FUV survey of GCs:

Interacting Binaries in the Globular Cluster M15

Andrea Dieball (University of Southampton, UK)
Christian Knigge (University of Southampton, UK)

D.R. Zurek (AMNH, New York)
M.M. Shara (AMNH, New York)

K.S. Long (STScI, Baltimore)

Phil Charles (SAAO, South Africa)

Diana Hannikainen (University of Helsinki, Finland)

Why IBs in Globular Clusters?

- GCs are old stellar systems with high stellar densities in the core (up to 10^6 stars/pc^3)
- Dynamical interactions inevitable
- Produce exotic stellar populations: Blue Stragglers, CVs, LMXBs
- Close binaries, in turn, play a vital role in the evolution of GCs

Why IBs in Globular Clusters?

CBs play a vital role in the evolution of GCs:

- *Binding energy of a (few) CBs rivals that of a modest GC*

- *GC core get denser due to mass segregation, the timescales depend on the binary population of the cluster*

- *Few CBs → long-term interactions dominate cluster evolution*

- *Many CBs → heat the cluster and cause its expansion and evaporation on significantly shorter timescales*

→ Knowledge of close binary population in GCs is important if we are to understand the evolution of GCs

Formation scenarios of CVs in GCs:

Dynamical interaction:

- *Tidal capture scenario*
  - *originally proposed to explain overabundance of LMXBs in GCs compared to the Galactic field (Fabian et al. 1975)*
- *Three-body interactions: exchange interaction with a primordial binary (e.g. Davies & Benz 1995, Ivanova 2006)*
- *Since WDs are far more common than NSs, we also expect more CVs than LMXBs in GCs*
- *More than 100 CVs predicted in 47 Tuc (Di Stefano & Rappaport 1994, Ivanova et al. 2006)*

Formation scenarios of CVs in GCs:

Evolution of primordial binaries:

(Davies 1997)

- *Primordial binaries produce CVs in the Galactic field*
- *Dynamical interactions with other stars in the dense core of a GC will likely destroy such primordial binaries*
- *In low-dense regions (cluster outskirts) such primordial binaries might survive*

Townsley & Bildsten 2005:

all CVs in 47 Tuc can be explained by primordial binaries

Pooley & Hut 2006:

no of X-ray sources scales with encounter rate rather than with mass, all CVs in 47 Tuc have dynamical origin

→ Still ongoing discussion!

Why FUV?

- *Exotic stellar populations show a SED bluer than that of other cluster members*
- *MS & red giants too cool to show up*

→ crowding is not an issue in the core region!

→ FUV is ideally suited to detect and study these hot stellar populations!

But: so far only very few FUV studies

- *FUV counterparts to known CVs, confirm their status and detect new ones (47 Tuc)*
- *Study HB morphology in the FUV (NGC 2808)*
- *BS sequence*
- *WD and CV candidates*

Why M15?

- One of the oldest and most metal-poor GCs
- Compact core
- Core-collapsed?
- IMBH or concentration of compact stellar objects?
- Only GC with 2 LMXBs!

- Other interesting stellar populations: BSs, RRLyrae, SX Phoenicis, Cepheids, MSPs, BHBs & EHBs

From observational point of view:

- Small core
- Low reddening!

→ less expensive in observing time

The data:

- *HST ACS*
- *SBC FUV:*

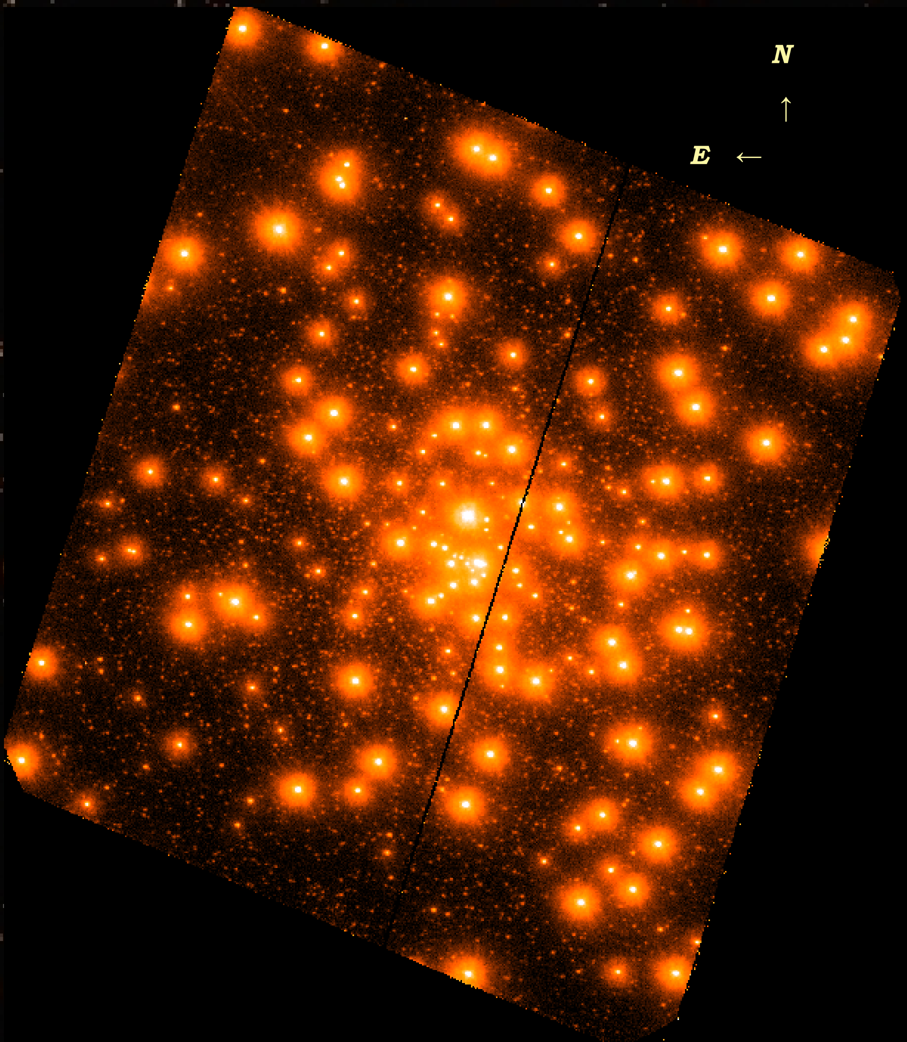
  10 orbits (spread over 3 months) F140LP

  1 orbit F150LP, 1 orbit F165LP
- *HRC NUV:*

  1 orbit F220W

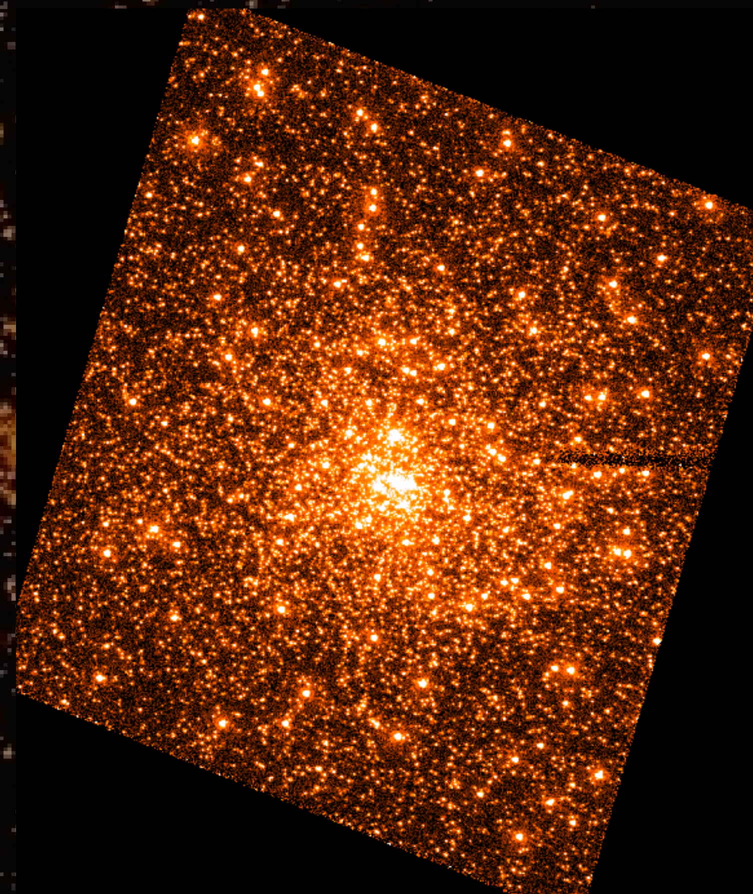
→ *we're limited by our NUV data*

FUV



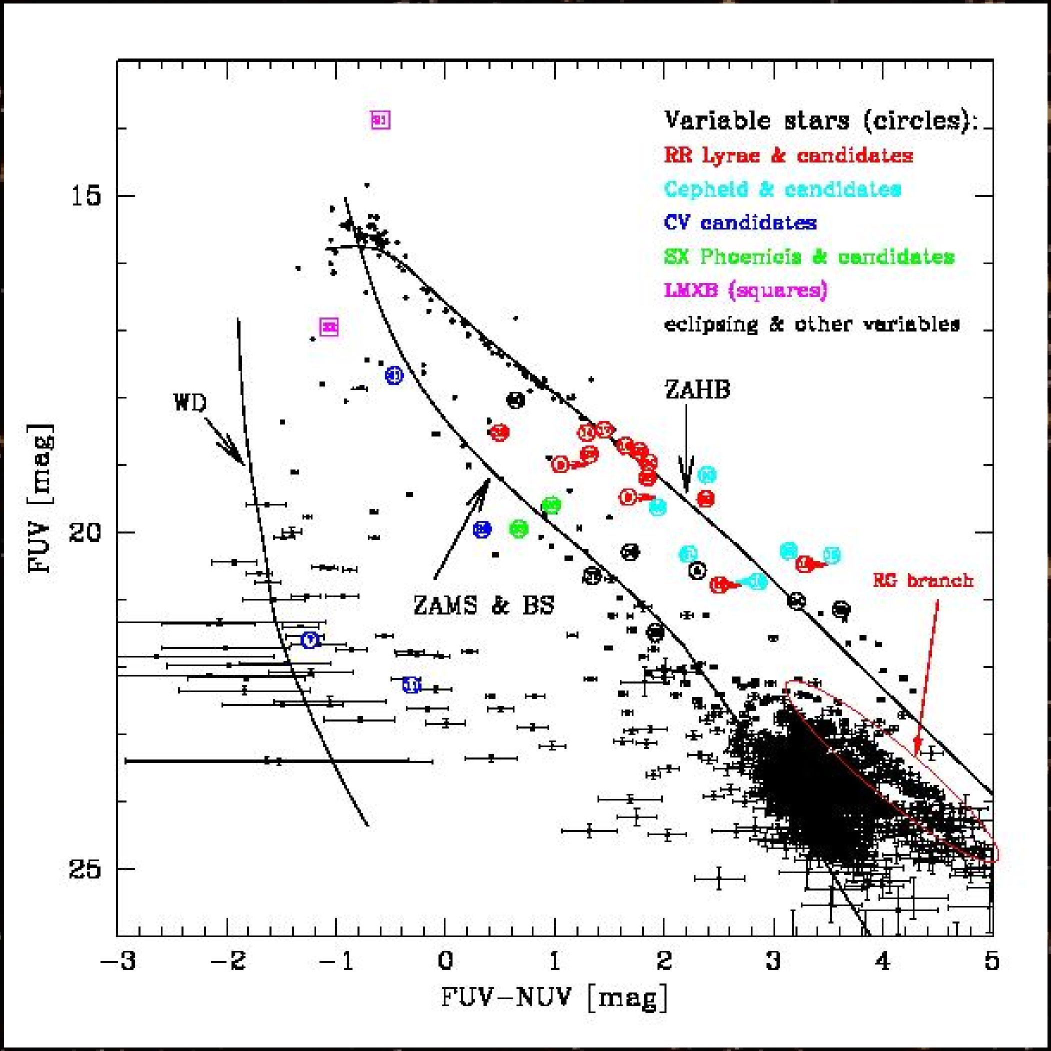
31”

NUV



26”

The FUV-NUV CMD:



- 2731 FUV sources
- 9164 NUV sources
- 2137 common sources

- BS & HB sequences
- WDs
- gap sources → CVs & MS-WD binaries
- MS & red giants

→ deepest FUV-NUV CMD of a GC so far!

White Dwarfs:

- 25 WD candidates with FUV ≤ 22.5 mag

How many WDs can be expected?

- Scale from no. of HB stars
  (133 BHB & EHB)
- HB lifetime ≈ 10^8 yrs
- WD in M15 at FUV≈ 22.5 mag:
  T_{eff} ≈ 26,000K & cooling age ≈ 4*10^7 yrs

→ ≈ 50 WDs can be expected

→ most of our candidates are indeed WDs

Cataclysmic Variables:

- ≈ 60 gap sources in our CMD

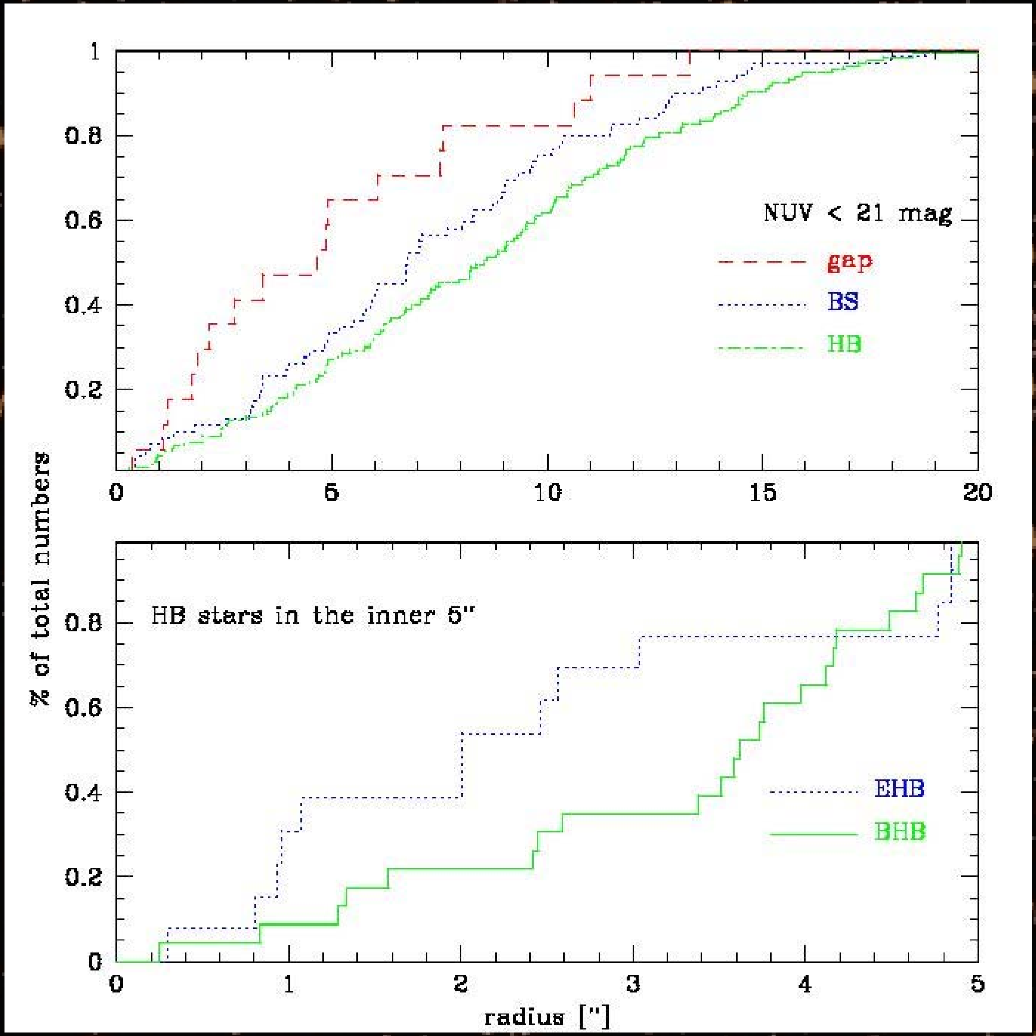
How many CVs can be expected?

- *In 47 Tuc, ≈ 200 dynamically formed CVs are expected (Di Stefano & Rappaport 1994, Ivanova et al. 2006)*

- *Scale with central luminosity density and core radius:*
  $\Gamma \sim \rho^{1.5} * r_{core}^2$ *(Heinke et al. 2003)*

Given our detection limits and FOV, we expect 10–20 CVs
→ some, but not all, gap sources are CVs

Radial Distribution:



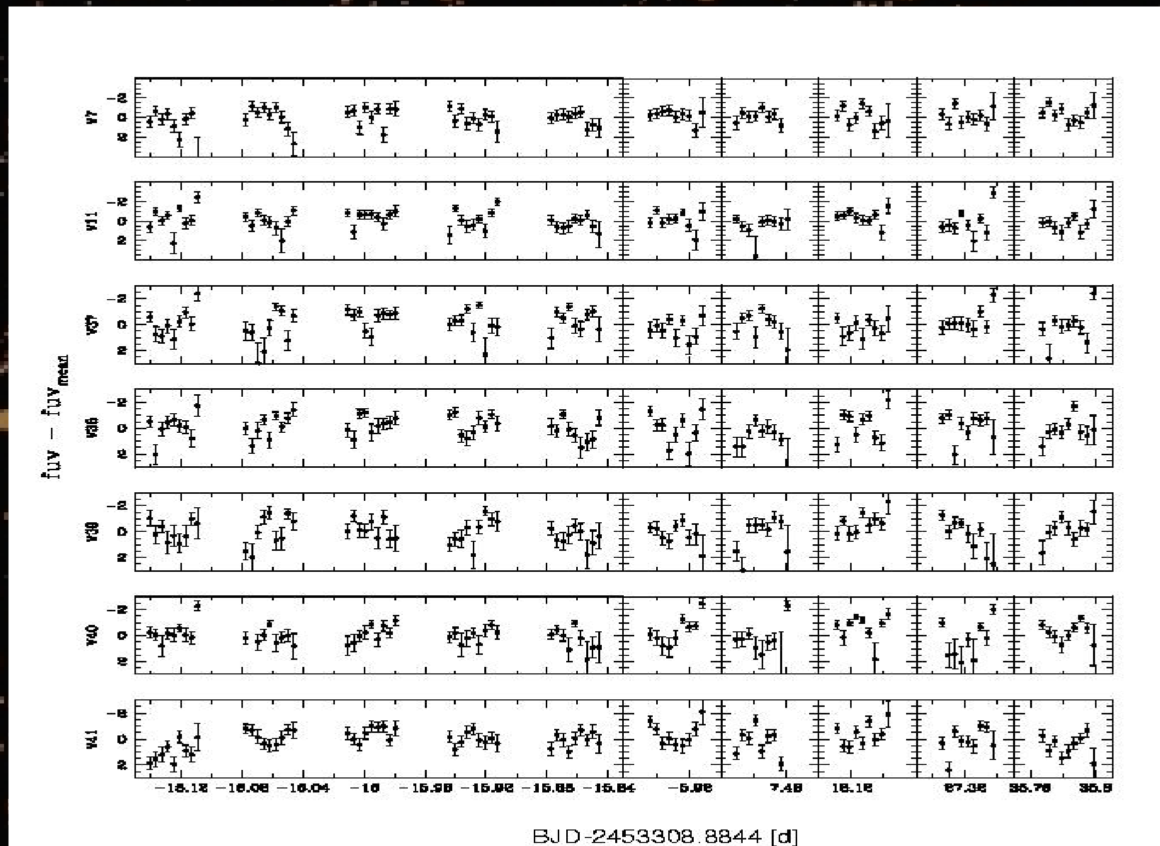
- *gap sources are the most centrally concentrated*
- *BS more centrally concentrated than HB*

→ mass segregation?

→ preferred birth place?

- *EHB more concentrated than BHB in the cluster core → dynamical origin, i.e. WD mergers?*

CV lightcurves:



- *Short timescale variation with a few tenths mags*

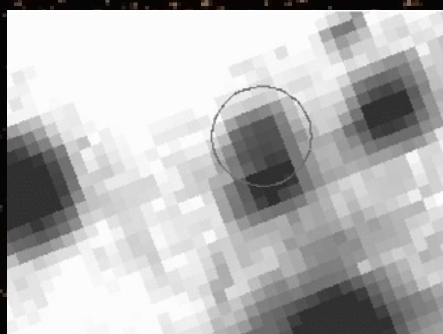
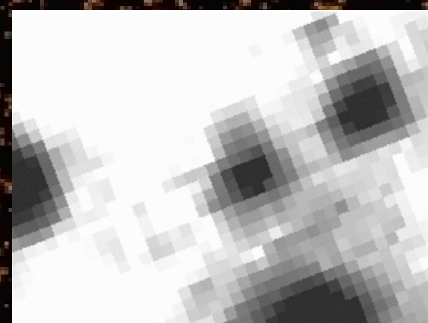
→ Flickering (common in CVs)

Suspected dwarf novae:

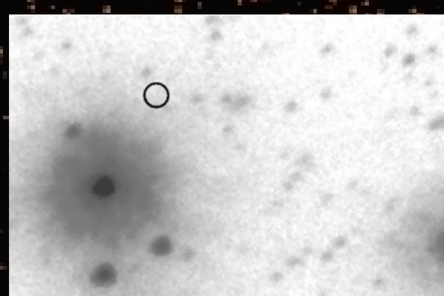
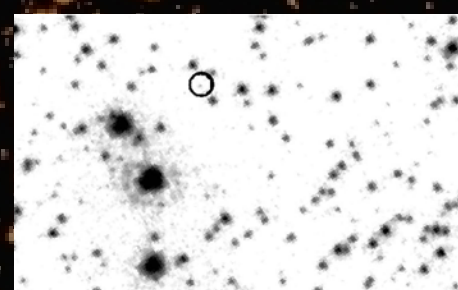
Two faint X-ray sources within our FOV

(Hannikainen et al. 2005)

- HCV2005-A: only detectable in our fourth FUV observing epoch, too faint in the master image


- HCV2005-B: only in NUV image

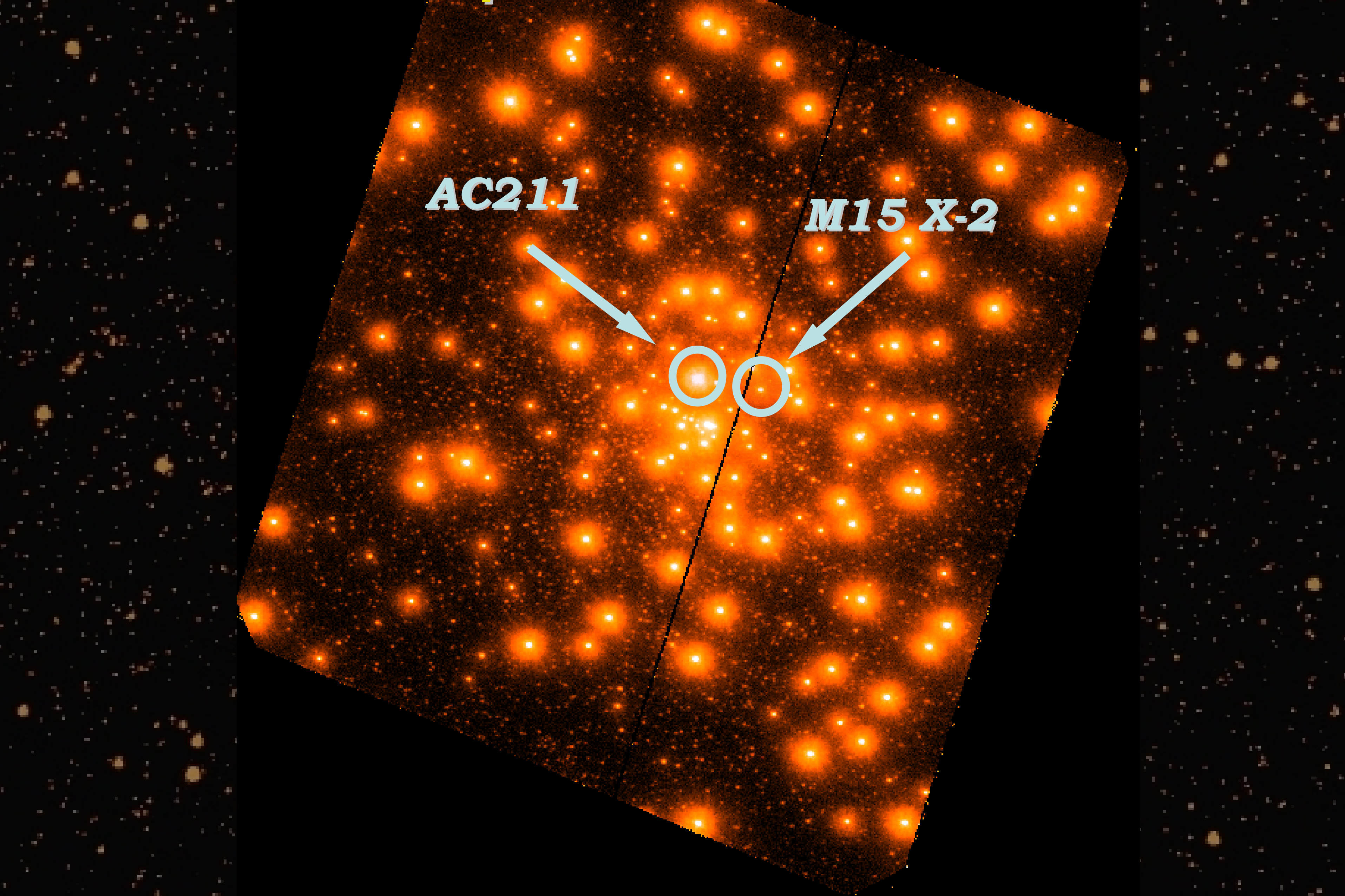



LMXBs in M15: AC211 & M15 X-2

- *Early observations suggested just one X-ray bright source: 4U 2127+119*
- *Accretion disc corona source*
- *1988, 2000: 2 bright X-ray bursts → NS directly observed*
- *Chandra data revealed 2 X-ray sources, separated by only 2.7”* *(White & Angelini 2001)*
- *New source: CXO J21298.1+121002 or M15 X-2 ≈2.5× brighter than AC211*

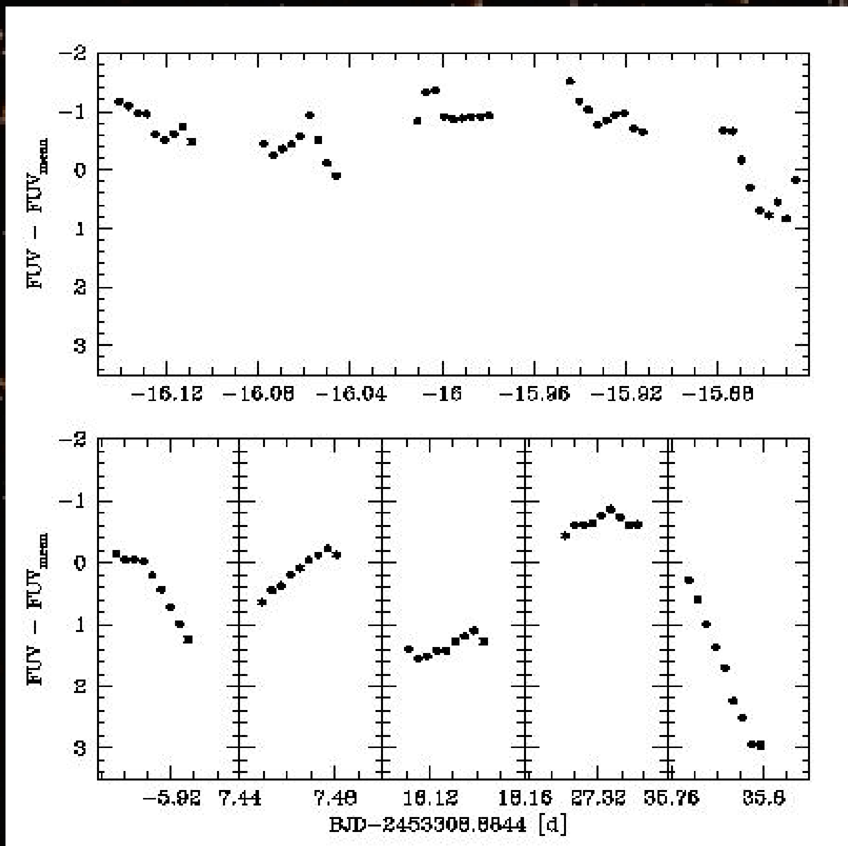
→ M15 only GC with 2 LMXBs

FUV counterparts to AC211 & M15 X-2:

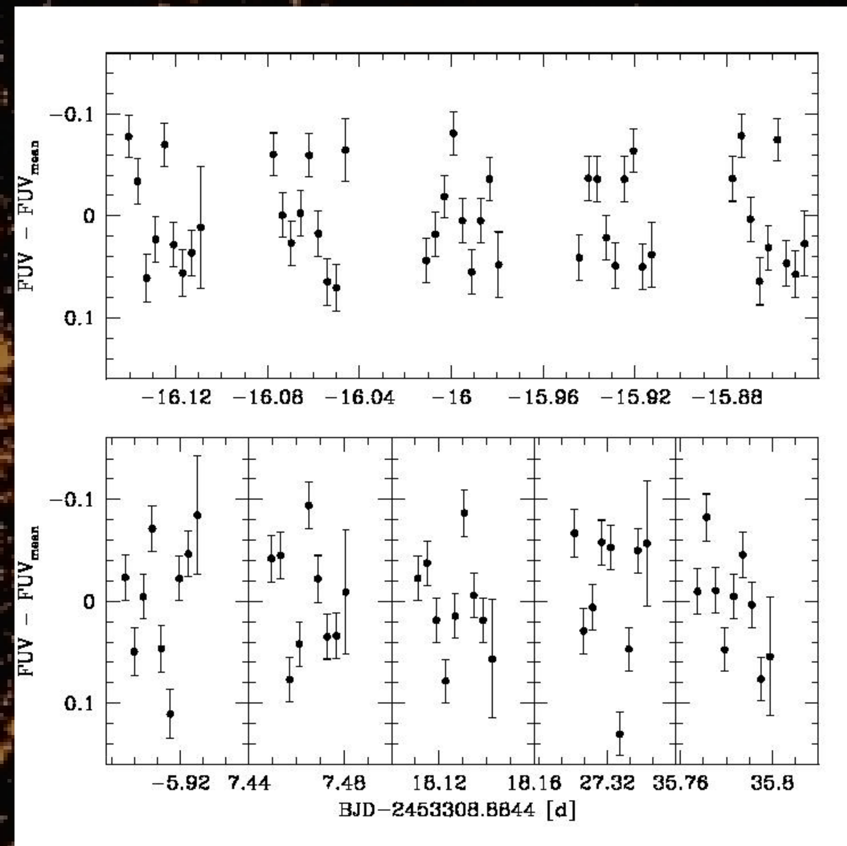


Lightcurves of AC211 & M15 X-2:

AC211



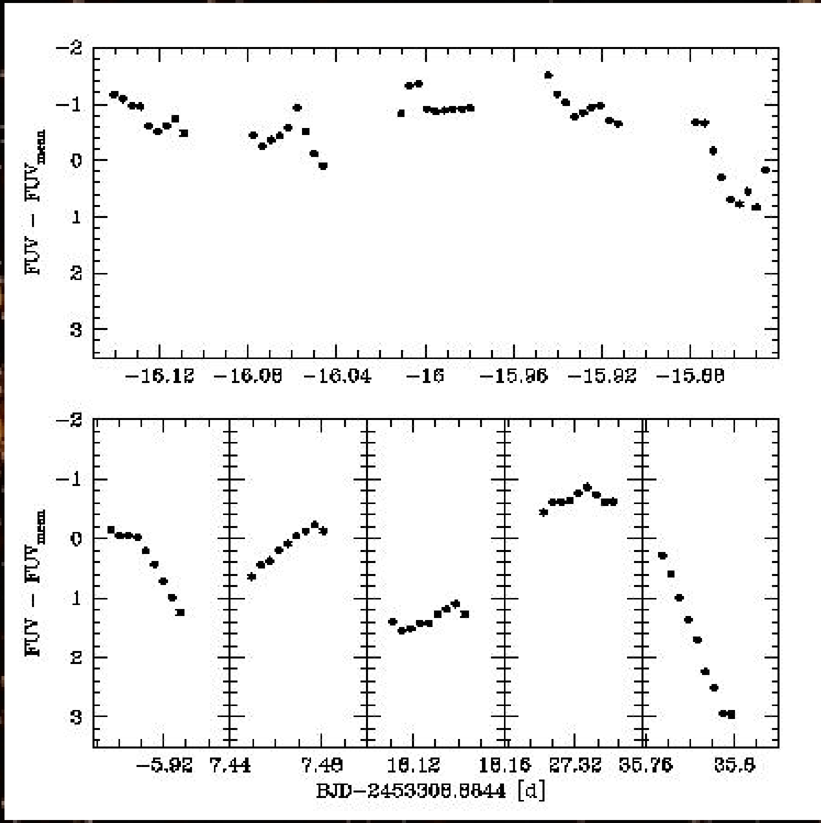
M15 X-2



- *Both LMXBs clearly variable*
- *Note the different amplitudes!*

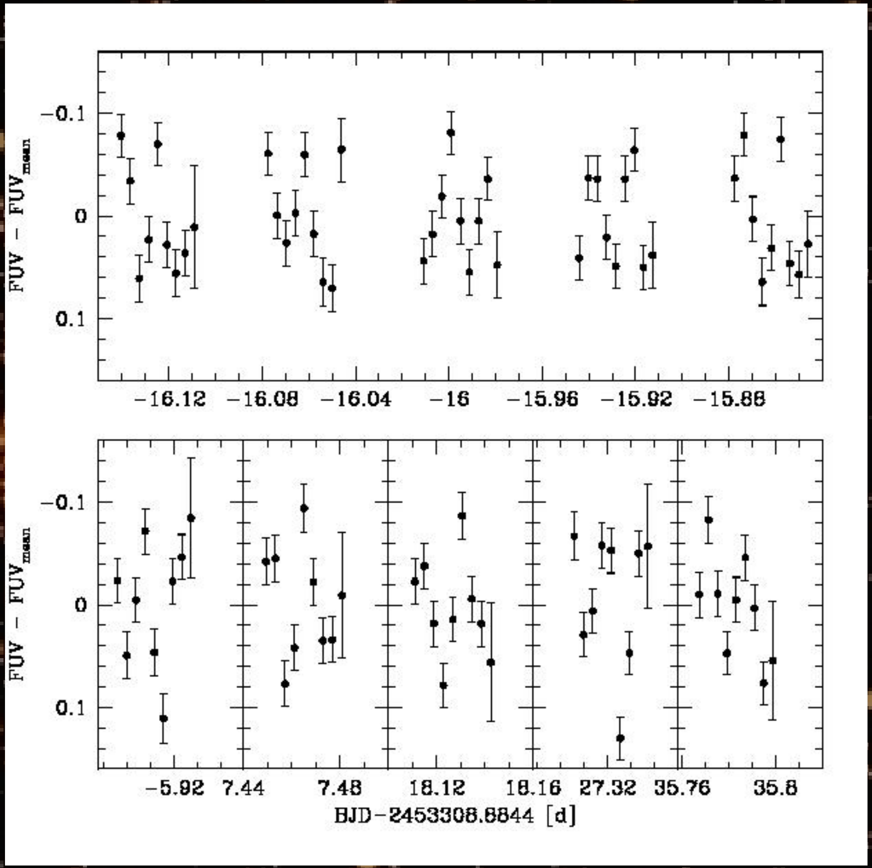
AC211:

- One of the optically brightest LMXBs know (U = 15.53 mag)
- Is the brightest FUV source in our CMD (FUV = 13.88 mag)
- Lightcurve indicates eclipse in our last epoch
- AC211: period 17.1 hrs
  (Ilovaisky et al. 1993)



M15 X-2

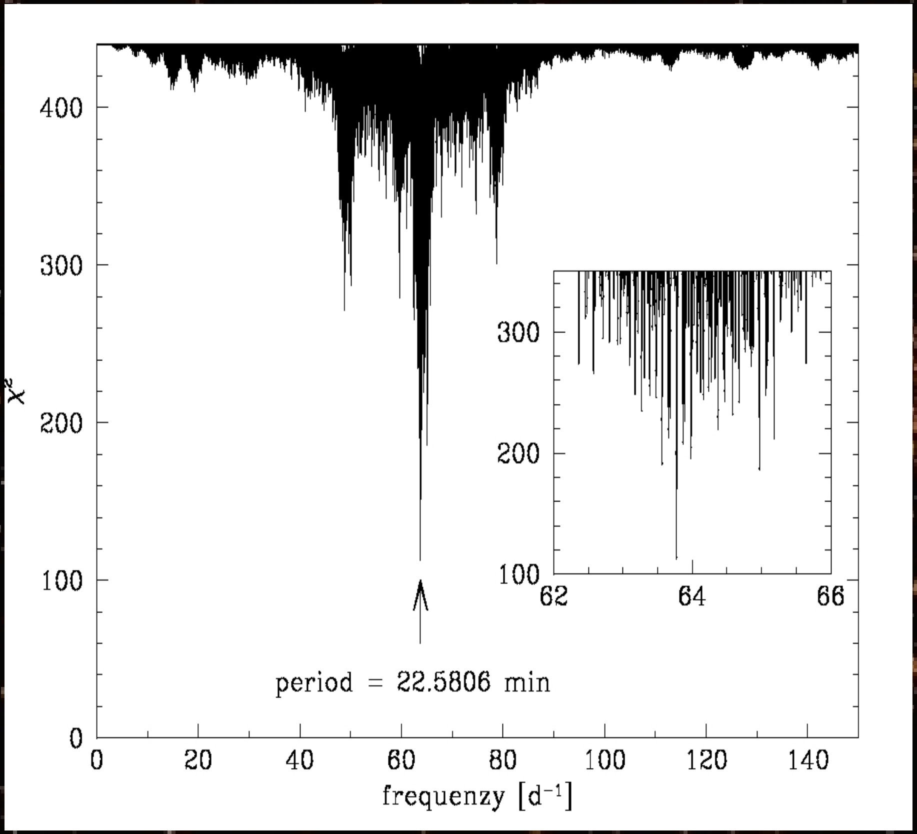
- *Semi-amplitude < 0.1 mag*
- *Variability on much smaller timescale*
- *FUV = 16.96 mag*
- *U = 19 mag*
- *Suspected UCXB due to its L_X/L_{opt} ratio*



Ultracompact X-ray binaries

- *UCXBs are a subclass of LMXBs*
- *tight (10^{10} cm orbit) interacting binaries*
- *consisting of a NS (BH?) and a low-mass (<0.1 $M_{\odot}$) degenerate companion*
- *periods < 80 min*
- *might be preferentially formed in dense globular cluster cores*
- *are most LMXBs in GCs UCXBs? (e.g. Homer 2003)*

The period of M15 XB-2:

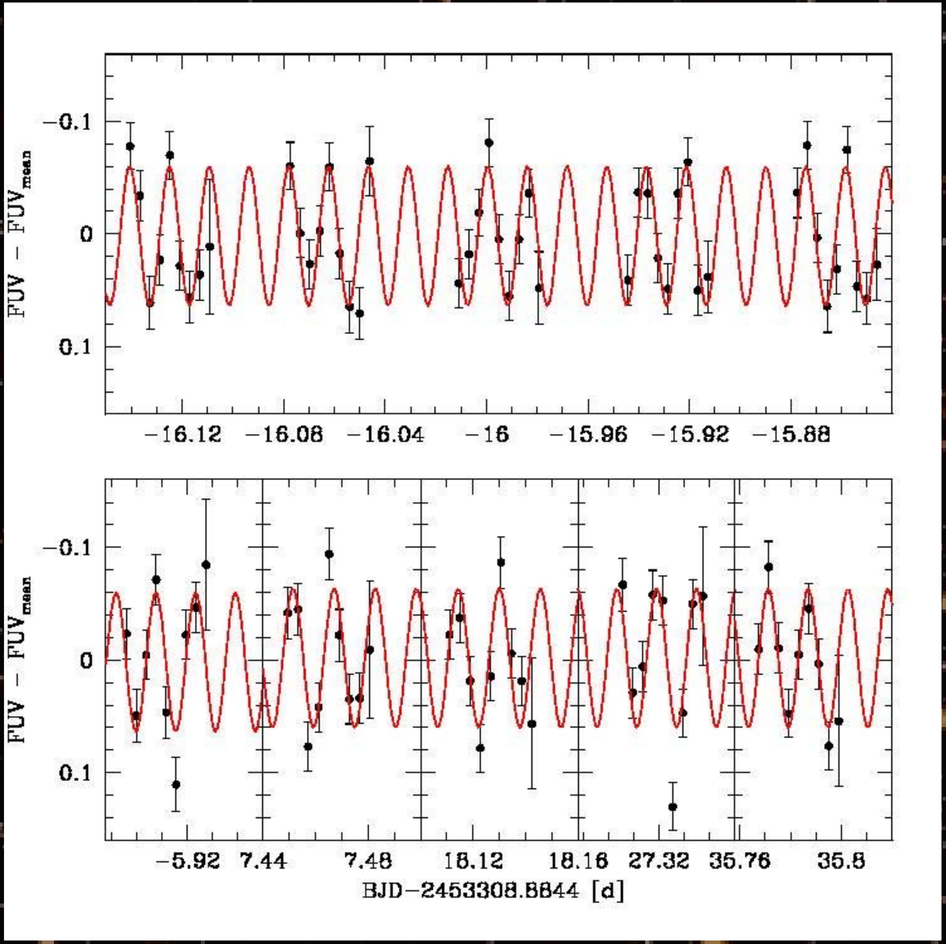


- Relative photometry from 90 images, covering 3 months
- χ^2 fits to trial frequencies

→ periodogram peaks at 22.58 min

- Extensive Monte Carlo simulations: signal is consistent with being coherent over entire time coverage

The period of M15 X-2:

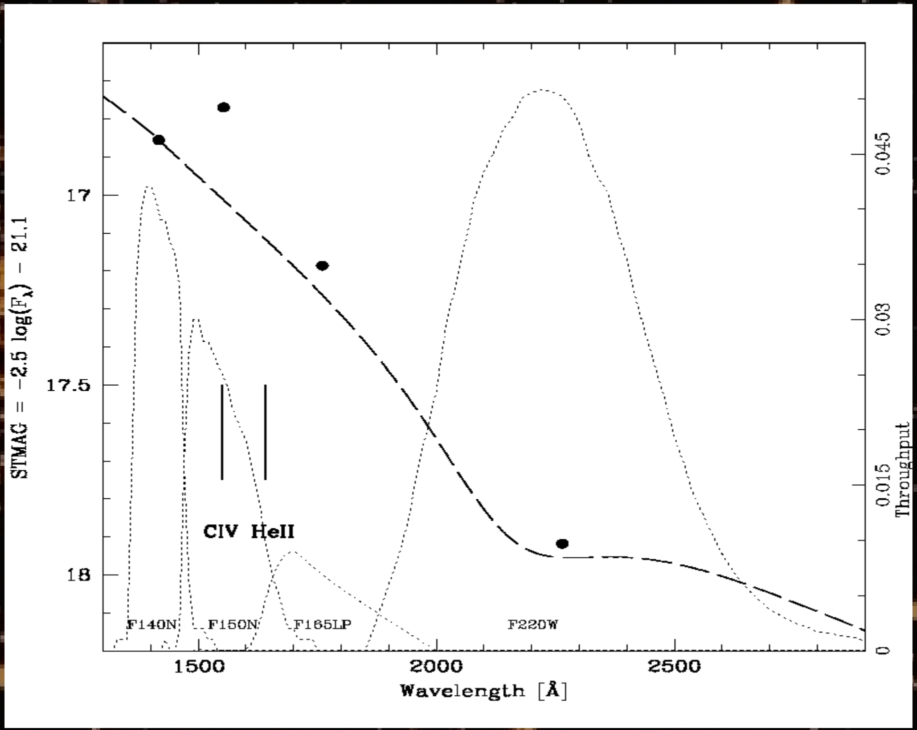


- *Sine wave with 22.5806 min period*
- *Fit coherent over 3300 cycles*

The Spectral Energy Distribution:

- *SED from additional narrow band photometry*
- *SED rises towards bluer wavelengths*
- *Can be fitted with Power law $F_\lambda \sim \lambda^{-2.0}$*
- *Excess flux in F150N*

→ additional C IV (λ = 1550 Å) and He II (λ = 1640 Å) line emission

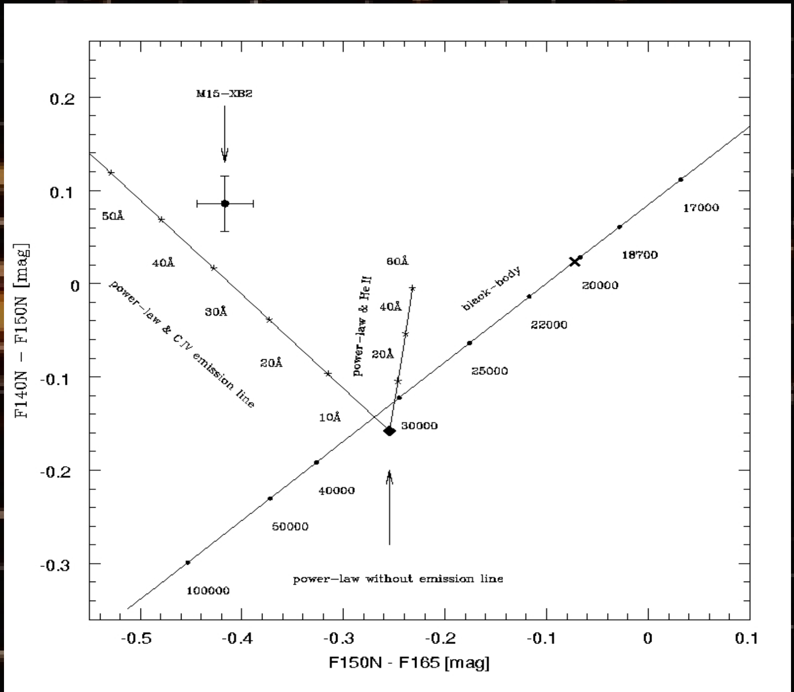


Evidence for line emission:

Peak in SED might either be caused by additional line emission, or by a turnover in an otherwise smooth continuum

Colour colour diagram:

- *Blackbodies*
- *Power law with C IV emission*
- *Power law with He II emission*



→ *SED best described with power law (index -2.0) + C IV 1550 EW ≈ 30 Å + He II 1640 EW ≈ 30 Å*

M15 X-2: geometry of the system

- *For small mass ratio, density of donor is a function of P_{orb} mainly (Eggleton 1983)*
  → consistent with a low-mass WD
- *Mass-radius relationship (Deloye & Bildsten 2003)*
  → minimum donor mass 0.02 – 0.03 $M_{\odot}$
  → minimum donor radius 0.03 – 0.04 $R_{\odot}$
- *Binary separation 2.1×10^{10} cm*

M15 X-2: geometry of the system

- BB with $T_{eff} = 32000$ K → $r_{BB} \approx 0.1\ R_{\odot}$ Accretion disk $r_{circ} \approx 0.2\ R_{\odot}$

→ FUV light from accretion disk, not WD

- Inclination angle ≈ 30° (Arons & King 1993)
- $L_X \approx 1.4 \times 10^{36}$ erg sec^{-1} (White & Angelini 2001)
  → accretion rate $\delta M/\delta t > 10^{-10}\ M_{\odot}\ yr^{-1}$
- Accretion rate from mass transfer driven by gravitational radiation:
  → $2.4 \times 10^{-10}\ M_{\odot}$ yr-1

→ Observed X-ray emission can be powered by gravitational radiation-driven mass transfer

Summary:

- FUV extremely useful to detect and study IBs and other exotic stellar population in GCs
- Gap sources include some CVs
- Gap sources & BS most centrally concentrated
  - mass segregation?
  - Preferred birth place?
- Both LMXBs are (among) the brightest FUV sources and are clearly variable

Summary:

- *M15 X-2:*
  - *Period of 22.58 min*
  - *SED best described with power-law with α = -2 and additional C IV and He II line emission*
  - *FUV light comes from the accretion disk*
  - *X-ray emission powered by gravitational radiation-driven mass transfer*

→ 3rd confirmed UCXB in a GC

Dieball et al. 2005, ApJ 634, L105
Dieball et al. 2007, ApJ submitted