Magnetic CVs in Globular Clusters

Jonathan E. Grindlay

Harvard-Smithsonian Center for Astrophysics, Cambridge, MA, U.S.A.

Abstract. Cataclysmic variables (CVs) are tracers of dynamical evolution in globular clusters. A significant sample has been found by the relatively shallow Hα surveys conducted with HST thus far in just three globulars: NGC 6397 (3), NGC 6752 (2), and ω-Cen (2). These are identified with the low luminosity x-ray sources discovered in these globulars with similarly moderate-depth ROSAT surveys. Follow-up spectroscopy of the initial 3 CV candidates in NGC 6397 with the FOS on HST suggests they may be magnetic CVs of the intermediate polar (IP) type, and follow-up deep imaging with both HST and ROSAT yield a 4th confirmed and 5th strong candidate CV near the center of this collapsed core cluster. The optical vs. x-ray properties of the 4 confirmed IP candidates in NGC 6397 are compared with disk IPs, and arguments for and against this interpretation are presented. The possible strong excess of magnetic CVs in globulars will be tested with much deeper HST/AXAF surveys.

1. Introduction

With the advent of high resolution imaging telescopes in space, the cores of globular clusters have become available for studies of compact binaries (CBs), defined (here) as short period (<1 d) systems containing a compact object (white dwarf (WD), neutron star (NS) or black hole). CBs are observable as cataclysmic variables (CVs), low mass x-ray binaries (LMXBs), and millisecond pulsars (MSPs) and play a particularly important role in globulars: as the most compact (hard) binaries, they are not only the survivors of “binary burning” which dynamically heat the cluster cores while destroying wide binaries, but are the saviors of the cluster against complete core collapse (cf. Hut et al 1992). CVs are likely to be dominant, since white dwarfs (WDs) should vastly outnumber neutron stars (NSs) in clusters: for a Salpeter IMF with differential mass index ~2.4, the WD progenitors (~8 M⊙) must exceed those for NSs by a factor ~$(8/0.8)^{1.4} \sim 25$. Conversely, the measured fraction, $F$, of CBs containing WDs (CVs) vs. NSs (LMXBs + MSPs) then limits the primordial IMF of the cluster and subsequent dynamical evolution of its stellar remnants. A reduction in $F$ is expected, for example, by considerations of stable mass transfer and mass segregation (e.g. Bailyn, Garcia and Grindlay 1990). Thus the study of CVs in globulars constrains both stellar and dynamical evolution.

Not only the number and spatial distribution, but the very nature of CVs in globulars is emerging as a clue to their origin. On the basis of HST/FOS spectra (Grindlay et al 1995; GC95) showing moderately strong HeII (λ4686) emission
for the three Hα emission objects discovered (Cool et al 1995; CG95) in the core of the nearest core-collapsed globular, NGC 6397, we have suggested they may be magnetic CVs (MCVs) of the DQ Her (hereafter intermediate polar, IP) type in which the accreting WD has a magnetic field $B_{\text{WD}} \sim 0.1-1$ MG sufficient to truncate the inner edge of the accretion disk. More detailed analysis of NGC 6397, including a fourth CV candidate found in deep HST imaging (Cool et al 1998; CG98) and spectroscopy (Edmonds et al 1999; EG99), provides additional evidence that these first 4 spectroscopically confirmed CVs in a globular cluster core may be IPs (EG99), whereas only $\sim 10\%$ of CVs in the field are of the DQ Her type (cf. Patterson 1994). If confirmed with both more detailed optical (and x-ray studies) and larger samples, this would suggest MCVs and magnetic WDs are somehow enhanced in globular cluster cores, providing yet more evidence that stellar evolution in globulars is affected by close encounters. One possibility (Grindlay 1996) is that since rotation of stellar cores increases in encounters or mergers, dynamo production of magnetic fields may result and the resulting WDs may be preferentially magnetic.

In this paper, we briefly discuss the various search techniques for finding (and then studying) CVs and MCVs in globulars. We summarize the Hα-imaging technique conducted with HST which has yielded 3 CV candidates in NGC 6397 (CG95) and 2 each in NGC 6752 (Bailyn et al 1996; BR96) and ω-Cen (Carson et al 1999). We focus on NGC 6397 for which the initial spectroscopic followup studies (GC95) as well as UBVI photometry revealed a fourth CV (CG98). We compare the optical emission line and continuum spectra of the 4 CVs in NGC 6397 with correlations found for field CVs and find they are consistent with those for IPs. Using the new spectrophotometry of EG99, and the preliminary results of our follow-up deep (75ksec) ROSAT observation (Grindlay, Metchev and Cool 1999; GMC99), we compare the x-ray vs. optical properties of the brightest 4 spectroscopically confirmed CVs and find they are consistent with the optical vs. x-ray correlations displayed by IPs in the disk. We report a fifth CV candidate in the cluster core from the deep ROSAT study and find a likely optical counterpart as a near uv-excess star measured by CG98 that would also be consistent in its x-ray/optical flux ratio. Although the dim x-ray sources in NGC 6397 resemble IPs, we also briefly reconsider whether they might instead be very low accretion rate and optically thin disks as expected for either quiescent dwarf novae containing WDs or quiescent LMXBs containing NSs.

We conclude with a brief comparison of our current results for NGC 6397 with those for 47 Tuc, for which Verbunt and Hasinger (1998; VH98) have a moderate ROSAT exposure. Interesting differences and similarities in the CV and CB populations may already be apparent. Upcoming HST and AXAF observations will provide much more sensitive tests of the possible MCV excess in globulars.

2. CV Searches in Globulars

CVs have long been sought in globular clusters for a variety of (good) reasons: known distances to then fix mass transfer rates $\dot{m}$; Pop II environments to test halo models; formation histories likely to include stellar encounters to contrast
with primordial binary evolution (only) for field objects; and many others. Here we briefly review the search techniques and their completeness for finding MCVs.

2.1. UV-excess and Variability

Since most CVs have been discovered in the field as blue variables, with dwarf novae (DNe) being the most common and novae the most extreme examples, initial searches in globulars have emphasized these properties. Indeed the only pre-HST spectroscopically confirmed CV in a globular (V101 in M5; Margon et al 1981) is a DN as originally suggested by Oosterhoff on the basis of outbursts. We note below that the total CV (and perhaps CB) population in globulars is strongly centrally concentrated so that V101, which could never be detected (from the ground) in the core, requires either formation from a primordial cluster binary or ejection from the core.

The cores of two clusters have been moderately well searched with HST imaging for blue variables: NGC 6752 (Shara et al 1996) has yielded only upper limits for DNe, whereas 47 Tuc has produced only one confirmed and one possible DN system (Paresce and de Marchi 1994). Although these searches have certainly been sensitive to DN outbursts, the ability to detect $\sim 0.1-0.2$ mag flickering typical of quiescent DNe (with apparent magnitudes $\approx 21$ for either cluster) is questionable for blind searches (though less so for identified objects, where neighbor subtraction can be accomplished more reliably). The fact that the CV candidates in NGC 6397 and NGC 6752 have now been found to be so red that in V-I they are nearly on the cluster main sequence (CG98), though still with moderate U-B excess, also suggests that uv-excess alone is not a requirement for cluster CVs. This is reinforced by the relatively uv-deficient spectral distribution of the one cluster CV studied now in the far-uv, CV1 in NGC 6397 (EG99). If the cluster CVs are dominated by MCVs then both uv-excess and dwarf nova type variability are expected to be suppressed due to the truncation of the inner portion of the accretion disk. Thus CV searches should be constructed to be independent of these criteria.

2.2. H$\alpha$ Emission Imaging

All CVs except some DNe in outburst show emission lines, with the Balmer lines and H$\alpha$ most intense. This motivated our search strategy, developed initially in relatively shallow ground-based searches (e.g. Cool 1993) and culminating with HST and the initial results for NGC 6397 (CG95). An emission line search using narrow-band imaging would ideally use three filters: one centered on the emission line and two flanking continuum filters to measure both local continuum and slope while averaging over adjacent absorption line features (as used in our CTIO search of NGC 6752 (cf. Cool 1993)). Given the WFPC filter set, we have chosen the available H$\alpha$ filter F656N (with width $W_L \sim 20$ Å) and a single broad continuum filter (F675W with width $W_L \sim 913$ Å; yielding $\mathcal{R}$ magnitudes). H$\alpha$ emission candidates are then identified in the color magnitude diagram formed by $\mathcal{R}$ vs. H$\alpha$ - $\mathcal{R}$ as “blue” objects. Calibration of this photometry is self contained by the measure of blue stragglers and horizontal branch stars, with their stronger H$\alpha$ absorption, which show up as a separate track of “red” objects offset by $\sim 0.15$mag in the CMD (cf. CG95).
If MCVs dominate, the Hα searches should be relatively sensitive. However, the searches are per force limited by the narrow-band throughput of the F656N filter and consequent long total effective integrations to achieve interestingly deep limiting magnitudes. In NGC 6397, the closest globular with a high density core, we shall obtain (in cycle 7) 15 HST orbits to reach an effective limiting magnitude of \( \sim 24 \) (\( M_V \sim 11.5; \sim 10\sigma \)). This would span \( \gtrsim 3-4 \) binary orbits of the \(< 6h \) expected orbital periods (given the limits on secondary mass as well as disk absolute magnitudes derived by EG99) of the cluster CVs. However, once identified in Hα, variability studies can be conducted and the likely orbital periods \( P_b \) (e.g. \( \sim 3.5 - 5h \) for CVs 1-4 in NGC 6397; cf. EG99) can be measured from the accompanying short R exposures as done successfully for the 2 CV candidates in NGC 6752 (BR96). Detection of pulsation periods \( P_p < P_b \) would provide direct confirmation that they are indeed IPs and may be possible for the brightest candidates by searching for modulations in the B continuum by temporal analysis of STIS spectra as we have proposed.

### 2.3. Dim X-ray Sources

A new population of dim x-ray sources was discovered in globular cluster cores and proposed as most likely to be CVs (Hertz and Grindlay 1983; HG83). Given the usual advantage of known distances to globular clusters, the luminosities of these dim sources could be derived with greater accuracy than for field CVs (although the fainter source fluxes precluded spectral determinations). Since the initial (relatively shallow) Einstein surveys yielded luminosities \( L_x (0.2-4 keV) \sim 10^{32.5-34.5} \) erg/s, and since at least one of the dim sources (in NGC 6440) was regarded as the likely detection of a quiescent NS transient, HG83 concluded the dim sources were likely a mixture of both CVs and quiescent LMXBs (qLMXBs). Verbunt et al (1984) argued that all the dim sources discovered with the Einstein survey were most likely qLMXBs although it was already evident from studies of field CVs (e.g. Patterson and Raymond, 1985a,b; PRa,b) that the luminosities of field CVs extended above \( \sim 10^{32.5} \) erg/s in the 0.5-4.5 keV Einstein band.

Much greater sensitivity surveys have now been conducted with ROSAT. Here we only consider the initial (shallow) survey of NGC 6397 (Cool et al 1993; CG93) and the current (deepest) results on NGC 6397 (GMC99) and 47 Tuc (VH98). CG93 discovered three sources with \( L_x \sim 10^{31.5-32} \) erg/s within \( \sim 10'' \) of the center of NGC 6397. These comfortably overlap typical CV luminosities, and indeed our initial Hα imaging survey of NGC 6397 with HST (CG95) revealed three optical candidates, with spectra showing them to be most likely IPs (GC95). The deeper survey of GMC99 shows at least a 4th source (and probably several more) in the central core, as discussed below. MCVs might be expected to dominate the ROSAT survey since they typically have \( F_x/F_{opt} \) values greater than non-magnetic CVs (PRa, Patterson 1994, Beuermann 1998). However, the Hα survey found (blindly) the same sources within the expected sensitivity limits suggesting that any possible MCV excess in globulars is not a result of x-ray selection alone.
3. Evidence for MCVs

MCVs in globulars were suggested as a possible observable class by Chanmugam, Ray and Singh (1991). The first evidence for their detection was contained within the HST/FOS spectra of CV candidates 1-3 in NGC 6397 which showed all to have moderately strong HeII emission (GC95). Although HeII ($\lambda$4686) emission is not unique to MCVs, and in fact PRb show that it is correlated with accretion rate $\dot{m}$ and present with EW(HeII) $\sim$3Å in most CVs, Silber (1992) has shown that the apparent excitation as measured by the ratio of equivalent widths $\lambda' = EW(\text{HeII})/EW(H\beta)$ correlates with magnetic nature, with $\lambda' > 0.3$ for intermediate polar (IP; or DQ Her type) or polar (or AM Her type) systems. Although CVs 1 - 3 in fact have $\lambda' = 0.32$, 0.34, and 0.25, and CV 4 has $\lambda' = 0.07$, EG99 show that their spectra (cf. Figure 1) and continuum properties are in fact most consistent with IPs.

Why should the MCVs have enhanced HeII emission? The likely reason is the larger optically thin coronal region inside the inner edge of a magnetically truncated accretion disk, which is then more readily photoionized by soft x-ray emission from the accretion column onto the WD. Doppler imaging maps of HeII vs. H$\beta$ support this general picture.

Fig. 1. Mean spectra of CVs 1-3 (GC95) and CV4 in NGC 6397 (from EG99) showing the higher excitation HeI and HeII emission (particularly CVs 1-3) expected for IP type MCVs. (the feature at $\sim$5560 is instrumental).

3.1. Colors and Spectrophotometry with HST

EG99 have investigated the question of how the four CV candidates in NGC 6397 (the only spectra available for CVs in the cores of globulars) compare in both their continuum and line ratio properties with CVs generally. Since the V-I colors of these objects are nearly coincident with the main sequence for the cluster (CG98), reasonably accurate magnitudes and masses for the secondaries can be derived (CG98, EG99) and the disk absolute magnitudes determined.
From plotting these disk magnitudes and the continuum ratios at Hβ/Hα vs. the excitation parameter, $\lambda$, the objects closely resemble correlations in these quantities obeyed by MCVs, as seen in Figure 2.

Fig. 2. Correlations of continuum fluxes at Hβ vs. Hα and derived disk absolute magnitude vs. the excitation ratio, $\lambda$, which support the hypothesis that CVs 1-4 in NGC 6397 are DQ Her types (from EG99).

In Figure 3 we explore the apparent relationship between $\lambda$ and EW(Hβ), which itself is proportional to the relative x-ray to optical flux (see below), for the 4 CVs in NGC 6397 as well as 7 IPs in the field. The emission line data (EW values for HeII and Hβ) for the disk IPs are taken from Williams (1983) (for GK Per, EX Hya, YY Dra, FO Aqr and AO Psc), Steiner et al (1981) (V1 223 Sgr) and Motch et al (1996) (V709 Cas) and from EG99 for the four CVs in NGC 6397. This emission line “CMD” shows that $\lambda$ is (weakly) anti-correlated with EW(Hβ). This could reflect a variation in inner disk radius (from either WD magnetic field, $B_{WD}$, or accretion rate, $\dot{m}$) if the HeII emission from within the inner disk increases less with increasing accretion rate $\dot{m}$ than does Hβ from the outer disk. Although not noted, a similar correlation may be inferred from the data plotted by Echevarria (1988). The cluster CVs could define the lower B field end of the sequence, since the alternative of higher $\dot{m}$ (alone) is not consistent with their relatively faint disk absolute magnitudes (cf. Figure 2). Comparison with $P_b$ and $F_p$ values given by Hellier (1996) reveals no correlation.
3.2. X-ray vs. Optical Properties of CVs in NGC 6397

Additional tests for the MCV nature of the globular cluster CVs are possible by comparing their x-ray vs. optical properties with those of IPs in the disk. Using the initial ROSAT x-ray fluxes of the three dim sources, C1-C3, in the central core of NGC 6397 (CG93) and their probable optical counterpart CVs 1-3 (cf. CG95 for associations), CG95 found these three objects were consistent with the distance-independent correlation between $F_x/F_{opt}$ and EW(H$\beta$) found by PRa for disk CVs. Using the actual measured EW(H$\beta$) values (rather than inferred from H$\alpha$ magnitudes, as in CG95), Grindlay and Cool (1996) refined this correlation and compared CVs 1-3 with the qLMXB Cen X-4 (cf. discussion below). Here we use our more accurate spectrophotometry given in EG99 and preliminary results from our deep (75ksec) ROSAT/HRI observation (GMC99).

We find at least one additional dim source, C4, in the core of NGC 6397 as well as additional fainter sources near the core. C4 is $\sim$8$''$ due west of C3 (=CV2) and in the 75ksec ROSAT/HRI observation had total flux $\sim$80 counts vs. $\sim$160, 70 and 150 counts for dim sources C1-C3, respectively. Since the positions for CV1 and CV4 (CG98) are only $\sim$3$''$ apart, they are not resolved by the HRI (with $\sim$5$''$ resolution) and we divide the detected counts for the dim source C2 between them. The derived positions for C1-C3 are each within $\sim$2$''$ of the positions for CVs 1-4, lending confidence to the optical identifications and allowing us to search for the possible counterpart of the new source, C4. Re-examination of the HST/UBVI images reported in CG98 in fact yields a very probable identification for a 5th(!) CV in the core of NGC 6397: candidate CV5, with apparent magnitude $V = 21.7$ and $(U-B) = -0.8$ (visible in Figure 3 of CG98) is within the $\sim$3$''$ error circle of dim source C4. This star was too faint to be detectable in our original H$\alpha$ search (CG95) but with $F_x/F_{opt} \sim$3.2, it should be easily detected in our forthcoming deep (HST cycle 7) H$\alpha$ survey of NGC 6397, given the strong correlation between $F_x/F_{opt}$ and EW(H$\beta$) (PRa).

In Figure 4 we show the derived relation between the ratio of x-ray (ROSAT band) to optical (V band) fluxes, $F_x/F_{opt}$, vs. EW(H$\beta$). Only CVs1-4 (with measured EW(H$\beta$) values) are shown, along with the same field IPs as plotted.
in Figure 3, so that their optical vs. x-ray properties may be compared. The flux ratio $F_x/F_{opt}$ has been computed for each object as the measured flux in the V band (5000 - 6000Å) and the ROSAT band (0.5 - 2.5 keV) in order to use measured (not extrapolated) values. We use the visual magnitude without interstellar reddening so that the NGC 6397 CVs, with measured cluster extinction of $A_V = 0.58$ (cf. CG98) may be more properly compared with the disk CVs which are all within (typically) 500 pc and only moderately reddened. If this correction is not made for the cluster CVs, e.g. if some disk CVs are also reddened, their flux ratios would increase by $\sim$0.2 on the log scales plotted in the figures below. The x-ray fluxes have been computed for all objects assuming a relatively hard bremsstrahlung spectrum with $kT = 10$ keV since this is generally appropriate for disk IPs (cf. Patterson 1994), and with an absorption column of $N_H = 1. \times 10^{21}$ cm$^{-2}$. This $N_H$ is the interstellar value for NGC 6397 and thus a lower limit since disk IPs generally appear to be self-absorbed with $N_H$ values well in excess of interstellar values (Patterson 1994, Hellier 1996).

A measure of the uncertainty in $F_X$ from both $N_H$ and spectral differences for the disk IPs can be obtained by comparing the ROSAT 0.5-2.5 keV fluxes (from PSPC survey fluxes given by Verbunt et al 1997 for all but YY Dra and V709 Cas, for which HRI fluxes from Norton et al 1998 are used) with extrapolating the 2-10 keV fluxes and spectral fits given by Patterson (1994) (for all but V709 Cas) into the 0.5-2.5 keV band. The error bars on the $F_x/F_{opt}$ plots denote this hard vs. soft flux spectral uncertainty, and the line plotted is

$$\log(F_x/F_{opt}) = -2.21 + 1.45 \log [\text{EW}(H\beta)]$$

as found by PR85a for all CVs. Note that only 4/7 of the disk IPs are above the line and that the $F_x/F_{opt}$ values for CV1 and CV4 are particularly uncertain.

![Fig. 4: X-ray/optical flux ratio vs. EW(Hβ) values for CVs 1-4 in NGC 6397 vs. disk IPs compared with PR relation for field CVs as well as Cen X-4.](image)

For comparison we show in Figure 5 the same relation for HeII vs. $F_x/F_{opt}$. 

8
Fig. 5: \( F_x/F_{opt} \) vs. EW(HeII) and approximate fit.

The approximate linear fit to the log-log data plotted is given by

\[
\log(F_x/F_{opt}) = -2.5 + 2.5 \log \text{[EW(HeII)]}
\]

Thus the x-ray/optical flux is more strongly dependent on the HeII line strength than on H\(\beta\).

Finally, we investigate the possible relation between \( \mathcal{X} \) and \( F_x/F_{opt} \) directly since the correlations of \( F_x/F_{opt} \) with both EW(H\(\beta\)) and EW(HeII) might at first suggest a positive correlation with \( \mathcal{X} \). However, algebraically, the approximate log-log relations given above would predict \( \mathcal{X} \sim (F_x/F_{opt})^{-4/15} \), which is plotted in Figure 6 with the same data points.
Fig. 6: Excitation ratio, $X$, vs. $F_x/F_{opt}$ for CVs 1-4 in NGC 6397 vs. disk IPs.

We note that since both CV1 and GK Per have their $F_x/F_{opt}$ ratios most strongly affected by their relatively massive secondary companions, their $F_x/F_{opt}$ ratios in Figures 3-6 may be anomalously low.

3.3. Are the Objects in NCG 6397 Really MCVs?

The spectra, photometry and x-ray/optical properties of CVs 1-4 in NGC 6397 (cf. EG99) are consistent with them being MCVs (IPs), yet until pulsations or other signatures unique to IPs are detected there are still questions:

*Are they quiescent Dwarf Novae?* Their faint disks, and the apparent lack of DNe generally in globulars (Shara et al 1996) could both be indicative of WZ Sge type systems in which the recurrence time for DN outbursts has become very long at the low accretion rates possibly implied by the faint (optically thin) disks.

*Are they quiescent LMXBs?* In Figures 4 and 5 we have plotted the $F_x/F_{opt}$ and EW(H$\beta$), EW(HeII) values, respectively, for the classic qLMXB Cen X-4. The x-ray flux is from the recent ASCA spectral measurement (Campagna et al 1997) and the optical magnitudes and EW values are from Chevalier et al (1989) and McClintock and Remillard (1990). It is clear that Cen X-4 is offset from the bulk of the IPs in both correlations, and even more so from CVs1-4 (the forthcoming measurement of EW(H$\alpha$) $\sim$EW(H$\beta$) for CV5, with $\log(F_x/F_{opt}) \sim 0.5$, will provide an additional test). However, since the qLMXB x-ray luminosities (e.g. Cen X-4) are $\gtrsim 10 \times$ larger than the $\sim 1-4 \times 10^{31}$ erg/s values for CVs1-4 (and also CV5), a qLMXB interpretation is less likely.

4. Discussion

It is striking that CVs 1-5 are all within $\sim 7''$ ($\sim 0.08$pc) of their centroid position in NGC 6397, which is itself $\sim 3''$ NW of the position given by Sosin (1997) for
the cluster center. The radial extent of these central CVs is comparable with
the 5″ core radius derived by Sosin (1997) for this post core collapse (PCC)
cluster as well as for the distribution of bright central blue stragglers (BSs)
noted by Auriere et al (1990). This may support the suggestion (Grindlay 1996)
that the required magnetic WDs in cluster cores (if indeed the CVs are IPs) are
produced in BSs. If the core is in equipartition and BSs have masses ~2× the
turnoff value or ~1.5\(M_\odot\), the implied WD masses in CVs1-4 are ~1\(M_\odot\) given
their ~0.5\(M_\odot\) (EG99) secondaries.

The distribution of dim sources in 47 Tuc reported by VH98 is similar:
the central 5 are within ~20″ of the cluster center, or again comparable to the
cluster core radius and BS distribution of this non-PCC cluster, although the
dim sources are each typically ~10-50× more luminous (the brightest may be
qLMXBs). The underlying extended emission in the core quoted by VH98, with
total luminosity ~4 \times 10^{32} \text{ erg/s}, is about twice the total core luminosity of
NGC 6397 and may reflect a similar distribution of (~10) fainter CVs. Since
the core of 47 Tuc contains \(\sim 10\times\) the mass of the NGC 6397 core, the nearly
comparable numbers of CVs suggest the core collapse may have triggered a burst
of CB production in NGC 6397. If so, it is remarkable that NGC 6397 as yet
contains no compelling evidence for CBs containing NSs: no MSPs have yet
been reported (despite at least two surveys) whereas at least 11 are known in
47 Tuc. This may reflect differences in the cluster IMFs or NS retention.

Upcoming high resolution x-ray imaging and spectra with AXAF of both
clusters, and the deep Hα survey of NGC 6397 (with 47 Tuc still needed), will
help measure the CV nature and content. AXAF, in particular, will resolve CVs
1 vs. 4 in NGC 6397 (thus removing the uncertainties in their \(F_x/F_{\text{opt}}\) values as
plotted in Figures 4 and 5) as well as the fainter sources in both clusters. ACIS
spectra can also test for whether the sources have the hard spectra typical of
IPs. However, deep STIS spectra and temporal analysis for pulsations are also
needed to clarify if the objects are indeed dominated by IPs.

Acknowledgments. I thank A. Cool, P. Edmonds, and S. Metchev for
assistance with analysis and HST grant GO-6742 for partial support.

References

Auriere, M., Ortolani, S. & Lauzeral, C. 1990, Nature, 344, 638.
Bailyn, C., Garcia, M. and Grindlay, J. 1990, ApJ, 357, L35.
Bailyn, C. et al 1996, ApJ, 473, L31 (BR96).
Beuermann, K. 1998, in Perspectives in High Energy Astronomy & Astrophysics
(P.C. Agrawal & P.K. Visvanathan, eds.), Universities Press, p. 100.
Campagna, S. et al 1997, A&A, 324, 941.
Carson, J., Cool, A., Grindlay, J. et al 1999, in preparation.
Chanmugam, G., Ray, A. and Singh, K. 1991, ApJ, 375, 600.
Chevalier, C. et al 1989, A&A, 210, 114.
Cool, A. 1993, Ph.D. Thesis (Harvard).
Cool, A. et al 1993, ApJ, 410, L103 (CG93).
Cool, A. et al 1995, ApJ, 439, 695 (CG95).
Cool, A. et al 1998, ApJ, 508, L75 (CG98).
De Marchi, G. and Paresce, F. 1994, A&A, 281, L13.
Echevarria, J. 1988, MNRAS, 233, 513.
Edmonds, P. et al 1999, ApJ, in press (EG99).
Grindlay, J. et al 1995, ApJ, 455, L47 (GC95).
Grindlay, J. 1996, Proc. IAU Symp. 174 (J. Makino & P. Hut, eds.), 171.
Grindlay, J. and Cool, A. 1996, Proc. IAU Symp. 174 (J. Makino & P. Hut, eds.), 349.
Grindlay, J., Metchev, S. and Cool, A. 1999, in preparation.
Hellier, C. 1996, Proc. IAU Colloq. 158 (A. Evans & J. Wood, eds.), 143.
Hertz, P. and Grindlay, J. 1983, ApJ, 275. 105 (HG83).
Hut, P. et al 1992, PASP, 104, 981.
Margon, B., Downes, R. and Gunn, J. 1981, ApJ, 247, L89.
McClintock, R. and Remillard, R. 1990, ApJ, 350, 386.
Motch, C. et al 1996, A&A, 307, 459.
Norton, A.J. et al 1998, A&A, in press (astro-ph/9811310).
Paresce, F. and De Marchi, G. 1994, ApJ, 427, L33.
Patterson, J. 1994, PASP, 106, 209.
Patterson, J. and Raymond, J. 1985a, ApJ, 292, 535 (PRa).
Patterson, J. and Raymond, J. 1985b, ApJ, 292, 550 (PRb).
Shara, M. et al 1996, ApJ, 471, 804.
Silber, A. 1992, Ph.D. Thesis (MIT).
Sosin, C. 1997, Ph.D. Thesis (U.C. Berkeley).
Steiner, J.E. et al 1981, ApJ, 249, L21.
Verbunt, F., van Paradijs, J. and Elson, R. 1984, MNRAS 210, 899.
Verbunt, F. et al 1997, A&A, 327, 602.
Verbunt, F. and Hasinger, G. 1998, A&A, 336, 895 (VH98).
Williams, G. 1983, ApJS, 53, 523.