

# A far-ultraviolet variable with an 18-minute period in the globular cluster NGC 1851\*

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Accepted; 2016 May 16. Received; 2016 March 21

## ABSTRACT

We present the detection of a variable star with an 18.05 minute period in far-ultraviolet (FUV) images of the globular cluster NGC 1851 taken with the Hubble Space Telescope (HST). A candidate optical counterpart lies on the red horizontal branch or the asymptotic giant branch star of the cluster, but it is statistically possible that this is a chance superposition. This interpretation is supported by optical spectroscopy obtained with HST/STIS: the spectrum contains none of the strong emission lines that would be expected if the object was a symbiotic star (i.e. a compact accretor fed by a giant donor). We therefore consider two other possibilities for the nature of FUV variable: (i) an intermediate polar (i.e. a compact binary containing an accreting magnetic white dwarf), or (ii) an AM CVn star (i.e. an interacting double-degenerate system). In the intermediate polar scenario, the object is expected to be an X-ray source. However, no X-rays are detected at its location in  $\simeq 65$  ksec of *Chandra* imaging, which limits the X-ray luminosity to  $L_X \leq 10^{32}$  erg s $^{-1}$ . We therefore favour the AM CVn interpretation, but a FUV spectrum is needed to distinguish conclusively between the two possibilities. If the object is an AM CVn binary, it would be the first such system known in any globular cluster.

**Key words:** Stellar Populations – Ultraviolet: stars – Globular Clusters: binaries

## 1 INTRODUCTION

Globular clusters (GCs) are well known for containing interacting binaries, such as low-mass X-ray binaries (LMXBs; Clark 1975; see Pooley 2010 for a recent review) and cataclysmic variables (CVs; Margon et al 1981; see Knigge 2011 for a recent review), as well as the remnants of binary interactions and collisions, such as Helium white dwarfs (HeWDs; Cool et al 1998), blue stragglers (BSs; Sandage 1953; Gilliland et al 1998) and millisecond pulsars (MSPs; Lyne et al 1987). As a result of the dynamical interactions taking place in dense star clusters, the populations of LMXBs and MSPs in GCs are significantly enhanced relative to the Galactic field (Clarke 1975; Camilo & Rasio 2005). Some theoretical simulations suggest that the numbers of CVs and HeWDs should also be enhanced in GCs (Di Stefano & Rappaport 1994; Davies 1997), though this effect is tempered by gravitational hardening (Shara &

Hurley 2006). Conclusive observational evidence of an enhancement or deficit of CVs and HeWDs has yet to be found, but the importance of dynamics in regulating the size of the CV populations in GCs has already been established (Pooley & Hut 2006).

The expected enhancement of compact interacting binaries is ultimately due to the high encounter rates in GCs (Pooley et al 2003; Heinke et al 2003; Bahramian et al 2013). The encounter rate is a function of the stellar density and velocity dispersion, and, since the stellar density in a GC is high compared to the field, interactions occur much more frequently. NGC 1851 has an encounter rate that is one of the ten largest among the Galactic GCs (Bahramian et al 2013). The large number of star-star, star-binary and binary-binary encounters results in the tightening of binaries, exchanges of stars into and out of binaries, and stellar collisions (Leigh & Geller 2012; Geller & Leigh 2015). It is expected that these interactions lead to the formation of interacting compact binaries containing accreting black holes, neutron stars and white dwarfs.

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Multiple examples of all three types of accreting compact binaries have already been discovered in GCs (Strader et al 2012; Chomiuk et al 2013; Maccarone et al 2007; Heinke et al 2003). However, all accreting WDs found to date in GCs are located in binary systems with main sequence or sub-giant donor stars (Knigge 2012). Theoretically, accreting WDs fed by red giants (“symbiotic stars”) or by low-mass WD donors (AM CVn stars) are also predicted, but no such systems have been discovered to date. Here, we report the discovery of the first strong candidate AM CVn star in a GC. This source, N1851-FUV1, is almost certainly an accreting WD binary system, so the main challenge is to determine the nature of its binary companion. We therefore begin by summarizing the main possibilities.

Interacting binaries composed of a WD and a Roche-lobe-filling main-sequence star are known as CVs (Warner 1995; Knigge et al. 2011). The orbital periods of these systems typically range from  $\simeq 75$  minutes to about a day. The WDs in CVs can have varying magnetic field strengths. The magnetically weakest (“non-magnetic”) CVs have accretion disks which extend all the way to the surface of the WD. Conversely, the magnetically strongest CVs, known as polars, have no accretion disks at all. In polars, the gas from the Roche-lobe-filling companion instead flows along the magnetic field lines to impact on the magnetic poles of the WD. Finally, CVs hosting WDs with intermediate magnetic fields, known as intermediate polars (IPs), contain truncated accretion disks whose inner edge lies well outside the WD radius (Patterson 1994). Material reaching the truncation radius then flows along the magnetic field lines and again lands on the WD’s magnetic poles. The impact region is hotter than the surrounding WD surface, and the magnetic poles are often not aligned with the rotational axis. As a result, the impact regions rotate in and out of view for many lines of sight, causing periodic variation in observed light curves that are associated with the WD spin (Patterson 1994).

The class of interacting binaries known as AM CVn stars are similar to CVs in that they contain a Roche-lobe-filling secondary that supplies material to an accretion disk around a WD primary. However, while the secondaries in CVs are typically main-sequence stars, those in AM CVns are degenerate or semi-degenerate objects, such as Helium WDs (HeWDs). Thus the evolutionary paths of AM CVn binaries are very different from that of the general CV population (Solheim 2010). AM CVn stars are extremely compact binaries, with orbital periods less than  $\simeq 65$  minutes (Solheim 2010). They are also relatively rare ( $\simeq 40$  are known to date; Levitan et al. 2015), and, without dynamical enhancement, only about one AM CVn would be expected to exist in each GC (Nelemans et al 2001). In addition, AM CVns are generally faint at optical wavelengths, and the detection of the orbital period can be difficult.

Symbiotic binaries are also generally accreting WD binary systems (although a rare subset may have neutron star or black hole primaries). However, the donor star in symbiotics is on either the red giant branch (RGB) or the asymptotic giant branch (AGB) (Kenyon 1990; Mikolajewska 2002). In the field, symbiotic binaries have periods of hundreds to thousands of days (Mikolajewska 2002). In a GC, tight binaries are expected to become tighter and wide binaries are expected to become wider through interactions with other stars (Heggie’s Law: Heggie 1975). Very wide binaries will eventually become detached through these interactions, so systems with periods greater than about 500 days should be extremely rare (Heggie 1975). Near misses or fly-by encounters may also result in highly eccentric orbits (Heggie & Rasio 1996). An orbital period shorter than about 100 days would then lead to mass ex-

change through Roche-lobe overflow or a common envelope phase. Thus, in a GC, symbiotic binaries would likely be limited to orbital periods in the range of  $\simeq 100 - 500$  days and may have highly eccentric orbits. Due to their long periods and the dominant contribution of the donor star at longer wavelengths, symbiotic stars will usually be missed by optical variability surveys. In fact, such systems can generally only be discovered by searches sensitive to emission lines (Kenyon 1990; Mikolajewska 2002), blue/UV excess and/or fast variability associated with accretion-induced flickering or the spin period of an accreting magnetic WD.

Here, we present observations of a short-period variable star (N1851-FUV1) with a significant blue excess in the core of the GC NGC 1851. Based on its X-ray, photometric and spectroscopic properties, we suggest that it is most likely an AM CVn star or perhaps an unusual X-ray weak IP. In Section 2 we present a summary of the data sets used and our analysis of the photometry, variability, spectra and X-ray observations. We discuss the possible interpretations and fits to the SED in Section 3 and present our conclusions in Section 4.

## 2 DATA AND ANALYSIS

We obtained FUV timeseries observations of the core of NGC 1851 using ACS/SBC on HST (GO program 10184). We supplemented these observations with archival WFPC2, ACS/WFC and STIS/FUV-MAMA images. These datasets are listed in Table 1 and described in Sections 2.1 and 2.2.

Our initial analysis suggested a symbiotic binary or an IP as the most likely scenarios for N1851-FUV1. In order to test these ideas, we obtained additional optical spectroscopy with HST and deep X-ray imaging with *Chandra*. The spectroscopy was obtained with the STIS/CCD/G430L instrument/detector/grating combination (GO program 13394) and is discussed in Section 2.3. The archival ((ObsID 8966) and new (ObsID 15735) X-ray observations are described in Section 2.4.

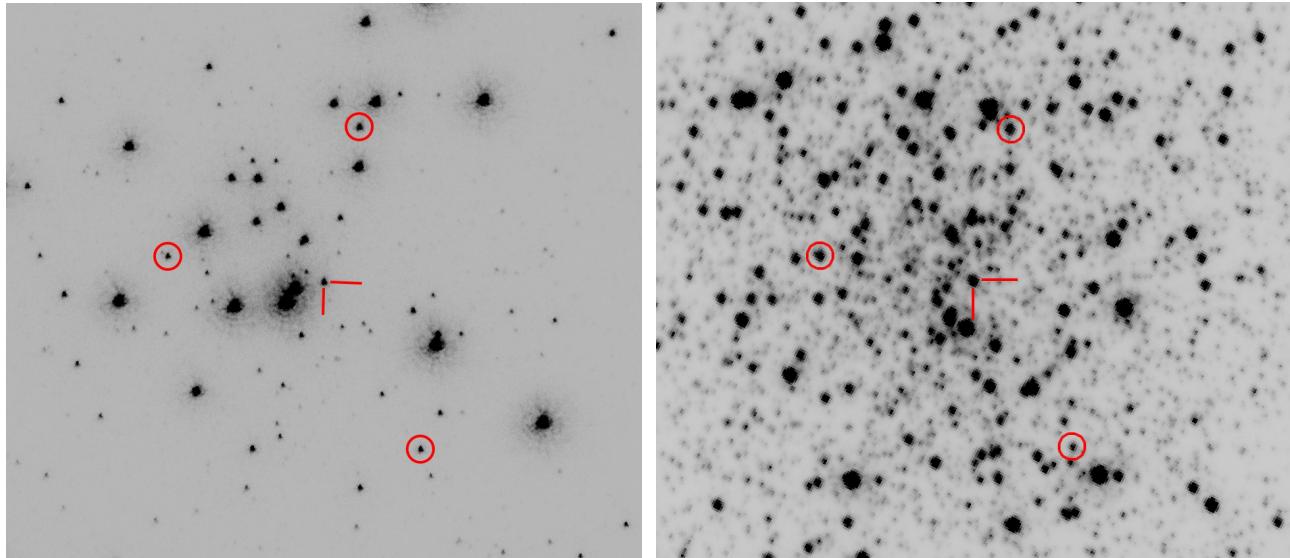
### 2.1 Optical and Ultraviolet Imaging

The WFPC2 PC images of the core of NGC 1851 contain about 50 stars per arcsec<sup>2</sup> (Figure 1, right panel). We therefore carried out point spread function (PSF) fitting photometry using ALLSTAR (Stetson 94) in order to minimize errors due to crowding. The ultraviolet images taken with the ACS/SBC and STIS/FUV-MAMA (Figure 1, left panel) require only aperture photometry, as the crowding in the ultraviolet is considerably reduced. The ACS/WFC photometry was taken from Milone et al (2008), who carried out PSF-fitting photometry as fully described in Anderson et al (2008). Our photometry for all ultraviolet-bright sources in the cluster core will be presented in a future paper (Zurek et al in prep).

In order to match sources across cameras, detectors and filters, we started by considering a small set of bright sources common among the filters and cameras. These bright sources are nearly exclusively hot horizontal branch stars, and we used their positions as fiducial points to calculate preliminary spatial transformations. These preliminary transformations were then used to extend the matching to all detected sources and to refine the transformations. We consider a source in one filter/camera to be matched with a detection in another filter/camera if the separation is at most one optical pixel or two far-UV pixels. Both optical detectors used have pixel sizes of  $\simeq 0.05''$ , while both far-UV detectors have pixel sizes of  $\simeq 0.025''$ .

**Table 1.** Hubble Space Telescope imaging observations

Proposal #	Date of Observations	Instrument	Filter	Number of Exposures	Total Exposure time (sec)
GO-6095	1995-10-05	WFPC2	F218W	2	1600
GO-6095	1995-10-05	WFPC2	F439W	4	360
GO-6095	1995-10-05	WFPC2	F555W	2	46
GO-5696	1996-04-10	WFPC2	F336W	4	3600
GO-5696	1996-04-10	WFPC2	F439W	3	1200
GO-7363	1999-03-24	STIS/FUV-MAMA	F25QTZ	8	11000
GO-10775	2006-05-01	ACS/WFC	F814W	1	20
GO-10775	2006-05-01	ACS/WFC	F606W	1	20
GO-10184	2006-08-15	ACS/SBC	F140LP	273	24390
GO-11975	2009-05-02	WFPC2	F170W	3	2100
GO-11975	2009-05-02	WFPC2	F255W	3	3700
GO-11975	2009-05-02	WFPC2	F336W	4	2440
GO-11975	2009-05-02	WFPC2	F555W	4	141



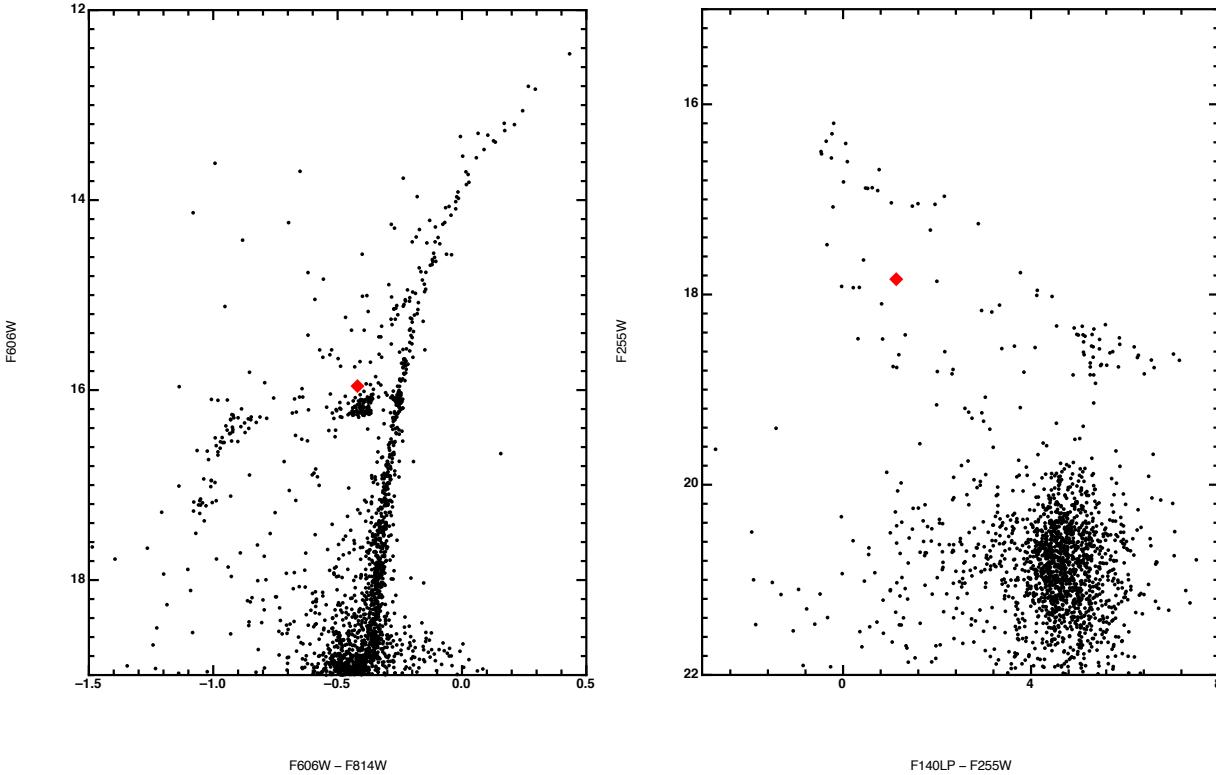
**Figure 1.** The central 11'' of NGC 1851 (North up and East left) with the FUV image on the left and the optical (F555W) image on the right. The position of the variable object is identified by the red tick marks. We have circled 3 stars in common between the two images to assist in identifying stars in common as the stellar density is very high in this core collapsed cluster. The field of view is 11'' in both North-South and East-West.

Our photometric measurements for N1851-FUV1 are listed in Table 2 and shown in the context of the relevant cluster colour-magnitude diagrams (CMDs) in Figure 2. In the left panel, we show the optical V vs V-I CMD ( $V=F606W$  &  $I=F814W$ ) constructed from the photometric catalog of Milone et al. (2008), where  $V = m(F606W)$  and  $I = m(F814W)$ . In the right panel, we show our matched ultraviolet NUV vs FUV-NUV CMD, where  $FUV = m(F140LP)$  and  $NUV = m(F255W)$ . In both CMDs, the location of N1851-FUV1 is indicated with a large red diamond symbol. The key point to note is that N1851-FUV1 appears blue in the ultraviolet CMD, but red in the optical CMD, indicating that it must be composed of both a hot and a cool component.

The crowding in the core of NGC 1851 is quite severe, so it is important to consider the possibility that the unusual location of N1851-FUV1 in the UV and optical CMDs is due to a chance superposition of unrelated hot and cool objects in the cluster. We therefore estimated the probability of such a chance superposition

happening via a simple Monte Carlo simulation based on the actual number and locations of the relevant sources in our far-UV field of view. Specifically, we took the positions of all far-UV sources brighter than the main sequence (200 sources), as well as the positions of all sources that are at least as bright and red as the red horizontal branch in the optical CMD (205 sources). We then created a mock data set by randomly shifting the positions of the UV and red sources independently of each other, by amounts much greater than our matching radius, but much smaller than the field of view. Finally, we recorded the number of matches within this mock data set, adopting the same matching radius as for the real data. We repeated this simulation hundreds of times to estimate the probability of finding at least one chance match in our data. The resulting probability is  $p \simeq 8\%$ .

We also looked into how often a randomly placed source matches with any object in the optical catalog of sources (not re-



**Figure 2.** The F606W/F814W CMD (Left Panel) from the photometric catalog of Milone et al. The location of the variable source is marked with a red diamond. It is located just above the red horizontal branch clump. The F255W/F140LP CMD (Right Panel) from our photometric reductions. The location of the variable source is marked with a red diamond. It is in the same locus as the bright blue straggler stars below the blue end of the horizontal branch.

stricting ourselves to red giants). Globally the value is  $\sim 7\%$  and within about 10 arcseconds of the cluster center the value is  $\sim 10\%$ .

These probabilities are not negligible and may even be somewhat higher near the cluster center where N1851-FUV1 is located. Thus the possibility that the anomalous colours of N1851-FUV1 could be due to a chance superposition must be seriously considered. The probability that *one specific* UV-bright object – e.g. selected on the basis of exhibiting an 18-min periodic signal – should suffer a chance superposition with a red giant is, of course, much smaller, at  $p \simeq 0.3\%$ . However, this estimate relies even more on *a posteriori* statistics and should therefore be enjoyed responsibly.

It is worth emphasizing that our estimated chance coincidence probabilities are officially p-values: they represent the probability of finding as good a match as observed under the null hypothesis that there is no physical association (and  $1 - p$  is not the probability that there is an association). In order to explore this issue further, we have therefore examined the possibility that N1851-FUV1's optical counterpart is a chance superposition by examining the distribution of separations between all FUV sources and optical counterparts in our matched photometry (Figure 3). The vertical line in this figure is our maximum allowed separation for matches (in ACS/SBC pixels - see above). The arrow indicates the separation between N1851-FUV1 and its optical counterpart, which lies quite far in the tail of the distribution. We also inspected the ACS/SBC and WFC3/UVIS images in the vicinity of N1851-FUV1 visually. By eye, there appears to be a shift of about 0.3 WFC3/UVIS pixels between the center of flux in the ACS/SBC image and the WFC3/UVIS images. Thus, overall, there is at least circumstantial

evidence to indicate that N1851-FUV1 is, in fact, a chance superposition.

## 2.2 Time-Resolved Far-Ultraviolet Photometry

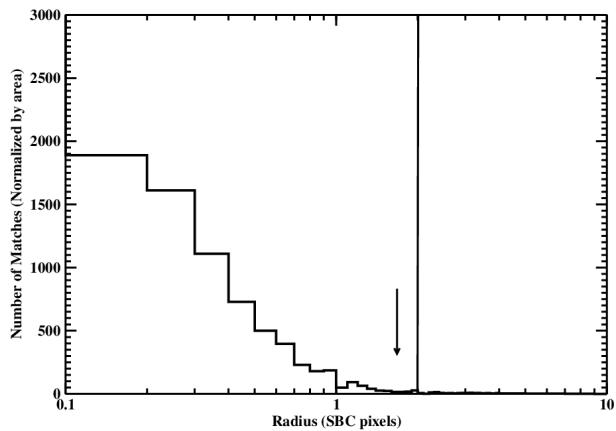
The ACS/SBC data are well suited to a search for short timescale variations among the far-UV sources. A full discussion of all far-UV variable sources will be presented in a future paper (Zurek et al., in prep). There were 273 90-second exposures taken over 3 visits of 4 HST orbits (a total of 12 orbits), spanning about 8 days from the first visit to the third. The second visit was taken 2 days after the first visit, with the third taking place another 6 days later.

The fractional RMS variability for N1851-FUV1 is small ( $< 5\%$ ), and the star was not initially classified as a variable on this basis. However, we also carried out a search for periodic variability for all the bright sources, by calculating the Lomb-Scargle power spectrum for their light curves. The power spectrum for N1851-FUV1 is shown in Figure 4 and reveals a clear signal at  $f = 79.79 \text{ d}^{-1}$ . This corresponds to a period of  $P = 18.05 \text{ min}$ . The far-UV light curve phased on this period is shown in Figure 5; for comparison, we also show a simple sinusoid with 0.06 mag amplitude. The precision of our period estimate is limited to about 0.1 minutes because of aliasing (see inset of Figure 4).

We checked all other bright far-UV sources, but found none with the same period. This argues against an instrumental origin of the signal. The ultra-compact X-ray binary (4U 0513-40) has a 17-minute period (Zurek et al. 2010), but is located  $\sim 6.6$  arcseconds from this source (about 150 times the full-width-half-maximum of the PSF).

**Table 2.** N1851-FUV1 magnitudes

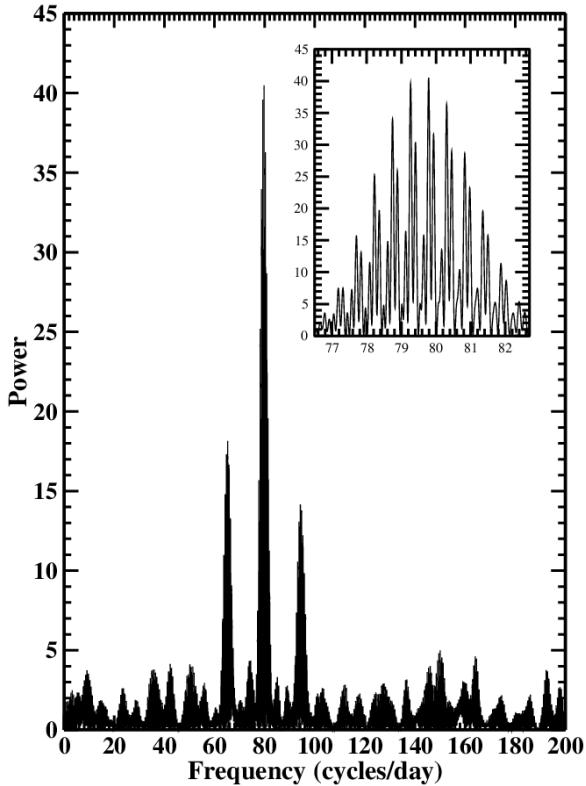
Filter	Pivot Wavelength (Å)	Year	N1851-FUV1 (ST mags)
F814W	8058.8	2006	16.378
F606W	5921.6	2006	15.958
F555W	5442.9	1995	16.089
F555W	5442.9	2009	16.067
F439W	4312.1	1995	15.963
F439W	4312.1	1996	16.061
F336W	3359.5	1996	16.847
F336W	3359.5	2009	16.873
F255W	2600.4	2009	17.839
F218W	2204.4	1995	18.135
F170W	1831.2	2009	18.079
F25QTZ	1595.7	1999	18.971
F140LP	1528.0	2006	18.886



**Figure 3.** The distribution of matches between the far-ultraviolet and the optical as a function of separation. We indicate our radius (solid vertical line) of acceptance at 2 ACS/SBC pixels. We indicate with the arrow the separation between the FUV and optical components of N1851-FUV1.

### 2.3 Optical Spectroscopy

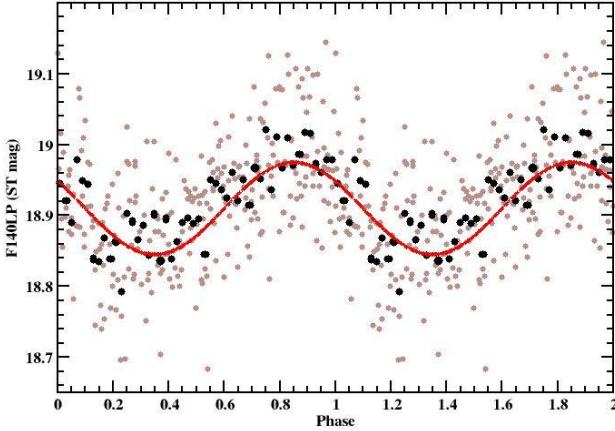
In order to test whether the hot and cool components contributing to the colours of N1851-FUV1 are physically related, we obtained an optical spectrum of N1851-FUV1 with the STIS/CCD/G430L instrument/detector/grating combination on HST. If the system is a close binary consisting of a hot WD and a cool giant, the giant's wind will be irradiated by the ionizing flux of the WD. This should produce extremely strong emission lines (such as [OIII] and the Balmer recombination lines; Kenyon 1990), as is seen, for exam-



**Figure 4.** The power spectrum of the FUV variable source. The central and strongest peak corresponds to 79.79 cycles/day which is 18.05 minutes. The smaller peaks on either side are the aliases of the stronger central peak. The inset shows a magnification of the strongest peak. The multiple peaks are due to aliasing. The 3 visits were separated by 2 days between visits 1 and 2 and 6 days between visits 2 and 3.

ple, in essentially all symbiotic binaries (Munari & Zwitter 2002). The classification of a symbiotic binary depends on the detection of emission lines (Kenyon 1990; Mikolajewska 2002) and the most common emission lines would be within the spectral region covered in Figure 6. In such a symbiotic scenario, the  $\simeq 18$  min signal would have to be associated with the spin period of an accreting magnetic WD.

However, the spectrum, shown in Figure 6, clearly lacks any



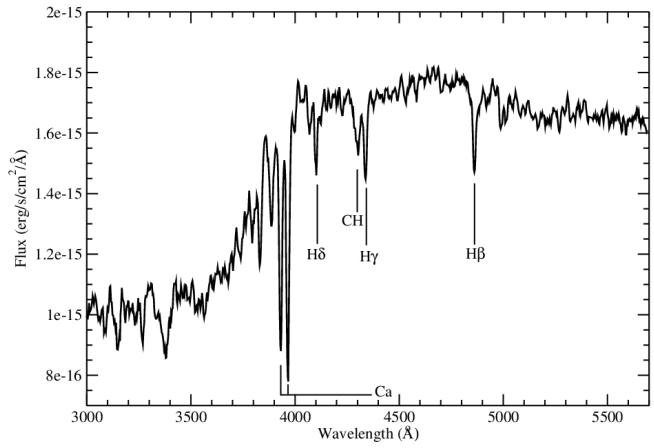
**Figure 5.** The phased light curve of the FUV variable source. The data between the phase of 0 and 1 is duplicated between phases 1 and 2. The data has been phased around the 18.05 minute period. All 273 individual measurements are plotted as the faint dots. The black solid dots are the average values in phase bins of 0.02. A sine wave with an amplitude of  $\sim 0.06$  mag has been fit to the data to guide the eye.

emission lines. If emission lines existed as in typical symbiotic binaries (Munari & Zwitter 2002) we would have easily detected them. Instead, the spectrum is consistent with the expected SED of a single, cool star with  $T_{\text{eff}} \simeq 5200$  K. We do note that a few symbiotic binaries have been seen to enter a quiescent period where the emission lines are absent or very weak (Munari & Zwitter 2002), indicating a change in the system. We therefore conclude that the absence of emission lines in our data does not entirely preclude a symbiotic nature for the system, but certainly means that we cannot classify it as such.

## 2.4 X-ray

The Chandra X-ray Observatory (CXO) observed NGC 1851 on three occasions. First, on 2008 Apr 04 for an exposure time of 18.8 ks (ObsID 8966); second, on 2015 Feb 04, for an exposure time of 19.8 ks (ObsID 15735); and third, on 2015 Feb 07, for an exposure time of 27.7 ks. The total combined exposure time was just over 66 ks.

All data were taken in timed exposure mode with the aimpoint on the ACIS S3 chip and telemetered in “Very Faint” mode. We reprocessed all of the data with the Chandra Interactive Analysis of



**Figure 6.** The HST/STIS/G430L spectra of N1851-FUV1. We have indicated the  $H\beta$ ,  $H\gamma$ , and  $H\delta$  which are all in absorption. There is clearly no optical emission lines visible. The absorption feature CH also known as the g-band is a clear indication of the temperature as this feature is only seen in stars of spectral types G and K.

Observations (CIAO) software version 4.5 (Fruscione et al 2006) using the latest calibration files (CALDB 4.5.1). Periods of background flaring were searched for, but none were found.

N1851-FUV1 is located  $\simeq 10''$  from the bright X-ray source 4U 0513–40 and  $\simeq 1.''5$  from one of the brighter of the low-luminosity X-ray sources in the globular cluster. We therefore applied the subpixel event repositioning (SER) algorithm of Li et al (2004) and considered only split-pixel events, i.e. events whose charge clouds that were spread over multiple pixels. Such events can be located more precisely than single-pixel events. This improves the already sharp angular resolution of Chandra at the cost of  $\simeq 25\%$  of the total counts.

We estimated the number of X-ray photons that may be associated with N1851-FUV1 by counting all events in the energy range 0.5 keV - 6.0 keV within a  $0.''5$  radius aperture centered on its expected location. For this purpose, the X-ray images were registered onto the optical/UV frames by a simple boresight correction determined from 3 bright X-ray sources with optical/UV counterparts. We then estimated the expected number of background events in this aperture by placing identical apertures at roughly the same distance from 4U 0513–40, while also avoiding other real X-ray sources. We find no evidence for a statistically significant excess associated with N1851-FUV1 in any of the three individual images, nor in the combined data. Specifically, our best estimate for the excess number of counts in the combined data is  $6.8 \pm 4.6$ .

The absence of X-ray emission is primarily a constraint on

the IP scenario for N1851-FUV1. We therefore assume a 15 keV bremsstrahlung model (e.g. Patterson 1994) to convert our measured count rate into an upper limit on the X-ray luminosity of the system. Adopting a cluster distance of  $d = 12.1$  kpc and a foreground neutral hydrogen column  $N_{\text{H}} = 4 \times 10^{20} \text{ cm}^{-2}$ , we obtain  $3\sigma$  upper limits on the unabsorbed X-ray luminosity of  $L_{\text{X},0.5-6} < 5 \times 10^{31} \text{ erg s}^{-1}$  (between 0.5 keV and 6 keV) or, equivalently,  $L_{\text{X},2-10} < 5 \times 10^{31} \text{ erg s}^{-1}$  (between 2 keV and 10 keV). The corresponding limit on the bolometric X-ray luminosity is  $L_{\text{X,bol}} < 10^{32} \text{ erg s}^{-1}$ .

### 3 DISCUSSION

Our analysis of all of the available observations of N1851-FUV1 has led to the following set of constraints on the system:

- N1851-FUV1 is a bright far-UV source in the cluster core that exhibits periodic variability with  $P = 18.05$  min and an amplitude of  $\approx 6\%$ ;
- its position matches that of a star on the red or asymptotic giant branch in the cluster, but there is a non-negligible possibility that this match is the result of a chance superposition of two unrelated objects;
- its optical spectrum contains no detectable emission lines;
- its X-ray luminosity is  $L_{\text{X},2-10} < 5 \times 10^{31} \text{ erg/s}$  ( $3\sigma$ ).

There are only a few classes of UV-bright stars that are capable of producing such a fast periodic signal: ZZ Ceti stars (i.e. pulsating WDs), pulsating subdwarf B stars (sdBs), symbiotic binaries, IPs and AM CVn (accreting double WD) binaries. The symbiotic scenario is the only one in which the blue far-UV and the red optical sources are physically related. However, it is unlikely given the absence of emission lines in the optical spectrum, which are a defining feature of symbiotic systems (Munari & Zwitter 2002). ZZ Ceti stars and sdBs are also ruled out for N1851-FUV1: even a WD near the upper edge of the instability strip (at  $T_{\text{WD}} \approx 12,500$  K) would be more than 2 mag fainter than observed and a pulsating sdB would be  $\sim 3$  magnitudes brighter in F140LP as it would be among the hottest horizontal branch stars (Heber 2009). This leaves only the IP and AM CVn scenarios, which we now discuss in turn. Note that in both of these scenarios, the astrometric match of the UV source to the red giant would probably have to be a chance superposition. If the two objects were physically associated, we would again expect to see optical emission lines due to the photoionization of the giant's envelope (as in the case of symbiotic binaries).

#### 3.1 N1851-FUV1 as an Intermediate Polar

As explained in Section 1, intermediate polars are accreting WD binary systems composed of a Roche-lobe-filling main sequence star and a magnetic WD. In IPs, the accretion onto the WD takes place via an accretion disk that is truncated by the magnetic field of the white dwarf. The gas from the inner edge of the accretion disk is then channelled along field lines onto the magnetic poles of the WD, producing X-ray and UV emission at and near the impact point. Since the rotational and spin axes of the WD are generally not aligned, this emission is modulated on the WD spin period. Both the period and amplitude of the N1851-FUV1's far-UV variability can be explained quite naturally in an IP scenario.

Figure 7 shows a fit to the SED of N1851-FUV1, in which the cool component is represented by a model atmosphere with

the cluster [Fe/H] (Castelli & Kurucz 2003), and the hot component is modelled as a blackbody. The residuals around this fit are  $\approx 0.09$  mag, and the best fit parameters for the hot component are  $T_{\text{hot}} \approx 12,000$  K,  $R_{\text{hot}} \approx 0.4 R_{\odot}$ . These are reasonable numbers for the inner accretion flow in an IP. The corresponding parameters for the cool component are  $T_{\text{cool}} \approx 5,200$  K,  $R_{\text{cool}} \approx 9.5 R_{\odot}$ . Again, these are sensible values for a red giant in NGC 1851. We also show in Figure 7 the UV spectrum of FO Aqr, a well-known field IP with a spin period of  $P_{\text{spin}} \approx 18$  min, scaled to the distance and reddening of the cluster. This spectrum lies reasonably close to the UV photometry of N1851-FUV1. We conclude that an IP scenario can plausibly explain the UV spectrum and variability of N1851-FUV1.

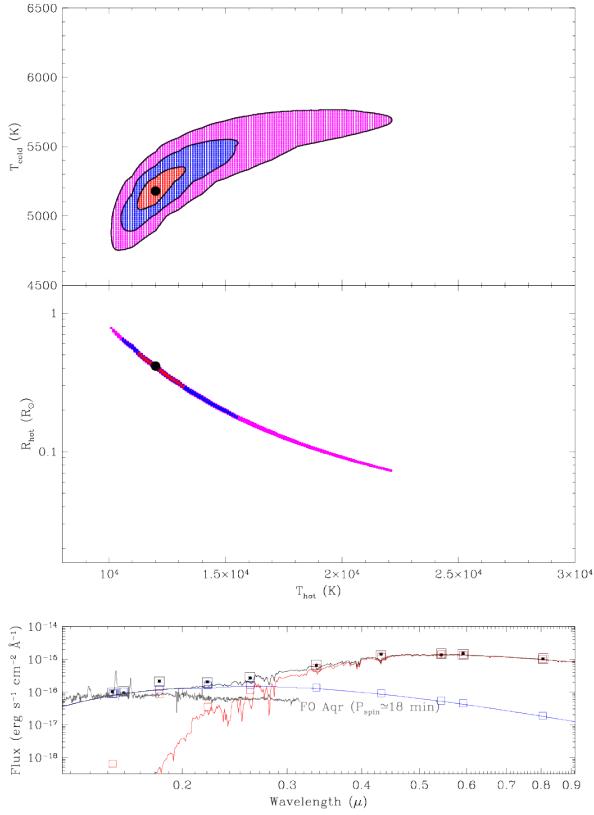
However, our non-detection of the system in X-rays is a significant challenge to an IP model. As discussed in Section 2.4, adopting a bremsstrahlung X-ray spectrum typical of IPs, this non-detection implies an upper limit of  $L_{\text{X},2-10} < 5 \times 10^{31} \text{ erg s}^{-1}$ . Such a low level of X-ray luminosity is unusual for IPs. This is illustrated in Figure 8, which compares the period and X-ray luminosity of N1851-FUV to the spin periods and X-ray luminosities of known field IPs. X-ray fluxes for field IPs were taken from Yuasa et al. (2010), where available, and from Patterson (1994) otherwise. Distances and spin periods were taken from Patterson (1994), where available, and from Pretorius & Mukai (2014 and personal communication) otherwise.

Only three field IPs have X-ray luminosities that may be as low as that of N1851-FUV1, and all of these have extremely short spin periods,  $P_{\text{spin}} < 100$  seconds. As discussed by Patterson (1994), the X-ray weakness of the fastest rotators may be due to the smaller potential difference between the inner disk edge and the WD surface, as well to a different accretion shock geometry in these systems. Such arguments cannot explain the X-ray weakness of N1851-FUV1, however, given its implied spin period of  $P_{\text{spin}} \approx 1080$  seconds.

#### 3.2 N1851-FUV1 as a double degenerate AM CVn star

AM CVn stars have orbital periods in the range 5 min - 65 min. The period of N1851-FUV1, at  $\approx 18$  min, lies well within this range. Moreover, in an AM CVn scenario, the lack of an X-ray detection is actually expected, since most of these systems are X-ray weak. This is illustrated in Figure 9, which compares the upper limit on  $L_{\text{X,bol}}$  for N1851-FUV1 with the bolometric X-ray luminosities for a sample of AM CVn stars compiled by Ramsay et al. (2006). All but one of the systems in this sample lie below the upper limit on N1851-FUV1.

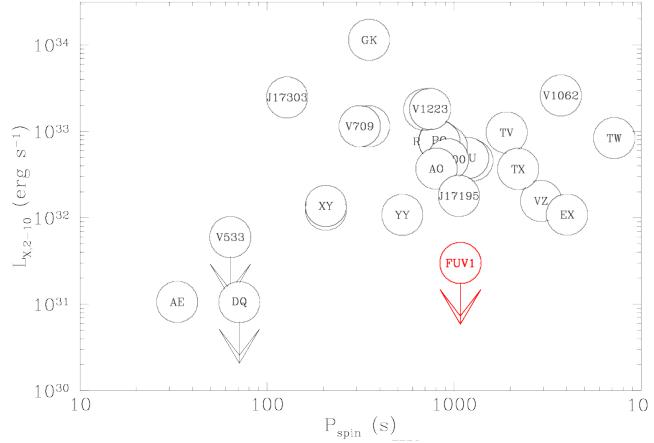
The variability amplitude seen in N1851-FUV1 is  $\approx 0.06$  magnitudes. This is about  $\sim 10$  times larger than that of the orbital signal seen in optical light curves of HP Lib, an AM CVn star with a similar orbital period of  $P_{\text{orb}} \approx 18$  min (Patterson et al 2002; Roelofs et al 2007). However, HP Lib also displays "superhumps", which are thought to be associated with an eccentricity of the accretion disk. The superhump period,  $P_{\text{sh}}$  is only a few percent longer than  $P_{\text{orb}}$ , but the amplitude of this signal in HP Lib is much larger, at least 0.03 mag. (Patterson et al 2002). Similarly, AM CVn itself has an orbital period of  $P_{\text{orb}} \approx 17.5$  min and displays optical variability amplitudes of  $\approx 0.005$  mag on  $P_{\text{orb}}$  and  $\sim 0.01$  mag on  $P_{\text{sh}}$  (Skillman et al. 1999). In the slightly longer period system CP Eri ( $P_{\text{orb}} \approx 28.6$  min), the superhump signal has an amplitude in excess of  $\sim 0.1$  magnitudes (Armstrong et al. 2012). If N1851-FUV1 is an AM CVn star, this suggests that the 18-min signal we have detected might actually be due to superhumps, rather than to a true



**Figure 7.** A two-component model fit to the SED of N1851-FUV1 representing an IP scenario. The cool component is modelled as a stellar model atmosphere, while the hot component is modelled as a blackbody (both components are modelled using SYNPHOT). The top panel shows the best fit (black dot) and 1, 2 and 3  $\sigma$  contours in the parameter plane defined by the temperature of the cool component and the accretion rate. The middle panel shows the constraints on inclination and accretion rate. In the bottom panel, the predicted spectrum and photometry for the best-fit cool component are shown in red, the predicted spectrum and photometry for the best-fit hot component are shown in blue, and the combined best-fit spectrum and photometry are shown in black (solid curves and open squares). The observed photometry for N1851-FUV1 is shown by the black dots (which are mostly located near the center of the black squares). We also show an example blue/ultraviolet spectrum of the IP (FO Aqr), which has a spin period similar to the period of N1851-FUV1.

orbital signal. It is also worth noting, however, that the variability amplitudes tend to increase towards the blue. For example, AM CVn's variability amplitude rises to  $\sim 0.03$  in the FUV (Solheim et al 1997), and multi-channel optical observations of the ultra-short period system ES Ceti ( $P_{\text{orb}} \simeq 10$  min) with ULTRACM also show larger amplitudes at shorter wavelengths (Copperwheat et al. 2011). We therefore conclude that the amplitude of the 18-min signal in N1851-FUV is compatible with an AM CVn interpretation.

The AM CVn model is also consistent with the UV flux and the overall SED of N1851-FUV1. This is illustrated in Figure 10, which again shows a two-component model fit to the SED. We once again fit the cool component with the stellar model atmosphere spectrum appropriate for a red giant, but the hot component is now described by a multi-temperature blackbody disk. For the purpose of this fit, the disk is assumed to asymptotically follow the standard  $T_{\text{eff}} \propto R^{-3/4}$  effective temperature distribution, the accreting WD is assumed to have a mass of  $M_1 = 0.7 M_{\odot}$  and a radius of



**Figure 8.** X-ray luminosity vs white dwarf spin period for the known intermediate polars (Yausa et al 2010; Patterson 1994; Pretorius & Mukai 2014). The X-ray luminosity limit and observed period for N1851-FUV1 are shown in red. It is clearly much less luminous than sources with a comparable period. Sources with a comparable X-ray flux to N1851-FUV1 all have spin periods more than an order of magnitude smaller. The labels in the symbols identify the objects shown (e.g. AE = AE Aqr).

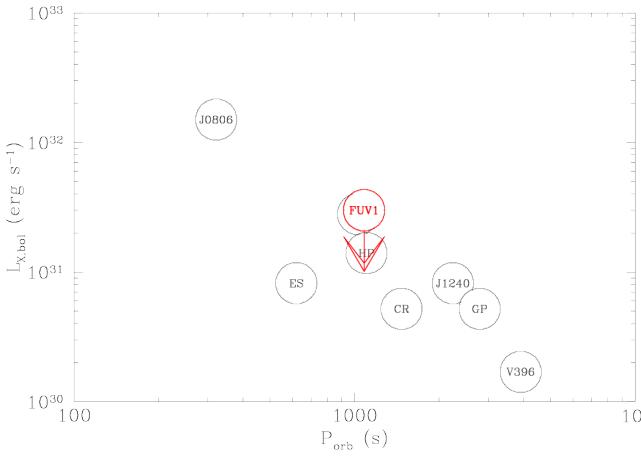
$R_1 = 8 \times 10^8$  cm, the mass ratio is taken to be  $q = M_2/M_1 = 0.1$ , and the accretion disk is assumed to extend all the way to the last non-intersecting orbit around the accretor,  $R_{\text{d/a}} = 0.6/(1+q)$  (Warner 1995). The inclination of the disk with respect to the observer is a free parameter in this model, subject to the constraint that  $\cos i < 1$ . The best fit parameters for the cool component in this case are given by  $T_{\text{cool}} \simeq 5700$  K and  $R_{\text{cool}} \simeq 7.6 R_{\odot}$ . The best-fitting disk parameters are  $\dot{M}_{\text{acc}} \simeq 10^{-9} M_{\odot} \text{ yr}^{-1}$  and  $\cos i \simeq 1$ . With residuals of  $\simeq 0.12$  mag, formally, this fit is slightly worse than that shown in Figure 7, in which the hot component was a single temperature blackbody. However, both residuals are comparable to the level of variability seen in the UV data.

We also show Figure 10 the UV spectrum of HP Lib, a well-known AM CVn star with an orbital period of  $P_{\text{orb}} \simeq 18$  min. Again, this lies quite close to the data in the FUV and also to our model for the hot component. We therefore conclude that the AM CVn model is a viable explanation for N1851-FUV1: it accounts for the 18 min periodic signal, the UV flux level and spectrum, and for the overall SED (albeit by invoking a chance superposition with a red giant to explain the cool component that dominates in the optical region). Unlike the IP scenario, it also naturally accounts for the X-ray weakness of the system. Based on all this, the AM CVn scenario is our preferred interpretation for N1851-FUV1.

#### 4 CONCLUSION

We have presented the discovery N1851-FUV1, an 18 min FUV variable star in the globular cluster NGC 1851. The position of this hot FUV source coincides with a star on the red or asymptotic giant branch in the optical region. However, there is a non-negligible chance that this astrometric match could be the result of a chance superposition. An optical spectrum shows none of the emission lines that might be expected if the two components were physically associated. This makes the obvious interpretation of N1851-FUV1 as a symbiotic star in the cluster unlikely.

If the cool component is unrelated to N1851-FUV1, there are



**Figure 9.** X-ray luminosity vs orbital period for known AM CVn binaries (Ramsay et al 2014). The X-ray luminosity limit and observed period for N1851-FUV1 are shown in red. The position of N1851-FUV1 is consistent with the location of known AM CVn in this diagram. The labels in the symbols identify the objects shown (e.g. ES = ES Cet).

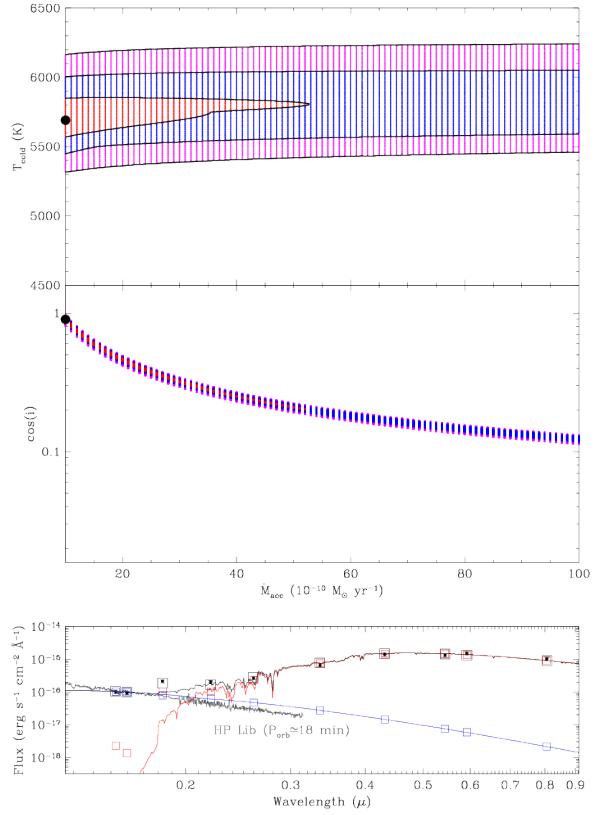
two other obvious interpretations. First, the system may be an IP, i.e. an accreting magnetic WD that is fed by a Roche-lobe-filling main sequence donor star. In this scenario, the 18 min periodic signal represents the spin period of the WD. Second, the system may be an AM CVn star, i.e. a double degenerate interacting binary in which both the accretor and the donor are WDs. In this case, the 18 min signal is the orbital period of the system.

Both the IP and AM CVn models can account for the observed periodic signal, the UV flux level and the overall SED of the system. However, no X-rays are detected from N1851-FUV1 in  $\simeq 66$  ksec of exposure with *Chandra*, which implies  $L_{X,2-10} < 5 \times 10^{31}$  erg s $^{-1}$ . This is inconsistent with the observed X-ray luminosities of field IPs with comparable spin periods. It is, however, consistent with the X-ray luminosities of field AM CVn stars. Based on this, we favour the latter scenario for N1851-FUV1, making it the first strong AM CVn candidate known in any globular cluster.

In order to discriminate definitively between the IP and AM CVn models, a FUV spectrum is required. If N1851-FUV1 is an IP, the C IV and He II lines will be preferentially formed in the optically thin accretion curtain surrounding the WD and will therefore be in emission. By contrast, the same transitions will be in absorption if the system is an AM CVn star, since in this case the lines will be formed in the optically thick disk. The presence or absence of a strong Ly  $\alpha$  feature would, of course, also favour the IP or AM CVn scenario, respectively.

## ACKNOWLEDGMENTS

Support for program GO-10184 and GO-13394 was provided by NASA through a grant from Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555. All of the data presented in this paper were obtained from the Mikulski Archive for Space Telescopes (MAST). ST ScI is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555. We thank Jeno Sokoloski for many helpful conversations. We are also grateful to Retha Pretorius and



**Figure 10.** A two-component model fit to the SED of N1851-FUV1 representing the AM CVn scenario. The cool component is modelled as a stellar model atmosphere, while the hot component is assumed to arise from a multi-temperature accretion disk that locally emits as a blackbody. The top panel shows the best fit (black dot) and 1, 2 and 3  $\sigma$  contours in the parameter plane defined by the temperature of the cool component and the accretion rate. The middle panel shows the constraints on inclination and accretion rate. In the bottom panel, the predicted spectrum and photometry for the best-fit cool component are shown in red, the predicted spectrum and photometry for the best-fit hot component are shown in red, and the combined best-fit spectrum and photometry are shown in black (solid curves and open squares). The observed photometry for N1851-FUV1 is shown by the black dots (which are mostly located near the center of the black squares). We also show an example blue/ultraviolet spectrum of an AM CVn (HP Lib) with an orbital period similar to the period of N1851-FUV1.

Koji Mukai for helpful discussions regarding IPs and for providing distances for some of the systems shown in Figure 7.

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