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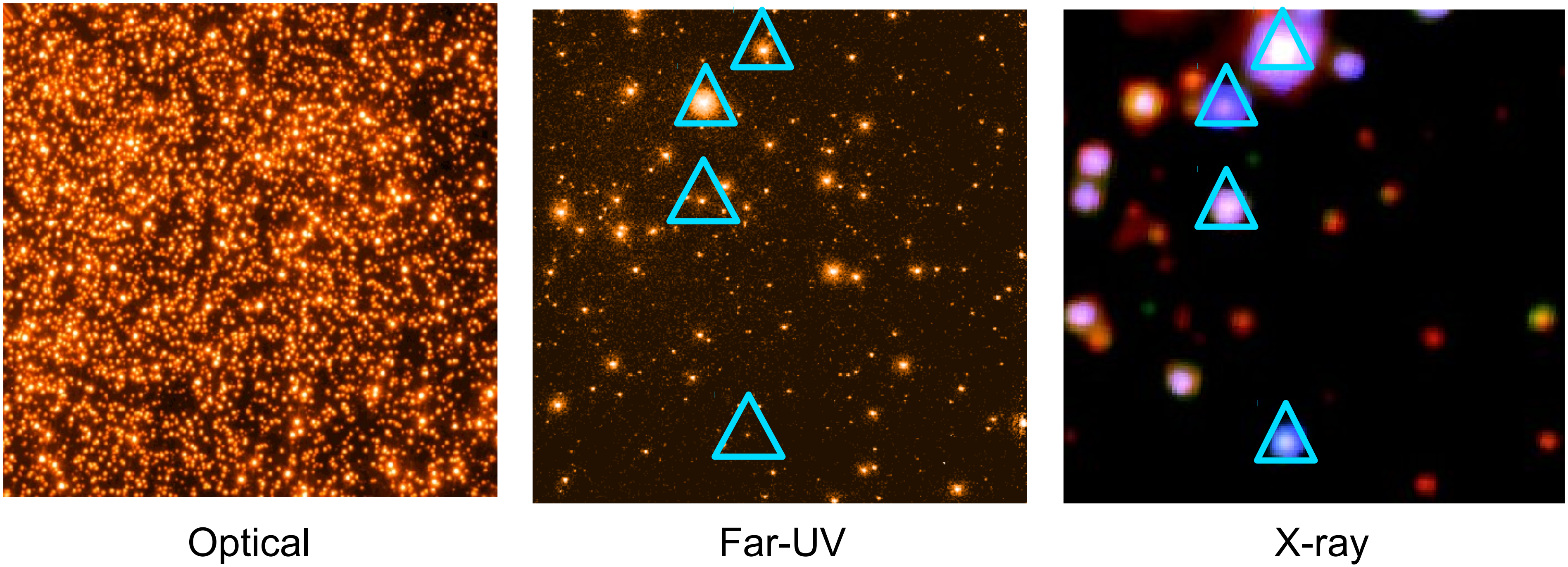
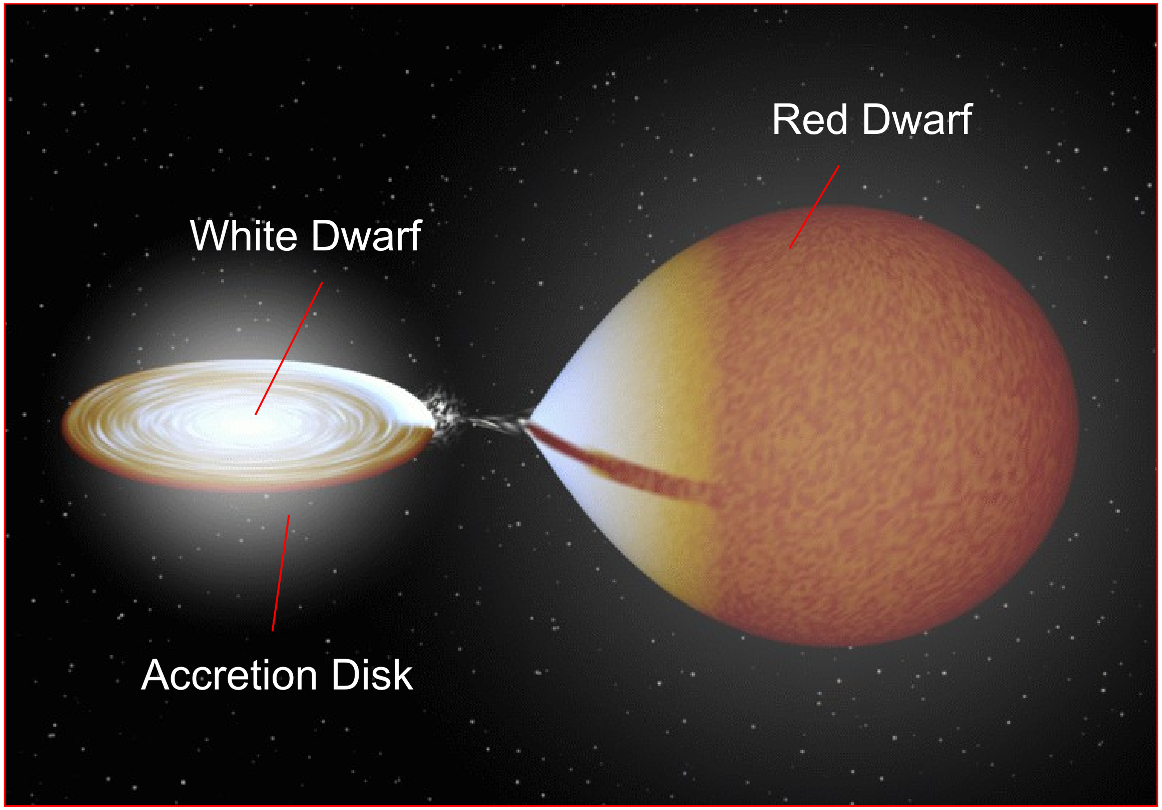
Cataclysmic Variables in Globular Clusters



Christian Knigge

University of Southampton

A CV Primer: The Physical Structure of CVs



Credit: Rob Hynes

- White dwarf primary
- "Main-sequence" secondary
- 75 mins < Porb < 6 hrs
- Roche-lobe overflow
- Accretion usually via a disk (if WD is not strongly magnetic)
- Disk accretion is unstable if accretion rate below critical rate

  → **dwarf novae**
- Mass transfer and evolution driven by angular momentum loss
- Evolution is (initially) from long to short periods

A CV Primer:
The Orbital Period Distribution and Evolution of CVs

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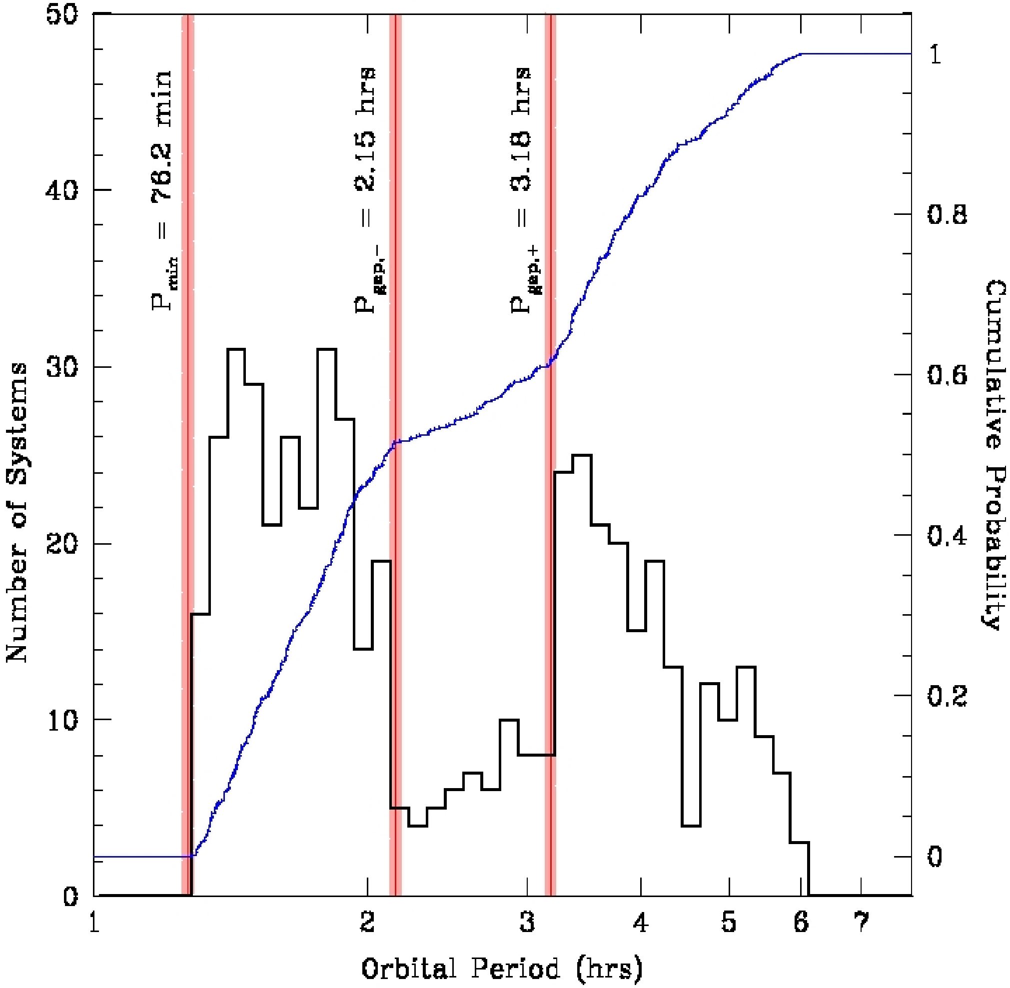
Knigge 2006



- Clear "period gap" between 2-3 hrs
- Suggests a change in the dominant angular momentum loss mechanism:
  - Above the gap:
    - Magnetic Braking
    - Fast AML → High Mdot → stable disks
  - Below the gap:
    - Gravitational Radiation
    - Slow AML → Low Mdot → DNs
- Minimum period at P_{min} = 80 min
  - Donor transitions from MS → BD
  - Beyond this, P_{orb} increases again
  - Most CVs (at least in the field) should be ultra-faint "period bouncers"
- This disrupted magnetic braking scenario is the standard model for CV evolution

Why Study CVs in GCs?

- The Globular Cluster Perspective:
  - CVs are key tracers of the close binary populations that drive the dynamical evolution of GCs

    → Important for understanding GC evolution

- The Cataclysmic Variable Perspective:
  - GCs can provide us with sizeable samples of CVs at known distance and (to some extent) age

    → Important for understanding CV evolution

- The Supernova/Cosmology Perspective:
  - The dynamical production of accreting WDs in GCs may make these clusters significant SN Ia factories

    → Important for understanding SN Ia and cosmology

How large a CV population can we expect in GCs?

- CV space density in the field (e.g. Pretorius & Knigge 2007, 2011) $\rho_{cv} \simeq 10^{-5}\mathrm{pc}^{-3}$
- Effective volume of Milky Way $V_{MW} \simeq 10^{12} pc^3$
- So expected number of CVs in Milky Way $N_{cv} \sim 10^7$
- Fraction of Galactic mass bound up in GC system $f_{gc} \sim 0.001$
- Number of GCs in the Milky Way $N_{gc} \sim 100$

→ Other things being equal, the number of CVs expected in a GC would be

$$N_{cv,gc} \sim f_{gc} \times N_{cv}/N_{gc} \sim 100$$

But other things aren't equal!

In GCs, dynamical effects can both create and destroy CVs

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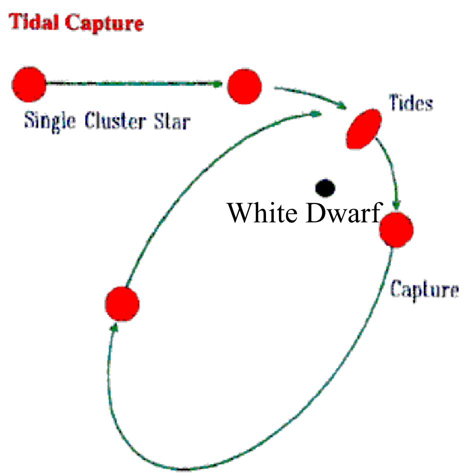
Theoretical Predictions: Three Classes of CVs

- "Primordial" CVs
  - CVs formed from binaries that would have produced CVs in the field as well
  - Progenitors destroyed in GC cores, but may survive in halos

$$N_{cv,p} \sim 100$$ (Davies 1997)

- Dynamically-formed CVs
  - Tidal Capture



$$N_{cv,tc} \sim 100$$ (di Stefano & Rappaport 1994)

  - Three-Body Interactions

S. McMillan

$$N_{cv,3b} \sim 100$$ (Davies 1995, 1997)

Theoretical Predictions: N Classes of CVs

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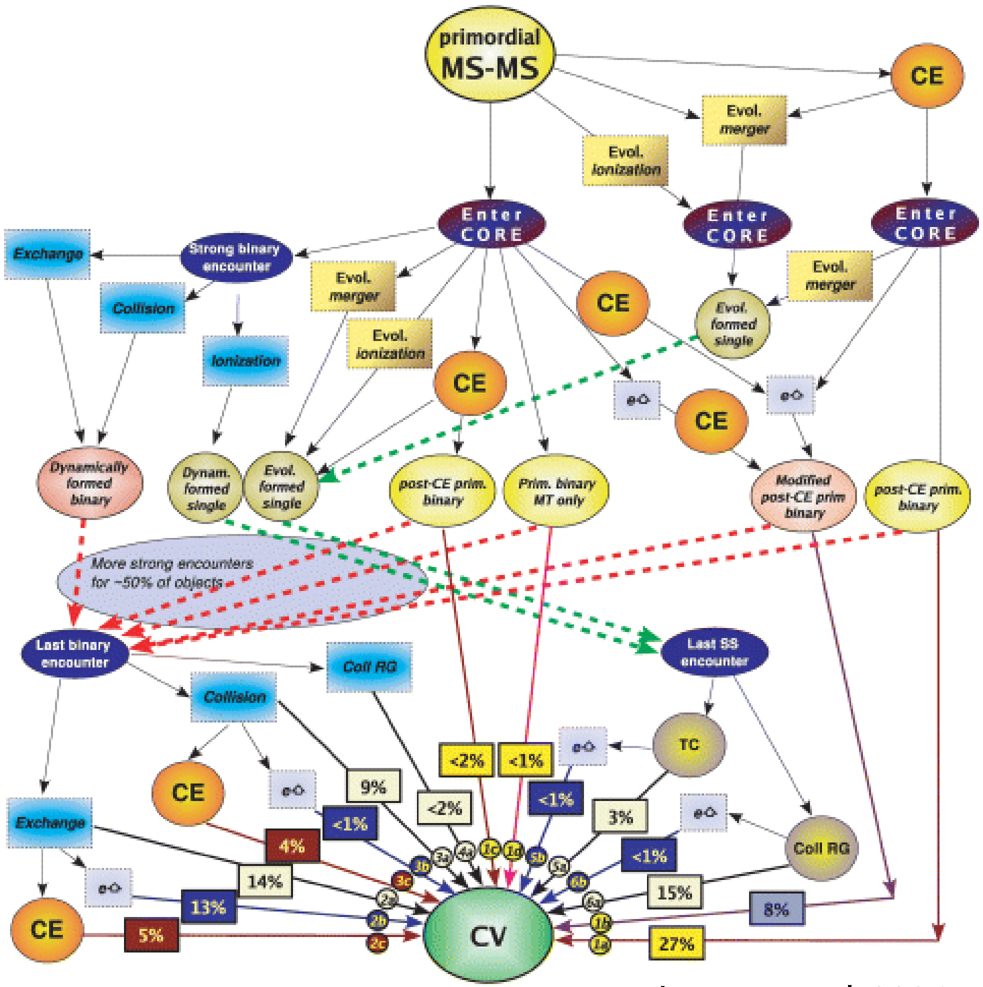
- Recent theoretical predictions are more, well, *nuanced*...



Ivanova et al. 2006

- But the predicted totals have not changed all that much:

$$N_{cv,tot} \sim 200$$

Observations: Finding CVs in GCs

- So there should be hundreds of CVs in any massive GC!
  - How do we go about detecting them?
- Pretty much the same way we might in the field!
  - Variability → DN outbursts
  - Emission Lines → photometric Hα excess
  - Blue Colour → (F)UV excess
  - X-rays → search for faint X-ray sources (Maureen van den Berg's talk!)
- Challenges
  - Distance/Faintness → Compared to nearby field CVs, GC CVs are 10-100 times more distant and 100-10,000 times fainter
  - Crowding → stellar surface density in GC cores can easily reach or exceed 10 stars per arcsec^2

Finding CVs in GCs: Blueness

- The light of most CVs is dominated by accretion light
  - This is almost inevitably very blue compared to ordinary stars
  - Especially true in GCs, where hot stars have turned off the MS long ago
  - Can therefore try to identify CVs as UV excess sources

NGC6397 (Cool et al. 1998)

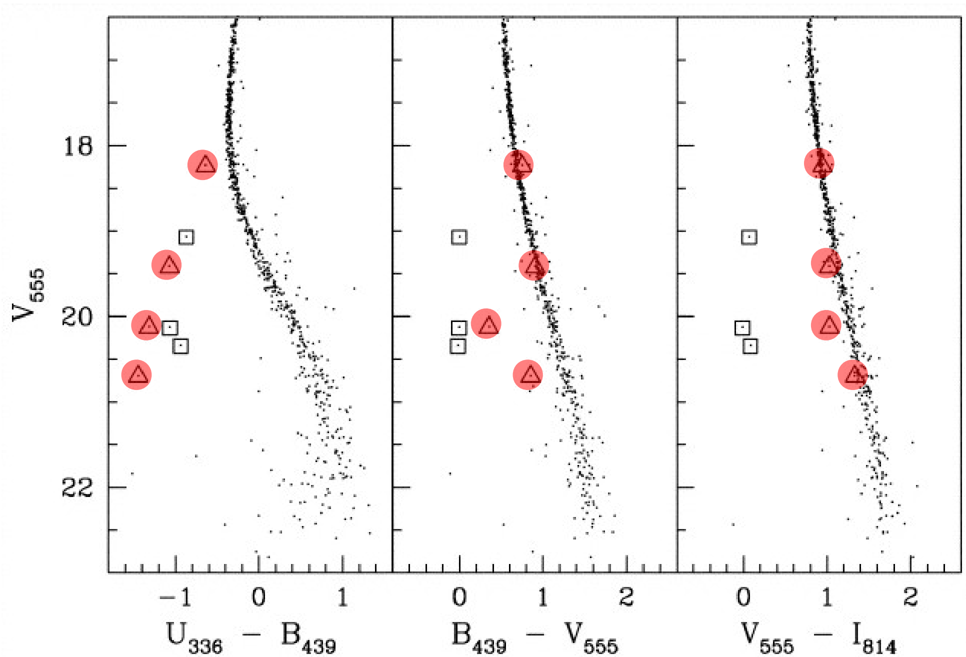


TABLE 1
Faint UV Stars in NGC 6397

Star	x	y	M_V	$(U-B)_0$	$(B-V)_0$	$(V-I)_0$	Δr (arcsec)	Identification Number
CV 1	451	589	5.95	−0.84	0.56	0.69	10.7	1
CV 2	513	349	7.13	−1.27	0.72	0.77	0.9	2
CV 3	314	436	7.84	−1.51	0.16	0.78	9.9	3
CV 4	454	525	8.41	−1.65	0.67	1.08	7.8	New
NF 1	584	717	6.79	−1.06	−0.20	−0.18	16.4	New
NF 2	647	551	7.84	−1.27	−0.19	−0.27	10.3	7
NF 3	442	303	8.06	−1.13	−0.21	−0.17	4.6	6

Note.—Star coordinates refer to archive exposure u33r0101t. For the conversions to absolute magnitudes, we adopted $(m-M)_0 = 11.71$, $A_U = 0.97$, $A_B = 0.77$, $A_V = 0.58$, and $A_I = 0.33$. Radial offsets are based on a cluster center at $(x, y) = (529, 378)$, following Sosin 1997.

Finding CVs in GCs: Blueness

- With the arrival of true far-UV imaging detectors on HST, could extend this into the FUV

- Main advantage: crowding ceases to be a problem!

- (F)UV excess searches have yielded 1 – 50 CV *candidates* per cluster
  (Knigge et al. 2002; Dieball et al. 2005; 2009; 2010)

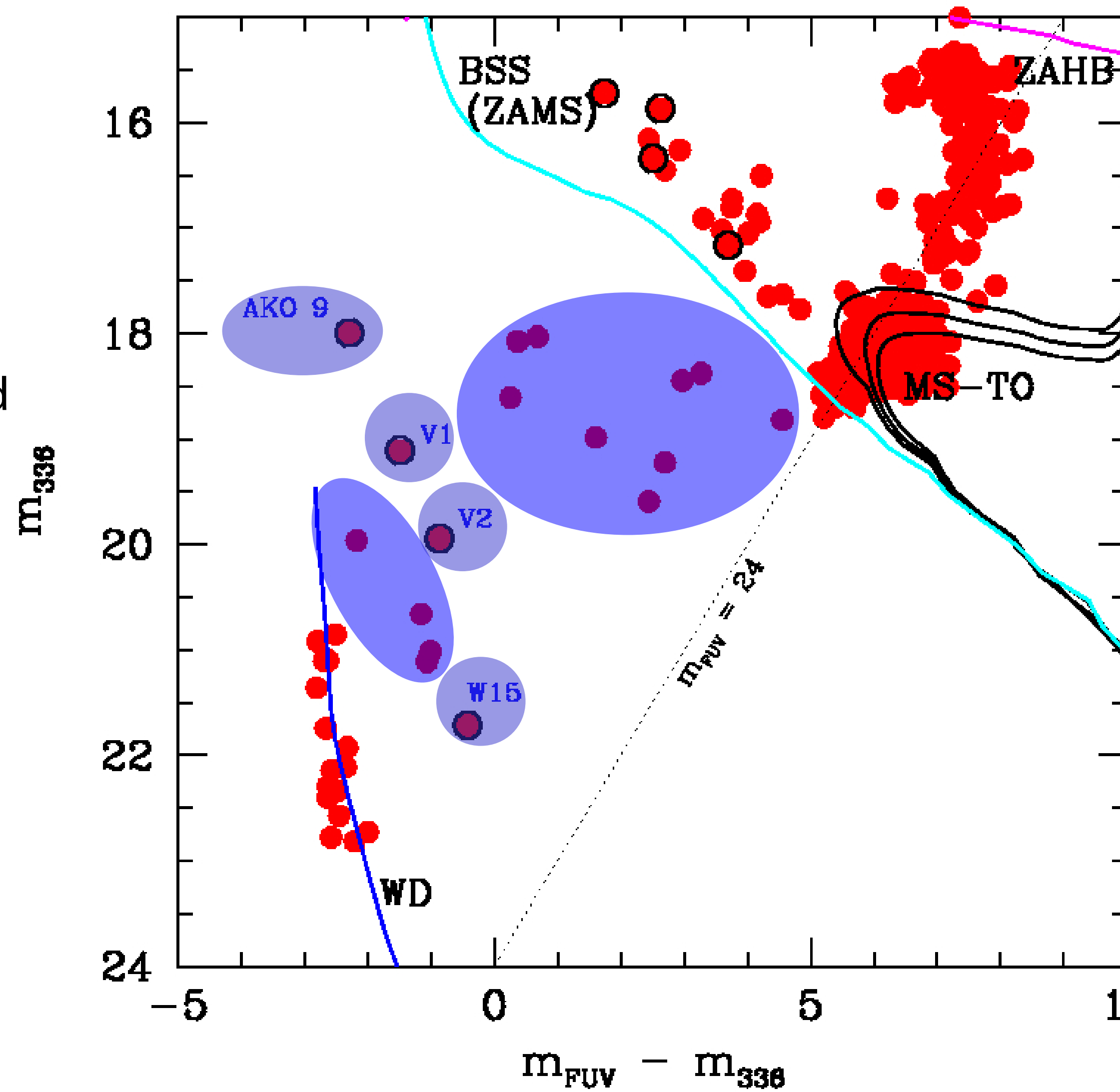
  - In 47 Tuc, FUV imaging of 1/3 of the core yields

  → Confirmation of all 4 previously known CVs in FoV

  → >10 new candidates

- Main disadvantage: small FoV

The core of 47 Tuc: FUV (~1500A)



Confirming CVs in GCs

- On their own, all methods discussed so far produce only *candidates*
- As always, spectroscopic confirmation defines the gold standard
  - But this is extremely difficult in GCs → crowding and faintness
  - Most attempts used HST with a long-slit spectrograph

- But we can try to be sneaky
  - GCs are not crowded in the FUV, so why bother with a slit?

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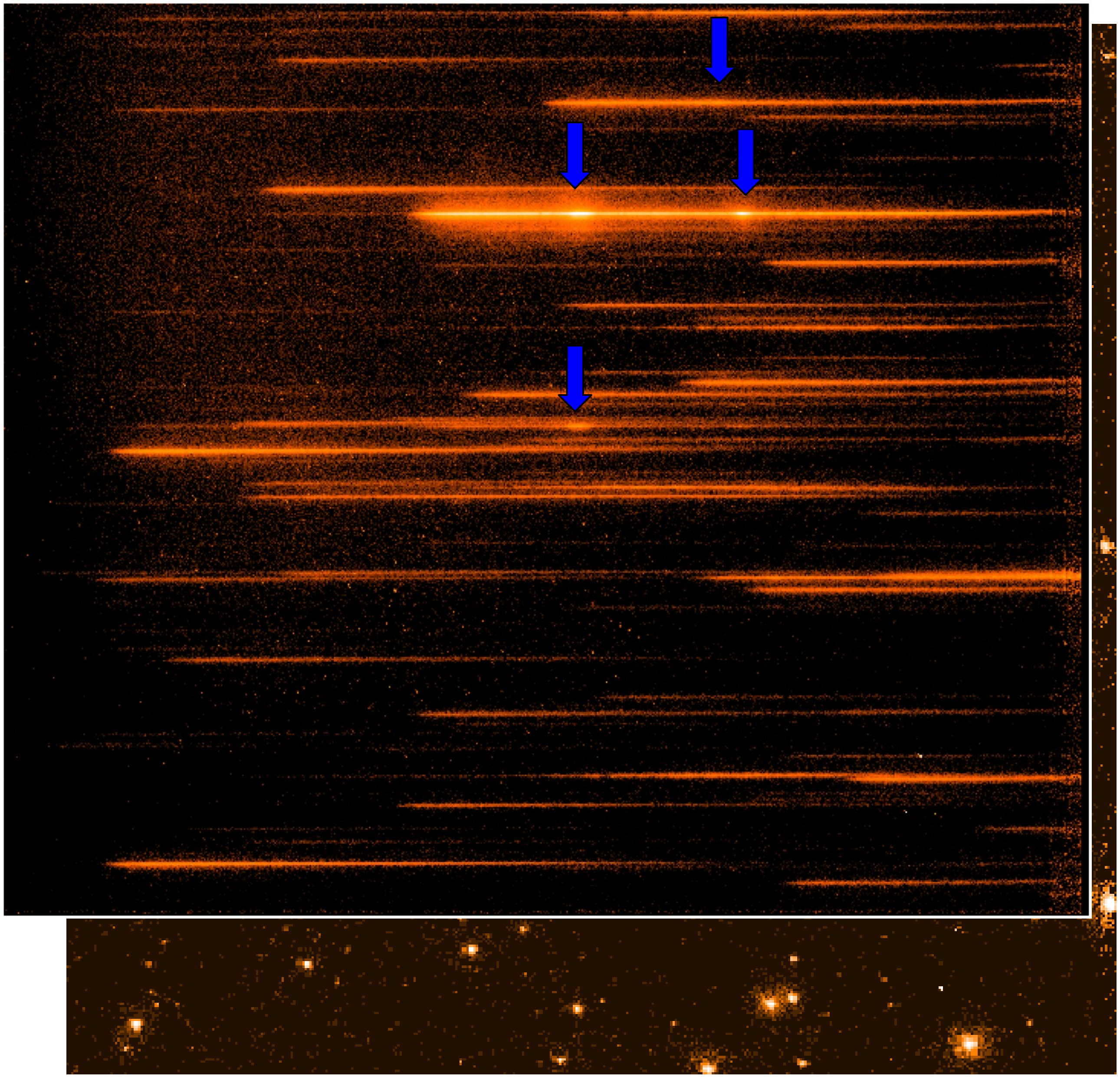
Confirming CVs in GCs: The Lazy Way



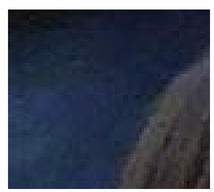
Slitless far-UV spectroscopy in the core of 47 Tuc
(Knigge et al. 2003, 2008)

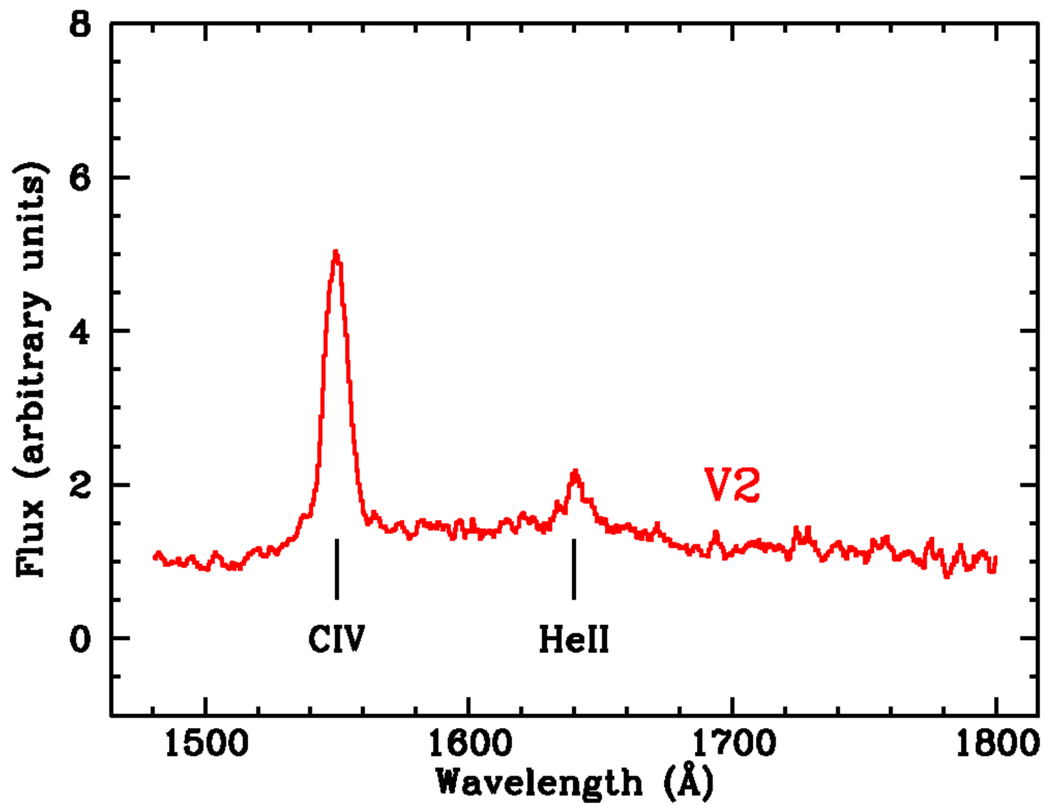
- Spectroscopic confirmation of 3 CVs simultaneously:
  - AKO9, V1, V2

Confirming CVs in GCs

- Only 6 studies have definitively succeeded in spectroscopically confirming one or more GC CVs to date

- Margon, Downes & Gunn (1981)
  - V101 in M 5
  - ground-based, outskirts
- Grindlay et al. (1995)
  - CV1, CV2 & CV3 in NGC 6397
  - HST, core → He II lines!
- Edmonds et al. (1998)
  - CV4 in NGC 6397
  - HST, core
- Deutsch et al. (1999)
  - CV in NGC 6624
  - HST, FUV, serendipitous
- Knigge et al. (2003)
  - AKO 9 in 47 Tuc
  - HST, FUV, slitless
- Knigge et al. (2008)
  - XXXX V1 and V2
  - HST, FUV, slitless

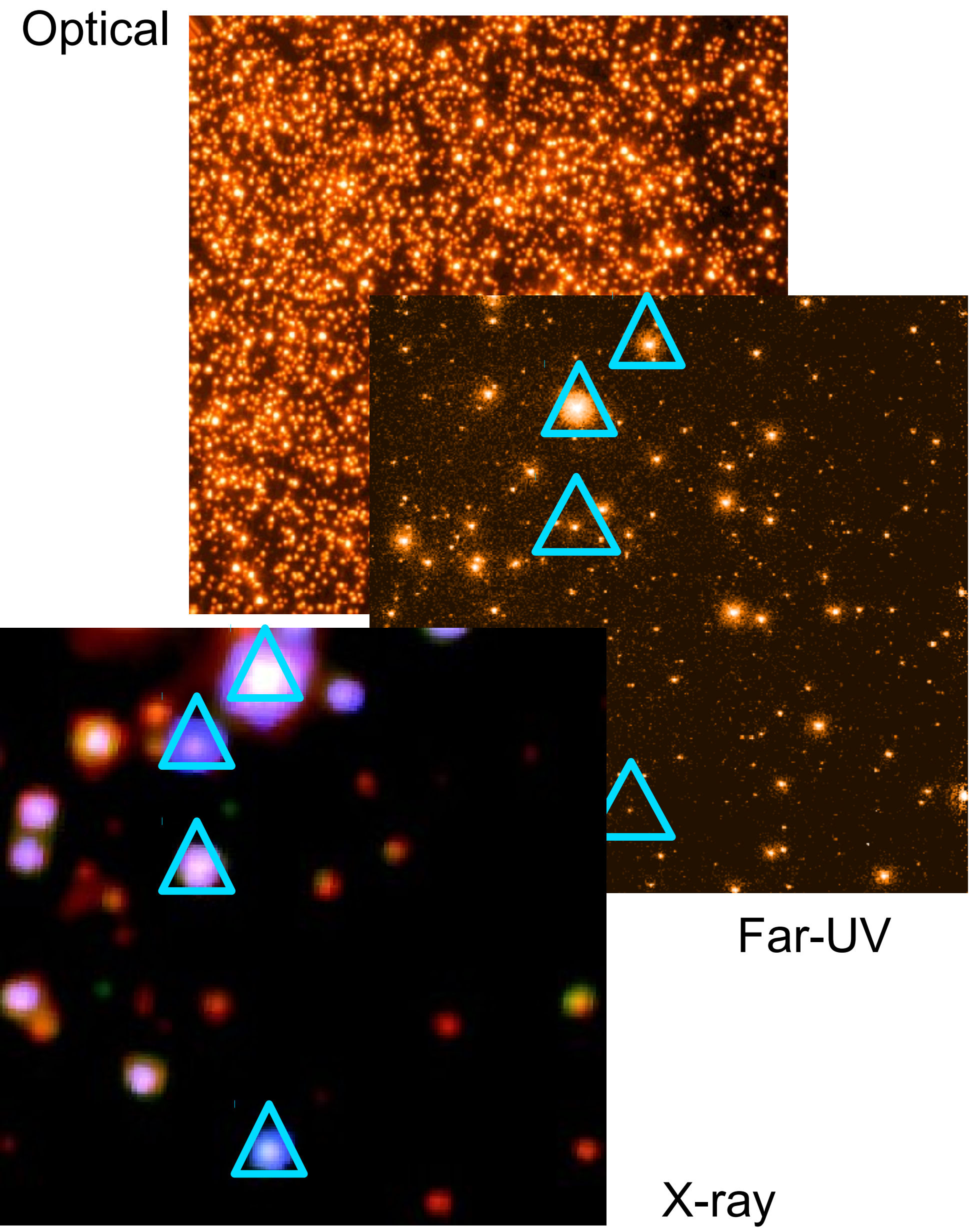




Only 8 spectroscopically confirmed CVs in just 4 GCs overall!

Å

Confirming CVs in GCs



- Usually have to settle for "silver standard"

  → confirmation by multiple methods

- This sort of thing has been done for quite a few CV candidates in quite a few Gcs

- For example, 47 Tuc:
  - X-rays (Grindlay01, Heinke05)
  - optical imaging (Edmonds03a)
  - optical variability (Edmonds03b)
  - FUV imaging (Knigge02)
  - FUV spectroscopy (Knigge03, Knigge08)

- But this approach has left us with a highly heterogenous sample of GC CVs!

  → Selection Effects!

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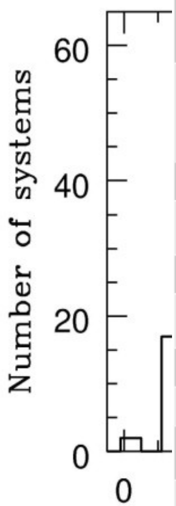
Population Properties: Orbital Periods

- N(P_{orb}) is the most powerful tracer of CV evolution
- **We know orbital periods for only 16 CVs in 7 GCs!**

Pretorius, Knigge & Kolb 2007



Clus				d	Data	References	Comments
47 Tuc	AKO9	26.6	DN	Eclipse	Optical	Edmonds et al. 1996, Albrow et al. 2001, Knigge et al. 2003	similar to GK Per
	V3,W27?	4.7	polar?	Var	X-ray	Shara et al. 1996; Heinke et al. 2005	Grindlay et al. 2001) claimed 3.8 hrs; might be qLMXB
	W15	4.2		Eclipse	Optical	Edmonds et al. 2003ab	
	W1	5.8		Ellipsoidal	Optical	Edmonds et al. 2003ab	could be 5.8/2 if not ellipsoidal
	W8	2.9		Eclipse	Optical	Edmonds et al. 2003ab	
	W2	6.3		Var	X-ray	Edmonds et al. 2003ab	no clear optical signal
	W21	1.7		Var	Optical	Edmonds et al. 2003ab	Mv ~ 7.5
	W120	5.3?		Var	Optical	Edmonds et al. 2003ab	
	W71?	2.4		Var	Optical	Edmonds et al. 2003ab	marginal CV candidate
NGC 6397	CV1	11.3		Eclipse	Optical	Kaluzny & Thompson 2003; Kaluzny et al. 2006	
	CV6	5.6		Var	Optical	Kaluzny & Thompson 2003; Kaluzny et al. 2006	
M 5	V101	5.8	DN	RV	Optical	Neil et al. 2002	
NGC 6752	V1	5.1		Var	Optical	Bailyn et al. 1996	
NGC 6752	V2	3.7?		Var	Optical	Bailyn et al. 1996	reality of signal seems uncertain
M 22	CV2	2.1	DN	SH	Optical	Pietrukowicz et al. 2005	P_{orb} inferred via P_{sh}
NGC 6624	Star 1	1.6		Var	Optical	Dalessandro et al. 2014	

d CVs anyway....

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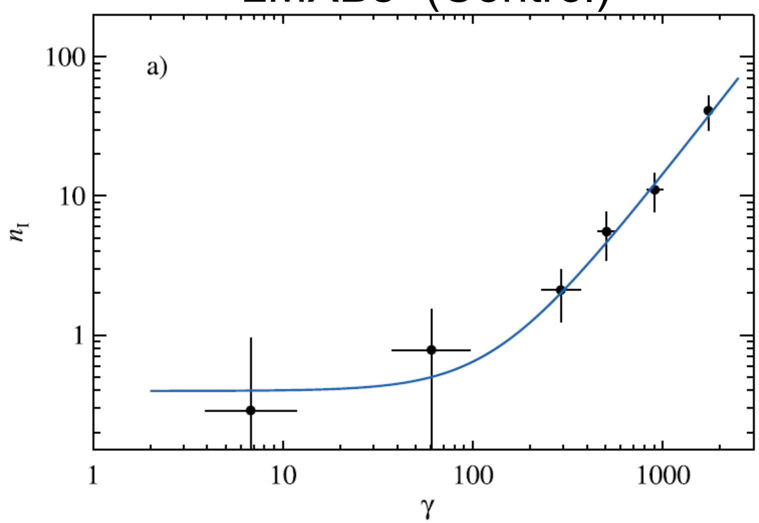
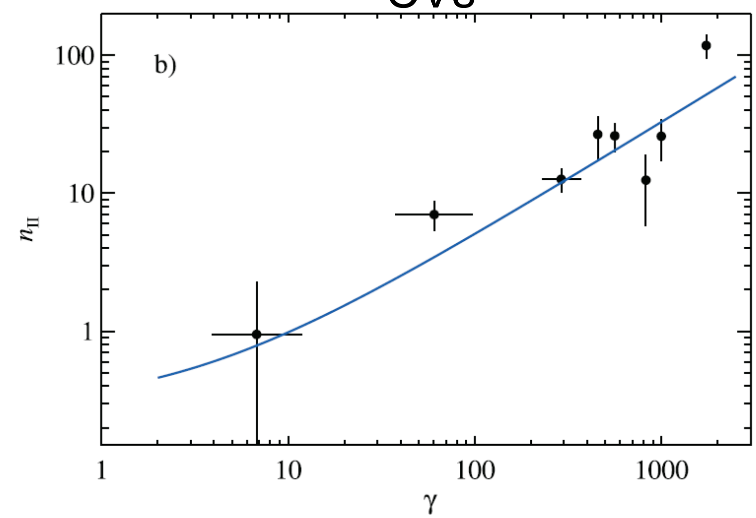
Population Properties: Do Dynamics Matter?

- There is an independent way to test if dynamics matter
  - If CV numbers scale with stellar collision rate, (some) CVs must be dynamically formed (cf LMXBs)
  - If you're willing to assume that most hard X-ray sources above $L_x = 4 \times 10^{31}$ erg/s are CVs, you can do this test (Pooley & Hut 2006)

"LMXBs" (Control)



"CVs"



  - CV numbers do scale with specific collision rates!

    → Dynamics matter!

Population Properties: Are They All Magnetic?

- Grindlay et al. (1995) found He II lines in the spectra of all 3 CVs they observed in NGC 6397
  - This is often seen in magnetic CVs

    → are CVs in GCs preferentially magnetic?

- Not a crazy idea
  - mWDs tend to be more massive, so more likely to interact and produce CVs in GCs (Ivanova et al. 2006)

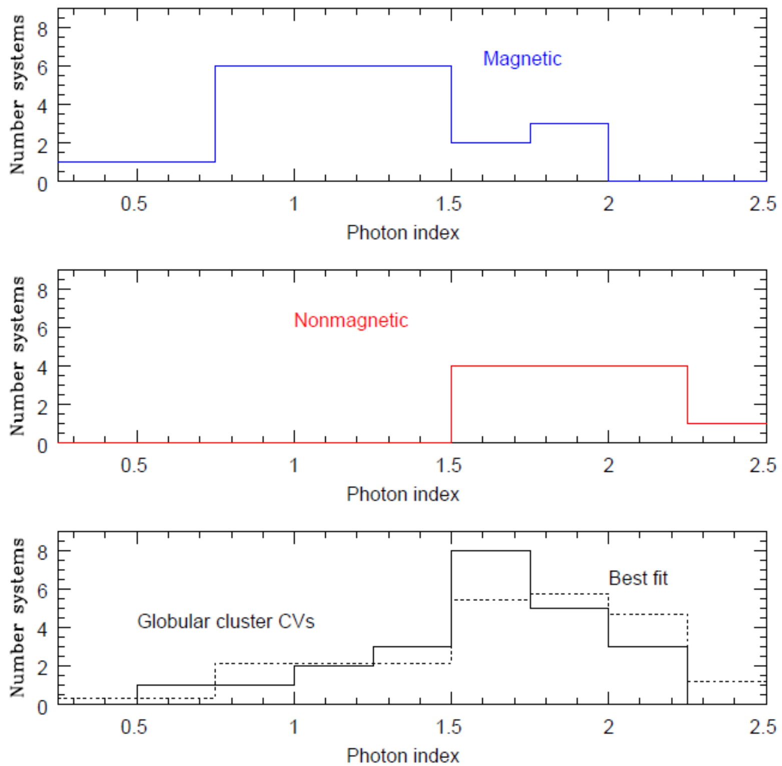
- BUT: He II is only weak evidence for magnetism

  → non-magnetic CVs can also produce this line

- BUT: X-ray colours suggest $f_m \simeq 0.4$
  - This is an X-ray-selected, flux-limited sample
  - $f_m \simeq 0.6$ in the ROSAT bright survey (Schwope et al. 2002)

→ No evidence that f_m is abnormally high in GCs

Heinke et al. (2008)



Population Properties: Are They All Magnetic?

- This idea has nevertheless gained a lot of traction
  - e.g. could this explain the claimed dearth of DN outbursts (e.g. Shara et al. 2005; Dobrotka et al. 2006; Pietrukowicz et al 2008)?

CATACLYSMIC AND CLOSE BINARIES IN STAR CLUSTERS. IV. THE UNEXPECTEDLY LOW NUMBER OF ERUPTING DWARF NOVAE DETECTED BY THE *HUBBLE SPACE TELESCOPE* IN THE CORE OF 47 TUCANAE[1]

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Received 1995 August 7; accepted 1996 May 24

ABSTRACT

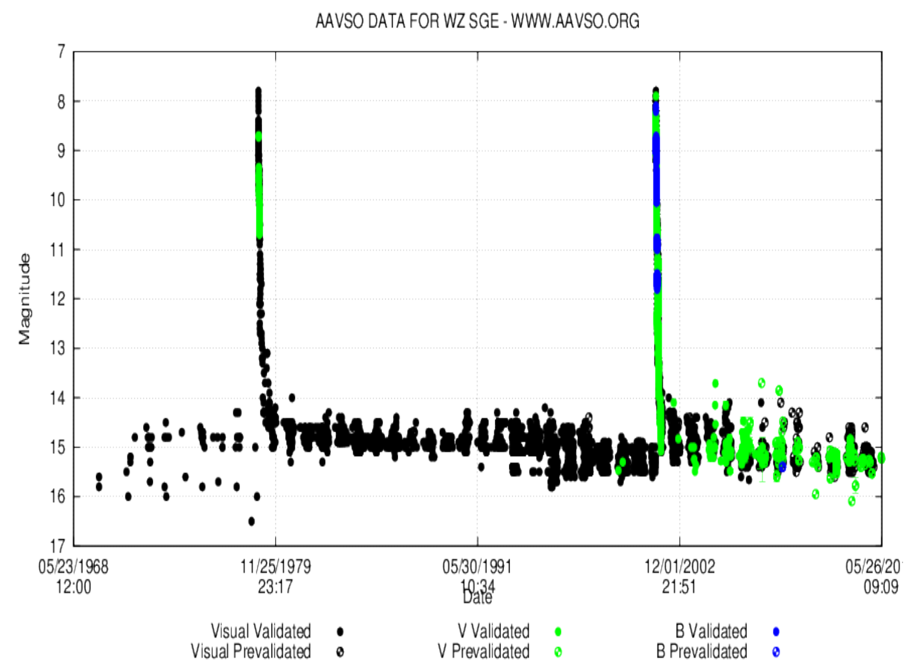
The standard model of tidal capture predicts that ~45 moderately bright cataclysmic binaries should exist today in 47 Tuc. To test this prediction, we have conducted a search for erupting dwarf novae in the center of 47 Tuc with 12 separate epochs of *Hubble Space Telescope* (*HST*) images in visual through near-UV bands. We have found a second eruption of the dwarf nova V2 discovered by Paresce and De Marchi. In addition, we have discovered a faint blue variable with period ~4.7 hr and amplitude 1.5 mag, which may be a cataclysmic variable. Detailed simulations demonstrate that our areal and temporal coverage and detection sensitivity is sufficient to have detected one-third of all dwarf novae (via their eruptions) in the center of 47 Tuc; even the very faint U Gem–type objects. We therefore claim that there are probably no more than three dwarf novae in the core of 47 Tuc, in significant disagreement with a key prediction of the standard model of tidal capture, unless the properties of dwarf novae in globulars differ (e.g., in outburst frequency) from those in the field. In addition, the cluster color-magnitude diagram reveals zero novalike variable candidates.

...let's take a closer look at the evidence that there actually is a dearth of DNe...

Population Properties: A Dearth of DNe?

- Shara et al. (1996) estimated DN recovery rates from semi-empirical outburst templates
- These are heavily biased towards bright, long-period, frequently erupting systems!
  - effectively assumed duty cycle ~30%
- If GC CVs are anything like field ones (not clear, but sensible null hypothesis)
  - → ~90% should be short-P_{orb} systems
  - → ~70% should be ultra-faint "period bouncers" (field prototype: WZ Sge)
- Implications?
  - WZ Sge erupts every ~25 yrs for ~1 month
    - → duty cycle is ~ 0.3%
    - → recovery efficiency for similar CVs is down by ~100x !

The jury is actually still out!



ID Number	Name	P (days)	t_r (days)	t_1 (days)	t_d (days)	d_{m_v}	$M_{v_{min}}$	P_{orb}(h) (hr)
1 ……	AR And	23	2	6	3	5.2	8.6	2.82
2 ……	SS Aur	53	2	11	5	4.0	8.9	4.38
3 ……	SS Cyg	40	3	16	7	3.8	8.4	6.63
4 ……	U Gem	118	2	12	6	5.3	9.6	4.17
5 ……	X Leo	20	2	8	4	3.5	8.1	3.94
6 ……	CY Lyr	16	1.5	5.5	3	3.8	8.4	2.50
7 ……	CZ Ori	26	2	8	5	3.4	8.0	4.00
8 ……	TW Vir	32	1	5	2	4.2	7.7	4.38
9 ……	RX And	13	2	8	4	2.8	7.3	5.08
10 ……	Z Cam	23	2	11	7	3.1	7.7	6.96
11 ……	SY Cnc	27	6	16.5	6	2.6	6.4	9.10
12 ……	EM Cyg	24	2	7	5	1.4	7.2	7.00
13 ……	AH Her	18	5	11	7	3.0	7.6	6.19
14 ……	CN Ori	17	3	12	6	2.3	6.9	3.91
15 ……	TZ Per	17	3	11	4	1.6	6.2	6.50
16 ……	KT Per	26	1	7	4	3.0	6.9	7.10
17 ……	YZ Cnc	12	1	3.5	2	2.3	7.7	2.10
18 ……	IR Gem	34	1	5	3	3.8	8.8	1.70
19 ……	AY Lyr	24	1	3	2	3.8	9.0	1.75
20 ……	TY Psc	24	4	3	3	4.1	9.0	1.85
21 ……	SU UMa	19	1	4	3	2.2	7.9	1.83

Conclusions

- CVs in GCs matter: GC evolution, binary evolution, SN Ia

- Chandra and HST are finally finding significant numbers of CVs in GCs...
  - ...though still not the hundreds predicted to lurk there

- There are hints that field and GC populations may turn out to be different...
  - ...but much common lore – eg a dearth of DNe and a preference for magnetic systems in GCs – is at best weakly supported by observations

- The next big step change will come from
  - Going deeper

    → if we really want to test for the predicted ~200 CVs we need to be sensitive to faint, short-period CVs → $\mathbf{m_v \sim 27}$! This is doable (e.g. Cohn et al. 2010)
  - Orbital periods

    → for meaningful comparisons between theory and observations, we desperately need statistically significant period distributions

Things I didn't have time to talk about

Novae: thermonuclear runaways in CVs

– important for clearing and enriching GCs (Moore & Bildsten 2011, Maccarone & Zurek 2012)

→ link to 2nd populations?

– only 1 definite in MW: T Sco in M80 (Luther 1860; Sawyer 1938; Shara & Drissen 1995)

→ finally recovered (Dieball et al. 2010; Thomson et al. 2010)

– 2 additional candidates in MW:

- N1938 in M14 (Hogg & Wehldau 1964; Shara et al. 1986)
- N1943 near NGC6553 (Mayall 1949; Webbink 1980)

→ but are they actually associated with the GCs?

– 1 in M87 (Shara et al. 2004)

– 2 in M31 (Shafter & Quimby 2007; Henze et al. 2009, 2010; Cao et al. 2012)

→ Implied CV frequency consistent with field population (Cao et al. 2012)

AM CVn Stars: accreting double WDs

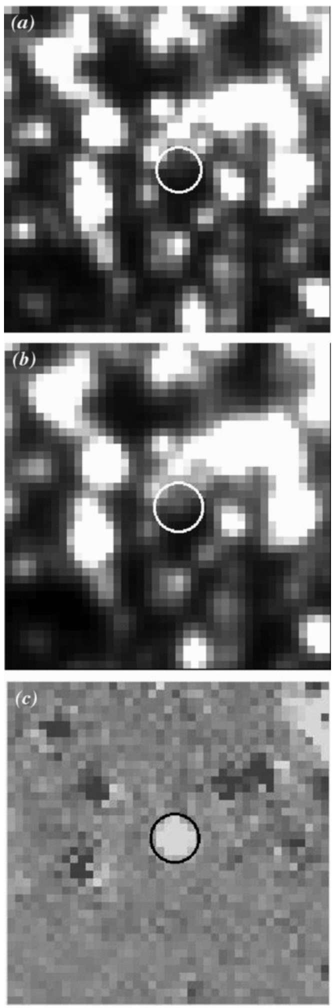
– should exist in sizeable numbers (Ivanova et al. 2007), but not a single one known!

Symbiotic stars: accreting WDs with red giant companions

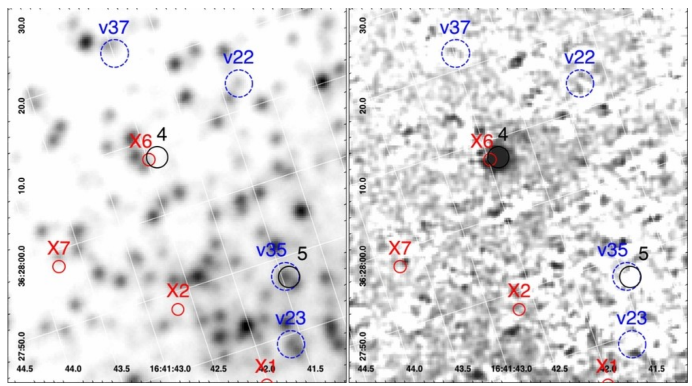
– we may (just) have discovered the first one (Zurek et al. 2014)

Finding CVs in GCs: Variability

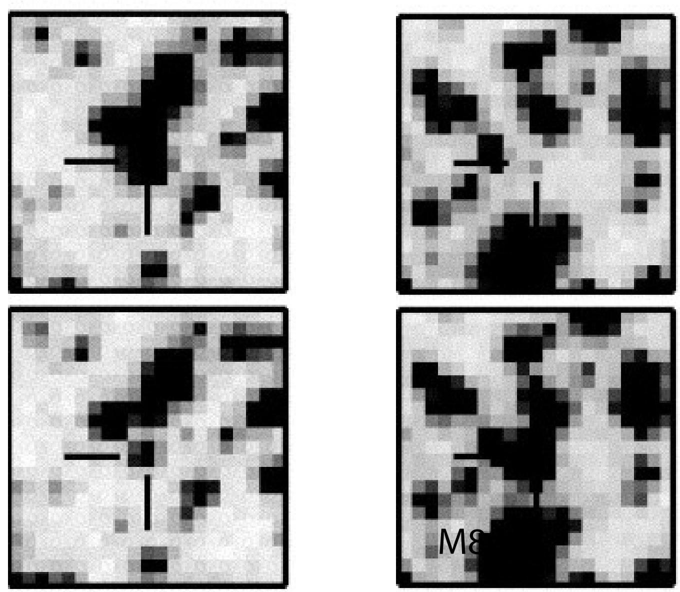
- Some more recent examples



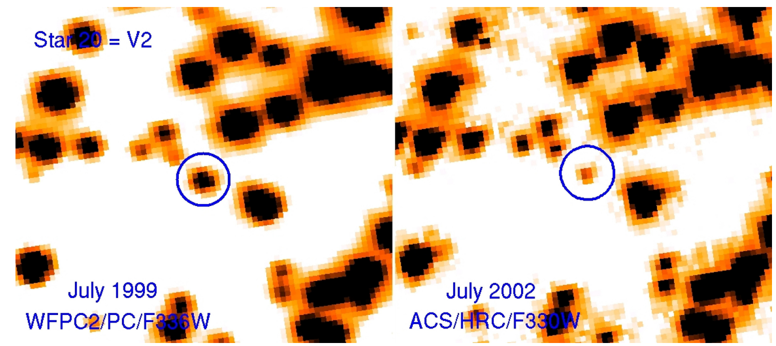
M22 CV1
(Hourihane et al. 2011)



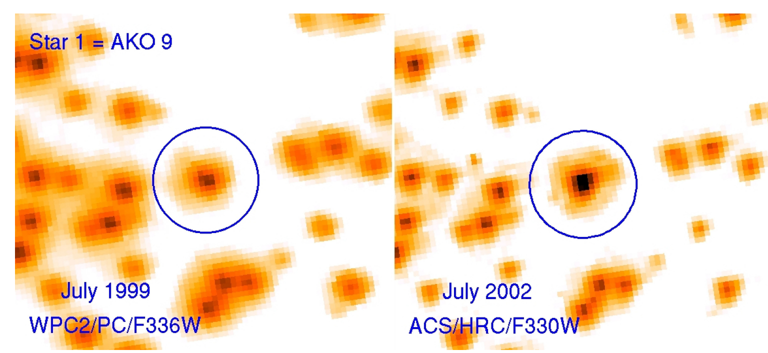
M13 Star 4/X6 (Servillat et al. 2011)



DN1 (Shara et al. 2005) DN2



47 Tuc V2
(Knigge et al. 2008)



47 Tuc AKO9
(Knigge et al. 2008)

Finding CVs in GCs: Variability

- A recent summary by Pietrukowicz et al 2008:
  - Including these, as of 2008, 12 DNe known in all Galactic Gcs

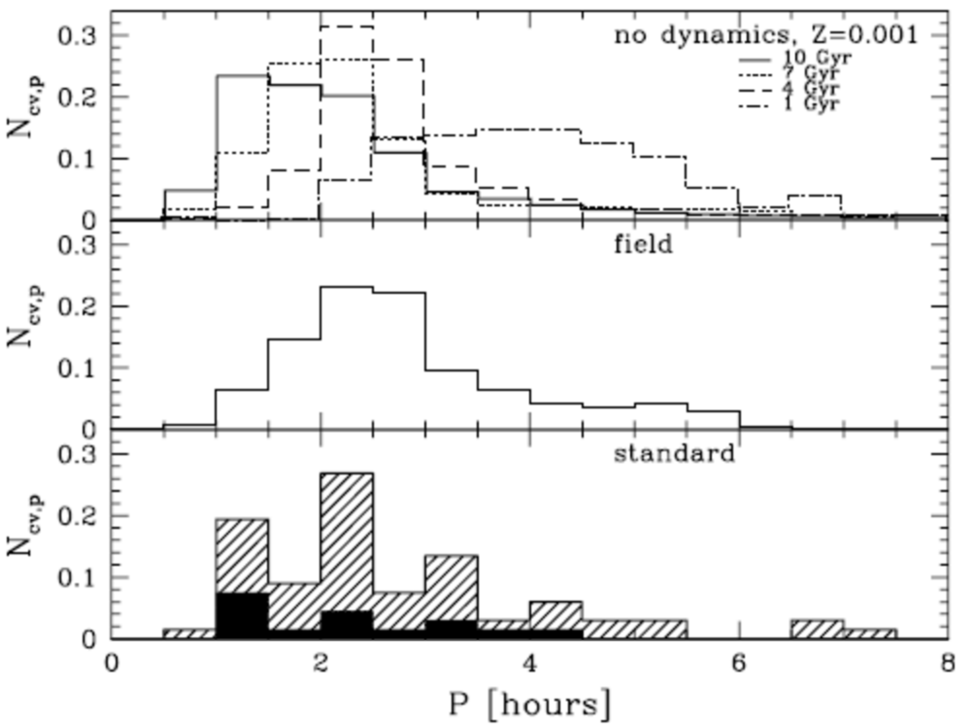
"The results of our extensive survey provide new evidence ... that ordinary DNe are indeed very rare in Gcs."

We will come back to this...

Population Properties: Orbital Periods

Hey,where is the period gap???

Ivanova et al. 2006



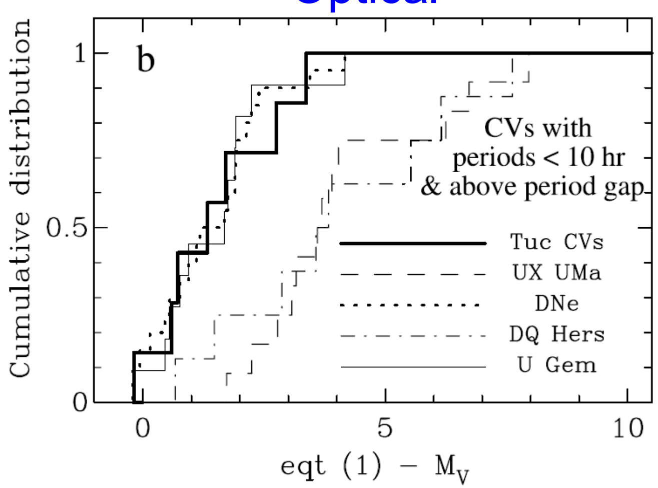
- N(P_{orb}) is the most important empirical tracer of CV formation/evolution
- It also immediately tells us something about a given CV
  - donor:
    - If near MS, P_{orb} immediately gives M_2
  - mass transfer rate:
    - long-period CVs are bright
    - short-period CVs are faint
- In GCs, the P_{orb} distribution will be different
  - low metallicity (Stehle et al. 1997)
  - all primordial CVs are co-eval
  - dynamics will destroy/create CVs (di Stefano, Rappaport & Politano 1995; Ivanova et al. 2006)
  - dynamics will alter (pre-)CV evolution (Shara & Hurley 2006; Ivanova et al. 2006)
- But it is much harder to get P_{orb} for GC CVs

Population Properties: X-ray and Optical

- Let's compare the optical and X-ray properties of CVs in GCs and in the field

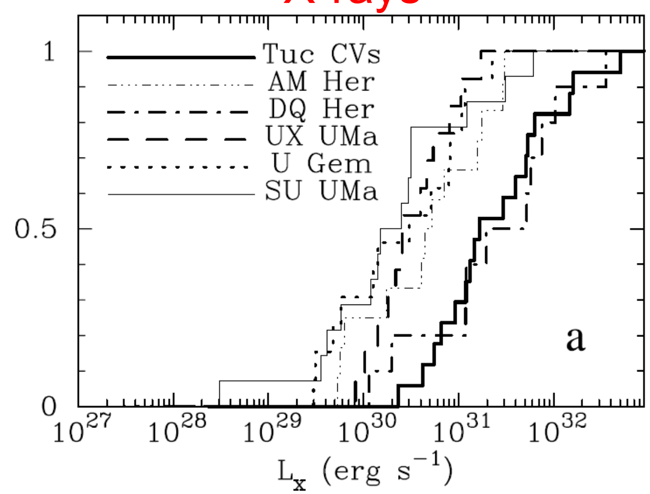
47 Tuc (Edmonds et al. 2003ab)

Optical



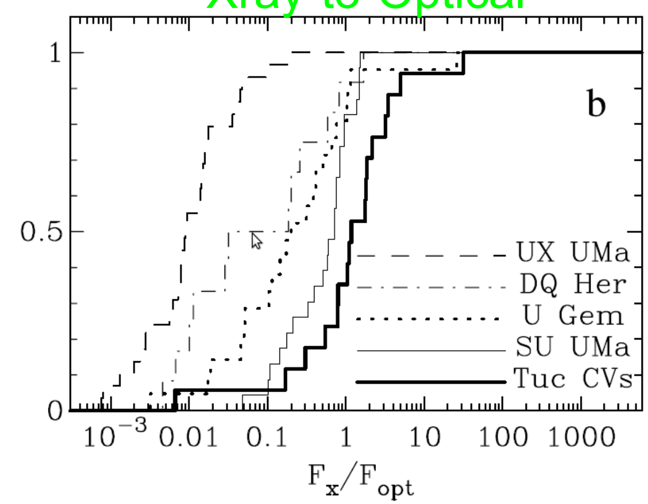
Most like long-period DNe

X-rays



Most like IPs

Xray-to-Optical



Not much like anything

- So does that mean GCs are physically different from field ones?
  - Probably, at least to some extent...
- But let's not forget the role of <u>selection effects</u> here again!

→ The GC sample is purely X-ray selected!

→ The field sample is totally heterogenous!

Population Properties: Are They All Magnetic?

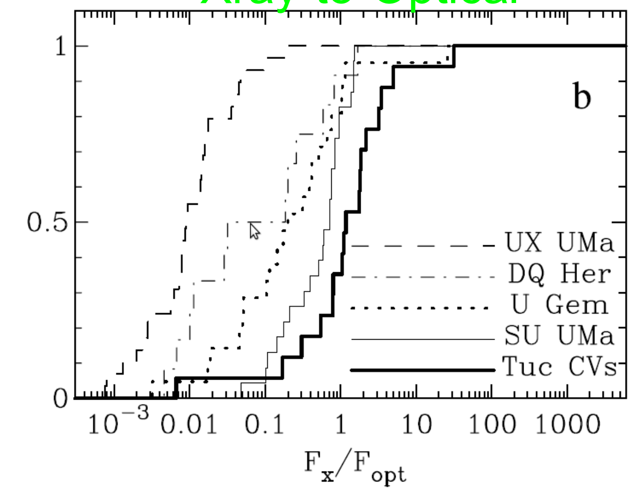
- This idea has nevertheless gained a lot of traction
  - could this account for strange X-ray to optical ratios (e.g. Edmonds et al. 2003ab)

...but optical properties are more like DNe

  - could it also explain the claimed dearth of DN outbursts (e.g. Shara et al. 2005; Dobrotka et al. 2006; Pietrukowicz et al 2008)?

...let's take a closer look at the evidence

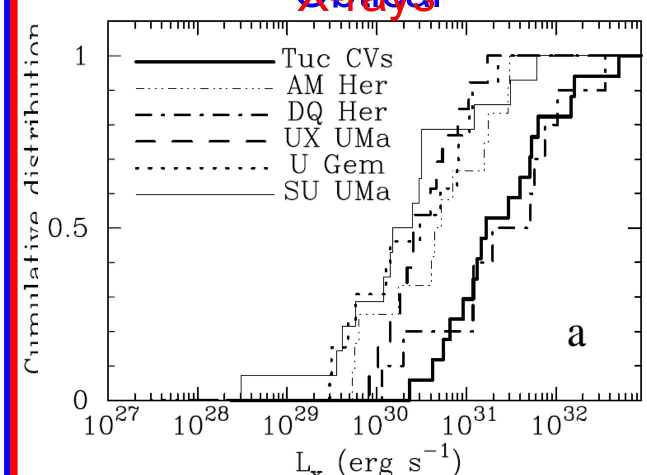
Xray-to-Optical



Not much like anything

Optical

X-rays



Most like long-period DNe

Most like IPs

WD Binaries in GCs: Discussion Points

- Where are the "missing" CVs in GCs?
  - Selection effects?
- Are CVs in GVs different from field CVs?
  - Magnetism? Outburst properties? Period distribution?
- Where are the AM CVns, Symbiotics and detached WD/WD binaries?
  - What's the optimal way to search for these populations?
- Could WD binaries in GCs be a significant SN Ia progenitor population?
  - How do we find out?
- What are the most *fundamental* questions we should focus on?
  - From the CV point of view?
  - From the GC/dynamics point of view?

Why Study CVs in GCs?

- The Globular Cluster Perspective:
  - CVs are key tracers of the close binary populations that drive the dynamical evolution of GCs

    → Important for understanding GC evolution
- The Cataclysmic Variable Perspective:
  - GCs can provide us with sizeable samples of CVs at known distance and (to some extent) age

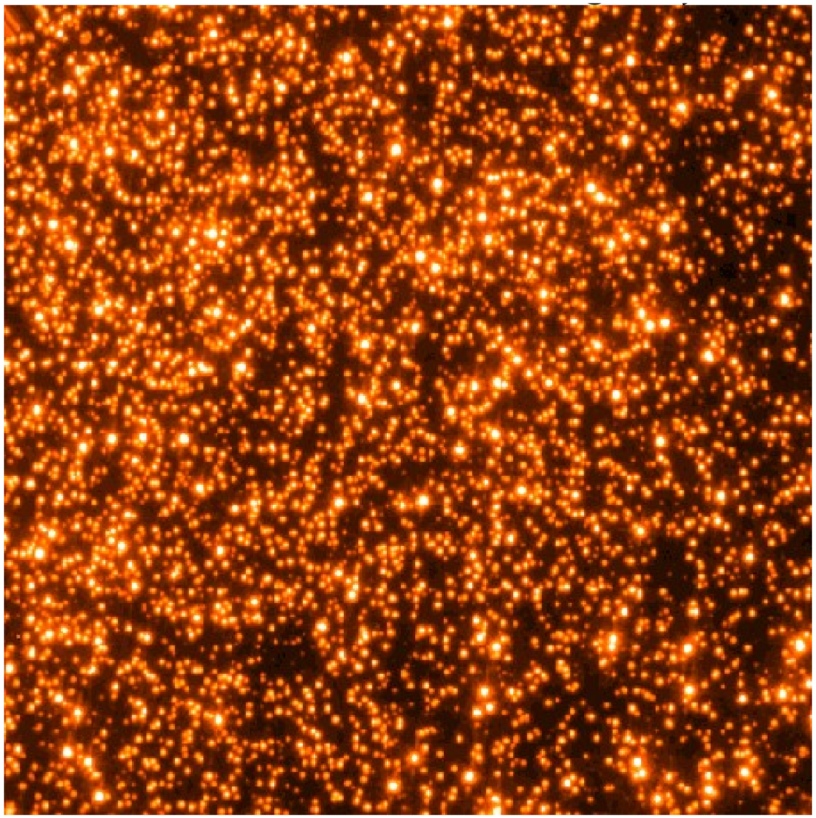
    → Important for understanding CV evolution
- The Supernova/Cosmology Perspective:
  - The dynamical production of accreting WDs in GCs may make these clusters significant SN Ia factories

    → Important for understanding SN Ia and cosmology

Globular Clusters as Dynamical CV Factories

GCs cores are incredibly dense!

The core of 47 Tucanae



Knigge et al. 2002

→ Close encounters are inevitable and will alter the CV populations in GCs

- Direct collisions
  - WD + RG → CV
- Near misses
  - Destruction of wide binaries (including some CV progenitors)
  - Production of tight binaries (including many new CVs)

Are globular cluster cores efficient CV factories?

- Bright LMXBs are known to be ~100x overabundant compared to the field!

.. but the interaction cross-section of a WD is smaller than that of a NS

Finding CVs in GCs: Emission Lines

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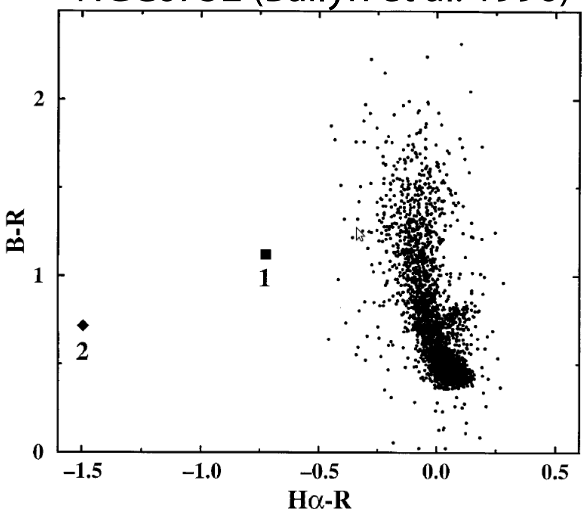
- This method has traditionally meant narrow-band Hα imaging
  - Crowding means that it still usually requires HST
  - Examples:

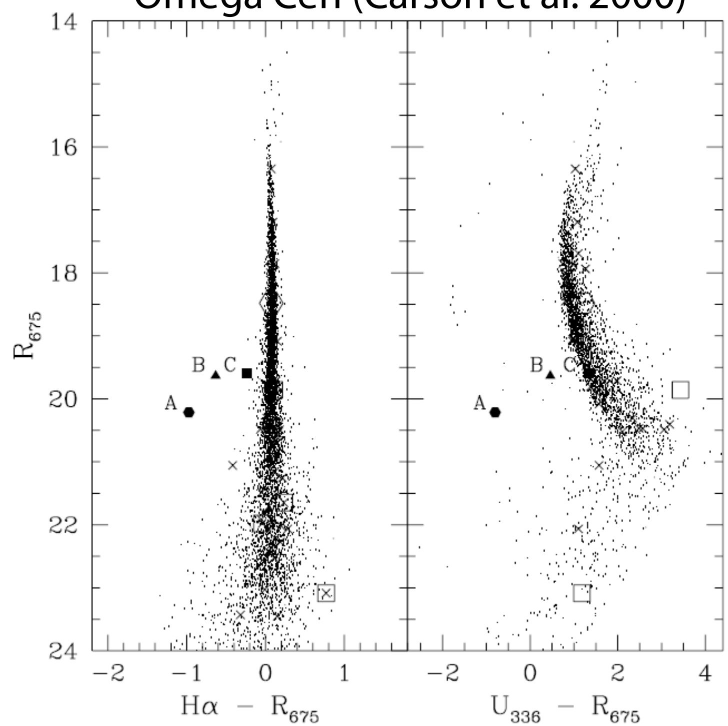
NGC6752 (Bailyn et al. 1996)



CV CANDIDATES

Parameter	Star 1	Star 2
R.A. (J2000)	$19^h10^m51^s.27$	$19^h10^m51^s.18$
Decl. (J2000).....	−59°58′53″	−59°58′49″
B[a]	21.0	21.5
V[b]	20.55	20.89
R[a]	19.9	20.8
I[b]	19.29	19.70
Hα − R[a]	−0.7	−1.5
m_{220} − R[a]	0.9	...
M_V[c]	7.31	7.65

Omega Cen (Carson et al. 2000)



CATACLYSMIC VARIABLE CANDIDATES IN ω CENTAURI

Star	R.A.	Decl.	X Position	Y Position	m_R	$H\alpha - R_{675}$	$U_{336} - R_{675}$
A......	13 26 52.1	−47 29 36.2	392.4	295.9	20.2	−0.97	−0.80
B......	13 26 53.5	−47 29 01.0	265.6	588.2	19.6	−0.63	0.46

Typical yields have been a handful of CVs per cluster...

...a long way from the ~200 predicted!

...we'll come back to this, too!

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Finding CVs in GCs: X-rays

- X-rays are a great way to search for accreting compact objects
  - But it used to be really hard!

- Chandra has revolutionized this!
  - Great Advantages

n

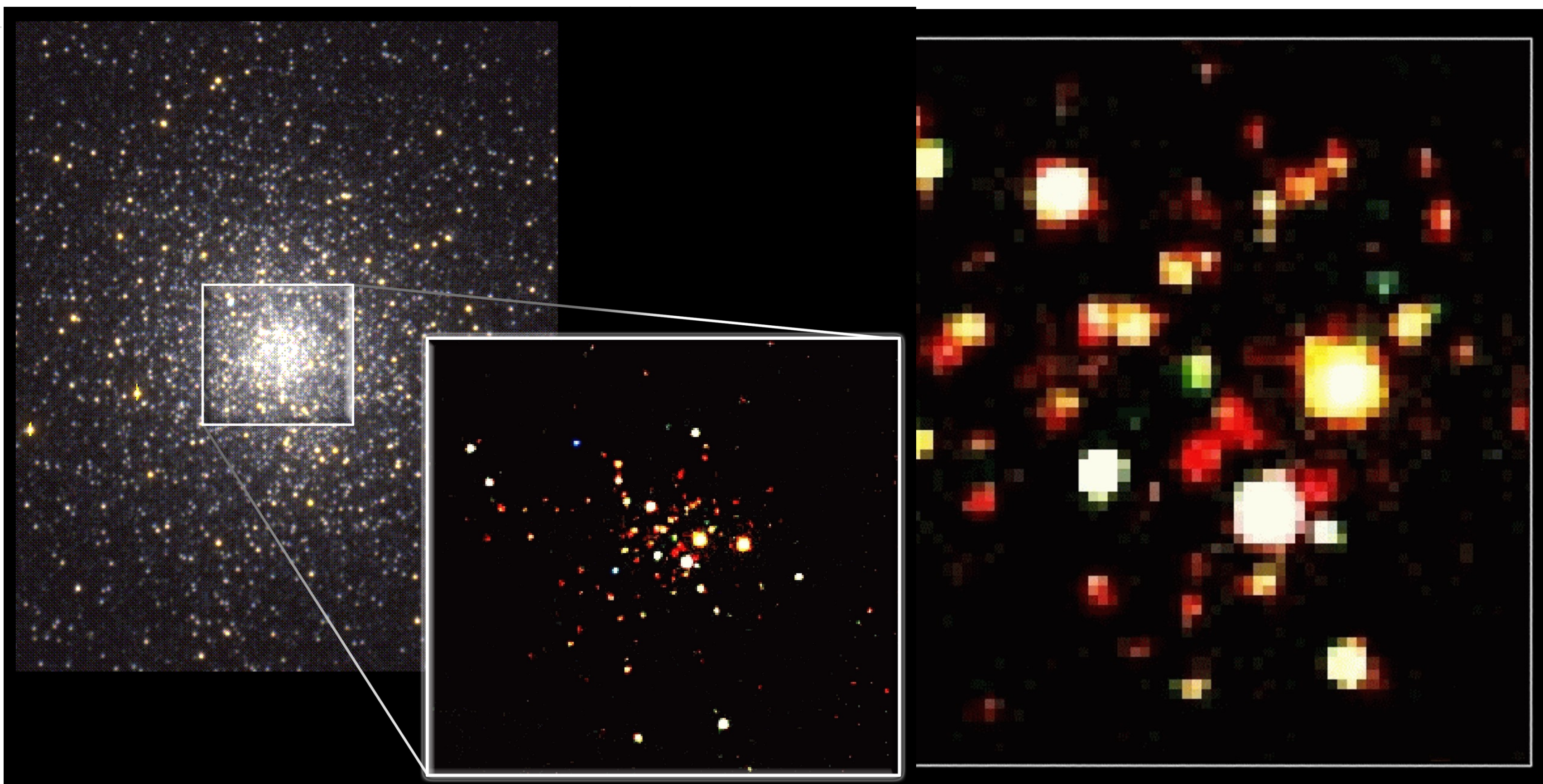
d be CVs

to be sure

down to

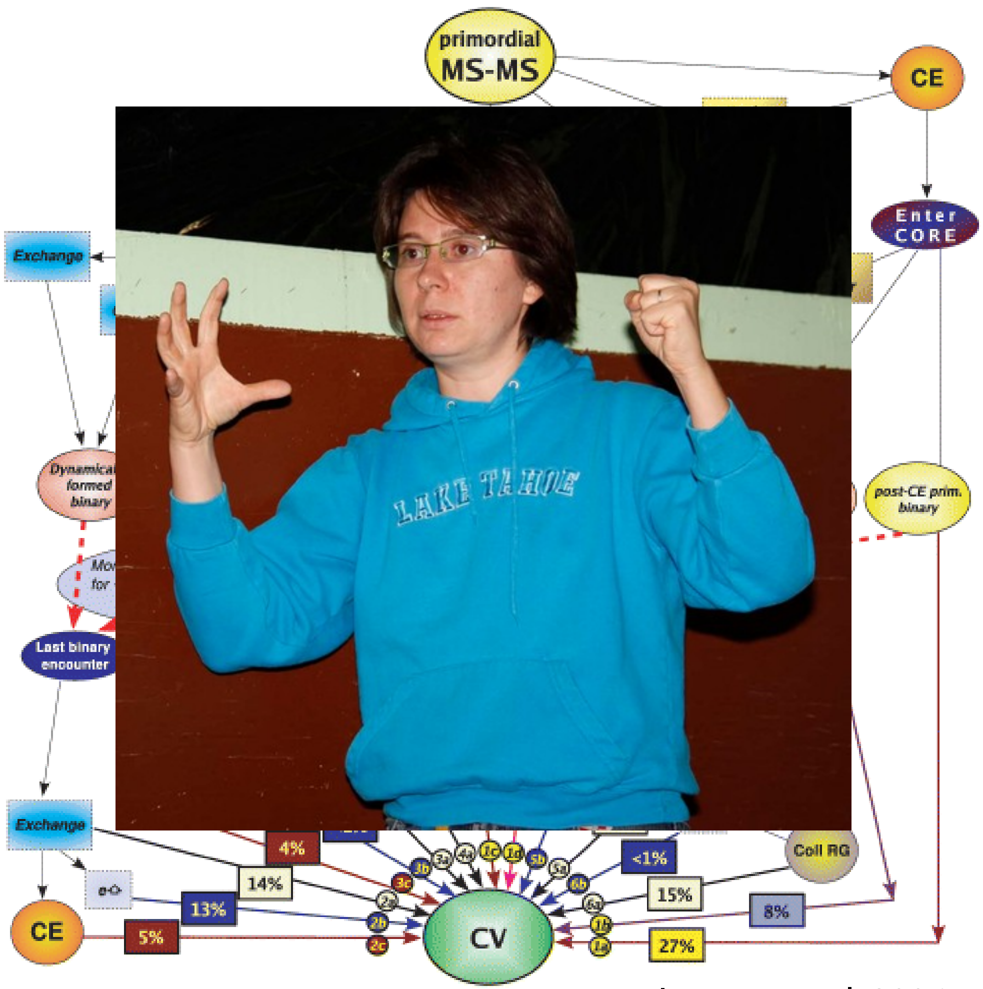
s of CV

47 Tuc with Chandra
(Grindlay et al. 2001; Heinke et al. 2005)



Theoretical Predictions: N Classes of CVs

- Recent theoretical predictions are more, well, *nuanced*...



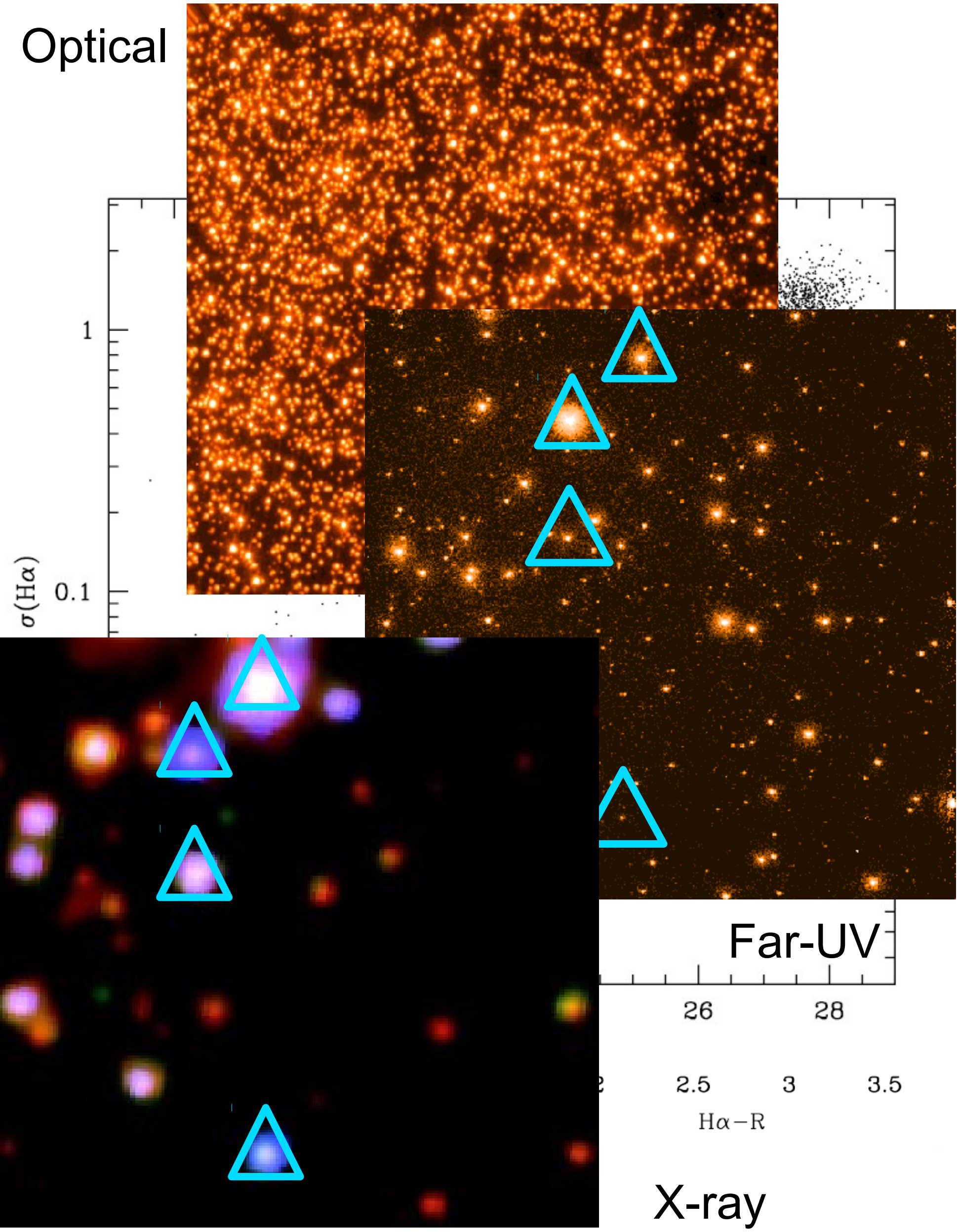
Ivanova et al. 2006

- But the predicted totals have not changed all that much:

$$N_{cv,tot} \sim 200$$ Ivanova et al. 2006

- Things to note:
  - Primordial CVs matter, but survival rate is only 25%
  - CV abundance is enhanced overall, by ~2x, due to dynamical formation
  - 60% of GC CVs did not evolve via a common envelope phase
  - 50% of CVs form in some sort of binary encounter
  - Tidal capture is not important
  - Default model uses non-standard AML recipe (results do depend on that)

Confirming CVs in GCs



- Usually have to settle for "silver standard"

  → confirmation by multiple methods
- Some of this can come almost for free
  - e.g. for confirming X-ray sources via Hα...
  - ...you may as well get multiple broad- band colours (blueness)...
  - ...and use multiple short exposures (variability/flickering)
- This sort of thing has been done for quite a few CV candidates in quite a few GCs, e.g. 47 Tuc:
  - X-rays (Grindlay01, Heinke05)
  - optical imaging (Edmonds03a)
  - optical variability (Edmonds03b)
  - FUV imaging (Knigge02)
  - FUV spectroscopy (Knigge03, Knigge08)
- But it has left us with a highly heterogenous sample of GC CVs!