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1ES 1113+432: LUMINOUS, SOFT X-RAY OUTBURST FROM A NEARBY CATACLYSMIC VARIABLE (AR URSAE MAJORIS)

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ABSTRACT

A remarkable X-ray transient from the *Einstein* Slew Survey, 1ES 1113+432, is identified with a nearby, short-period cataclysmic variable. Wenzel (1993) has confirmed that the optical counterpart is the variable star, AR UMa (cataloged as "semiregular"), erroneously reported 5'.7 southeast of the true position. One of the *Einstein* slew obsevations recorded a flux of 43 IPC counts s^{-1}, which is an order of magnitude above the flux observed from the brightest cataclysmic variables in other X-ray surveys. The outburst spectrum is extremely "soft," with an implied blackbody temperature ~22 eV. The optical counterpart ($V = 16.5$) exhibits a strong UV component, TiO bands from an M star, and broadened Balmer emission lines. Optical states as bright as $V \sim 13$ were found on photographs from the Harvard Plate Library, confirming outburst behavior in the optical counterpart. The historical photographic record suggests that 1ES 1113+432 remains in a low-accretion state most of the time. Both the soft X-ray spectrum and the transitions between high and low-accretion states are suggestive of the AM Her (magnetic) subclass. Photometric observations in the *I* band show 0.18 mag modulations at a period of 0.966 hr. These are interpreted as ellipsoidal variations in the secondary star for a binary period of 1.932 hr, which is near the lower boundary of the "period gap" in the histogram of orbital periods of accreting white dwarfs. Thus 1ES 1113+432 provides the rare opportunity to study a secondary star in a cataclysmic binary that has evolved through the period gap. The optical spectral features from the secondary imply a spectral type ~M6 and a distance ~88 pc. The peak luminosity in the soft X-ray component (unabsorbed) is then estimated to be 3×10^{33} ergs s^{-1}, assuming emission from a blackbody slab with a temperature of 22 eV. While this luminosity is higher than previous measures of the soft X-ray component, it does not exceed the amount of radiation that could be emitted from the accretion-heated surface of a white dwarf.

Subject headings: binaries: spectroscopic — novae, cataclysmic variables — stars: individual (1ES 1113+432) — X-rays: bursts — X-rays: stars

1. THE X-RAY TRANSIENT, 1ES 1113+432

The succession of X-ray surveys and pointing missions during the last 20 yr has demonstrated that the brightest examples of many high-energy classes are highly variable X-ray sources (see Bradt & McClintock 1983). The X-ray novae displayed by accreting black holes and neutron stars exhibit X-ray flux increases by a factor that may exceed 10^6, while more modest X-ray transients with relative maxima as high as 10^2 have been associated with coronal flares from RS Canum Venaticorum binaries. X-ray variations by a factor of 10 have been seen in a few cataclysmic variables (CV), BL Lac objects, and coronally active main-sequence stars. In many of these cases, the measurement of X-ray variability promoted the recognition of prototypical objects and motivated detailed studies of the mechanism of high-energy radiation.

The analysis of observations with the Imaging Proportional Counter (IPC) during slew maneuvers of the *Einstein Observatory* created a catalog of 819 X-ray sources (0.3–3.5 keV) with imaging exposure to a majority of the celestial sphere (Elvis et al. 1992). The *Einstein* Slew Survey included 313 sources that had not been measured previously in X-rays, and the results implied substantial X-ray variability for many objects (Slane, Plummer, & Elvis 1991). Perhaps the most dramatic variability case is the high-latitude transient, 1ES 1113+432. The Slew Survey catalog reports an average flux of 10.2 IPC counts s^{-1} (~10 mCrab), which was derived from two slews that were widely separated in time. Among previous X-ray surveys (*Uhuru*, *Ariel V*, and *HEAO 1*), the only detection that could be related to 1ES 1113+432 is a weak source from the *HEAO 1* Large Area Sky Survey (Wood et al. 1984), 1H 1120+423 (0.9 ± 0.3 mCrab at 2–20 keV).

The analysis of the two IPC observations of 1ES 1113+432 reveals directly that the X-ray source is highly variable. On 1979 November 22.393 (UT), a slew across the source yielded 12 IPC counts during 5.1 s of exposure, while the slew of 1980 May 10.603 netted 52 counts with only 1.2 s exposure time. The higher count rate (43.3 ± 6.0 IPC counts s^{-1} or ~40 mCrab) represents an unusually bright X-ray source at high galactic latitude ($b = 65°.0$), while the two IPC count rates are inconsistent at the confidence level of 6.7 σ.

The pulse height distribution of the events during the brighter appearance of 1ES 1113+432 further reveals an extremely "soft" X-ray spectrum, which is displayed in Figure 1. Only a small percentage of the photons have energy above 1 keV. The best fit to the data ($\chi^2 = 1.13$ for 3 degrees of freedom) is obtained for a blackbody spectrum with a temperature of 22 eV (2.55×10^5 K), a column density of 7×10^{19} cm^{-2}, and an X-ray flux of 4.59×10^{-10} ergs cm^{-2} s^{-1} in the range of 0.1–3.0 keV. Despite the large statistical uncertainty inherent to this analysis, temperatures above 80 eV are excluded at a 90% level of confidence. Furthermore, if the column density is $\leq 2.0 \times 10^{20}$, which is the Galactic H column derived from

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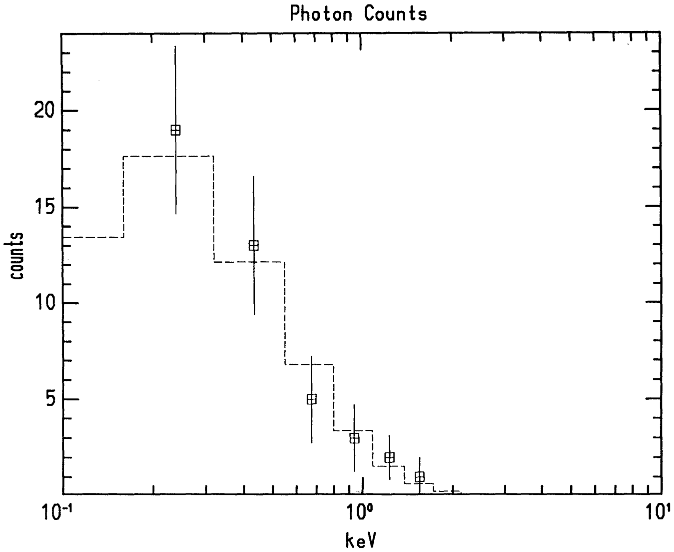

FIG. 1.—IPC spectrum of 1ES 1113+432 during the 1980 May slew maneuver (52 counts in 1.2 s exposure). Nine counts in the first energy bin were withdrawn prior to spectral analysis since the IPC response calibration is poorly determined there. The best fit is obtained for a blackbody spectrum with a temperature of 22 eV (*solid line*).

21 cm measurements (Stark et al. 1992), then the spectral fit implies a blackbody temperature less than 40 eV.

The absence of any optical objects brighter than $V \sim 16$ within 2′ of the X-ray position contradicts any expectations that 1ES 1113+432 might be associated with a coronal flare from a nearby RS CVn binary, e.g., the ~75 mCrab outburst in hard X-rays from HD 224085 ($V = 7.5$; Schwartz et al. 1981). Neither would it be possible to attribute the X-ray source to a distant X-ray nova without an implication that the source lies ~20 kpc above the galactic plane. Thus, 1ES 1113+432 seems to provide a new type of X-ray transient at high galactic latitude characterized by an extremely soft spectrum and a high value of X-ray to optical luminosity.

2. OPTICAL SPECTROSCOPY OF 1ES 1113+432

Optical investigations at the location of the X-ray position concentrated on a very blue object of 16th mag on the Palomar Observatory Sky Survey (see Fig. 2 [Pl. 5]). The celestial coordinate of this object (epoch 1950; ±0″.5) is $\alpha = 11^h12^m58^s.8$ and $\delta = +43°14'45''$, as derived from the digitized images of the Palomar survey. The center of the IPC position is offset 24″ east and 29″ north of the object marked in Figure 2, and this offset is well within the 1′.2 radius of the X-ray error circle (90% confidence).

Optical spectra of the object marked in Figure 2 were obtained during 1991 June with the 1.3 m McGraw-Hill telescope at MDM Observatory.[4] The instrumentation included the Mark III spectrograph, a 300 line mm^{-1} grism, and the TI no. 4849 CCD. The observed wavelength range was 4400–7100 Å with ~12 Å resolution, and the observations were autoguided to maintain the position of the star within the 3″.5 entrance slit. The average air mass was 1.35, and the data were recorded in sequences of 5–7 minute exposures during the time intervals (UT) 1991 June 12 (03:48–04:24), June 15 (04:16–04:43), and June 18 (05:02–05:48). All of the data reductions were performed with the software package IRAF (NOAO).

There were no significant differences among the spectra obtained on each night, and the overall average is displayed in Figure 3. The results show the combined appearance of TiO absorption bands from an M star, a very blue spectral component (white dwarf or accretion disk), and broad emission lines of Hα and Hβ (27 Å FWHM at Hα). These characteristics resemble a CV with a very low rate of mass transfer, such as AM Her in its low state. The latter case, observed with the same instrumentation on 1990 May 21, is shown for comparison in the lower panel of Figure 3.

The optical counterpart was observed again with the same telescope and spectrograph on 1993 May 5 (03:20–06:53), and the results (not shown) are very similar to the spectrum displayed in Figure 3. Additional measurements were obtained with a red-blazed grism on 1993 May 6(03:58–06:07), in order to further investigate the spectral features of the M star. The observed wavelength range was 6300–9000 Å, with a resolution of 12 Å. The results are shown in Figure 4. The flux density at both Hα and the continuum near 7000 Å appear higher in this spectrum, compared with previous observations. However, the red spectrum clearly displays the absorption bands from a mid-to-late M star continuing out to 9000 Å. Since the blue spectral component influences the continuum slope in Figure 4, the estimate of the spectral type is derived from spectral features alone, using the classification sequences given by Kirkpatrick, Henry, & McCarthy (1991). The strength of the Na I doublet at 8183 and 8195 Å clearly represent a dwarf M star, as opposed to the giant subclasses, while the

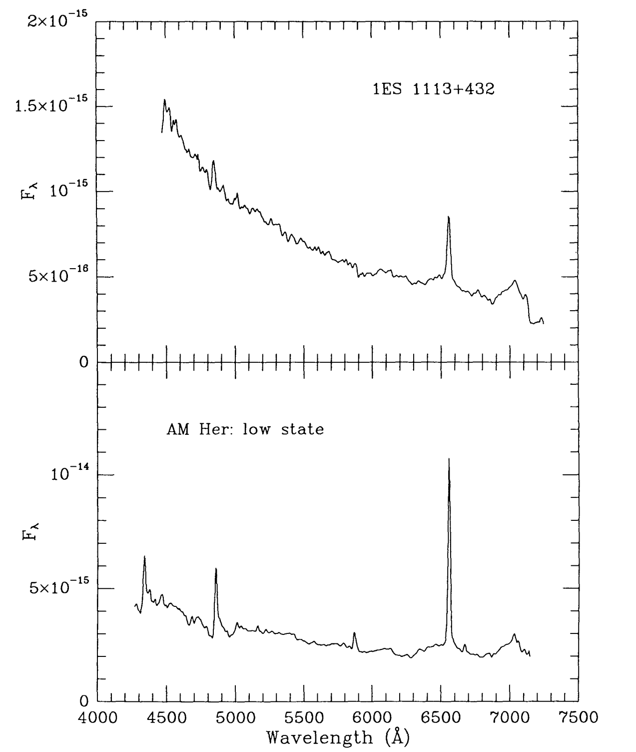

FIG. 3.—Optical spectrum of 1ES 1113+432 obtained at MDM Observatory during 1991 June. An observation of AM Her in a low state (MDM 1990 May) is shown for comparison.

[4] Observations reported herein were carried out in part at the Michigan-Dartmouth-MIT (MDM) Observatory (Kitt Peak, AZ), which is operated by a consortium consisting of the University of Michigan, Dartmouth College, and MIT.

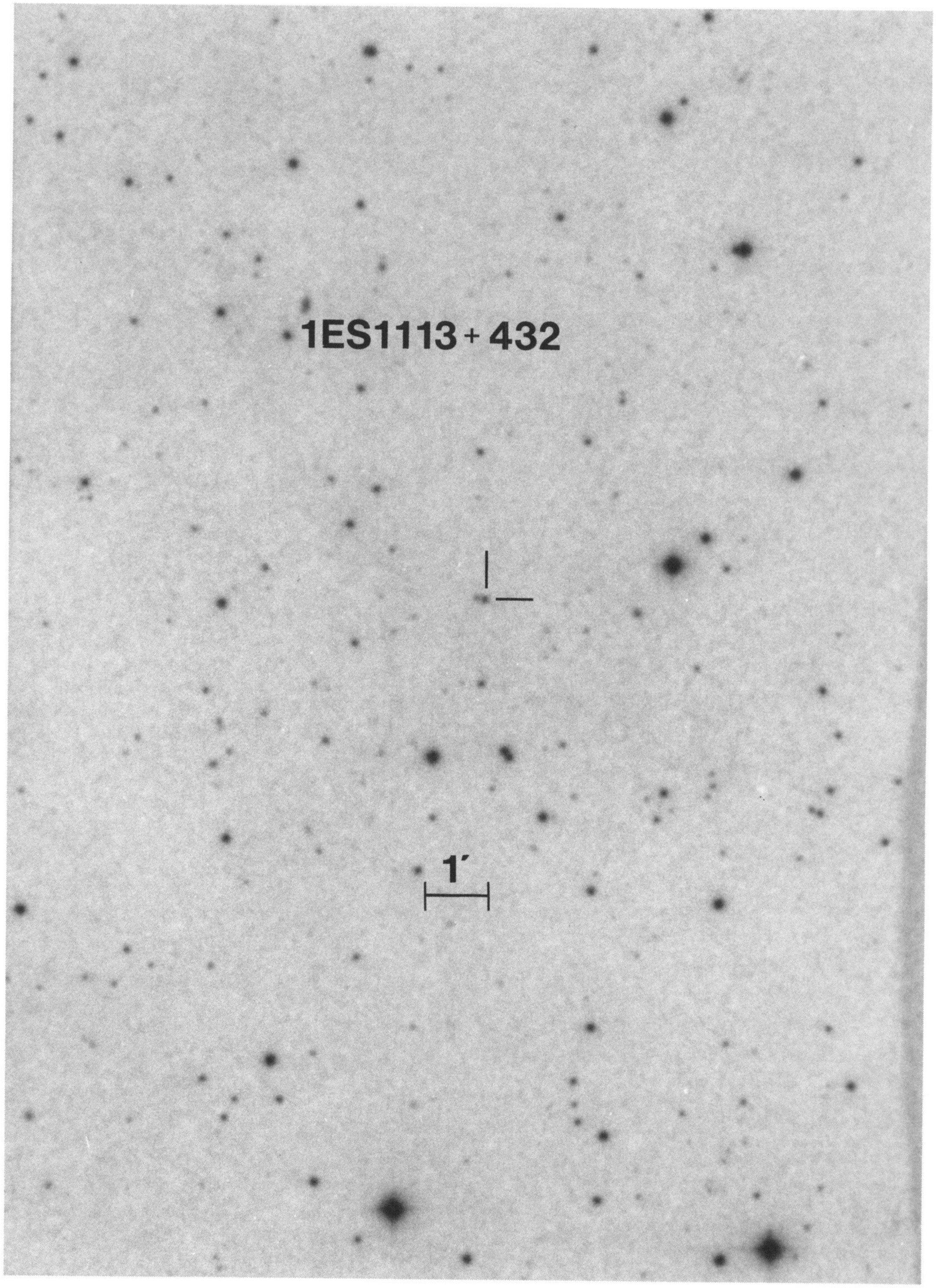

FIG. 2.—Finding chart for 1ES 1113+432, photographed from the E print of the Palomar Observatory sky survey (c. National Geographic Society). North is toward the top, and east is to the left. The coordinates for the CV (epoch B1950.0, ±0″.5) are $\alpha = 11^h12^m58^s.8$, $\delta = 43°14'45''$. The IPC Slew Survey position, with 1′.2 radius at 90% confidence, is centered 24″ east and 27″ north of the CV. Thus the CV is well within the X-ray error circle.

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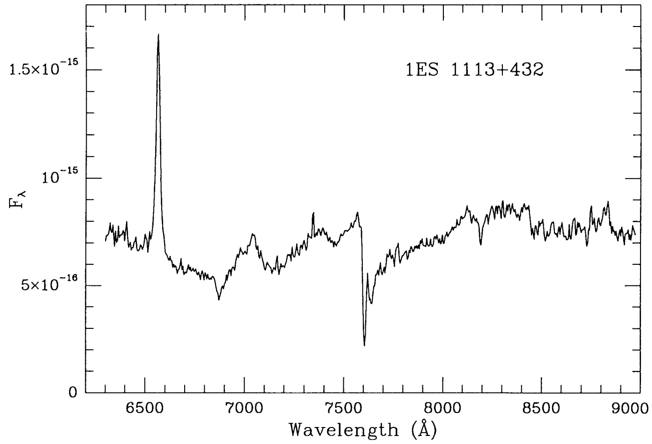

FIG. 4.—Red spectrum of 1ES 1113+432 obtained at MDM Observatory during 1993 May. The spectral features suggest an ~M6 V secondary star with an additional blue continuum and broadened Hα emission.

sharp definition of the TiO bandhead at 8432 Å and the shape of the continuum blueward of the TiO band at 8859 Å suggest a classification of M6 ± 1.

While the broadened H lines and the dual spectroscopic components clearly signify some type of CV, this classification would be made more secure if an orbital period were demonstrated. There is also a need for evidence of optical brightening that would reflect the behavior of the X-ray source and thereby help to confirm the X-ray identification. In the next two sections of this paper, we show positive results for both of these concerns. We describe the evidence leading to the conclusion: 1ES 1113+432 is a nearby, short-period CV that occasionally erupts into bright states that signify a high rate of mass accretion.

Wenzel (1993) used the optical finding chart in a draft version of this paper to associate 1ES 1113+432 with the variable star, AR UMa. The variable star, which was classified as "semiregular" on the basis of limited photographic exposures (Kholopov et al. 1987), had been erroneously positioned 5'.7 to the southeast of the true location.

3. OPTICAL PHOTOMETRY OF 1ES 1113+432

Time series of CCD images of 1ES 1113+432 were obtained with a CCD camera at MDM Observatory, using the 1.3 m McGraw-Hill telescope during 1992 June 2, 3, and 5, and 1993 May 7, 8, and 9. During both observing runs, the CCD images were obtained with an *I*-band filter to maximize the response to the M star component. The data obtained during 1992 contain 7.9 hr of monitoring coverage, divided into integrations of 100 s per CCD image, while the 1993 data span 12.4 hr with ~50 s time resolution.

The instrument and data reduction techniques follow the description of Remillard et al. (1991). The intensities of 1ES 1113+432 and selected field stars are first determined on a linear scale using a χ^2 fit to the point spread function of each CCD image. The resulting light curves are subsequently calibrated to the *I*-band magnitude scale by computing aperture photometry (synthetic apertures of 10" diameter) for both the local reference stars and selected standards from Landolt (1983). The average uncertainties (0.01 and 0.02 mag, respectively) that pertain to individual measurements of 1ES 1113+432 are deduced empirically from the relationship between the local field stars' brightness and the statistical deviations in their light curves.

A sample time series of the *I*-band measurement of 1ES 1113+432 during 1992 June 3 is displayed in Figure 5; the quasi-sinusoidal modulations stand out in sharp contrast to the behavior of a local field star. For each observing run, we determined the best period over the 3 days of *I*-band observations by computing the Θ-statistic of Stellingwerf (1978). This technique folds the data at a sequence of trial periods in the effort to search for the period value that minimizes the variance within individual phase bins (50 in this case) of the folded data. The results are shown in Figure 6. For the 1992 data, the variance statistic reaches a minimum at a period of 0.9660 ± 0.0009 hr. The adjacent minima at 0.9291 and 1.0058 hr are sampling aliases; they lead to folded light curves of diminished amplitude and are therefore rejected. The variance analysis for the 1993 observations (lower panel of Fig. 6) are entirely consistent with the former results, as the fundamental period is found to be 0.9662 ± 0.0010 hr, while the other significant variance minima occur at trial periods associated with sampling aliases or period multiples.

The average brightness levels of the 1992 and 1993 photometry are roughly consistent with the spectrophotometry shown in Figure 3, implying a low state of accretion during the photometric measurements. We interpret the *I*-band brightness modulations as ellipsoidal variations in the M star, i.e., changes in brightness due to the projected surface area of a gravitationally distorted star rotating in the field of view. The orbital period of the CV is therefore twice the fundamental modulation, or 1.9322 hr (averaging the two results). Ellipsoidal variations have been seen in the secondary stars of other CVs such as U Gem (Panek & Eaton 1982) and TW Vir (Mateo, Szkody, & Bolte 1985), although the latter cases can only be observed in the infrared bands because of the dominance of the accretion disk at optical wavelengths.

All of the *I*-band measurements of 1ES 1113+432, folded at the orbital period and averaged in 0.05 phase intervals, are shown in Figure 7. An epoch that designates an *I*-band minimum is used to define the zero point in photometric phase.

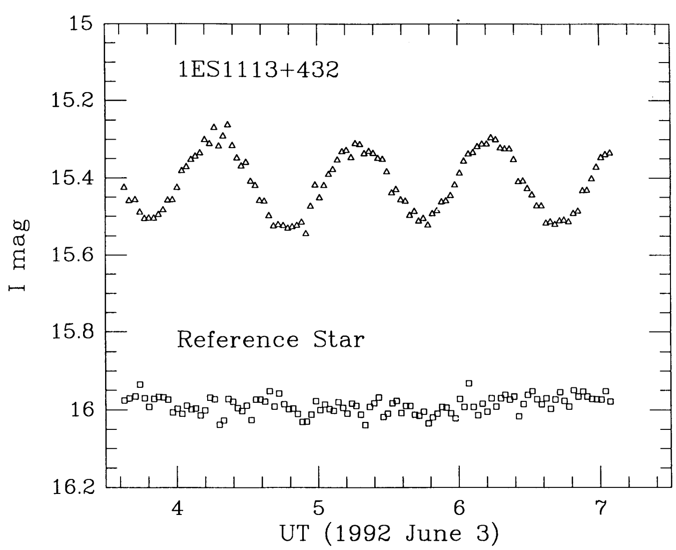

FIG. 5.—A sample of the optical light curves (*I* band) of 1ES 1113+432 (*triangles*) and a field star (*boxes*) obtained on 1992 June 3 with an imaging CCD camera.

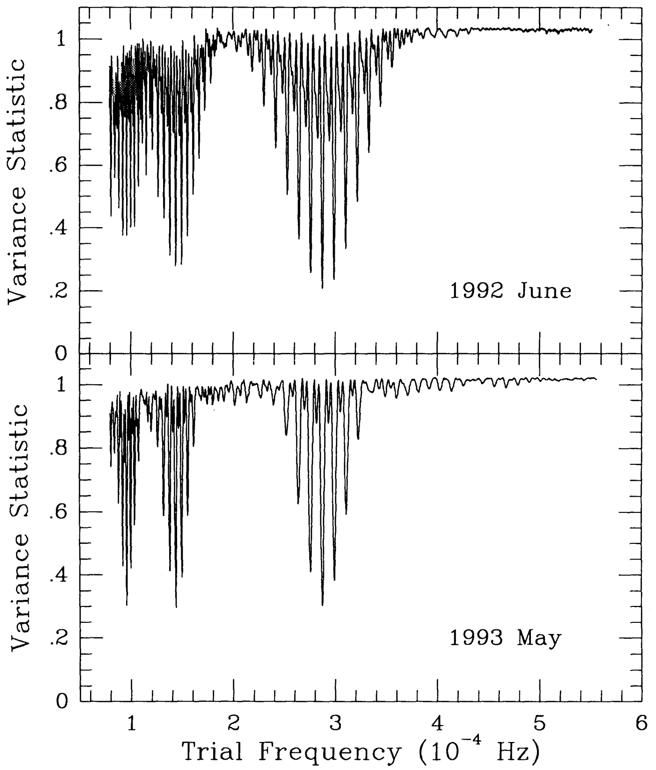

FIG. 6.—Variance analysis of the *I*-band measurements, combining three nights of observations obtained during 1992 June (*top panel*) and three nights during 1993 May (*bottom panel*). The fundamental modulation frequency appears as a deep minimum near 2.9×10^{-4} Hz (a period of 0.9661 hr). The interpretation of ellipsoidal variations in the secondary star implies two minima per cycle, corresponding to a binary period of 1.9322 hr.

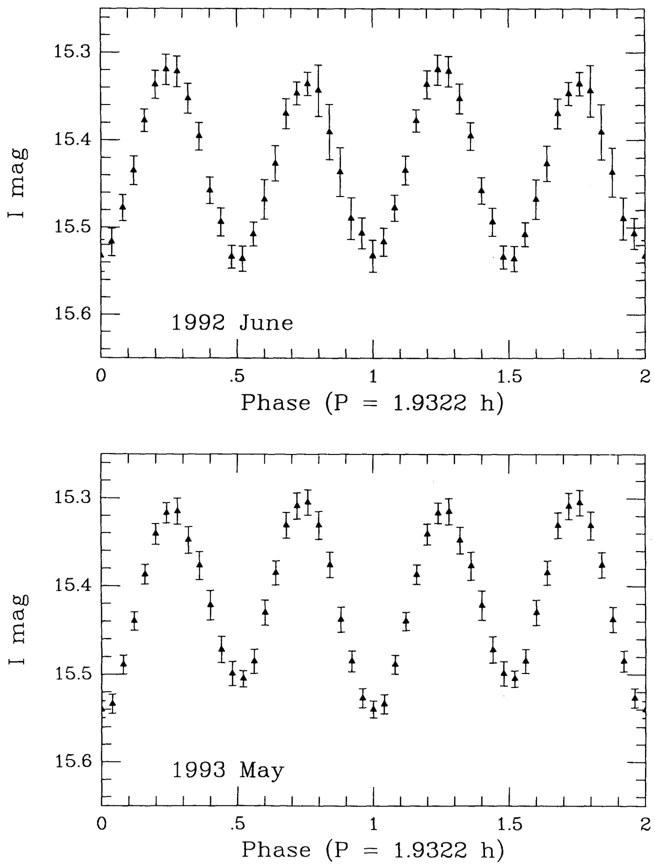

FIG. 7.—Folded light curves of 1ES 1113+432 in the *I* band, assuming a period of 1.9322 hr. The double-wave modulation represents ellipsoidal variations of the secondary star. The minima at phase 0.0 may represent either superior conjunction of the secondary star or the white dwarf.

Converted to Heliocentric Julian Day (2,440,000+), the times of phase zero are 8775.6895 ($\pm$0.0008) and 9114.7184 ($\pm$0.0008), respectively. As expected, there are two minima per cycle, and there is ambiguity whether the minima at zero phase correspond to superior conjunction of the M star or the white dwarf. We note that the 1 yr gap between data sets and the ambiguity in cross-correlating the respective minima both impede efforts to determine a highly accurate period using the available data.

4. PHOTOGRAPHIC RECORDS OF THE HARVARD PLATE LIBRARY

The historical record gained from the Harvard Plate Library confirms brightening episodes for the optical counterpart of 1ES 1113+432 (Silber 1992). The distribution of brightness measurements and upper limits are shown in Figure 8. The magnitudes were calibrated via CCD photometry (*B* band) of 10 field stars used as comparison standards for the evaluation of 1ES 1113+432 on each photographic plate. The results indicate that 14 of 181 plates exhibit *B* mag in the range of 13.5–14.0 (excluding the nondetectons with upper limits less than *B* mag of 14.5). The discovery of these optical outbursts (compared to the average brightness equivalent of $V \sim 16.5$ shown in Figs. 3 and 4) strengthens the case that the CV binary presented above, despite the obvious low rate of accretion, is the correct identification of the transient X-ray source.

The bright appearances of 1ES 1113+432 in the historical study appear highly correlated, unlike the pattern typical of subclasses with frequent outburst recurrence, such as dwarf novae. The available plates originated in a wide distribution between 1923 and 1989. However, 13 of the 14 optical bright states ($B < 14$) of 1ES 1113+432 were concentrated in the 8 yr period between 1943 December 25 and 1952 February 29. Wenzel (1993) reexamined plate material from the Sonneberg Observatory and found states as bright as 12.8 (pg mag), and one outburst was observed to persist for at least 8 days.

5. ESTIMATE OF THE DISTANCE TO 1ES 1113+432

The distance to the binary system can be estimated by isolating the M star component from the spectrophotometry results (Figs. 3 and 4) and then comparing the derived fluxes with the absolute brightness expected for an M6 secondary in an accreting binary system. The method of Bailey (1981) calibrates infrared surface brightness as a function of the secondary star's temperature and orbital period (assuming the secondary fills its Roche lobe), with a weak additional dependence on the secondary mass. This method was extended to the optical *I* band by Silber et al. (1994). The depth of the M star spectral features in 1ES 1113+432 (Fig. 4) was compared to isolated M6 stars in the sample of Kirkpatrick et al. (1991), leading to the estimate that 32% of the flux near 8000 Å is due to the M star. Using the passband and normalization described by Bessell (1983), the M star component is then estimated to

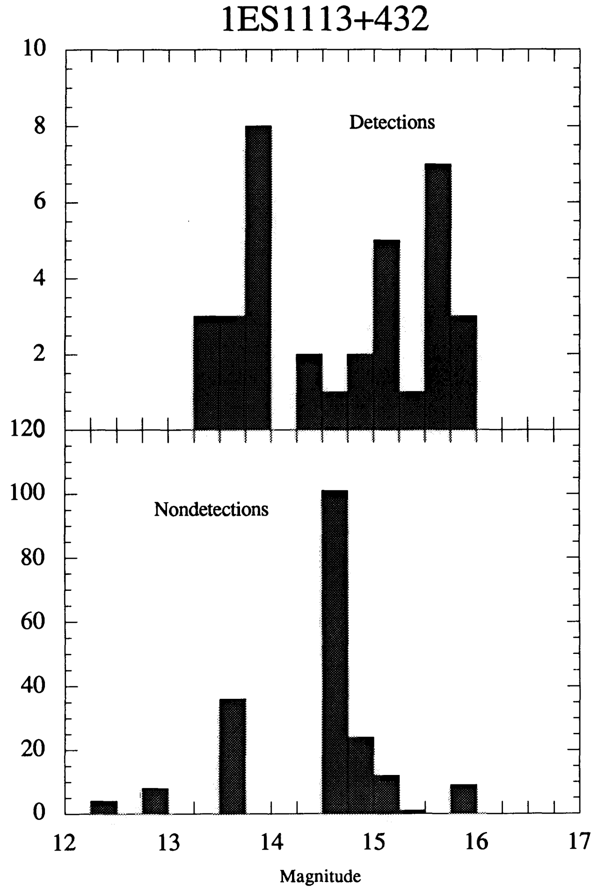

FIG. 8.—Histogram of *B* magnitudes of 1ES 1113+432 derived from the photographs of the Harvard Plate Library. Visual detections are shown in the top panel, and upper limits are shown in the bottom panel.

have an *I* mag (Cousins system) of 16.2 (± 0.2). Applying then the relations of Silber et al. (1994), and assuming the secondary mass is near the main-sequence value for M6 stars (i.e., allowing a range of 0.1–0.2 $M_\odot$), then we find a distance of 88 $\pm$ 18 pc to the binary system.

As an alternative course, we fit the blue-component flux densities in Figure 3 to a power-law function over the range of 4500–6000 Å and derive a spectral index of 4.5. After subtracting this component from the entire spectrum, the residual M star spectrum shows an average flux density of 5.4×10^{-17} ergs cm^{-2} s^{-1} Å^{-1} in the range of 5000–6000 Å. The normalization relation of Allen (1973) then implies an apparent magnitude for the M star, $V \sim 19.6$. The orbital period of 1ES 1113+432 and the spectral class of the secondary lead to an expected absolute magnitude, $M_V = 15$ (Patterson 1984). The *V*-band distance modulus then implies a distance $\sim$83 pc, with an uncertainty somewhat larger than that given for the *I*-band analysis. Therefore the derivation of apparent *V* and *I* magnitudes for the secondary star lead to consistent results. The $V-I$ index for the secondary (3.4 $\pm$ 1.0) is consistent with values for $\sim$M6 dwarfs (index $\sim$3.9) in the study of Leggett (1992). If the distance estimate (88 pc) is correct, 1ES 1113+432 is among the few cataclysmic variables that are within 100 pc of the Earth (Patterson 1984).

6. DISCUSSION

The orbital period of 1.93 hr is near the lower boundary of the "period gap" in the histogram of binary periods for accreting white dwarfs (see Patterson 1984). Since the historical record suggests that 1ES 1113+432 remains in a low accretion state for most of the time, this case provides the rare opportunity to study the secondary star in a CV that has evolved through the period gap. While there are no obvious differences between the secondary spectrum (Fig. 4) and normal M6 dwarfs, this judgment is limited by the available spectral resolution and the dilution of the spectral features by the other spectral component.

The combined characteristics of a CV with a "supersoft" X-ray spectrum and a tendency to exhibit optical quiescence is suggestive of the AM Her (or "polar") subclass, in which a strong magnetic field controls the accretion path from the secondary to the magnetic poles on the surface of the white dwarf (see Liebert & Stockman 1985; Lamb & Melia 1987). One such object, H0139−68, has spent a portion of its recent history in a low state ($V \sim 17.5$; e.g. Wickramasinghe, Visvanathan, & Tuohy 1984), and highly modulated, soft X-ray emission was observed during this interval (Beuermann et al. 1985).

The majority of AM Her stars exhibit both the soft X-ray component (blackbody) and a "hard" X-ray bremsstrahlung component (e.g., EF Eri; see Beuermann, Stella, & Patterson 1987). The standard model for AM Her stars attributes the soft X-ray component to thermal radiation from a heated portion of the white dwarf surface at the accretion spot(s) near the magnetic pole(s) of the white dwarf, while the bremsstrahlung component is direct emission from the hot ($\sim$20 keV) accreting gas that has passed through the shock front above the white dwarf surface. However, there are AM Her objects such as VV Puppis and E2003+225 that display X-ray spectra strongly dominated by the soft X-ray component, presumably due to the eclipse or obscuration of the geometrically smaller bremsstrahlung source (Patterson et al. 1984; Nousek et al. 1984). The X-ray spectrum of 1ES 1113+432 (Fig. 1) resembles these latter cases, particularly E2003+225 (22 eV blackbody; Nousek et al. 1984).

The X-ray spectral fit described in § 1 implies a total blackbody flux (i.e., integrating all photon energies and excluding the effects of column density) of 1.2×10^{-8} ergs cm^{-2} s^{-1}. Assuming a distance of 88 pc and a slab of emission (π sr solid angle) pointed in our direction, then the luminosity of the 22 eV blackbody is 3×10^{33} ergs s^{-1}. While there is an order of magnitude uncertainty in this luminosity, the value is substantially higher than previous results for other AM Her binaries (e.g., Patterson et al. 1984). Still, the implied radius of such an emitting region (600 km) is substantially smaller than the white dwarf.

The close distance of 1ES 1113+432 and the possibility of magnetically focused accretion (i.e., an AM Her classification) may help to explain why this CV appeared as such a bright X-ray transient, but there are many remaining questions. What is the range of mass transfer rates exhibited by this CV? What is the optical and polarization behavior during bright states? Why is the accretion rate chronically low? Further observations are encouraged, motivated in part by speculation that the secondary may not have fully reestablished contact with its Roche lobe after the binary system evolved through the period gap.

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