FIRST J102347.6+003841: The First Radio-selected Cataclysmic Variable

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ABSTRACT. We have identified the 1.4 GHz radio source FIRST J102347.6+003841 (hereafter FIRST J1023+0038) with a previously unknown 17th magnitude Galactic cataclysmic variable (CV). The optical spectrum resembles that of a magnetic (AM Herculis or DQ Herculis type) CV. Five nights of optical CCD photometry showed variations on timescales of minutes to hours, along with rapid flickering. A reexamination of the FIRST radio-survey data reveals that the radio detection was based on a single 6.6 mJy flare; on two other occasions, the source was below the ~1 mJy survey limit. Several other magnetic CVs are known to be variable radio sources, suggesting that FIRST J1023+0038 is a new member of this class (and the first CV to be discovered on the basis of radio emission). However, FIRST J1023+0038 is several optical magnitudes fainter than the other radio-detected magnetic CVs. It remains unclear whether the source simply had a very rare and extraordinarily intense radio flare at the time of the FIRST observation, or is really an unusually radio-luminous CV; thus, further observations are urged.

1. INTRODUCTION

Most of the known cataclysmic variables (CVs) were originally discovered because of their dramatic optical variability, exemplified by the outbursts of dwarf novae and classical novae. More recently, however, ultraviolet and X-ray sky surveys have led to discoveries of many new CVs, including members of subclasses that have less spectacular optical light variations (e.g., the novalike variables).

Follow-up investigations at radio wavelengths have led to detections of a few well-known, mostly nearby, CVs as radio sources. In this paper, we report what we believe to be the first detections of a few well-known, mostly nearby, CVs as radio sources, suggesting that FIRST J1023+0038 is a new member of this class (and the first CV to be discovered on the basis of radio emission). However, FIRST J1023+0038 is several optical magnitudes fainter than the other radio-detected magnetic CVs. It remains unclear whether the source simply had a very rare and extraordinarily intense radio flare at the time of the FIRST observation, or is really an unusually radio-luminous CV; thus, further observations are urged.

2. THE DISCOVERY OF FIRST J1023+0038

The Faint Images of the Radio Sky at Twenty Centimeters (FIRST) survey is aimed at producing a deep radio map of 10,000 deg² at the north and south Galactic caps (see Becker, White, & Helfand 1995; White et al. 1997). The survey is being carried out at 1.4 GHz with the Very Large Array (VLA) of the National Radio Astronomy Observatory (NRAO) and can be thought of as a radio analog of the optical Palomar Observatory Sky Survey (POSS). Source positions are provided to better than 1” accuracy, and the sensitivity limit is about 1 mJy.

The FIRST Bright Quasar Survey (FBQS; Gregg et al. 1996; White et al. 2000; Becker et al. 2001) is a follow-up effort aimed at finding large numbers of quasi-stellar objects (QSOs) and characterizing their properties. The FBQS candidates are FIRST radio sources that have a stellar-appearing optical counterpart in the APM catalog, which is based on Automatic Plate Measuring machine scans of the POSS-I plates (McMahon & Irwin 1992; McMahon et al. 2002). The majority of FBQS candidates are found to be QSOs, BL Lac objects, or other extragalactic sources. Only 8% of the candidates turn out to be Galactic stars, the bulk of which are merely chance coincidences of unrelated, ordinary foreground stars with the radio positions. Actual radio emission from Galactic stars is exceedingly rare, even at the 1 mJy limit of the FIRST survey, as discussed in detail by Helfand et al. (1999).

It was thus a surprise when one of the faint FBQS candidates proved to be a Galactic star with an unusual spectrum, which clearly showed it to be a previously unknown CV. This source, cataloged with a 1.4 GHz radio flux density of 3.58 mJy, lies at the J2000.0 coordinates given in the first row of Table 1. Lying 176 away from the radio source, at the coordinates listed in the second row of Table 1, is a faint stellar object contained in the APM catalog. Also listed in the bottom row of Table 1 are the coordinates and magnitudes of a nearby comparison star used in the CCD observations described in the next section. Figure 1 presents a finding chart for the optical candidate, with the radio contours superposed. The radio source is designated FIRST J102347.6+003841 (but hereafter the name will be shortened to FIRST J1023+0038).

Figure 2 shows the discovery spectrogram, which was obtained on 2000 May 6 by Mark Lacy with the Lick Observatory 3 m telescope. The spectrum is dominated by a blue continuum, with superposed emission lines of the Balmer series, He i, and
TABLE 1

| Object               | $\alpha_{\text{J2000.0}}$ | $\delta_{\text{J2000.0}}$ | $m_{\text{blue}}$ | $m_{\text{red}}$ |
|----------------------|-----------------------------|---------------------------|-------------------|-----------------|
| FIRST radio position | 10 23 47.621                | +00 38 41.60              | ...               | ...             |
| Optical candidate    | 10 23 47.713                | +00 38 42.40              | 18.05             | 16.98           |
| Comparison star      | 10 23 43.340                | +00 38 19.20              | 16.14             | 14.88           |

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

The spectrum is fairly typical of a CV in quiescence (see, for example, the spectroscopic atlas of Williams 1983). However, the lines of He $I$ and especially of He $II$ are rather stronger than in most dwarf novae and suggest that the object may be more closely related to the subset of magnetic or AM Herculis type CVs. The spectrum is, in fact, rather similar to that of AM Her itself, as illustrated in Williams’s Figure 13.

Fig. 1.—Finding chart for optical counterpart of FIRST J1023+0038, prepared from the second-epoch red Digitized Sky Survey POSS scans. Superposed are 0.8 and 2.0 mJy 1.4 GHz radio contours from the FIRST survey. North is at the top, and east is on the left.

3. OPTICAL PHOTOMETRY

If the optical candidate counterpart of FIRST J1023+0038 is a CV, then it would be expected to exhibit rapid optical variability. In order to search for such variations, H. E. B. and M. S. O. obtained photometric observations on five nights in 2000 November and December, using the 2.1 m reflector at Kitt Peak National Observatory (KPNO). A Tektronix 2048 × 2048 CCD was used, with 2 × 2 on-chip binning. In order to maximize the signal, we used a Schott BG39 glass filter, which yields a broadband blue bandpass. Only a 512 × 512 pixel subraster was read out, in order to reduce the

photometry for both the CV candidate and the comparison star. The SDSS position is 1" away from the radio position. The SDSS spectrum is quite similar to our Lick spectrum shown in Figure 2, although the equivalent widths of the emission lines appear to be slightly lower. Moreover, the emission lines are incipiently resolved into double-peaked profiles. This would suggest that there is an accretion disk present in the system, and that therefore it may be a DQ Herculis type magnetic CV rather than a full-fledged AM Herculis system (in which an accretion disk would be lacking).
Fig. 2.—Lick 3 m spectrum of FIRST J1023+0038. Emission lines of the Balmer series and of He i and He ii are marked, as are two terrestrial atmospheric absorption bands. The spectrum is typical of a cataclysmic variable in quiescence.

readout time between exposures but still produce a large enough field to contain both the target and a nearby comparison star. Even with this CCD setup, however, the readout time was still 25 s with the KPNO data acquisition system. Exposure times of 30–60 s were used in 2000 November and were shortened to 10 s for all of the 2000 December observations.

Table 3 contains a log of the CCD observations. As noted in the table, none of the nights were photometric, but accurate differential photometry is readily possible under nonphotometric conditions, as has been shown by Grauer & Bond (1981), Ciardullo & Bond (1996), and many others. We performed standard aperture photometry on the frames and reduced the data to differential magnitudes of the target with respect to the comparison star. In order to set an approximate photometric zero point, we adopted the blue magnitude of 16.14 given for the comparison star in the APM catalog.

Figure 3 shows our resulting light curves from the five nights of photometry. The differential magnitudes are generally accurate to better than 0.01 mag (i.e., smaller than the size of the plotting points), except on the very cloudy night of 2000 December 24, where the errors were typically several hundredths of a magnitude.

The object indeed shows variability on both slow and rapid timescales, confirming its classification as a CV. Although generally maintaining a level around magnitude 17.5, it showed a flare of ∼0.8 mag lasting about 20 minutes (apart from one rapid dip back to the baseline level) on 2000 December 23. On December 24, the target was more active, being initially about 0.5 mag brighter than on previous nights, declining briefly, and then ramping up by about 1 mag over about a half-hour and remaining at that level for over an hour (apart from two rapid dips).

The object also shows short-timescale flickering, which gives the light curves a noisy appearance. On the first four nights, and on the fifth night when the star was near its baseline level, the light curves show a curious “bimodal” appearance; i.e., the magnitudes tend to cluster near either “high” or “low” levels but rarely in between. We suspect that this appearance arises from our sparse sampling of a light curve that may have flickering with a timescale of approximately 10 s; we are thus missing about 1/7 of the points that we would have obtained with uninterrupted 10 s integrations.

Power spectra were calculated for all of the light curves but revealed no significant coherent signals; of course, we were not able to test for signals with periods shorter than ∼70 s, such as are seen in some of the DQ Her type subset of magnetic CVs (Patterson 1994), because of the ⩾35 s interval between integrations.

We see no evidence, in our fairly limited data set, for eclipses or other repetitive phenomena occurring on an orbital timescale. Determination of the orbital period of the system will require additional photometry or a radial velocity study.

4. RADIO VARIABILITY

A strong confirmation that the optical CV is indeed the counterpart of the radio source would come from variability of the radio source.

We therefore searched the FIRST database for evidence of such variability. The FIRST survey is based on data collected by the VLA on a hexagonal grid of field centers spaced by

| UT Date    | Observer | UTC (Start) | Run Length (hr) | Integration Time (s) | Sky        |
|------------|----------|-------------|----------------|----------------------|------------|
| 2000 Nov 21 | M. S. O. | 10:57       | 1.0            | 60, 30               | Cirrus     |
| 2000 Nov 22 | M. S. O. | 11:35       | 1.3            | 30                   | Thin haze  |
| 2000 Dec 22 | H. E. B. | 12:28       | 1.2            | 10                   | Thin cirrus|
| 2000 Dec 23 | H. E. B. | 10:15       | 3.5            | 10                   | Haze       |
| 2000 Dec 24 | H. E. B. | 9:28        | 3.0            | 10                   | Thick haze |

Table 2

SDSS Astrometry and Photometry

| Object               | SDSS Object ID | α2000.0 | δ2000.0 | u'   | g'   | r'   | i   | z    |
|----------------------|----------------|---------|---------|------|------|------|-----|------|
| Optical candidate    | 2255048168702071 | 10 23 47.683 | +00 38 40.999 | 19.418 | 17.794 | 17.206 | 17.053 | 16.999 |
| Comparison star      | 2255048168701986 | 10 23 43.308 | +00 38 19.14 | 16.281 | 14.906 | 15.513 | 14.226 | 14.168 |

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.
Fig. 3.—CCD broadband blue light curves of FIRST J1023+0038, obtained with the KPNO 2.1 m telescope and a BG39 filter on five nights in 2000 November–December. UT dates are indicated. The time axis is in days, with tick marks at intervals of 0.025 day = 36 minutes, and the scale bar at the upper left shows a 1 mag brightness interval. Differential magnitudes with respect to a nearby comparison star are plotted, with the approximate 17.5 mag zero-point levels for each night indicated by ticks down the right-hand edge. Photometric errors are generally smaller than the plotted points.

### Table 4

| Date       | UTC     | Right Ascension (h:m) | Declination (deg:m) | Radius (arcmin) | Response Function | $F_{\text{obs}}$ (mJy) | $F_{\text{corr}}$ (mJy) |
|------------|---------|-----------------------|---------------------|-----------------|-------------------|------------------------|------------------------|
| 1998 Aug 3 | 20:33   | 10 24.0               | +00 52              | 13.7            | 0.57              | <1.0                   | <1.8                   |
| 1998 Aug 8 | 21:08   | 10 22.5               | +00 39              | 19.4            | 0.30              | <1.0                   | <3.4                   |
| 1998 Aug 10| 21:24   | 10 24.0               | +00 26              | 13.1            | 0.60              | 3.91                   | 6.56                   |

Note.—Units of right ascension are hours and minutes, and units of declination are degrees and arcminutes.

5. DISCUSSION

The first CV to be detected at radio wavelengths was the prototypical magnetic CV AM Herculis, whose emission was discovered at the VLA by Chanmugam & Dulk (1982). They detected a flux density of 0.67 mJy at 4.9 GHz and suggested that the emission is from mildly relativistic electrons trapped in the magnetosphere of the white dwarf. Subsequent observations by Dulk, Bastian, & Chanmugam (1983) led to detection of a strong flare from AM Her, which lasted about 10 minutes and reached a peak of 9.7 mJy at 4.9 GHz; Dulk et al. were also able to set an upper limit on the quiescent flux density of AM Her at 1.4 GHz of 0.24 mJy.

The magnetic DQ Her type system AE Aqr has also been detected as a variable radio source, with the initial discovery having been made at the VLA by Bookbinder & Lamb (1987); they found a flux density at 1.4 GHz varying from 3 to 5 mJy. Other radio detections of AM Her and DQ Her type CVs have been reported by Pavelin, Spencer, & Davis (1994) and references therein. By contrast, nonmagnetic CVs in general are not detectable radio sources (Nelson & Spencer 1988), strongly suggesting that a highly magnetic white dwarf is a key element in the production of radio emission. For further information, the reader is directed to the summary of radio emission from CVs by Mason, Fisher, & Chanmugam (1996).

We thus strongly suspect that FIRST J1023+0038 is a new magnetic CV of either the DQ Her or the AM Her variety. Our detection of a 6.6 mJy flare at 1.4 GHz is remarkable because,
with a quiescent optical magnitude near 17.5, FIRST J1023+0038 is so optically inconspicuous. (By comparison, AE Aqr is an 11th magnitude object, and AM Her lies generally around 12th–13th magnitude, although with occasional drops to “low” states below 15th magnitude.) It remains to be seen whether the flare that led to our serendipitous discovery of FIRST J1023+0038 was simply a very rare and unusually energetic one, or whether this object is indeed much more radio luminous than the typical magnetic CVs.

We urge follow-up observations at radio, optical, and X-ray wavelengths. Optical spectroscopy should reveal the orbital period and might provide direct evidence for a strong magnetic field. Polarimetry would determine whether the object is a highly magnetic AM Her system. A search of archival plate collections, and future long-term photometric monitoring, might reveal either dwarf nova outbursts or AM Her–like low states, although the object is rather faint.

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