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H0538+608: A BRIGHT AM HERCULIS–TYPE X-RAY SOURCE

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ABSTRACT

We report the discovery of an AM Herculis–type magnetic variable, H0538+608. The object was located during a program to optically identify the X-ray sources detected with the *HEAO 1* Scanning Modulation Collimator. The source is also cataloged by the *Uhuru* survey and the *HEAO 1* Large Area Sky Survey. The X-ray flux (2–10 keV) of H0538+608 is exceeded by only two of the 10 previously observed AM Herculis–type systems. The optical spectrum shows very strong and broad emission lines of H, He I, and He II. Photometric observations show modulations by a factor of 2, with B magnitudes between 15 and 16, and the source exhibits rapid flickering at a time scale of 10 s. A search of the Harvard Plate Library reveals occasions when $B \geq 17$. Circular polarization measurements indicate variable optical polarization between 0 and 10%, and there is evidence of an irregular polarization cycle. The modulations in the polarization and the photometric magnitude suggest an orbital period of 3.1 ± 0.2 hr (3 σ uncertainty).

Subject headings: polarization — stars: variables — X-rays: binaries — X-rays: sources

I. INTRODUCTION

AM Herculis–type objects are accreting binary systems that contain a magnetic white dwarf and a late-type companion. They are distinguished by their large optical polarization (~ 10%–20%) which is strongly modulated at the orbital period (e.g., Liebert, *et al.* 1982; Stockman *et al.* 1983; Mason *et al.* 1983; Nousek *et al.* 1984; Biermann *et al.* 1985). The magnetic field (~ 10^7 G) is believed to control the accretion path from the companion star to the magnetic poles at the surface of the white dwarf. In addition to the polarization effects, AM Herculis–type objects are characterized by rapid optical flickering, strongly modulated photometric variations, and intense emission lines of H, He I, and He II. Prior to this *Letter*, there were 10 confirmed AM Herculis–type systems (Patterson 1984), five of which were discovered via their X-ray emission.

Recent studies have provided geometrical data on the locations of the emitting regions and the orientation of the magnetic dipole axis and the spin axis (see references above; also Imamura 1984). These data may help to elucidate the physical mechanism that causes the synchronism between the binary orbit and the rotation of the white dwarf (Lamb *et al.* 1983; Biermann *et al.* 1985, and references therein). Several other questions (e.g., models of the UV emission) remain unsolved; however, ultimately it may be possible to describe the behavior and evolution of these systems using only a few basic parameters, as suggested by the correlations involving the binary period, spectral type of the secondary, rate of mass loss, etc., given by Patterson (1984).

In this *Letter* we present evidence of another AM Her binary that was discovered from its X-ray emission. The object was located during a systematic program to identify optically the fainter sources detected by the *HEAO 1* Scanning Modulation Collimator experiment, hereafter called *HEAO* MC (Gursky *et al.* 1978). The search procedures have been described by Remillard *et al.* (1986). Earlier results from the *HEAO* MC have led to the identification of another AM Herculis–type object, 2A 0311−227 (= EF Eri; Griffiths *et al.* 1979), and several DQ Herculis–type (magnetic but unpolarized) systems (Steiner *et al.* 1981; Patterson and Price 1981; Tuohy *et al.* 1985).

As described herein, the proposed optical counterpart, which we designate H0538+608, exhibits all of the optical emission characteristics of its class: circular polarization, strongly modulated brightness variations, intense flickering on time scales of seconds, historical "low states," and intense emission lines, including very strong lines of He II.

II. X-RAY OBSERVATIONS AND IDENTIFICATION

An X-ray source in the vicinity of H0538+608 was detected by both the *Uhuru* and the *HEAO 1* LASS surveys and was cataloged as 4U 0541+60 (Forman *et al.* 1978) and 1H 0533+607 (Wood *et al.* 1984), respectively. In this *Letter*, we report a multiplicity of high-resolution positions that include the optical counterpart. All of the allowed X-ray positions are shown in Figure 1. The diamond-shaped *HEAO* MC error boxes arise from the intersection of positional bands from each of the instrument's two collimators. The number of standard deviations of the MC detections are 2.5 σ for MC1 and 4.0 σ for MC2 in the energy range of 1–13 keV for the sum of two 6 day scans of the source region (1977 September

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6–21 and 1978 September 16–21). The inclusion of data from an intermediate 6 day scan (1978 March 17–22) reduces the significances of the MC detections, implying that the X-ray flux was significantly less during that period. The 2–10 keV X-ray flux of H0538+608, as measured by both the *Uhuru* and *HEAO 1* LASS experiments (during the first 6 day scan), is 3×10^{-11} ergs cm^{-2} s^{-1} (~ 1.4 μJy at 5.2 keV). The source is too weak to allow a search for the expected X-ray periodicity.

The proposed optical counterpart lies at the edge of the 4U and LASS error boxes and is contained within one of the *HEAO* MC error diamonds (see Fig. 1). The object was selected for its strong UV color in U and B filtered photography performed with the 91/61 cm Burrell Schmidt telescope on Kitt Peak. The photographic double exposure was made on 1983 November 2 (UT). A finding chart is provided in Figure 2 (Plate L1).

An optical spectrum of H0538+608 was obtained on 1984 April 1 with the Mark II spectrograph and the 1.3 m telescope at the McGraw-Hill Observatory. The Mark II employs an intensified Reticon Scanner (see Shectman and Hiltner 1976), and the spectral flux calibration was accomplished by observing standard stars of Oke (1974). The sky conditions were clear, and the observation was made through a circular diaphragm with a diameter of 8″.

The spectrum is shown in Figure 3. The emission features include a flat continuum and very strong lines of H, He I, and He II. The He II lines are especially strong, as He II λ4686 is about equal to Hβ, and the He II line at λ5411 is almost as strong as the He I line at λ5876. The general appearance of the spectrum is typical of a cataclysmic variable (CV), and the great strength of the He II lines is suggestive of both a magnetic-type variable and strong X-ray emission. The emission lines are quite broad, with FWHM of 1400 km s^{-1}, and broad wings having velocities several times larger.

The ratio of the X-ray to optical luminosities (2–10 keV vs. 3000–7000 Å) is ~ 1.5. We note, however, that the X-ray and optical fluxes were not measured simultaneously.

III. OPTICAL PHOTOMETRY AND POLARIMETRY

The object was observed photometrically on 1983 November 6 with the 1.0 m telescope No. 2 at Kitt Peak National Observatory. The photometric observations were made with an RCA 31034 photomultiplier tube, and the diaphragm was 15″. The photometric colors were $U - B = -0.81$, $B - V = 0.54$, and $V = 14.62$, with 1 σ accuracies of about 0.05. The source exhibited rapid optical flickering during a 20 minute series of observations in the B bandpass. The semiamplitude (i.e., half the square root of the variance in excess of that due to Poisson statistics) of the flickering was 10% of the total flux at a time scale of 10 s.

A photometric light curve was obtained from a 5 hr sequence of CCD images (~ 6 minute time resolution) using the "MASCOT" instrument and the 1.3 m McGraw-Hill telescope on 1983 December 15. The MASCOT utilizes "virtual phase" CCD detector (245 × 328 pixels) from Texas Instruments (Ricker *et al.* 1981). Each array element is 25 μm × 25μm, which corresponds to a pixel size of 1″.2 for the optical configuration we used. A broad-band filter and the response of the CCD detector gave a bandpass of 4000–6400 Å (FWHM). Data reduction procedures included the subtraction of bias frames, a "flat field" normalization using observations of the morning sky, and photometric normalization with respect to nearby field stars.

The normalized CCD light curve is shown in Figure 4. The full amplitude of the modulation is approximately a factor of 2. The fractional uncertainty (1 σ) in an individual data point is about 2%, since field stars of comparable brightness show normalized CCD light curves that appear constant, with rms

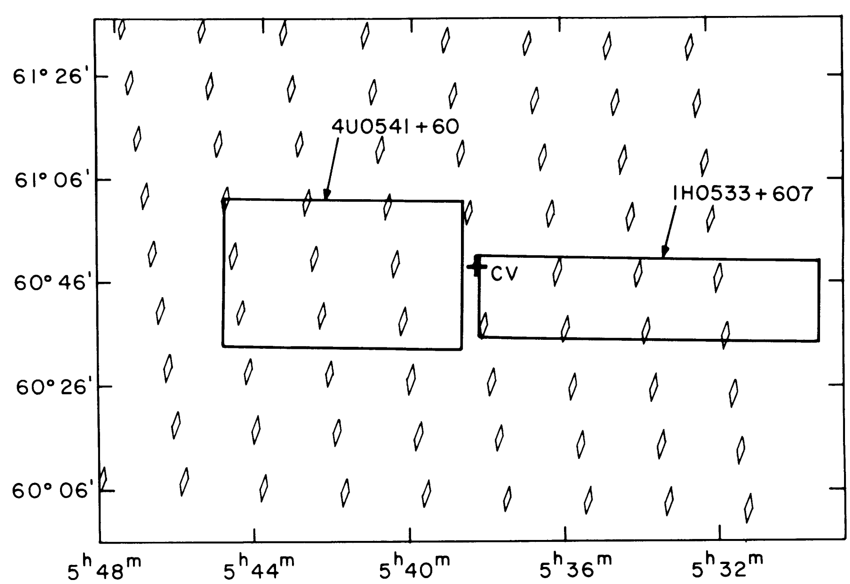

FIG. 1.—An X-ray map containing the allowed positions from the *HEAO 1* Modulation Collimator (*diamonds*), the *HEAO 1* Large Area Sky Survey ("1H"; Wood *et al.* 1984), and the *Uhuru* survey ("4U"; Forman *et al.* 1978). The position of the optical counterpart, an AM Her type cataclysmic variable ("CV"), falls inside the diamond at the position marked with a heavy plus sign.

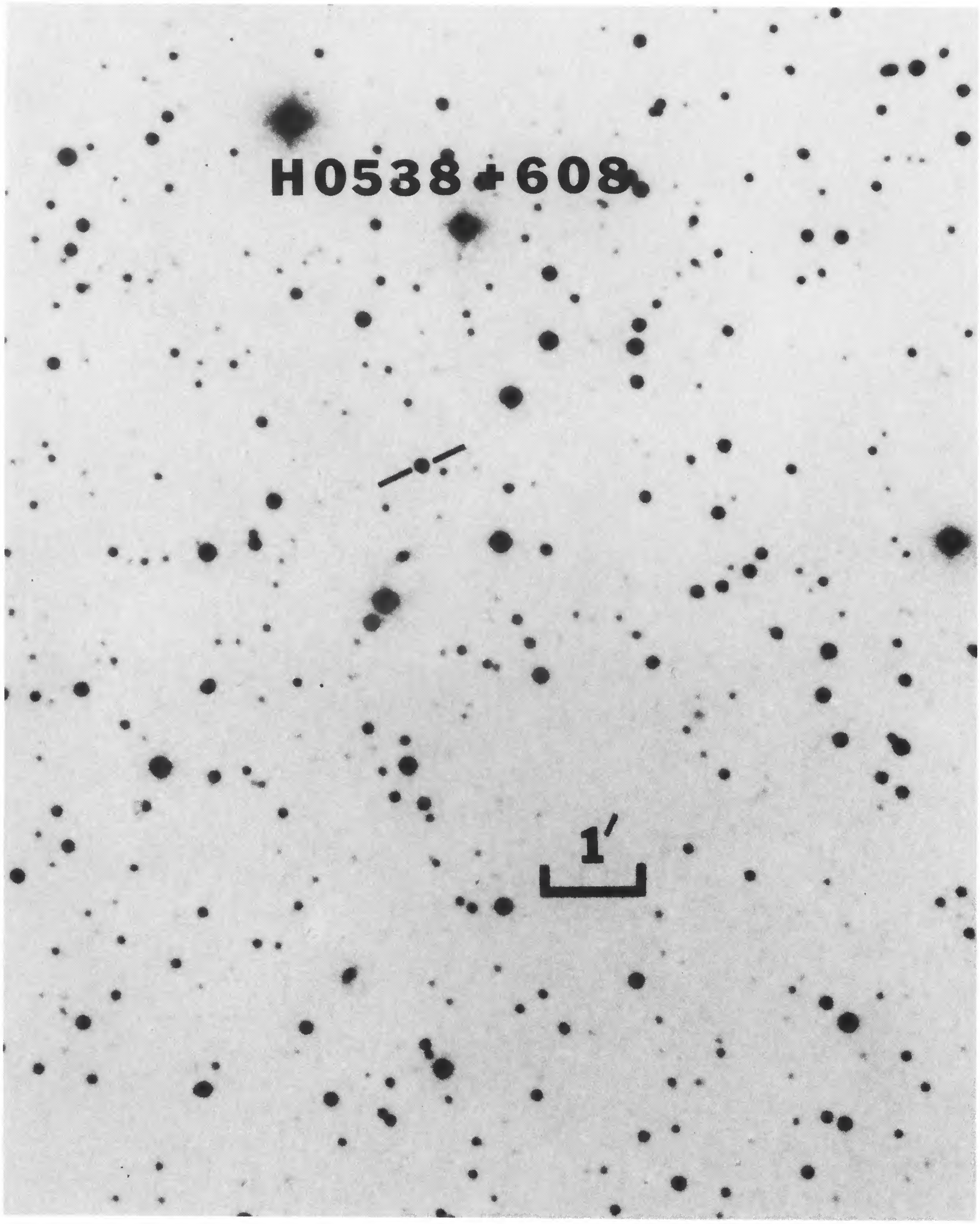

FIG. 2.—A finding chart for H0538+608 from the POSS E print. East is to the left, and north is toward the top. The coordinates are (1950.0) $05^h38^m 15^s.9$, 60°50′03″.

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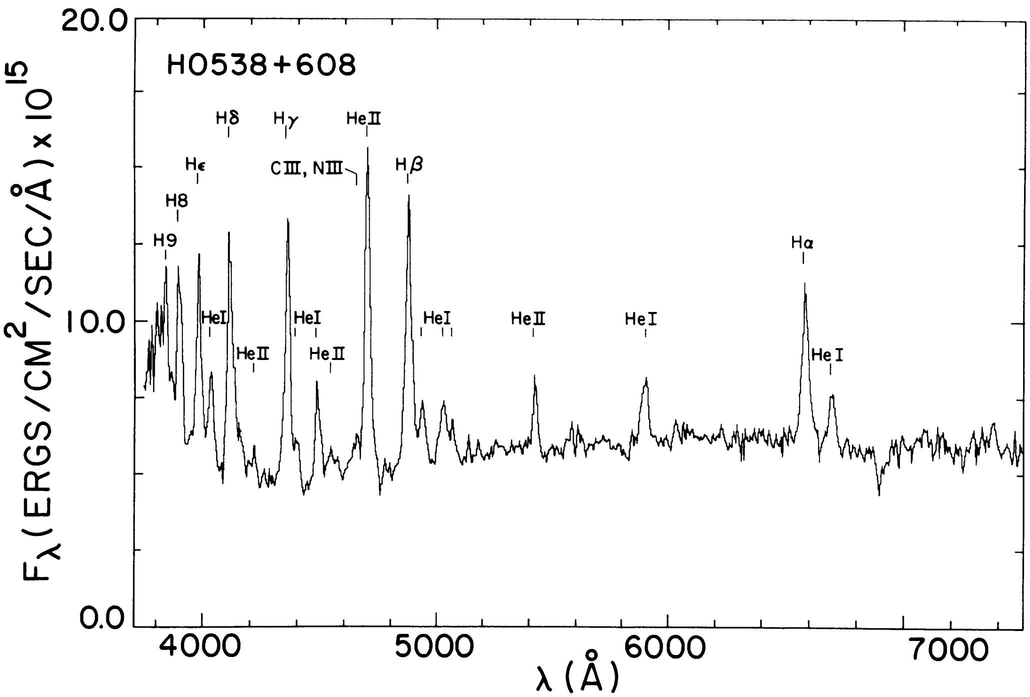

FIG. 3.—An optical spectrum of H0538+608 obtained on 1984 April 1 at McGraw-Hill Observatory. The integration time was 48 minutes, and the observed count rate is consistent with the bright phase of the photometric light curve.

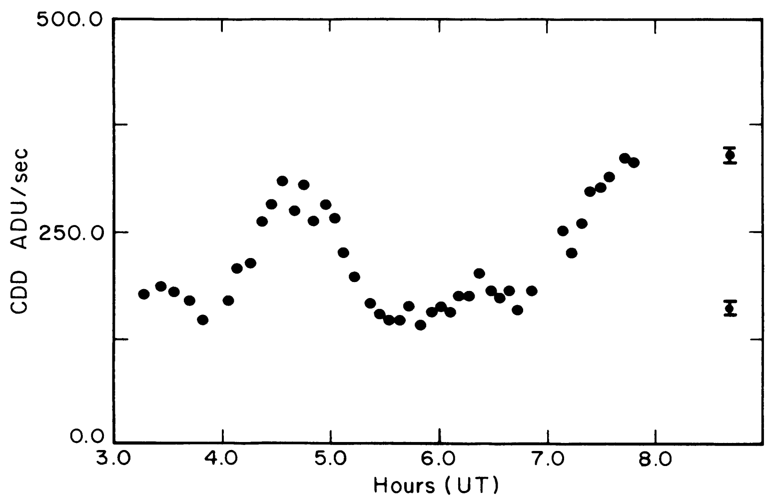

FIG. 4.—The CCD light curve observed with a 4000–6400 Å bandpass filter on 1983 December 15

deviations of only 2%. A minimum χ^2 fit was obtained for a period of 2.95 ± 0.10 hr. Several attempts to confirm this result and improve the accuracy of the period have been obstructed by poor weather.

We have searched the Harvard photographic collection for evidence of outbursts or low states in the history of H0538+608. Exposures of 1–2 hr had been made on 56 occasions between 1934 and 1951, and several of them show *B* magnitudes that are clearly fainter than those we have observed ($B \approx 15.2$–16.0). On 1934 December 31, 1939 January 17, and 1939 October 25, for example, the images of H0538+608 are fainter than the plate limit, implying $B > 17.0$ in each case. These faint states are typical of AM Herculis–type objects (e.g., Wickramasinghe, Visvanathan, and Tuohy 1984; Maraschi *et al.* 1984).

Optical polarimetry was performed with the "Minipol" polarimeter (Frecker and Serkowski 1976) on 1985 March 14 with the Steward Observatory 2.3 m telescope and on 1985 March 24 and 25 with the University of Arizona 1.55 m telescope. Time series of circular polarization measurements were made with temporal resolution ~ 2 minutes and sensitivity FWHM in the range of 7100–8800 Å. The results are

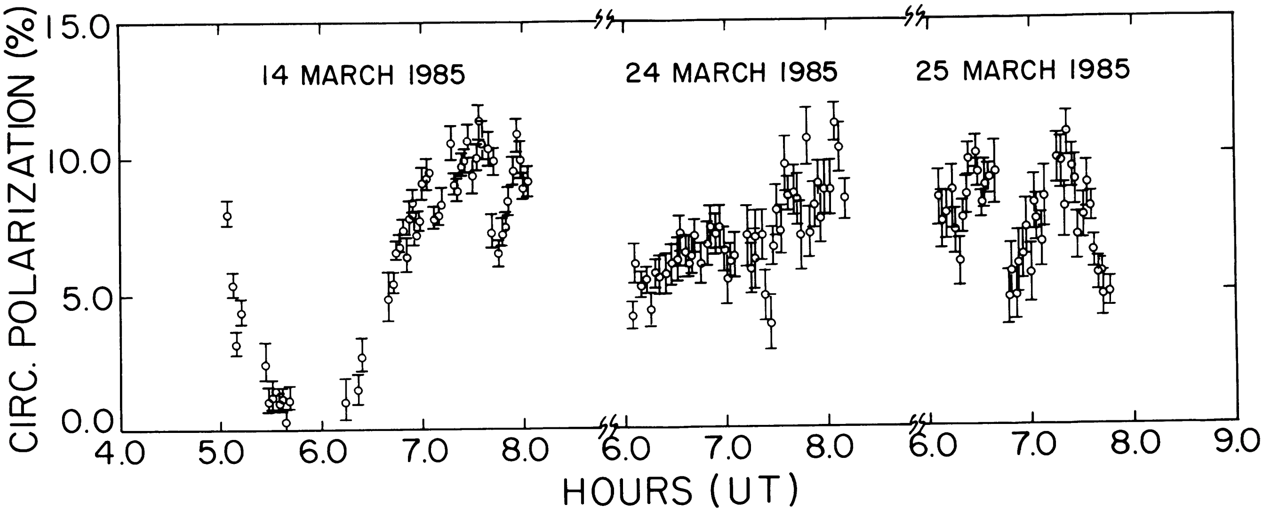

FIG. 5.—Circular polarization measurements made during 1985 March

shown in Figure 5. The data from 1985 March 14 appear to be nearly sinusoidal, with a minimum χ^2 fit at a period of 3.25 ± 0.1 hr. The data from 1985 March 24 and 25 show significantly less variability; the circular polarization is not strictly periodic. If the observations correspond to polarization maxima, then the orbital period must be either 3.332 or 3.376 (each ± 0.001) hr. The photometric light curve is not easily reconciled with these periods.

IV. DISCUSSION

It is highly likely that the AM Her binary discussed above is the optical counterpart of the X-ray source. The space density of all types of CVs (magnetic and nonmagnetic) that are brighter than visual magnitude 16.2 is 3.3×10^{-3} deg^{-2} (Green *et al.* 1982), while the celestial area within the 30 MC error diamonds that are close to the intersection of the *Uhuru* and LASS positions is only 0.03 deg^2. We have investigated about 100 unidentified X-ray source positions (Remillard 1985), and therefore, the probability of finding a spurious identification from chance occurrences of *any* bright cataclysmic variable within the MC error diamonds near the *HEAO*-LASS error boxes is less than 1%. Moreover, because the proposed counterpart is known from polarization studies to be an AM Herculis star, a type that is relatively rare and invariably produces strong X-ray emission, the probability that the identification is correct is further increased.

The value of $L_x/L_{\rm opt}$ (1.5) for H0538+608 is much greater than the values for optically selected, nonmagnetic examples (10^{-4} to 0.6; see Córdova and Mason 1984), and there are clear optical signs of high-energy activity, with strong He II lines and particularly broad emission features. H0538+608 is among the brightest known AM Her binaries at X-ray and optical wavelengths. In the *HEAO 1* survey in the range of 1–20 keV (Wood *et al.* 1984), the flux of H0538+608 is exceeded (among AM Herculis–type objects) only by AM Her itself and by 2A 0311−227 (= EF Eri). This will facilitate future observations, which promise to reveal the system's emission components and geometry in great detail.

The circular polarization light curve deserves special study. The result on 1985 March 14 (Fig. 5) is in good agreement with the CCD light curve (Fig. 4) and resembles the behavior of the simplest AM Her stars: VV Pup (Liebert *et al.* 1978) and CW 1103+254 (Schmidt, Stockman, and Grandi 1983). This behavior can be understood by supposing that most of the optical and circularly polarized light comes from a region near the white dwarf's polar cap which is carried in and out of view as the white dwarf rotates synchronously at the binary period. However, the latter two polarimetric observations do not reveal or suggest the eclipse of the polarized light; this is puzzling unless the eclipses are nearly missed and the period is near 3.332 or 3.376 hr. In any case, the observations are not consistent with a polarization cycle that is strictly periodic, while the other AM Her stars tend to exhibit repeatable polarization cycles during "on" states. The nonuniformity of the polarization behavior of H0538+608 suggests that the orientation of the accretion path may change significantly on short time scales. Further observations are required to confirm this effect and explain its cause.

The orbital period is certainly on the long side of the "period gap," which is the apparent absence of cataclysmic variables with orbital periods betwen 2.1 and 2.8 hr (see Patterson 1984). This is the third AM Herculis–type system shown to have a period longer than the gap. Such cases may test the various theoretical models seeking to explain the synchronism between the rotational and orbital periods in AM Herculis–type systems (Lamb *et al.* 1983; Chanmugam and Ray 1984).

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REFERENCES

Biermann, P., *et al.* 1985, *Ap. J.*, **293**, 303.
Córdova, F. A., and Mason, K. O. 1984, *M.N.R.A.S.*, **206**, 879.
Chanmugam, G., and Ray, A. 1984, *Ap. J.*, **285**, 252.
Frecker, J. E., and Serkowski, K. 1976, *Appl. Optics*, **15**, 605.
Forman, W., Jones, C., Cominsky, L., Julien, P., Murray, S., Peters, G., Tananbaum, H., and Giacconi, R. 1978, *Ap. J. Suppl.*, **38**, 357.
Green, R. F., Ferguson, D. H., Liebert, J., and Schmidt, M. 1982, *Pub. A.S.P.*, **94**, 560.
Griffiths, R. E., Ward, M. J., Blades, J. C., Wilson, A. S. Chaisson, L., and Johnston, M. D. 1979, *Ap. J.* (*Letters*), **232**, L27.
Gursky, H., *et al.* 1978, *Ap. J.*, **223**, 973.
Imamura, J. N. 1984, *Ap. J.*, **285**, 223.
Lamb, F. K., Aly, J. J., Cook, M. C., and Lamb, D. Q. 1983, *Ap. J.* (*Letters*), **274**, L71.
Liebert, J., Stockman, H. S. Angel, J. R. P. Woolf, N. J., Hege, K., and Margon, B. 1978, *Ap. J.*, **225**, 201.
Liebert, J., Stockman, H. S., Williams, R. E., Tapia, S., Green, R. F., Rautenkranz, D., Ferguson, D. H., and Szkody, P. 1982, *Ap. J.*, **256**, 594.
Maraschi, L., Treves, A., Tanzi, E. G., Mouchet, M., Lauberts, A., Motch, C., Bonnet Bidaud, I. M., and Philips, M. M. 1984, *Ap. J.*, **285**, 214.
Mason, K. O., Middleditch, J., Córdova, F. A., Jensen, K. A., Reichert, G., Murdin, P. G., Clark, D., and Bowyer, S. 1983, *Ap. J.*, **264**, 575.
Nousek, J. A., *et al.* 1984, *Ap. J.*, **277**, 682.
Oke, J. B. 1974, *Ap. J. Suppl.* **27**, 21.
Patterson, J. 1984, *Ap. J. Suppl.*, **54**, 443.
Patterson, J., and Price, C. 1981, *Ap. J.* (*Letters*), **243**, L83.
Remillard, R. A. 1985, Ph.D. thesis, Massachusetts Institute of Technology.
Remillard, R. A., Bradt, H. V., Buckley, D. A. H., Roberts, W., Schwartz, D. A., Tuocy, I. R., and Wood, K. 1986, *Ap. J.*, **301**, 742.
Ricker, G. R. Bautz, M. W., Dewey, D., and Meyer, S. S. 1981, *Proc. Soc. Photo-Opt Instrum. Eng.*, **290**, 190.
Schmidt, G. D., Stockman, H. S., and Grandi, S. A. 1983, *Ap. J.*, **271**, 735.
Shectman, S. A., and Hiltner, W. A. 1976, *Pub. A.S.P.*, **88**, 960.
Steiner, J. E., Schwartz, D. A., Jablonski, F. J., Busko, I. C., Watson, M. G., Pye, J. P., and McHardy, I. M. 1981, *Ap. J.* (*Letters*), **249**, L21.
Stockman, H. S., Foltz, C. B., Schmidt, G. D., and Tapia, S. 1983, *Ap. J.*, **271**, 725.
Tuohy, I. R., Buckley, D. A., Remillard, R. A., Bradt, H. V., and Schwartz, D. A. 1985, preprint.
Wickramasinghe, D. T., Visvanathan, N., and Tuohy, I. R. 1984, *Ap. J.*, **286**, 328.
Wood, K. *et al.* 1984, *Ap. J. Suppl.*, **56**, 507.

Note added in proof.—Recent observations have confirmed that the circular polarization of H0538+608 frequently changes from a sinusoidal curve to nearly constant high or low values. Photometric light curves have shown similar behavior.

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