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OPTICAL IDENTIFICATION OF THE X-RAY SOURCE E1405−451: A 101.5 MINUTE BINARY SYSTEM WITH EXTREMELY RAPID QUASI-PERIODIC VARIABILITY

K. O. MASON,[1,2,3] J. MIDDLEDITCH,[1,4] F. A. CÓRDOVA,[1,4] K. A. JENSEN,[4] G. REICHERT,[1,2]
P. G. MURDIN,[5] D. CLARK,[6] AND S. BOWYER[1,2]
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ABSTRACT

A 15th magnitude blue emission-line star is identified as the optical counterpart of the variable soft X-ray source E1405−451. The spectrum shows strong, asymmetric emission lines of H, He I, He II and Ca II which have a full width at base of 2000 km s^{-1}. Optical photometry reveals that the light of the star is modulated with a period of 101.52 ± 0.02 minutes. The morphology of the light curve is a function of color. A broad, asymmetric modulation of amplitude 1 mag is seen in white light, with a shallow secondary minimum occurring 0.4 of a cycle after the deep primary minimum. In the U band, however, the broad modulation is much less pronounced, and a narrow (FWHM ~ 2.5 minutes) eclipse-like feature that is coincident with the broad minimum is prominent. In addition to the 101.5 minute modulation, the star flickers on time scales of order 1 minute with an amplitude as high as 0.3 mag at all phases of the light curve. Fourier analysis of the data shows a broad peak of power at frequencies between 0.4 and 0.8 Hz ($\sim$1–3 s), corresponding to an rms variation of 1.2% of the stellar light. The peak remains broad when the data are analysed in intervals as short as ten minutes. The properties of E1405−451 suggest that it may be related to the magnetic cataclysmic variables of the AM Her type. We consider the probable geometry of the source and discuss various mechanisms that might produce the quasi periodicity, whose rapid time scale is thus far unique among cataclysmic variables.

Subject headings: stars: individual — stars: magnetic — stars: variables — X-rays: binaries

I. INTRODUCTION

A variable X-ray source, H1409−45, has been detected by Jensen, Nousek, and Nugent (1982) using the low energy detectors on the *HEAO 1* satellite. In subsequent observations with the *Einstein X-Ray Observatory* IPC detector, Jensen *et al.* found a moderately bright source, E1405−451 (~ 0.3 IPC counts s^{-1}), in the *HEAO 1* X-ray error region and suggested that the *Einstein* and *HEAO 1* sources were the same. We have examined the $\sim 1'$ diameter error region of E1405−451 and find that it contains a blue emission-line star of V mag ~ 15.5. The optical light curve shows a 1 mag modulation with a period of 101.5 minutes and quasi-periodic $0\overset{m}{.}017$ Hz$^{-1/2}$ variations on time scales between 1 and 3 s. The star exhibits many of the characteristics peculiar to the magnetic, AM Her variables.

[1]Visiting Astronomer, Cerro Tololo Inter-American Observatory, which is operated by AURA under contract with the National Science Foundation.
[2]Space Sciences Laboratory, University of California, Berkeley.
[3]Mullard Space Science Laboratory, University College London.
[4]University of California, Los Alamos National Laboratory.
[5]Royal Greenwich Observatory.
[6]Rutherford Appleton Laboratory.

II. OBSERVATIONS

Ultraviolet and red images of the field containing E1405−451 were obtained on the night of 1981 April 28 and 29 using the CTIO 1 m telescope and the image-tube camera. Part of each plate centered on the position of the X-ray source is reproduced in Figure 1 (Plate 6), upon which has been marked the X-ray error region. The star labeled 1 is clearly blue.

The spectrum of star 1 was measured using the Anglo-Australian Telescope (AAT) on 1981 June 7 under relatively poor weather conditions. The data are illustrated in Figure 2 and were recorded at a dispersion of 57 Å mm^{-1} with the Image Photon Counting System attached to the RGO spectrograph. Figure 2a is the blue spectrum of star 1 in the wavelength range 3300–4950 Å. A red spectrum covering the wavelength range 5200–6800 Å was taken immediately following that in the blue, and an expanded view of the region containing the Hα line is shown in Figure 2b. The data have been corrected for fluctuations in the image-tube response by reference to the spectrum of a quartz lamp, but no absolute flux calibration of the spectrum was attempted because of the non-photometric observing conditions.

E1405−451 star 1 has strong emission lines of hydrogen, He I, He II, and Ca II. The lines identified in the

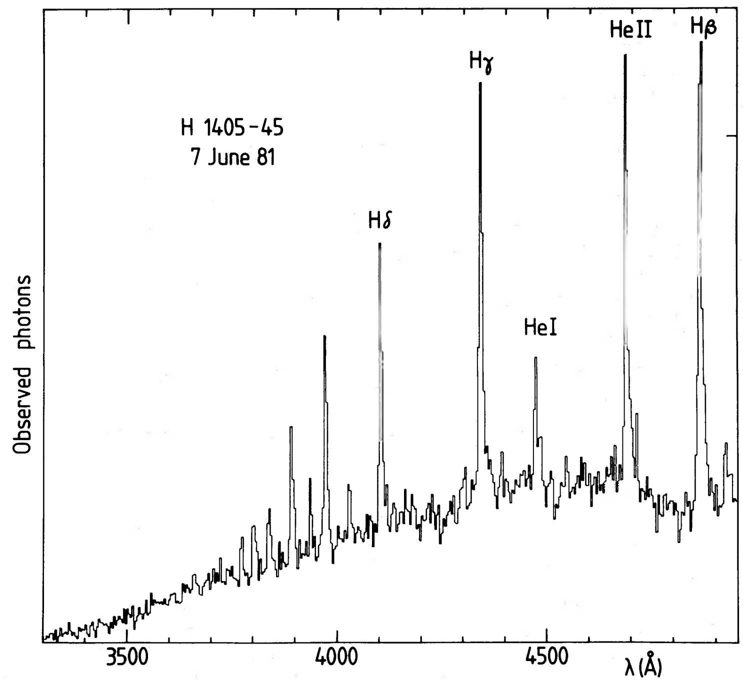

FIG. 2*a*

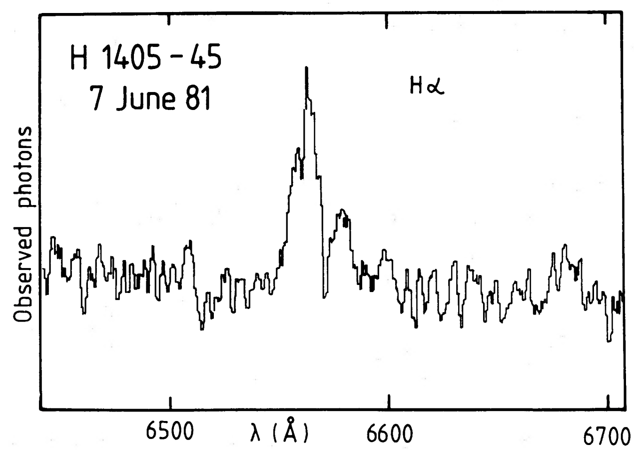

FIG. 2*b*

FIG. 2.—(*a*) The blue spectrum of E1405−451 taken with the AAT and IPCS on 1981 June 7 at a dispersion of 57 Å mm^{-1}. The phase interval covered is 0.86–1.03. (*b*) An expanded view of the Hα line in a red spectrum of star 1 taken immediately following that in the blue. The phase interval covered is 0.03–0.16. Orbital phase is measured from JD 2,444,779.5714 using a period of 0^{d}070502.

spectrum are listed in Table 1 together with their equivalent widths. The strong lines have a full width at base of ~ 2000 km s^{-1} and are asymmetric, being steeper on the blue wing than on the red. The Hα line (Fig. 2*b*) is double peaked. The He II λ4686 line is strong compared to the He I and hydrogen lines, a characteristic of AM Her stars and a number of classical novae and nova-like objects. The peak flux of He II λ4686 is equal to that of Hβ, but it is narrower so that the ratio of their equivalent widths is ~ 1:2. There is an indication of broad structure in the continuum of the star, particularly between Hγ and Hδ.

High speed photometry of star 1 was obtained on several nights between 1981 June 24 and June 28 at a time resolution of 0.01 s on the 1.5 m telescope at CTIO. Table 2 is a journal of the observations. Figure 3 shows

TABLE 1

OPTICAL LINE IDENTIFICATIONS

Line ID	Wavelength of Peak (Å)	FWHM (Å)	Width at Base (Å)	Equivalent Width (Å)
		Blue Spectrum		
3750 H12.......	...	...	...	...
3770 H11.......	3770	8	17	5
3797 H10.......	3798	12	21	8
3819 He I.......	3817	3	4	2
3835 H 9	3835	10	21	9
	3849 absn	...	...	...
3889 H 8	3889	9	22	13
3933 Ca II K ...	3932	8	14	4
3970 H 7	3968	9	19	17
4026 He I.......	4027	10	19	4
4101 Hδ........	4100	9	25	21
4340 Hγ........	4340	10	45	29
4471 He I.......	4470	13	30	9
4686 He II	4686	9	25	26
4713 He I.......	4712	4	7	2
4861 Hβ	4862	10	45	50
4921 He I.......	4923	14	20	7
		Red Spectrum		
5876 He I.......	5878	16	...	9
6563 Hα	6564	28	50	21
Hα absn	6571	...	...	...

TABLE 2

TIME SERIES OBSERVATIONS

Run	Start Time (JD −2,440,000.5)	Duration (hr)	Band	Comments
1	4779.02782	3.00	White	Possible clouds for first 10 minutes, then photometric
2	4780.02494	2.03	White	Possible clouds for first 10 minutes, then photometric
3	4780.97164	0.43	White	Clouds ended run
4	4782.06030	1.88	White	
5	4783.11763	1.70	*U*	Photometric

two time series of star 1 in white light that last 3 and 2 hours, respectively. The main features of these light curves can be summarized as follows:

1. There is flickering of amplitude 0.2–0.3 magnitudes on time scales of order 1 minute at all phases in the light curve.

2. A broad minimum of depth >1 mag occurs every ~ 101.5 minutes. This minimum is asymmetric with a sharp ingress and a more gradual egress.

3. A second, shallower broad minimum occurs ~ 40 minutes after the deep minimum (phase ~ 0.4 measured from the deep minimum). This could also be interpreted as a shoulder in the light curve at phase ~ 0.3.

4. There is a persistent narrow dip coincident with the center of the deep minimum which is 0.2 mag in depth and lasts about 2.5 minutes. There is a similar narrow dip at phase ~ 0.4 in the June 24 data (Fig. 3 [*lower*]), but this is not prominent on June 25 (Fig. 3 [*upper*]) or June 27.

Figure 4 is the light curve of star 1 taken with a *U* filter. The amplitude of the broad modulation is considerably reduced (~ 0.2 mag) compared to the white light data. The most striking feature of the *U* light curve is the prominence of the narrow dip at phase 0.0. The dip has a flat bottom, suggestive of a total eclipse (although the count rate does not go to zero), and a full width at

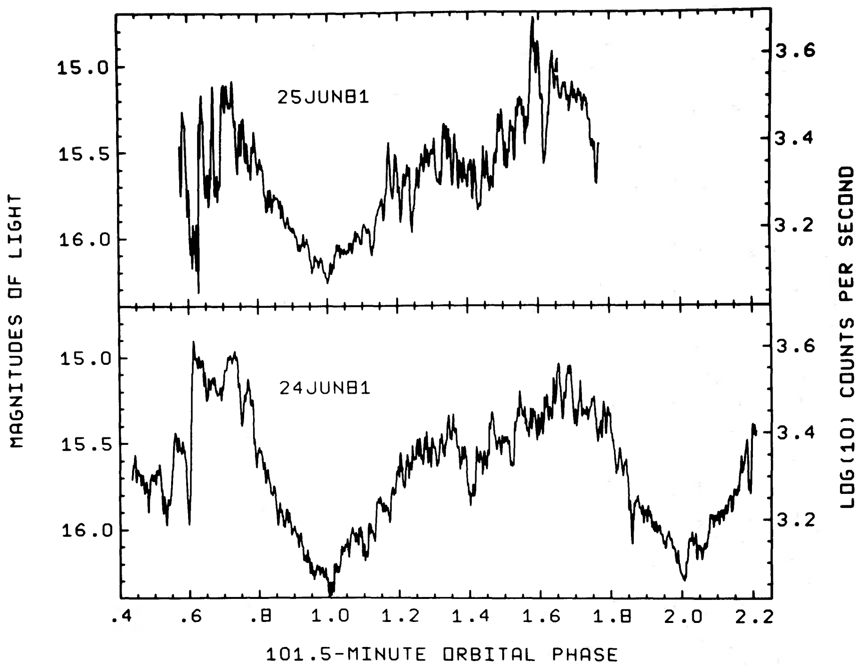

FIG. 3.—Time series of E1405−451 star 1 taken in white light on the CTIO 1.5 m telescope with an EMI 9658A photomultiplier tube (runs 1 and 2 of Table 2). Orbital phase is measured from JD 2,444,779.5714 using a period of $0\overset{d}{.}070502$.

half-light of 0.025 cycles (2.5 minutes). Ingress and egress from the dip occur in less than about 2 minutes, precise times being difficult to measure because of the flickering activity. The count deficit in the *U* band dip is 50 counts s^{-1}; the same dip in the white light data involves a deficit of 110 counts s^{-1}. If we make a reasonable estimate of the transmission of the *U* band filter (i.e., $\lesssim 75\%$) and assume that the depth of the dip did not vary between the white light and *U* band observations, it is clear that the source that is being extinguished during the narrow dip has very blue colors. It is certainly much bluer than the light eclipsed during the concurrent broad minimum. A flare of amplitude ~ 0.35 mag and lasting 2–3 minutes occurred near the end of the *U* band observation at phase 0.3. It is difficult to assess whether the drop at phase 0.4 is present in the *U* band because the observation started and ended at this phase.

Using the narrow dip (whose center is defined to be at phase 0.0) as a fiducial point, we calculate an ephemeris for the 101.5 minute modulation of

$$T_{\min} = JD2444779.5714 + N \times 0\overset{d}{.}070502 \pm 0\overset{d}{.}000014,$$

where N is the cycle number. According to this ephemeris, the blue spectrum of star 1 was taken at the AAT between orbital phases 0.86 and 0.03, while the red spectrum was taken between orbital phases 0.03 and 0.16.

Approximate colors of star 1 are $V = 15.8$, $U - B = -0.9$, $B - V = 0.5$, and $V - R = 0.6$, measured at orbital phase ~ 0.2. The flickering activity of the star makes these colors uncertain because the flux in each passband was measured sequentially, not simultaneously. Assuming that the star was at the same optical brightness during the *Einstein* observations, the ratio of X-ray to visual luminosity, $L_{(0.1-4\ \mathrm{keV})}/L_V$, is ~ 1.

The data for runs 1, 2, 4, and 5 (Table 2) were Fourier analyzed to test for periodic variations in the light level. No strictly periodic variations were detected in the white light time series (1, 2, and 4) to less than 0.2% for frequencies between 0.1 and 50 Hz, with the upper limit increasing at lower frequencies due to the flickering of the star. The run made in *U* light (run 5) has an upper limit of 0.7% for the same frequency range. However, when the power spectra for the individual runs were binned every 0.05 Hz, an obvious excess of power appears in all three white light runs between 0.4 and 0.8 Hz. Such a plot for run 1 is shown in Figure 5. This feature did not appear in the power spectra of other time series made on objects of similar, as well as brighter and fainter, magnitude which were observed on the same nights as E1405−451 at CTIO. We therefore interpret the feature as a real manifestation of rapid variability from E1405−451 star 1.

The excess power at 0.6 Hz (the peak of the feature) corresponds to an rms variation of 1.2% of the stellar light, or a persistent modulation of amplitude 0.00036

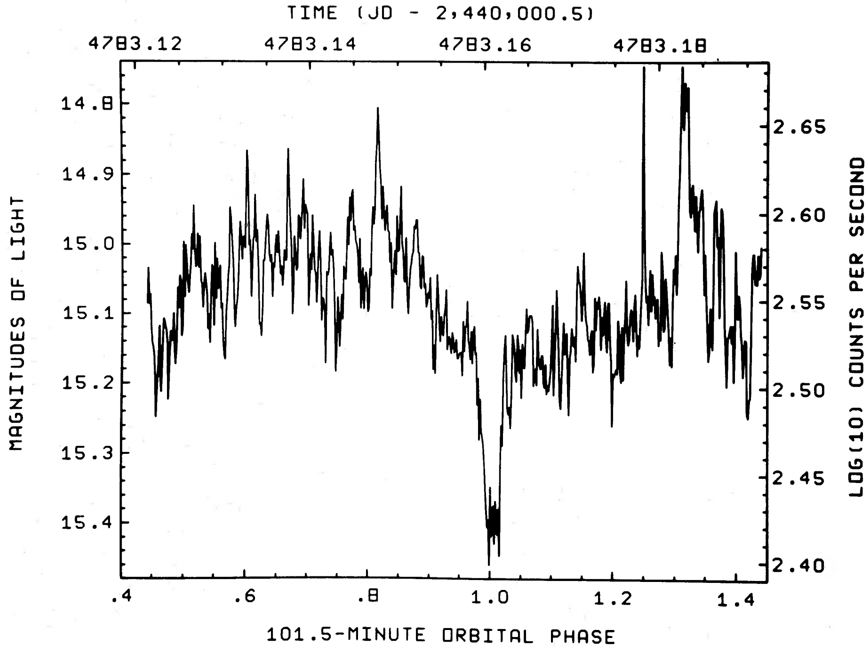

FIG. 4.—Time series of E1405−451 star 1 taken with a U band filter (run 5 in Table 2). Orbital phase is measured from JD 2,444,779.5714 using a period of $0^{d}.070502$.

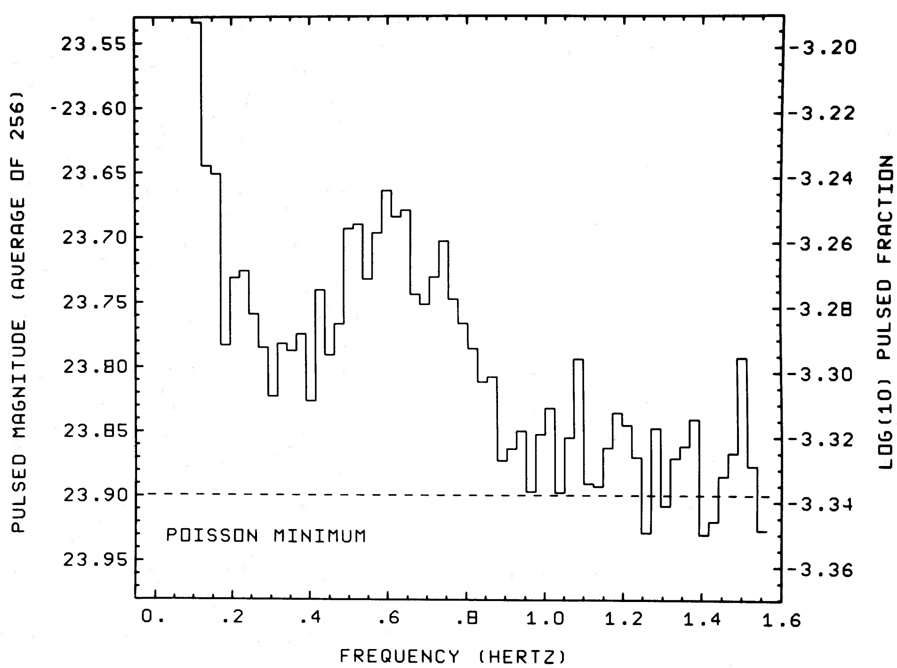

FIG. 5.—Power Spectrum of run 1 binned every 0.05 Hz

mag in the stellar light in every Fourier resolution element. The fraction of the light that varies in this manner does not change detectably with orbital phase indicating that the variable emission is subject to the same orbital modulation as the "steady" light. It is difficult to determine the exact nature of the noise process that produces the excess power. The width in frequency of this feature does not change when the data are analyzed in sections as short as 10 minutes, however, indicating that the mechanism broadening this feature operates on a time scale shorter than this.

III. DISCUSSION

a) The Magnetic Star Model

E1405−451 star 1 has the properties of a cataclysmic variable. Specifically these are a short (101.5 minute) modulation period; short time scale flickering (~ 60 s); a blue $U-B$ color; relatively broad emission lines; and variable soft X-ray emission. Among the cataclysmic variables, the properties of E1405−451 are most reminiscent of the magnetic variables or AM Her stars (cf. Córdova and Mason 1982 and references therein).

The AM Her stars have been modeled as accreting binaries containing a magnetic degenerate dwarf whose rotation is phase-locked to the orbital motion of the system. Matter accreted from the companion star is funneled by the magnetic field of the degenerate dwarf onto the magnetic poles of the latter. Much of the light radiated by the system comes from the accretion columns rather than from an accretion disk. Because of the absence of an optical and UV emitting disk, the ratio of the X-ray to V band flux emitted by AM Her stars is generally at the upper end of the distribution found for normal cataclysmic variables, most of which have $L_x/L_V < 1$ (Córdova and Mason 1981). In accordance with this, the ratio $L_{(0.1-4 \text{ keV})}/L_V$ for E1405−451 is probably about 1.

Following the initial report of its identification (Mason *et al.* 1982), Tapia (1982) detected circular and linear polarization in E1405−451. In addition to confirming the classification of E1405−451 as an AM Her variable, the polarization data provide constraints on the geometry of the source. Tapia finds that the circular polarization is approximately constant at the 5% level for half the cycle; there are two peaks of circular polarization with amplitudes 13% and 19%, respectively, in the other half, which are separated by a minimum in which the circular polarization drops to zero. A weak but persistent linear polarization pulse is observed at the time of minimum circular polarization. The circular polarization minimum and the linear polarization pulse coincide with the photometric minimum (phase 0.0) in the light curve (S. Tapia 1981, private communication).

It is generally thought that a linear polarization pulse occurs when the accretion column is viewed perpendicular to the magnetic field that permeates it; at this time, the circularly polarized light should vanish (Chanmugam and Dulk 1981; Meggitt and Wickramasinghe 1982). This is as observed in E1405−451, and it locates the emitting pole close to the limb of the degenerate dwarf at this phase. The circular polarization of E1405−451 does not reverse sign, so the pole never disappears over the limb. This is similar to the situation in two other AM Her stars, AN UMa, and PG 1550+191 (Chanmugam and Dulk 1981; Liebert *et al.* 1982). In a third star, EF Eri, the sign of the circular polarization reverses for only 10% of the cycle (Bailey, Hough, and Axon 1980) suggesting that the emitting pole is briefly occulted by the degenerate star.

E1405−451 is unusual, however, in the relative phasing of the linear polarization spike with respect to the photometric minimum. In AN UMa, EF Eri, and PG 1550+191, the linear polarization pulse is observed when the total light level from the source is comparatively high. The occurrence of the linear polarization spike should coincide with the time when the light from the polarized source is a maximum (Chanmugam and Dulk 1981; Meggitt and Wickramasinghe 1982), and thus much of the photometric variation in these stars can be accounted for as a modulation of the polarized light source. In contrast, the timing of the linear polarization pulse in E1405−451 suggests that the converse is true in this star. The percentage of circularly polarized light increases during the broad minimum in the photometry by an amount that indicates that the net polarized light remains relatively constant (except for the narrow minimum when the circularly polarized light drops to zero). One can immediately infer, therefore, that the broad minimum in the light curve of E1405−451 is caused primarily by a variation in an unpolarized or weakly polarized light source. Wickramasinghe and Meggitt (1982) have also argued for such an unpolarized light source in the star VV Pup based on a comparison of their models with the observed spectrum and degree of polarization of that star. The case of E1405−451, however, provides the most direct support so far for such a component.

Based on the observed phasing of the visual photometry and the polarization curves and assuming that all the light comes from one active pole, the simplest explanation of the broad 101.5 minute modulation seems to be that it is due to an aspect effect as the emitting pole approaches the stellar limb. For this to be viable, the emitting region would have to be optically thick in the direction perpendicular to the accretion column. There is also the possibility that the unpolarized emission might be partially occulted by the degenerate star if it is produced close to the surface of that star. In a simple picture of this kind, there is no obvious explanation for the brief dip in the light curve of E1405−451 at phase zero which is very pronounced in our U band observation. We cannot be completely certain that the marked difference between the ultraviolet and white light curves of E1405−451 is not due to temporal variability, because the measurements in the two wave bands were not simultaneous. However, such temporal variability seems unlikely in view of the fact that three observations in white light spread over 4 days showed no gross variation in the light curve, and the U band data were obtained on the night following the last white light observation (Table 2).

b) *The Rapid Variability*

The 1–3 s quasi-periodic oscillation found in the optical light of E1405−451 is the shortest such phenomenon observed thus far in a cataclysmic variable system. Following the discovery of rapid quasi-periodic pulsations in E1405−451, one of the authors has examined high time-resolution photometry on other magnetic variables (Middleditch 1982). Pulsations similar to those observed in E1405−451 were found in AN UMa. This suggests that pulsations of this kind may be a common property of these stars. The variable component in E1405−451 is modulated with the 101.5 minute period in approximately the same way as the total light of the star. This argues that it is not associated with the polarized light source. The time scale of the oscillations is shorter than the Keplerian period at the surface of a degenerate dwarf unless its mass is very close to the Chandrasekhar limit. Therefore, models which involve accretion disk instabilities or hot spots on the degenerate star are not likely to be applicable. Mechanisms which might account for the pulsation include: (1) free fall of blobs of matter onto the degenerate dwarf from a point close to its surface, (2) oscillations of the magnetic flux tubes conveying matter from the magnetospheric boundary to the surface of the degenerate dwarf, and (3) a thermal instability in the accretion flow.

If the 1–3 s pulses represent the time taken for blobs of matter to free fall onto the stellar surface, the material emitting the pulsed radiation must initially be only about two stellar radii above the star. In a magnetic accretor model, material falling pseudoradially along the field lines encounters a standoff shock at radial distances of this order (Lamb and Masters 1979). The observed periodicities might therefore represent the settling time of blobs of emitting gas in the postshock region.

Magnetic flux tube oscillations have been discussed by Tuohy *et al.* (1981) as a possible explanation for 20–60 s pulsations seen in AM Her. The characteristic oscillation period is

$$P = 2\times10^{-3}(r/10^8\ \mathrm{cm})^{11/4}(L/10^{34}\ \mathrm{ergs\ s^{-1}})^{1/2} \times (f/10^{-2})^{-1/2}(M/M_\odot)^{-3/4} \times (R/10^8\ \mathrm{cm})^{-2}(B/10^7\ \mathrm{G})^{-1}\ \mathrm{s},$$

where r is the magnetospheric radius, L is the luminosity of the source, f is the fraction of the stellar surface over which matter is accreted, and M, R, and B are the mass, radius, and magnetic field strength of the degenerate dwarf. If we adopt $L=10^{34}$ ergs s^{-1}, $f=10^{-2}$, $M=1$ $M_\odot$, $R=5\times10^8$ cm and $B=10^7$ G for illustration, a characteristic period of 2 s requires that $r\sim5\times10^9$ cm. In comparison, the orbital separation for a total mass of 1.5 $M_\odot$ and an orbital period of 101.5 minutes is 5×10^{10} cm.

A thermal instability in the accretion flow onto a degenerate dwarf has been identified by Langer, Chanmugam, and Shaviv (1981) who suggest that pulsations might result because of periodic variations in the height of the standoff shock which forms above the stellar surface. The characteristic timescale of the oscillation, assuming only bremsstrahlung cooling in the postshock region, is

$$P = 1.1\times2\pi(A/10^{16}\ \mathrm{cm^2})(\dot{m}/10^{16}\ \mathrm{g\ s^{-1}})^{-1} \times (R/10^9\ \mathrm{cm})^{-1}(M/M_\odot)\ \mathrm{s},$$

where A is the area of the stellar surface over which accretion is occurring. A period of about 2 s implies an accretion rate of $\sim10^{17}$ g s^{-1} for E1405−451 if we adopt the same parameters as for case (2).

IV. CONCLUSIONS

On the basis of its temporal, spectral, and polarization characteristics, we suggest that E1405−451 Star 1 is a cataclysmic variable of the AM Her class. This makes it an excellent candidate for identification with the *Einstein* X-ray source. Although the *Einstein* source was much fainter than the *HEAO 1* soft X-ray source H1409−45 (Jensen, Nousek, and Nugent 1981), it is probable that the two objects are the same, since several close binaries of this type are observed to be long term, variable soft X-ray emitters (e.g., U Gem: Mason *et al.* 1978; SS Cyg: Córdova *et al.* 1980; and AM Her: Tuohy *et al.* 1981).

These results suggest several follow-up observations. Simultaneous multicolor photometry of E1405−451 would be desirable to further investigate the energy dependence of the light curve. A measurement of the X-ray light curve would also be useful as a diagnostic of the source geometry. All the known AM Her variables show optical emission lines with broad and narrow components which vary out of phase with each other through the binary cycle (Córdova and Mason 1982 and references therein). High resolution radial velocity studies should therefore be made of E1405−451 star 1 throughout its 101.5 minute orbital cycle. The discovery of quasi-periodic oscillations in E1405−451 Star 1 on time scales between 1 and 3 s represents the shortest such period found in a cataclysmic variable system. Other magnetic variables should be searched for similar short time scale variability in both their high and low brightness states.

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S. Bowyer and G. Reichert: Space Sciences Laboratory, University of California, Berkeley, CA 94720

D. Clark: Rutherford Appleton Laboratory, Chilton, Didcot, Oxfordshire, OX11 OQX, U.K.

F. A. Córdova, K. A. Jensen, and J. Middleditch: MS D436, Los Alamos National Laboratory, Los Alamos, NM 87545

K. O. Mason: Mullard Space Science Laboratory, Holmbury St. Mary, Nr. Dorking, Surrey, RH5 6NT, U.K.

P. G. Murdin: Royal Greenwich Observatory, Herstmonceux Castle, Hailsham, E. Sussex, BN27 1RP, U.K.

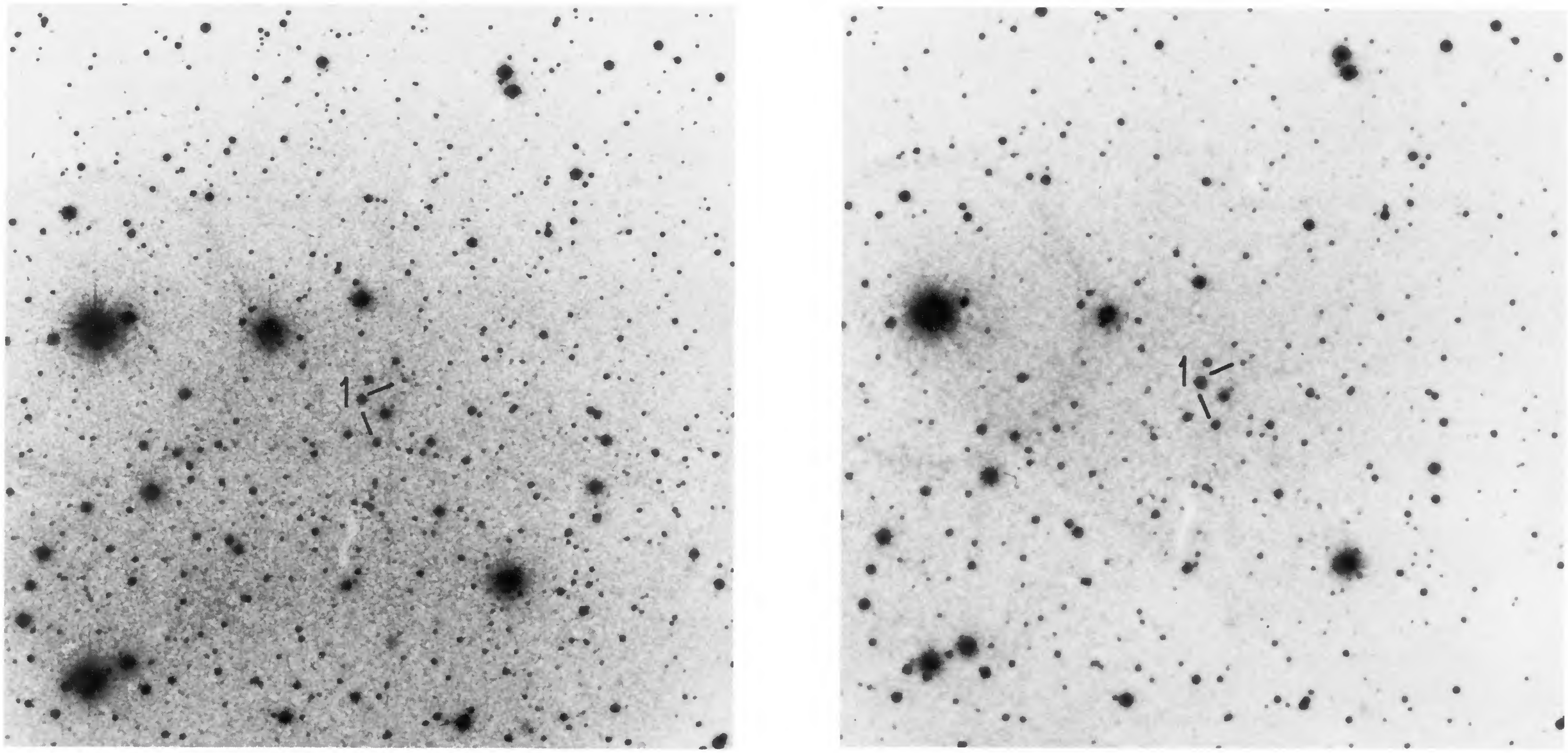

FIG. 1.—An approximately $10' \times 10'$ area of sky centered on the position of the X-ray source E1405−451. The plates were taken on the 1 m telescope at CTIO. The left-hand plate was taken in a red passband; the right-hand plate was taken in an ultraviolet passband. The candidate star, 1, is marked. Its 1950 coordinates are RA $14^h05^m58^s.2$, decl. $-45°03'06''$.

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