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A NEW MAGNETIC CATACLYSMIC VARIABLE: WGA J1047.1+6335

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ABSTRACT

A new ultrasoft X-ray source, WGA J1047.1+6335, was discovered during a search of the *ROSAT* PSPC pointed observations, data from which are publicly available (White, Giommi, & Angelini; Singh et al.). We identify the X-ray source with an optical object of $V \simeq 19.4$ mag in the error circle of the X-ray source position. Optical and X-ray photometry has revealed the presence of an ∼40 minute period. Strong emission lines of H and He have been detected in its optical spectrum. The X-ray spectrum of WGA J1047.1+6335 is best fitted with a blackbody ($kT \simeq 40$–50 eV) with negligible interstellar absorption and no X-rays with energies greater than 0.5 keV. Polarimetry shows a high amplitude (20% circular polarization) variation on an 80 minute timescale. These properties all suggest a polar with an 80 minute orbital period and either beaming/self-eclipsing effects from one pole or nearly equal emission from two poles.

Subject headings: novae, cataclysmic variables — stars: individual (WGA J1047.1+6335) — stars: variables: other — X-rays: stars

1. INTRODUCTION

A number of ultrasoft X-ray sources have recently been cataloged by Singh et al. (1995) based on a search of the WGACAT, a soft X-ray source catalog of 62,000 sources by White, Giommi, & Angelini (1994) constructed from 3 years of *ROSAT* pointings. One of the primary reasons for the search for ultrasoft sources was to find new magnetic cataclysmic variables (CVs) (Chanmugam 1992), since such objects can be identified from the considerable soft X-ray emission generated by the reprocessing of the hard photons that arise from accretion at the magnetic polar caps (Cropper 1990). In fact, a simple analysis of the X-ray colors of the ultrasoft sources that were in the catalog of Singh et al. (1995) had suggested that CVs may be the second most likely candidates, after hot white dwarfs, to be found on the basis of the softness of their X-ray spectra. Therefore, a search for optical counterparts in the error circles (radii of 13″–50″) of these sources, using CCD photometry and medium-resolution spectroscopy, was initiated. Here we report the discovery of a new and rather faint CV ($V \sim 19.4$) and identify it as the counterpart of the soft X-ray source WGA J1047.1+6335 (henceforth WGA 1047) from follow-up optical observations. Optical photometry, spectroscopy, polarimetry, and analysis of archival X-ray data are presented.

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2. OPTICAL OBSERVATIONS: SPECTROSCOPY AND PHOTOMETRY

A faint object of $V \simeq 19.4$ was found at the position of the X-ray source, in a 20 s exposure CCD frame (Fig. 1) taken on 1995 February 23 UT at the 3.5 m telescope at Apache Point Observatory (APO). The optical position of the source is R. A. (2000) = $10^h47^m09\overset{s}{.}9$, decl. (2000) = +63°35′13″ (errors of 2″). An optical spectrum was obtained immediately following the image, using the Double Imaging Spectrograph in low resolution (∼10 Å) mode and a 1″.5 slit. The spectra were placed on a flux system through use of standard stars, but the lack of good seeing and tracking resulted in the data not being spectrophotometric. The 12 minute spectrum revealed a source with prominent emission lines of H and He (Fig. 2). The EWs measured from the images are 65 Å for Hδ, 60 Å for Hγ, 74 Å for Hβ, 70 Å for Hα, and 49 Å for the He II λ4686 line.

CCD photometry with the University of Washington 0.76 m telescope at Manastash Ridge Observatory (MRO) was car-

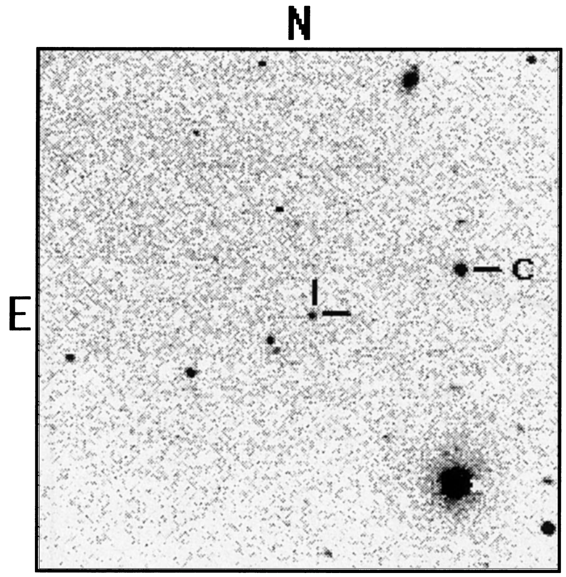

FIG. 1.—APO CCD frame for the optical counterpart of the X-ray source WGA J1047.1+6335, shown marked along with the $V = 16.7$ mag comparison star used in the photometry. The size of the frame is $4' \times 4'$.

ried out on the nights of 1995 April 22 (9 minute integrations from $4^h.67$ UT to $8^h.02$ UT) and 23 (8.3 minute integrations from $4^h.63$ UT to $5^h.97$ UT) using a V filter, and on 1995 April 30 (5 minute integrations from $6^h.34$ UT to $7^h.76$ UT) and May 20 (3.7 minute integrations from $6^h.08$ UT to $10^h.79$ UT) in an unfiltered mode to increase the signal. The data were reduced using IRAF routines to remove the bias, divide by the flat fields, and measure the magnitudes with aperture photometry. The magnitudes of WGA 1047 were measured relative to the comparison star "C" marked in Figure 1 (whose roughly calibrated V magnitude is ~16.7 and which is located 21″ N and 69″ W of WGA 1047). The light curve (in relative magnitudes) for the night of May 20 is shown in Figure 3. A periodic wave with a 40 minute period and an amplitude of about 1 mag can easily be seen in each night's data. Periodograms run on each of the four nights and on the combined data set all show the presence of a period of 40.075 ± 0.001 minutes with possible aliases at 38.989 and 41.217 minutes. In Figure 4 we show a periodogram (*lower curve*) derived from the May 20 data using a Bayesian parameter estimation method (Bretthorst 1990).

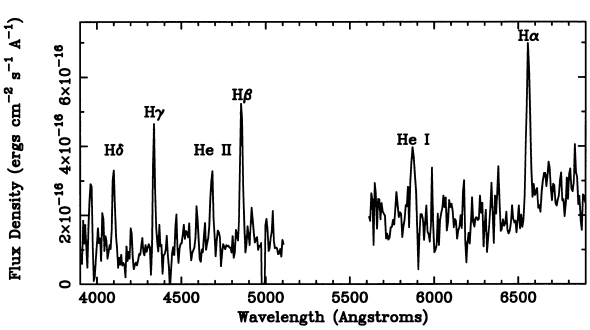

FIG. 2.—Optical spectrum of the $V \simeq 19.4$ mag object identified as the counterpart of the X-ray source observed on 1995 February 23 at APO. The observations were started at 3^h45^m UT, and the spectrum was accumulated for 12 minutes. The principal lines of H and He are marked.

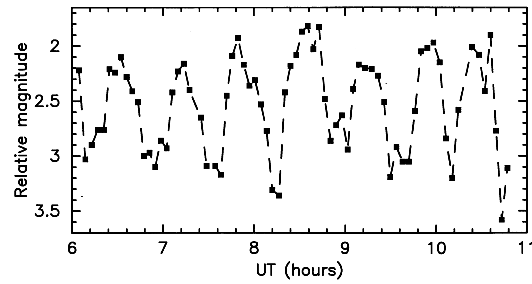

FIG. 3.—Unfiltered CCD optical light curve of the 19.4 mag star relative to the comparison star as observed on the night of 1995 May 20 at MRO. Each point is a 3.7 minute integration, and the statistical accuracy of each point is 0.1 mag, while the comparison stars on the frames are constant to 0.02 mag.

3. CIRCULAR POLARIMETRY

On 1995 May 30–31, WGA 1047 was observed with the 2.56 m Nordic Optical Telescope on La Palma as a part of the program to search for circular polarization in faint suspected AM Herculis systems. The observations were carried out using an EEV CCD chip together with a calcite crystal and a $\lambda/4$ plate. This configuration allows circular polarization to be determined from each individual CCD frame.

A series of 16 R-band CCD exposures was taken. Exposures of 300 s were used (except for the first frame which contains only 120 s of integration). The 90 minutes of data cover just two cycles of the system and are displayed in Figure 5. A standard star S100340 ($M_v = 10.117$; $B-V = -0.242$; $V-R = -0.101$) was used for the calibration of the magnitude scale for the differential photometry shown in the lower panel. The same double-humped modulation with an amplitude of ~1.5 mag as seen in the MRO data is present. More importantly, a circular polarimetric variation (Fig. 5) is seen on an 80 minute period. This variation has an amplitude of ~20% circular polarization and does not show a definitive indication of a second pole (no clear change of sign for the polarization), although it cannot conclusively be ruled out based on our data. The present low signal-to-noise polarimetric data are consistent with either of the two suggested periods, viz., 40 and 80 minutes.

The deeper minimum in the light curve coincides with the maximum of negative (left-handed) circular polarization. This

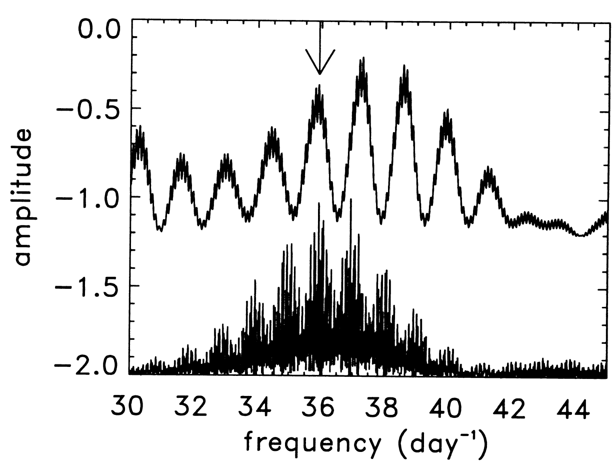

FIG. 4.—Periodograms of the X-ray (*top*) and optical (*bottom*) data. The arrow above the X-ray and optical peaks at 35.93 cycles day^{-1} indicates the most likely period.

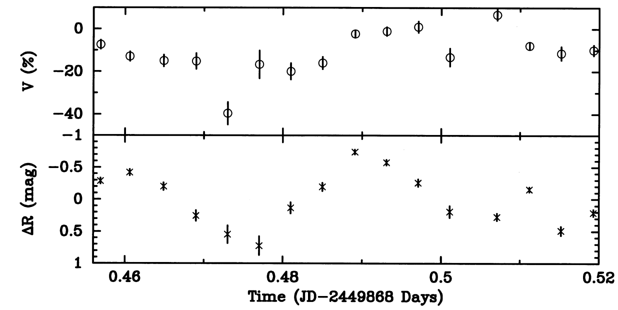

FIG. 5.—Percentage circular polarization (*top*) and the light curve based on differential photometry using R filter (*bottom*) of WGA J1047.1+6335 as observed on 1995 May 30–31. The zero point for the y-axis in the bottom panel corresponds to $R = 19.1 \pm 0.1$ mag.

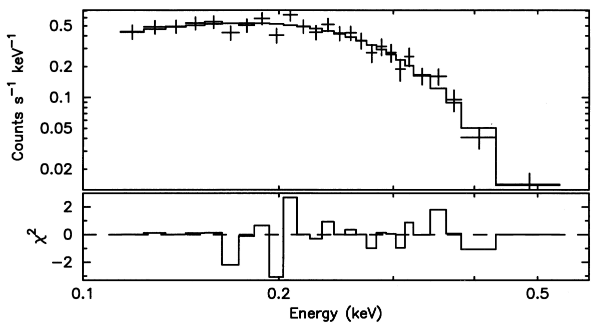

FIG. 6.—X-ray spectrum of WGA J1047.1+6335 as observed on 1993 May 12–22 (*top*). The best-fit blackbody model ($kT \simeq 50$ eV) is shown as a histogram. The contributions of the residuals to the χ^2 are shown in the bottom panel.

can be attributed to cyclotron beaming effects when the emission area is pointing closest to us. The circular polarization approaches zero at the two photometric maxima, as expected for viewing directions nearly perpendicular to the magnetic field lines, when the cyclotron region is closer to the limb. The weaker minimum could then be explained by having the emission region partially eclipsed by the white dwarf or be caused by a second pole. The lack of a consistent pattern of a deep and shallow minima in the long light curves (Fig. 3) means that there is a lot of variability present in the single or double pole structure. Higher signal-to-noise ratio polarimetric observations over a longer period of time are needed for more detailed geometric modeling.

4. X-RAY DATA: PERIODOGRAM AND SPECTRUM

The archival X-ray data were obtained from observations with the *ROSAT* X-ray telescope and the position sensitive proportional counter (PSPC) used as the detector (Trümper 1983; Pfeffermann et al. 1987). The PSPC has a bandwidth of 0.1–2.4 keV and a energy resolution ($\Delta E/E$) of $\simeq$0.42 at 1 keV. WGA 1047 appears at the center of the field of view in pointed observations from 1992 October 17–19 UT. An effective exposure of about 4760 s was obtained on source. In 1993 May 12–22 UT, it was observed serendipitously in the field of a spiral galaxy NGC 3359, about 21′ offset from the center of the PSPC detector. Effective exposure on source was about 10480 s. The total count rate (0.100 ± 0.005 s^{-1}) observed from the source was nearly the same in both the observations. Individual observations, however, indicate the presence of variability. We performed Fourier analysis and period-folding analysis of the X-ray light curve. The X-ray periodogram using Bayesian parameter estimation in shown in Figure 4 (*top periodogram*). Because of the weakness of the source, aliasing with the orbital period of the satellite, and large data gaps, the X-ray data alone are unable to clearly identify the exact period. However, a comparison of the X-ray and optical periodograms (Fig. 4) shows that the slightly less significant peaks in each periodogram at 35.93 cycles day^{-1} agree to within 0.01 cycles day^{-1}, whereas other peaks show much less agreement. Therefore, we conclude that the period at 40.08 minutes is the most likely period in both the optical and X-rays.

We have analyzed the X-ray spectra obtained from both observations. Spectra were extracted from source radii of $\sim$3.′5 in both cases. The background was estimated from the neighboring regions. The spectral data were grouped so that there were a minimum of 20 counts per channel. No X-rays were detected at energies $\geq$0.5 keV. For the data obtained from the off-axis detection of the source, we incorporated the corrections resulting from the point-spread function and the area of the telescope. The spectral data were analyzed using XSPEC, the best available response matrix, viz., pspcb_93jan12.rmf, and the absorption cross sections of Morrison & McCammon (1983). The spectra were best fitted ($\chi^2_\nu = 0.73$ for 22 degrees of freedom for the 1993 data, and $\chi^2_\nu = 1.25$ for 20 degrees of freedom for the 1992 data) with a blackbody model and negligible interstellar absorption. Both observations gave a consistent set of parameters. The temperature kT was found to be 40^{+9}_{-20} eV from the 1992 observation and 50^{+9}_{-25} eV from the 1993 observation, where the quoted errors are with 90% confidence. The equivalent column density, $N_{\rm H}$, of the interstellar matter in the line of sight to the source could not be determined from the low energy absorption of the spectrum and was found to be correlated with the blackbody temperature. The best-fit value for $N_{\rm H}$ is almost zero, and an upper limit of 2.5×10^{20} cm^{-2} is derived with 90% confidence. The average X-ray flux observed in the 0.1–0.5 keV energy band is found to be in the range $(3.1\text{–}3.8) \times 10^{-13}$ ergs cm^{-2} s^{-1}, depending on the spectral parameters, in both the observations. The spectrum from the 1993 observation with its better signal-to-noise is shown in Figure 6. The best-fit model is shown as a histogram.

5. DISCUSSION

Based on the normalization for the blackbody fit to the X-ray spectra, we find the total unabsorbed blackbody luminosity over the energy range of 0.05–0.5 keV to be $(5.3 \pm 0.3) \times 10^{31} D^2_{\rm kpc}$ ergs s^{-1}. The radius of such a blackbody would be $\simeq$7.8 $D_{\rm kpc}$ km. The lack of absorption, even though the source is located near the north galactic pole, and the fact that the accreting pole on the white dwarf may be smaller in size, suggest that the source is probably nearer to us than 1 kpc. A distance as large as 1 kpc, however, cannot be ruled out, based on an average density of 0.07 cm^{-3} (Paresce 1984) for interstellar matter and the upper limit of $N_{\rm H} = 2.5 \times 10^{20}$ derived from the X-ray spectra.

Haberl & Motch (1995) have recently identified a new class of very soft intermediate polars (IPs) which have a dominant blackbody with slightly higher kT (40–60 eV) compared to the polars (15–25 eV) and magnetic fields of the order of 5–6 MG which are at the lower end of the values found for the polars. The observed value of kT for WGA 1047 is similar to that of the new class of soft IPs. In addition, we find that the strength of the He II λ4686 line measured in the spectrum of WGA

1047 is less than that of Hβ, as is normally found in the case of IPs (Szkody et al. 1990). These data, therefore, would suggest that WGA 1047 may be another member of this new class of soft IPs.

The high circular polarization in J1047, however, implies a very high magnetic field (20–70 MG), as is normally observed in polars. The period in the system in this case would be $\sim$80 minutes, and the light curve can be interpreted as either two equally contributing poles or one pole with beaming effects and/or self-eclipse by the white dwarf. The highly soft nature of X-ray emission would then imply a ratio of $\geq$50 between the blackbody and the bremsstrahlung components. Time-resolved spectroscopy and further polarimetry should help to resolve some of these issues.

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