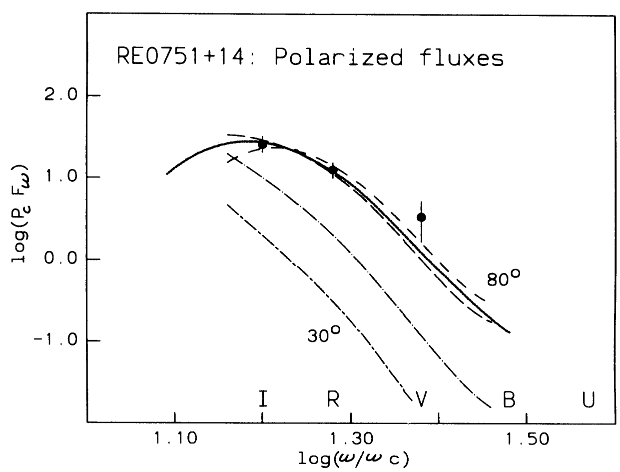

FIG. 3.—Observed peak circularly polarized fluxes of RE 0751+14, compared with those deduced from existing cyclotron models. The solid line corresponds to the extended emission region model (WWF) with a field of 8 MG and average view angle $\sim 60°$. The dashed lines give fits to a $kT = 20$ keV, $\Lambda = 10^6$ constant temperature model (WM) with a field of $B \sim 10$ MG, and view angles (*top to bottom*) of 80°, 60°, 40°, and 30°. Very similar fits are also obtained with a $kT = 10$ keV, $\Lambda = 10^5$, and $B \sim 18$ MG. The log (ω/ω_c) values refer to a 8 MG field.

Wickramasinghe, Wu, & Ferrario (1991, hereafter WWF) have presented calculations of polarization properties of extended ribbon-like accretion shocks, where allowance is made for field spread and for the change in shock height as a function of specific accretion rate. With the high $\Lambda \sim 10^8$ values involved, they predicted the cyclotron peak near 2 μm for a 5 MG field. The solid line in Figure 3 shows that the best fit of our observed circularly polarized fluxes in *R* and *I* to the model curve deduced from WWF is obtained, if the points are shifted along the log (ω/ω_c) axis corresponding to a field of $B \sim 8$ MG. For the 5 MG field, the *I* and *R* points would, again, locate at the portion of the model curve which is too steep. Also a comparison with the circular polarizations predicted for 3, 5, and 10 MG CVs in the *V* and *J* bands by Stockman et al. (1992) suggests that the field strength is between 5 and 10 MG. However, observations at wavelengths longer than our *I* band are required to determine the peak wavelength of the cyclotron flux and to have better estimates of the field.

3.3. *The System Geometry*

The presence of both negative and positive circular polarization during extended portions of the spin cycle suggests that cyclotron emission occurs near *two opposite* magnetic poles of the white dwarf. A single region can produce only a brief overshoot (change of sign), if the field lines are tilted with respect to the normal of the white dwarf.

Further constraints of the geometric model are obtained from the position angle curves (Fig. 1*c*). The continuous smooth variation between two extremes less than 180° apart means that the center of the white dwarf disk lies outside the apparent loop drawn by the emission region in the case of a simple point source model, i.e., $i > \beta$, where β is the colatitude of the emission region.

We give simulated polarization and light curves in Figure 4 for a geometric model containing two extended emission regions. Each strip of the regions was divided into 20 points for which all four of the Stokes parameters (*Q*, *U*, *V*, and *I*) were calculated applying the view angle dependences of the degree of polarization and the total flux from WM. Each emission point was treated independently, which is a good approximation for flat and extended emission regions where the adjacent volume elements do not obscure each other. We have also simplified the calculations here by assuming radial field lines, which is nearly the case if the emission region is not far from the magnetic pole. For distances $< 25°$, the field lines of a centered dipole deviate $< 13°$ from the white dwarf normal.

The asymmetry of the circular polarization and light curves suggests that the emission regions are seen along different cross sections at the self-eclipse ingress and egress (Fig. 5). The basic observed features, the sharp intensity maximum, and a stronger linear pulse just prior to the fast transition from negative to positive circular polarization are explained. Also, the position angle curve from the model (Fig. 4) is roughly in accordance with the observed pattern of variations (Figs. 1*a*–1*c*).

4. CONCLUSIONS

RE 0751+14 is the first intermediate polar (DQ Her star) for which a clear polarization modulation over the spin period has been discovered. The simultaneous multiwaveband (*UBVRI*) linear and circular polarization and light curves enable us to study the system and magnetic geometry. We have found evidence of accretion onto extended ribbon-like regions near two

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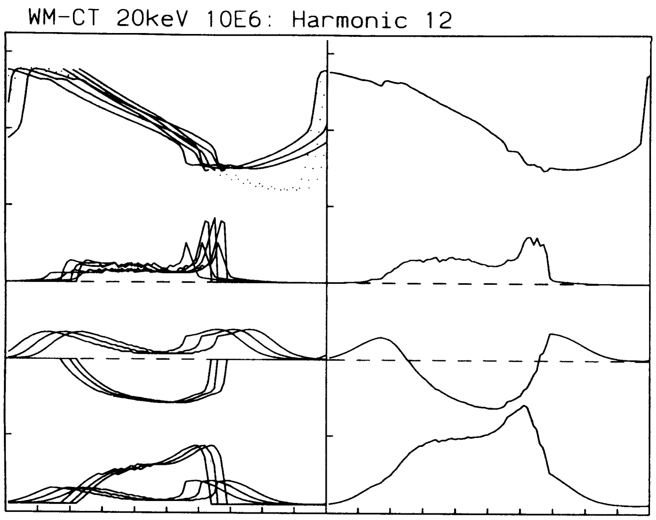

FIG. 4.—Simulated polarization and light curves for $i = 60°$ and two extended emission regions at mean colatitudes $\beta_1 = 45°$ and $\beta_2 = 125°$, as illustrated in Fig. 5. Curves from top to bottom give the position angle, linear and circular polarization, and the light curve. The curves shifted in phase correspond to individual strips with center transits at phases 0.9, 0.95, and 1.0 for the positive, and 0.45, 0.475, and 0.5 for the negative circular polarization region. The right-hand panels show the combined curves from the two extended regions. The $kT = 20$ keV, $\Lambda = 10^6$ model of WM is used for the dependences of the circular and linear polarization and the flux on the angle between the magnetic field and the line of sight. With a 10.8 MG field, the I- and R-band effective wavelengths correspond to harmonics $\omega/\omega_c = 12.0$ and 14.4, respectively.

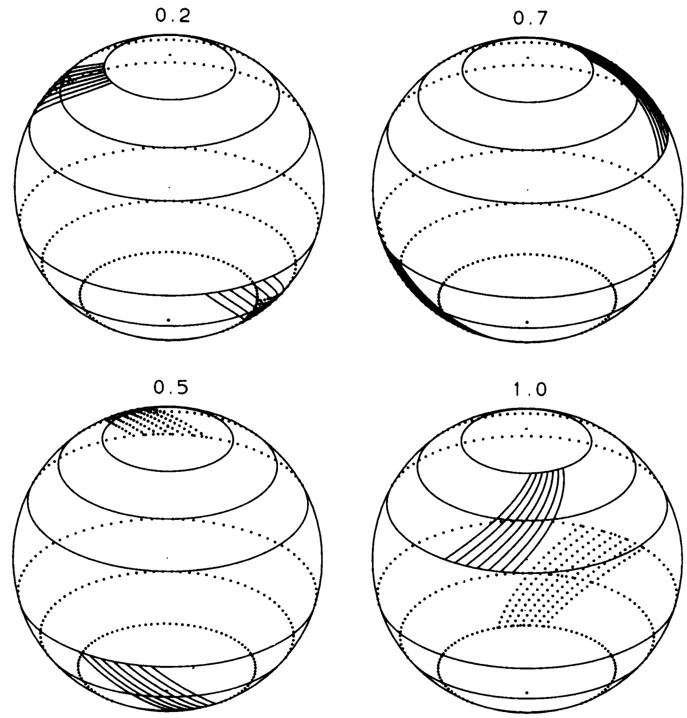

FIG. 5.—Illustration of the model used to compute the polarization curves in Fig. 4. The extended emission regions are seen along different cross sections at eclipse ingress and egress, which gives rise to the asymmetric circular polarization and light curves.

opposite magnetic poles. The polarized fluxes detected in the red (690 nm) and near-infrared (830 nm) bands suggest that RE 0751+14 has stronger magnetic field ($B > 5$ MG) than the other known IPs. Fits to the existing cyclotron models required field strengths in the range 8–18 MG, but with further polarimetric observations at longer wavelengths, and in particular from spectroscopy of cyclotron humps (harmonics) or Zeeman split photospheric absorption line components, better constraints for the field strength should be obtained. The existence of a highly asynchronous ($P_{spin} \sim 13.9$ minutes, $P_{orb} \sim$ 5 hr) magnetic binary with a field strength approaching those found in the strictly synchronous CV counterparts, polars (AM Her objects), if confirmed, would be important for checking the effects of magnetic torque on the binary evolution. The possible changes in the spin period of RE 0751+14 should be looked for. The unique properties of RE 0751+14 make it an extremely important object for the studies of intermediate polars and the magnetic CVs in general.

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