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ERUPTING CATACLYSMIC VARIABLE STARS IN THE NEAREST GLOBULAR CLUSTER, NGC 6397: INTERMEDIATE POLARS?[1]

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ABSTRACT

NGC 6397 is the closest globular cluster and hence the ideal place to search for faint stellar populations such as cataclysmic variables (CVs). *Hubble Space Telescope* (*HST*) and *Chandra* observers have identified nine certain and likely CVs in this nearby cluster, including several magnetic CV candidates. We have combined our recent UV imagery with archival *HST* images of NGC 6397 to search for new CV candidates and especially to look for dwarf nova–like eruptive events. We find remarkable and somewhat unexpected dwarf nova–like eruptions of the two well-known cataclysmic systems CV2 and CV3. These two objects have been claimed to be *magnetic* CVs, as indicated by their helium emission-line spectra. Magnetic fields in CVs are usually expected to prevent the disk instability that leads to dwarf nova eruptions. In fact, most field magnetic CVs are observed to *not* undergo eruptions. Our observations of the dwarf nova eruptions of CV2 and CV3 can be reconciled with these objects' He II emission lines if both objects are infrequently erupting intermediate polars, similar to EX Hya. If this is the case for most globular cluster CVs, then we can reconcile the many X-ray and UV-bright CV candidates seen by *Chandra* and *HST* with the very small numbers of erupting dwarf novae observed in cluster cores.

Key words: dwarf novae — novae, cataclysmic variables

1. INTRODUCTION

Galactic globular clusters are surprisingly rich in luminous X-ray sources (Clark 1975; Katz 1975). Scenarios involving tidal capture by two stars (Fabian et al. 1975) and/or exchange reactions involving three stars (Hut & Verbunt 1983) are widely believed to be the sources of these strongly interacting binaries in clusters. The remarkable correlation between stellar encounter rate and number of X-ray sources in globular cluster cores (Pooley et al. 2003) supports this viewpoint.

Accreting white dwarf–main-sequence star binaries—the cataclysmic variable (CV) stars—are almost certainly produced by the same mechanisms in clusters and should also be plentiful in globular clusters (Di Stefano & Rappaport 1994). Perhaps the best cluster to search for this predicted population is NGC 6397. At a mere 3.3 kpc (Gratton et al. 2003) it is the closest globular cluster to the Sun. Thus, even CVs resembling the least luminous known such objects (with $M \sim +11$) in this cluster should be detected with deep *Hubble Space Telescope* (*HST*) imagery.

The initial discoveries of multiple X-ray sources (Cool et al. 1993) and Hα-bright stars (Cool et al. 1995) in NGC 6397 were rapidly followed by spectrographic identification of essentially certain CVs with hydrogen and helium emission lines (Grindlay et al. 1995; Edmonds et al. 1999). Remarkably, all four CVs in this cluster with *HST* spectra show significant and, in three of four cases, prominent He II λ4686. This line is seen almost exclusively in magnetic CVs and nova-like variables (Williams 1983; Echevarria 1988), prompting Grindlay et al. (1995) and Grindlay (1999) to suggest that magnetic CVs might well be the dominant CV population in globular clusters.

About half of all known field CVs (Downes et al. 2001) are dwarf novae (DNe). Most field DNe have been discovered because they undergo 2–5 mag outbursts every few weeks to months (Warner 1995). In contrast, strongly magnetic CVs are *not* observed to undergo DN outbursts. This is because DN eruptions are likely caused by a disk instability (Mineshige & Osaki 1983), and the accretion disks of magnetic CVs have been truncated or are absent.

Since large archival *HST* data sets of globular cluster images are available, we have been systematically looking for erupting DNe in the cores of all such clusters (Shara et al. 1996). Here we report the results of a search of NGC 6397 to determine whether any of the magnetic CV candidates undergo eruptions. Remarkably, we do find DN eruptions of two of the putative NGC 6397 magnetic CVs.

2. OBSERVATIONS

The *HST* imaged NGC 6397 during five separate epochs from 1996 to 2003. Our own 2003 data sets focused on Space Telescope Imaging Spectrograph (STIS) UV imagery, heretofore unavailable and particularly useful in detecting CVs. The dates of observation, principal investigator (PI), number of the *HST* program, filters used, number of frames, and total exposure time in each filter are given in the observing log (Tables 1 and 2).

3. MULTIWAVELENGTH IMAGES AND LIGHT CURVES OF TWO DWARF NOVAE

We have carried out visual inspection and aperture photometry of each of the nine known CVs (referred to by Grindlay et al. [2001b] as CV1–CV9) in every available archival *HST* image. While a modest level of variability (up to a few tenths of a magnitude) is detectable in all nine CVs, and two of the objects

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TABLE 1
WFPC2 Observations of NGC 6397

WFPC2 Epochs	PI/Program Number	F336W (s)	F439W (s)	F555W (s)	F656N (s)	F675W (s)	F814W (s)
1: 1996 Mar 6.....	King/5929	700, 6 × 500, 28 × 400, 2 × 80, 2 × 10	4 × 500, 16 × 400, 2 × 80, 2 × 10	6 × 40, 8, 1	...	...	2 × 40, 8, 1
2: 1999 Apr 3	Grindlay/7335	...	...	24 × 40, 2 × 8, 2 × 1	1000, 4 × 900, 18 × 800, 7 × 700, 2 × 140	38 × 40, 2 × 8, 2 × 1	24 × 40, 2 × 8, 2 × 1
3: 2001 Nov 4.....	Noll/9313	3 × 160	2 × 160	...	...	...	3 × 40

Note.—Listed are the number of usable observations at each date, as well as their exposure times.

(CV1 and CV6) now have measured photometric periods (Kaluzny & Thompson 2003), none is yet reported to show a DN-like outburst.

The *HST* images of CV2 and CV3 are shown as photo montages in Figures 1 and 2, respectively. The median brightness in every epoch and every available filter is shown with mean filter wavelength running from blue (*left*) to red (*right*). We also show the five-epoch light curves of these two objects in Figure 3.

Each CV has been imaged in the Wide Field Planetary Camera 2 (WFPC2) F814W filter in epochs 1, 2, and 3 and in the STIS clear CCD filter in epochs 4 and 5. We have normalized epochs 1–3 with the first observation of each CV in epoch 1 and epochs 4 and 5 with the first observation in epoch 4.

The key result of this paper is that the putative magnetic cataclysmic variables CV2 and CV3 are clearly detected as erupting DNe. CV2 is seen to brighten (in epoch 5) in the STIS UV filter images. It is 2.7 mag brighter than it was in epoch 4. CV3 is seen in eruption in the second epoch in visible and near-infrared passband images taken with the *HST* WFPC2. It is 1.8 mag brighter in eruption than in quiescence. It is also seen in an intermediate brightness state (between eruption and quiescence) in blue and near-UV WFPC2 images in epoch 3. The rise time of CV3 in epoch 2 (about 2 days) is well in accord with field DN rise times.

4. ARE THE ERUPTING SYSTEMS MAGNETIC?

The *HST* spectra of CV1, CV2, and CV3 are presented in Grindlay et al. (1995); that of CV4 is given in Edmonds et al. (1999). He II emission with equivalent widths in the range 6–15 Å appears in the spectra of all four objects, as do strong Balmer lines. In particular, Edmonds et al. (1999) found, for CV2 and CV3, He II λ4686 equivalent widths of 11 and 15 Å, respectively. The Hβ equivalent widths of these same two objects are 32 and 59 Å, respectively.

The disks in all four objects are faint ($M \sim 8-10$). Edmonds et al. (1999) has carefully compared the disks and He II line ratios of CVs 1–4 with those of other cataclysmic systems. We refer the interested reader to that careful and exhaustive analysis, simply quoting here Edmonds et al.'s conclusions regarding CVs 1–3:

"They do not appear to be recent novae or nova-likes because of their faint disks (with extra evidence from their He II 4686 Å line ratios), nor do they appear to be dwarf novae because they have moderately strong He II lines. The final option is magnetic systems. To conclude, CVs 1–3 do not appear to be dwarf novae, but they could be DQ Her–type systems. A possible alternative to the DQ Her hypothesis is that some of the NGC 6397 CVs are old novae (possibly in deep hibernation between outbursts; see Shara et al. 1986)."

Figures 1 and 2 of this paper convincingly demonstrate that CV2 and CV3 are, in fact, erupting DNe despite their prominent He II emission. Intensive monitoring with *HST* is essential to determine if all the CV candidates in NGC 6397—and other globular clusters—eventually erupt as DNe.

The hibernation scenario of CVs (Shara et al. 1986) postulates that old novae eventually display DN-like outbursts. One old classical nova in the globular cluster M80 has been recovered (Shara & Drissen 1995) at DN-like luminosity, and one recent erupting classical nova in a globular cluster (of the giant elliptical galaxy M87) has been reported (Shara et al. 2004). CV2 and CV3 could be hibernating old novae, but we have, at present, no observational proof that they once underwent nova eruptions.

The suggestion of Edmonds et al. (1999) that the NGC 6397 CVs might be DQ Her–like magnetic systems (also known as intermediate polars, or IPs) might seem to be disproved with the observed DN eruptions of CV2 and CV3. However, there are a few well-documented cases of IPs that undergo DN eruptions, including GK Per, EX Hya, XY Ari, DO Dra, TV Col, HT Cam, and V1223 Sgr.

Most DNe show some He II emission (see, e.g., Patterson & Raymond [1985] for a compilation), so CV2 and CV3 are certainly not unique in this respect. A comparison of the He II and Hβ line strengths for the CVs in NGC 6397 and for field IPs is presented by Grindlay (1999). Both the line strengths and line ratios of He II and Hβ for CV2 and CV3 are comparable to those of other low mass transfer rate IPs, with EX Hya being a particularly good match.

Angelini & Verbunt (1989) have presented a model for DN-like outbursts in magnetic CVs, which they apply to TV Col and

TABLE 2
STIS Observations of NGC 6397

STIS Epochs	PI/Program Number	Clear CCD (s)	CCD LP (s)	Clear MAMA (s)	F25QTZ (s)	F25SRF2 (s)
4: 2003 Mar 28.....	Shara/8630	3 × 180	3 × 180	...	533, 865, 6 × 600	...
5: 2003 May 16.....	Shara/8630	3 × 180	3 × 180	3 × 1000	...	2 × 600, 883, 2 × 1021

Note.—Listed are the number of usable observations at each date, as well as their exposure times.

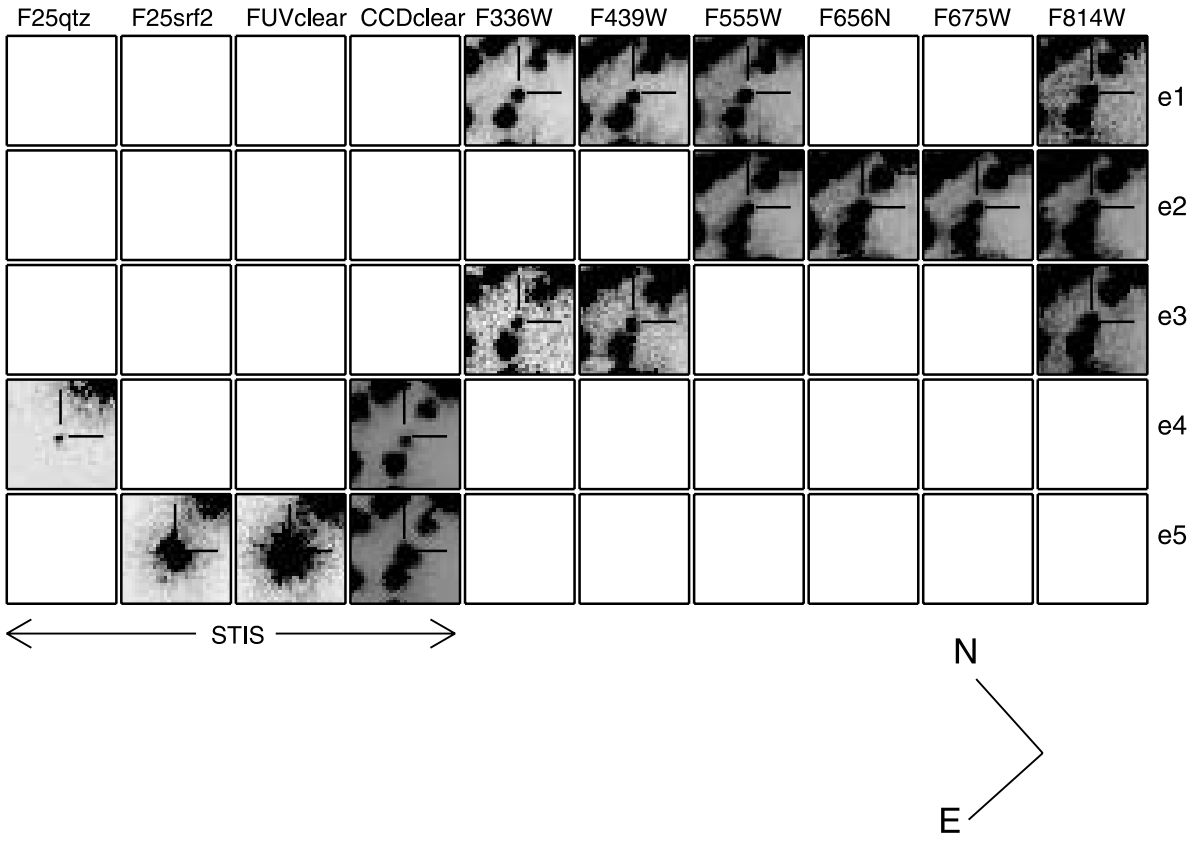

FIG. 1.—Matrix of *HST* images of the field of CV2 in NGC 6397. North and east are as indicated, and each postage-stamp-sized image is 1.″55 on a side. The top labels indicate the *HST* filter name and are roughly organized in increasing wavelength from blue (*left*) to red (*right*). CV2 is indicated in each image.

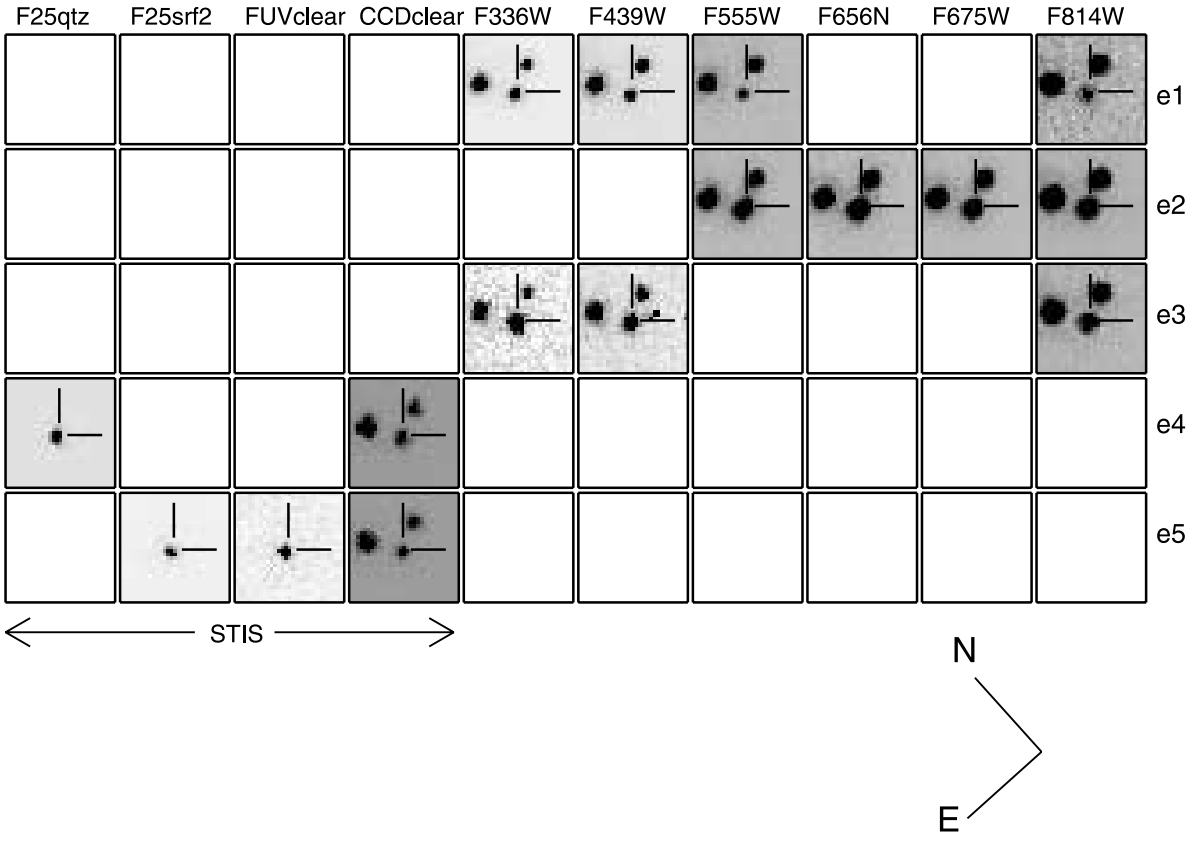

FIG. 2.—Same as Fig. 1, but for CV3.

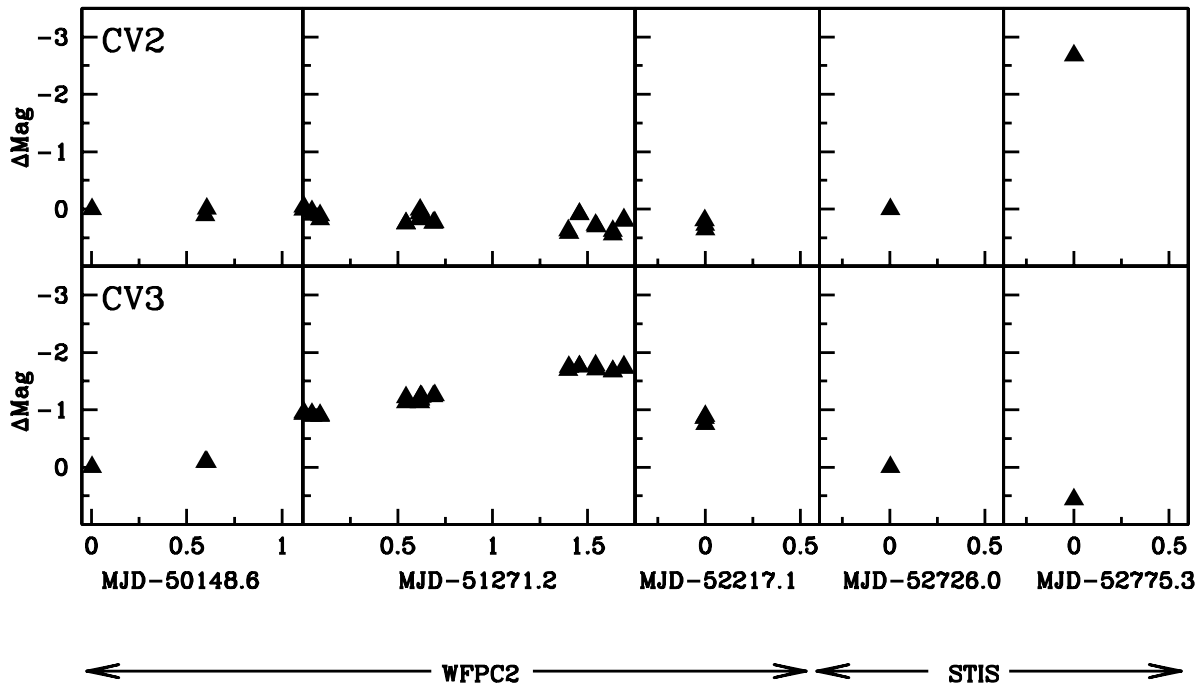

FIG. 3.—Five-epoch light curve for CV2 (*top*) and CV3 (*bottom*). The first three epochs show WFPC2 F814W photometry, while the last two show the STIS clear CCD data. The magnitudes are purely differential (see text), and the MJDs are indicated for each epoch.

GK Per. If the white dwarf in a CV has a strong magnetic field, the inner region of the accretion disk is disrupted. They found that disruption of the inner disk region leads to shorter outbursts and, for disk instabilities starting near the inner disk edge, to much longer intervals between outbursts.

The outbursts of most IPs tend to be rare, short, and of only moderate amplitude. As an example, Hellier et al. (1989) has noted that the EX Hya outbursts occur at ~2 yr intervals, last less than 4 days, and are of only ~3 mag amplitude. If the many globular cluster CV candidates identified by *Chandra* (Grindlay et al. 2001a) and *HST* (Knigge et al. 2002) are also IPs, then the remarkably small numbers of erupting DNe found by *HST* in globular clusters (Shara et al. 1996) can be explained. In particular, a population of even dozens of IPs will only occasionally show a DN near maximum light. Under this scenario we can predict that more of these CVs will eventually be seen to erupt if individual clusters are searched on dozens or hundreds of occasions.

5. CONCLUSIONS

We have observed NGC 6397 with *HST* during five separate epochs. Two of the four spectrographically confirmed CVs are observed to undergo dwarf nova (DN) eruptions with amplitudes of at least 1.8 and 2.7 mag. These eruptions were somewhat unexpected, as both objects display moderately strong He II λ4686 emission lines, generally associated with nonerupting, magnetic CVs. Some IPs in the galactic field are known to undergo DN eruptions. Thus, the detection of outbursts reported in this paper for two CVs in NGC 6397 is not necessarily inconsistent with these systems being magnetic. However, most field IPs do not show DN behavior, and those that do tend to erupt less frequently than nonmagnetic DNe. Thus, if a significant number of globular cluster CVs are IPs, this could help to explain the small number of eruptions detected in previous DN searches in globular clusters. The apparent rarity of erupting DNe in globular clusters with large CV candidate populations is reconciled if those CVs are infrequently erupting IPs.

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