Study of HST counterparts to Chandra X-ray in the Globular Cluster M71

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Outline

- Introduction -- X-ray sources in GCs
- X-ray and optical observations of M71
- Source identifications
- Summary and discussion

Globular Clusters

- The high stellar densities in globular clusters trigger various dynamical interaction:

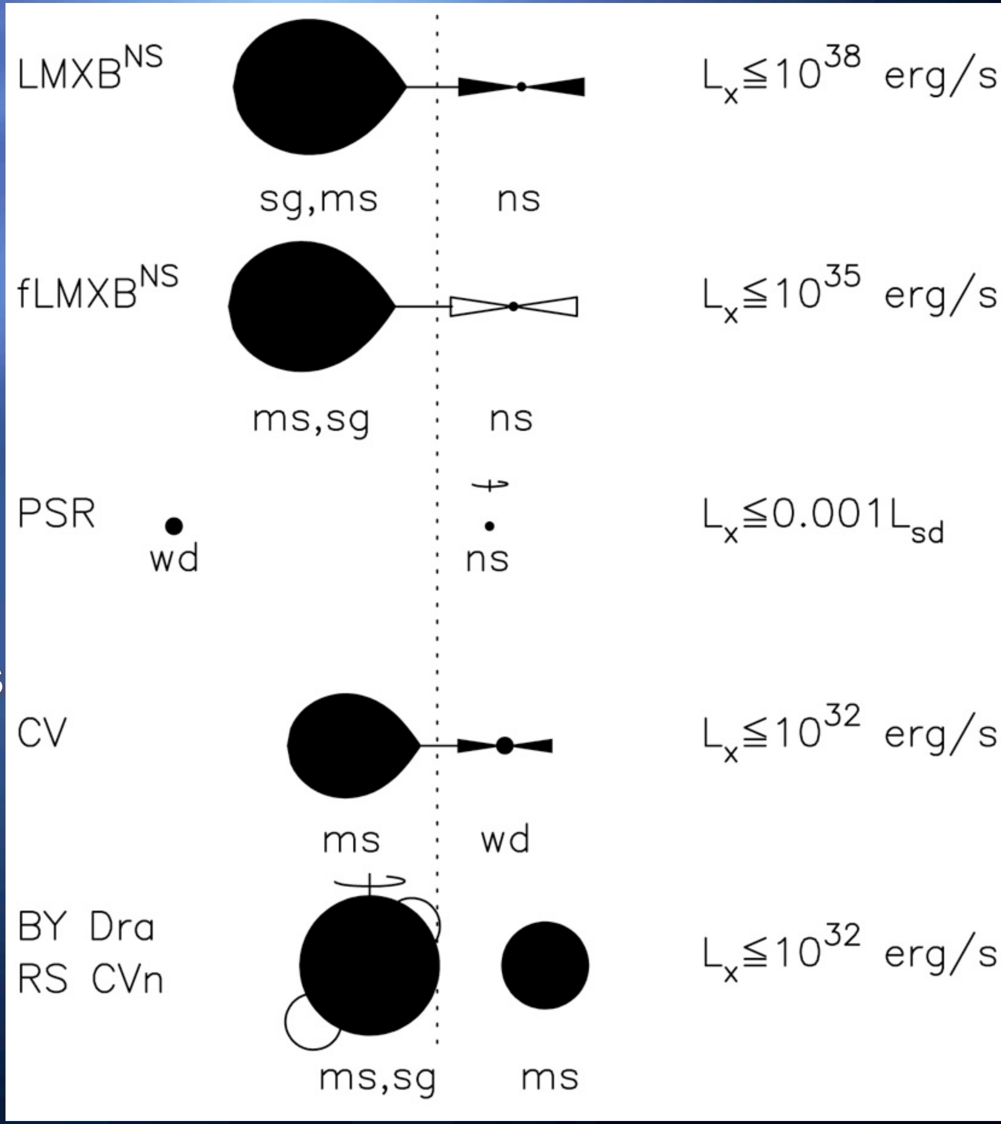
  exchanges in encounters with binaries,

  direct collision, destruction of binaries,

  and tidal capture.
- Globular clusters are very efficient in forming binaries, such as LMXBs, CVs, ABs, MSPs, blue stragglers.

Possible X-ray sources in GCs

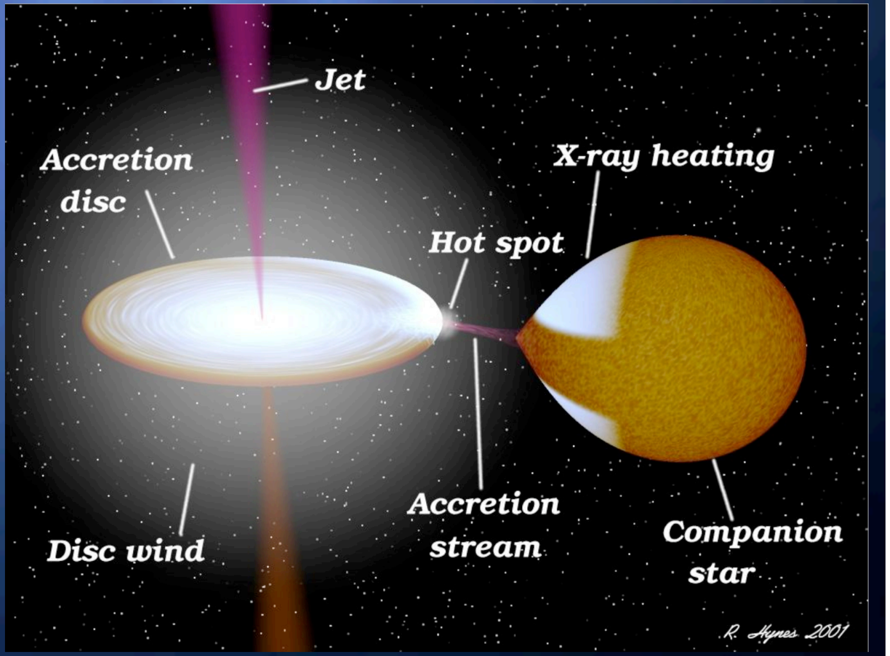
- Bright X-ray sources ($L_x > 10^{36}$ erg/s):
  - Low-mass X-ray Binaries (LMXBs)
- Dim X-ray sources ($L_x < 10^{34.5}$ erg/s):
  - qLMXB
  - Cataclysmic variables (CVs)
  - Millisecond pulsars (MSPs)
  - X-ray active binaries (ABs)
- Background AGNs and foreground stars



Low-mass X-ray Binaries (LMXBs)

- Low-mass X-ray binaries consist of either a neutron star or a black hole primary, and a low-mass secondary which is filling its Roche lobe.

- Due to the intense gravity of the compact object, the material from the companion is pulled into an accretion disk around the compact object though Roche lobe overflow and spirals into the compact object. This process heats up the material in the disk to the temperature of more than 10^6 K and emits X-rays. When actively accreting, the X-ray luminosity of LMXBs reach ~ 10^{36} - 10^{38} ergs/sec.

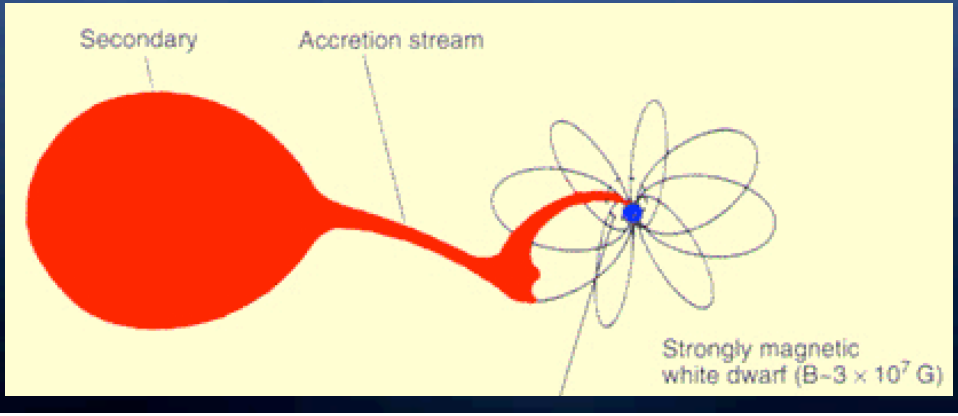


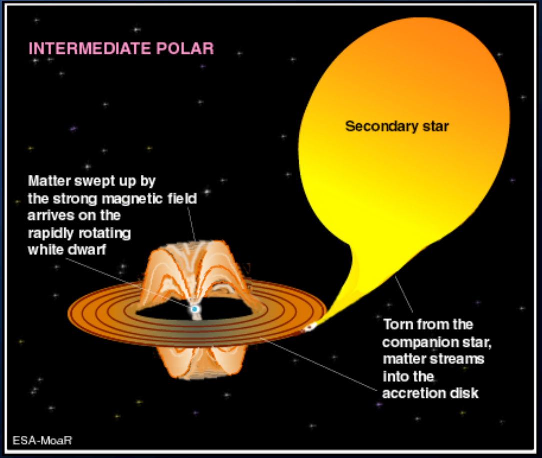
Low-mass X-ray Binaries in their quiescent states (qLMXBs)

- In addition to active LMXBs, Galactic globular clusters may contain 10 times as many LMXBs in their quiescent states (qLMXBs).
- A typical qLMXB emits its radiation in X-rays with the luminosity of $L_X \sim 10^{32}$ - 10^{34} ergs/s. The X-ray spectra of qLMXBs are dominated by a soft component with the temperature about 0.1 to 0.3 keV, which is thought to be thermal emission from the neutron-star surface due to the cooling of the neutron-star core, which has been heated during the outbursts.

Cataclysmic Variables (CVs)

- Cataclysmic variables are the systems containing a white dwarf accreting material from a low-mass companion.
- The infalling matter, usually rich in hydrogen, forms in most cases an accretion disk around the white dwarf, which radiates over a broad energy range from the optical through the far-UV band. Furthermore, X-ray emission also can be detected when material accretes onto the white dwarf.
- CVs are classified into various subgroups based primarily on the strength of the white dwarf's magnetic field.
  1. Non-magnetic CVs, e.g. classical novae and dwarf novae.
  2. Magnetic field of B > 10^6 Gauss: Polar (~ (10-200) x 10^6 Gauss), and Intermediate Polars (Ips, (1-10) x 10^6 Gauss)





Millisecond Pulsars (MSPs)

- The widely accepted scenario for the formation of millisecond pulsars (MSPs) is that an old neutron star has been spun up in a past accretion phase by mass and angular momentum transfer from a late-type companion.
- Possible scenarios of the X-ray emission:
  1. Pulsar magnetosphere
  2. Intra-binary shock

X-ray Active Binaries (ABs)

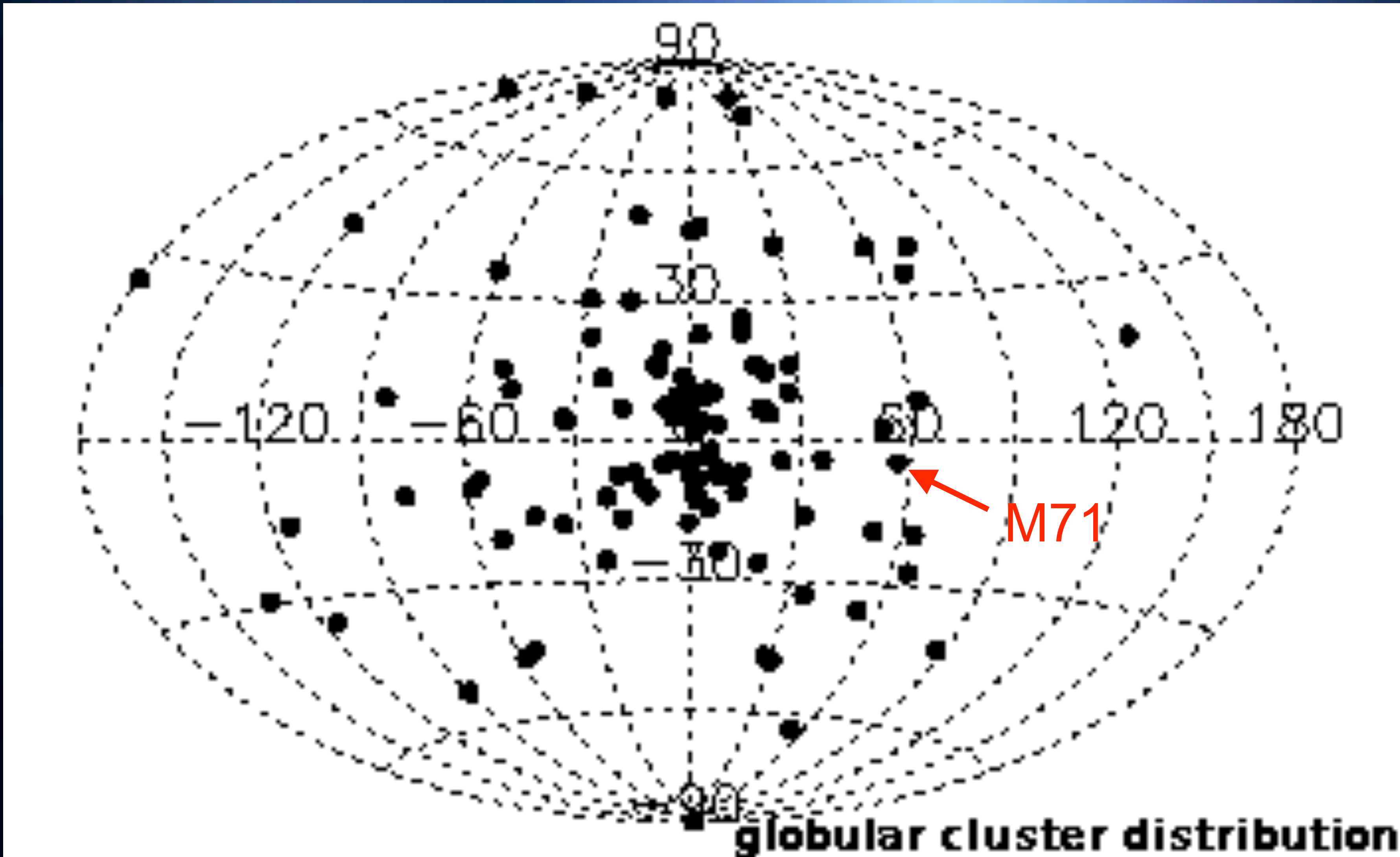
- There are three types of active binaries:
  1. two main-sequence stars (BY Dra systems)
  2. one main-sequence star and one (sub)giant (RS CVn systems)
  3. contact binaries (W UMa systems)
- X-ray sources in globular clusters can be classified as chromospherically or magnetically active binaries when a stellar flare is observed in the X-ray band.
- Differential rotation in late-type stars with convective envelopes drives a magnetic dynamo, leading to strong chromospheric emission and the formation of a corona. The rapid rotation combining with the convective motion act as a dynamo which enhances the magnetic field and coronal activity. The loops of the magnetic field sticking out of the stellar surface then emit X-rays.

M71 (NGC 6838)

- RA: 19h53m46.1s, Dec: +18°46'42"
- Distance: 4 kpc
- Central density ρ_c : $10^{3.05}$ $L_{\odot}/pc^3$

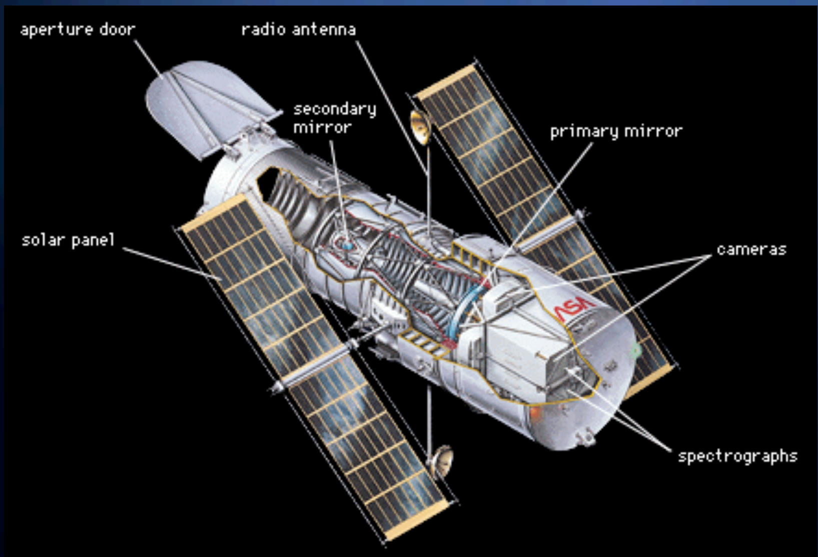
(T. Credner & S. Kohle 2005, Filter: B, V, I)

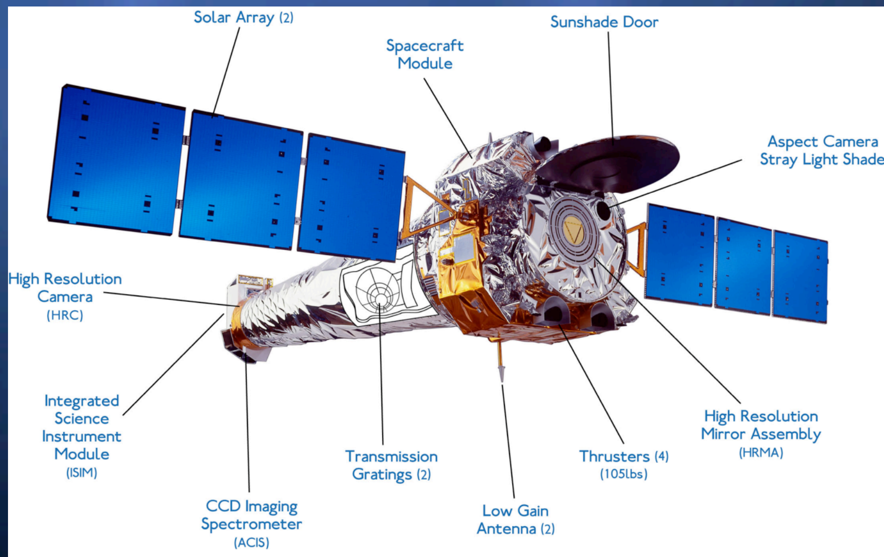
M71 (NGC 6838)



Observations

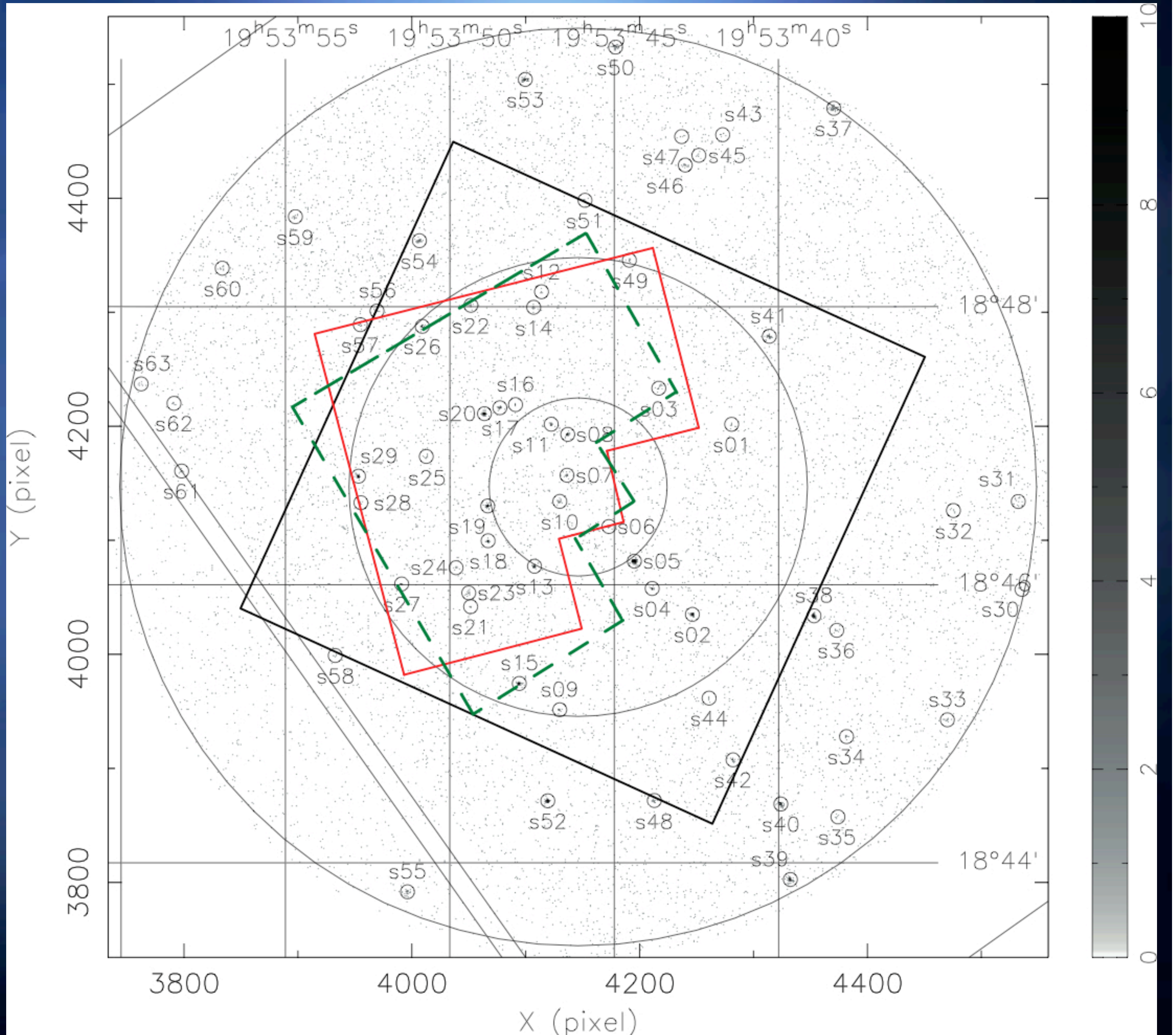
- Chandra X-ray observation:
  Advanced CCD Imaging Spectrometer (ACIS-S),
- Hubble Space Telescope observations:
  Advanced Camera for Surveys (ACS) and
  Wide Field Planetary Camera 2 (WFPC2)





Chandra ACIS-S image of M71

- The field of view of the HST ACS marked by the black square covers the entire half-mass radius (1.65’), and two polygons are the field of view of the HST WFPC2.
- Within the half-mass radius, we find 29 X-ray sources.



Source Identification

- X-ray properties (luminosity, spectral behavior)
- X-ray flux ratio ($f_{0.5\text{-}2.0keV}/f_{2.0\text{-}6.0keV}$)
- Color-magnitude diagram (CMDs)
- X-ray to optical flux ratio

X-ray Luminosity

- Bright X-ray sources ($L_x > 10^{36}$ ergs/s):
  Low-mass X-ray Binaries (LMXBs)
- Dim X-ray sources ($L_x < 10^{34.5}$ ergs/s):
  qLMXB -- $L_x \geq 10^{32}$ ergs/s
  CVs -- $L_x \sim 10^{31}$-10^{32} ergs/s
  ABs -- $L_x \sim 10^{29}$ - 10^{31} ergs/s
  MSPs -- $L_x \leq 10^{33}$ ergs/s (= PSR B1821-24A in M28)

X-ray flux ratio

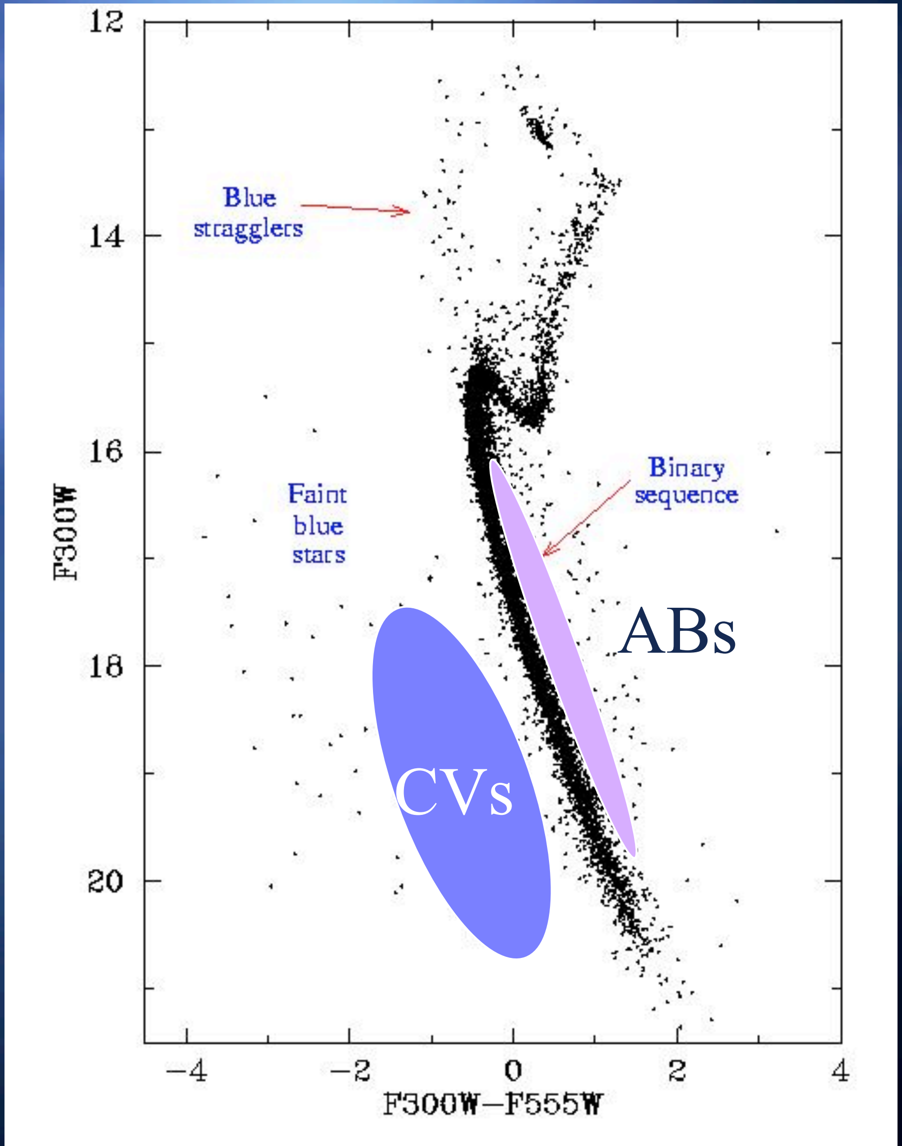
- $f_{0.5\text{-}2.0keV}/f_{2.0\text{-}6.0keV} \geq 1$, soft X-ray spectrum,
  --> qLMXB

- $f_{0.5\text{-}2.0keV}/f_{2.0\text{-}6.0keV} < 1$, hard X-ray spectrum,
  --> CV

(Webb & Barret 2005, Verbunt et al. 2007)

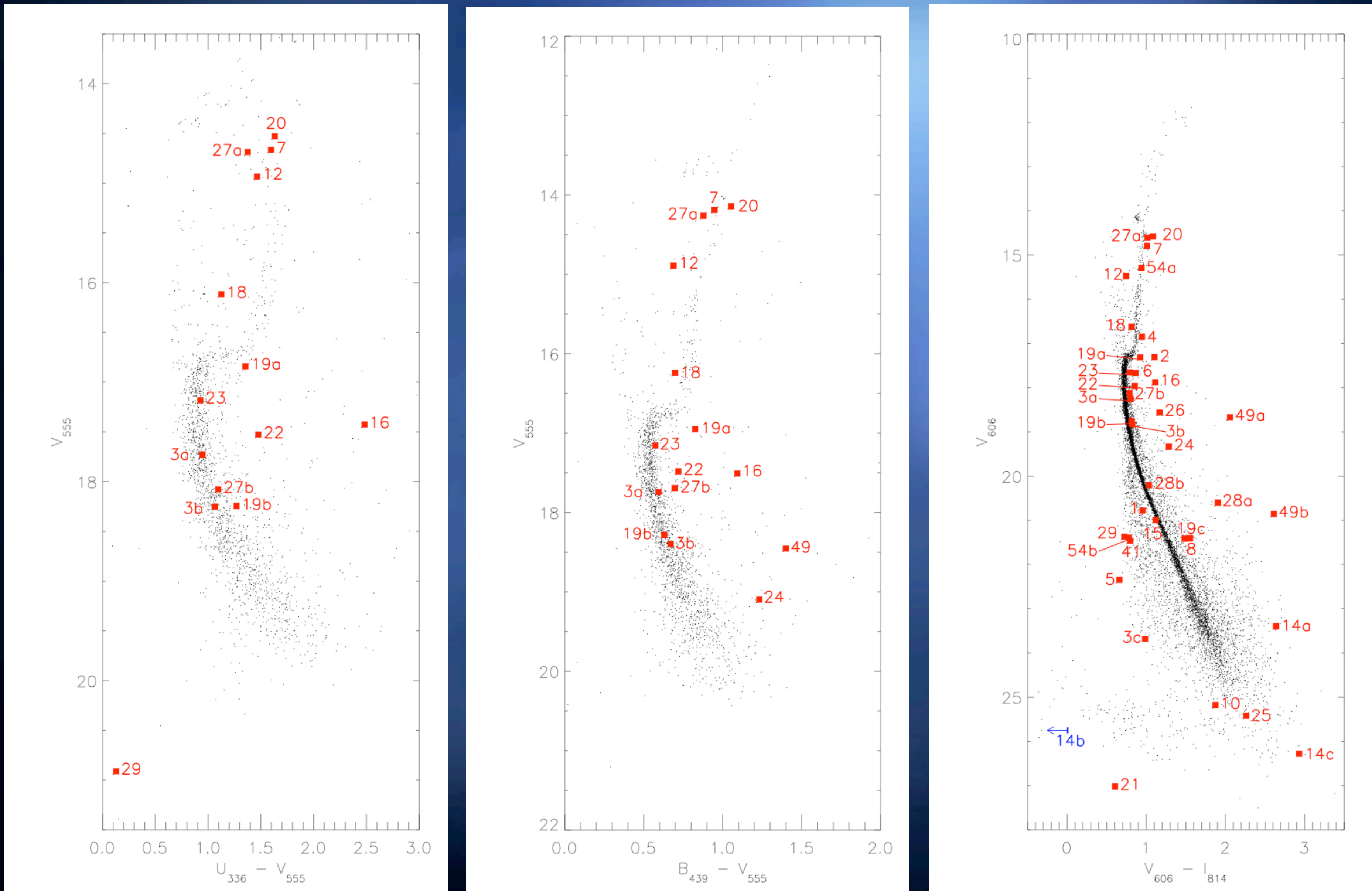
Color Magnitude Diagram (CMD)

- CVs: blueward of main sequence (m-s); Hα
- ABs: on the m-s, within binary sequence, or on the giant branch; weak Hα emission
- MSPs: have WD or m-s companions



(Josh Grindlay 2006)

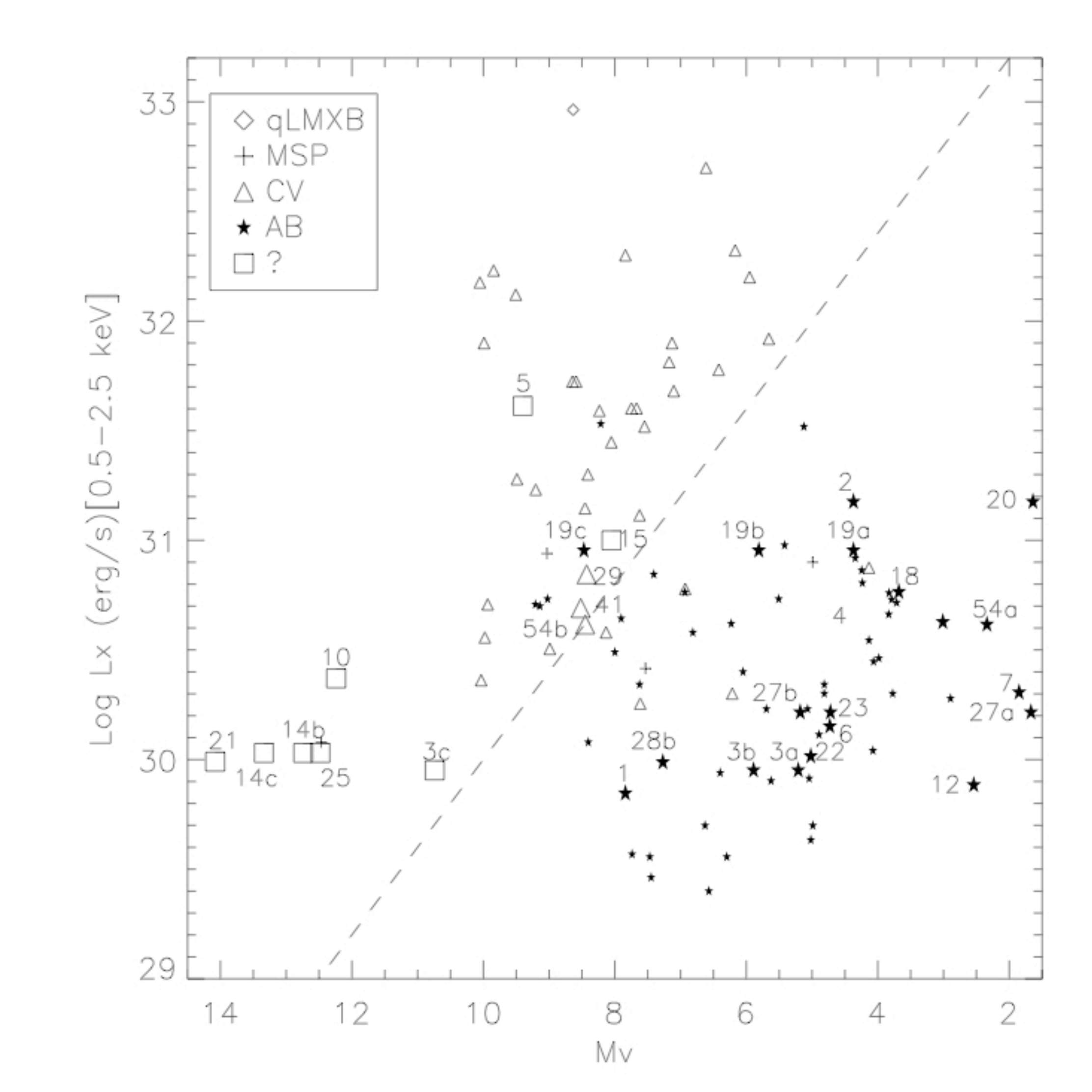
Color-Magnitude Diagrams (CMDs)



X-ray to optical flux ratio

- CVs: higher X-ray to optical flux ratio
- ABs: lower X-ray to optical ratio

X-ray luminosity as a function of the absolute magnitude for low-luminosity X-ray sources in GCs.



Results

- We search for optical counterparts within the 95% Chandra error circle. We find 33 candidate optical counterparts to 25 out of 29 Chandra X-ray sources inside the half-mass radius of M71, while 6 possible optical counterparts to 4 X-ray sources are found outside the half-mass radius.
- Based on the X-ray and optical properties of the identifications, we find 1 certain and 7 candidate cataclysmic variables (CVs). We also classify 2 X-ray sources as certain and 12 as potential chromospherically active binaries (ABs), respectively.
- We find the X-ray counterpart of the known millisecond pulsar (PSR J1953+1846A). However, no optical counterpart is found in our study.

Summary and Discussion

(1) Cluster	(2) log ρ_0 ($L_\odot$ pc^{-3})	(3) r_c ($''$)	(4) d (kpc)	(5) M_V	(6) Γ	(7) M_h	(8) Source	(9) Background	(10) Member	(11) IDs.	(12) Reference[a]
NGC 6266	5.14	10.8	6.9	−9.19	37.07	8.24	51	2–3	48–49	2[c]	1, 2, 3
47 Tuc	4.81	24.0	4.5	−9.4	24.91	10.0	79	~16	63 ± 4	53-63	4
M 28	4.75	14.4	5.6	−8.33	11.29	3.73	26	2–3	23–24	2[c]	1, 5
M 4	4.01	49.8	1.73	−6.9	1.0	1.0	6	1–3	3–5	5	1, 6
M 71	3.05	37.8	4.0	−5.6	0.11	0.30	14	1–7	10 ± 3	4–9	7
NGC 6366	2.42	109.8	3.6	−5.77	0.08	0.33	5	2–5	1^{+2}_{-1}	~1	8
M 55	2.15	169.8	5.3	−7.6	0.18	1.82	16	5–12	8^{+3}_{-4}	2–4	8
NGC 288[b]	1.80	85.0	8.4	−6.7	0.03	0.83	11	4-11	4^{+3}_{-4}	2-5	9

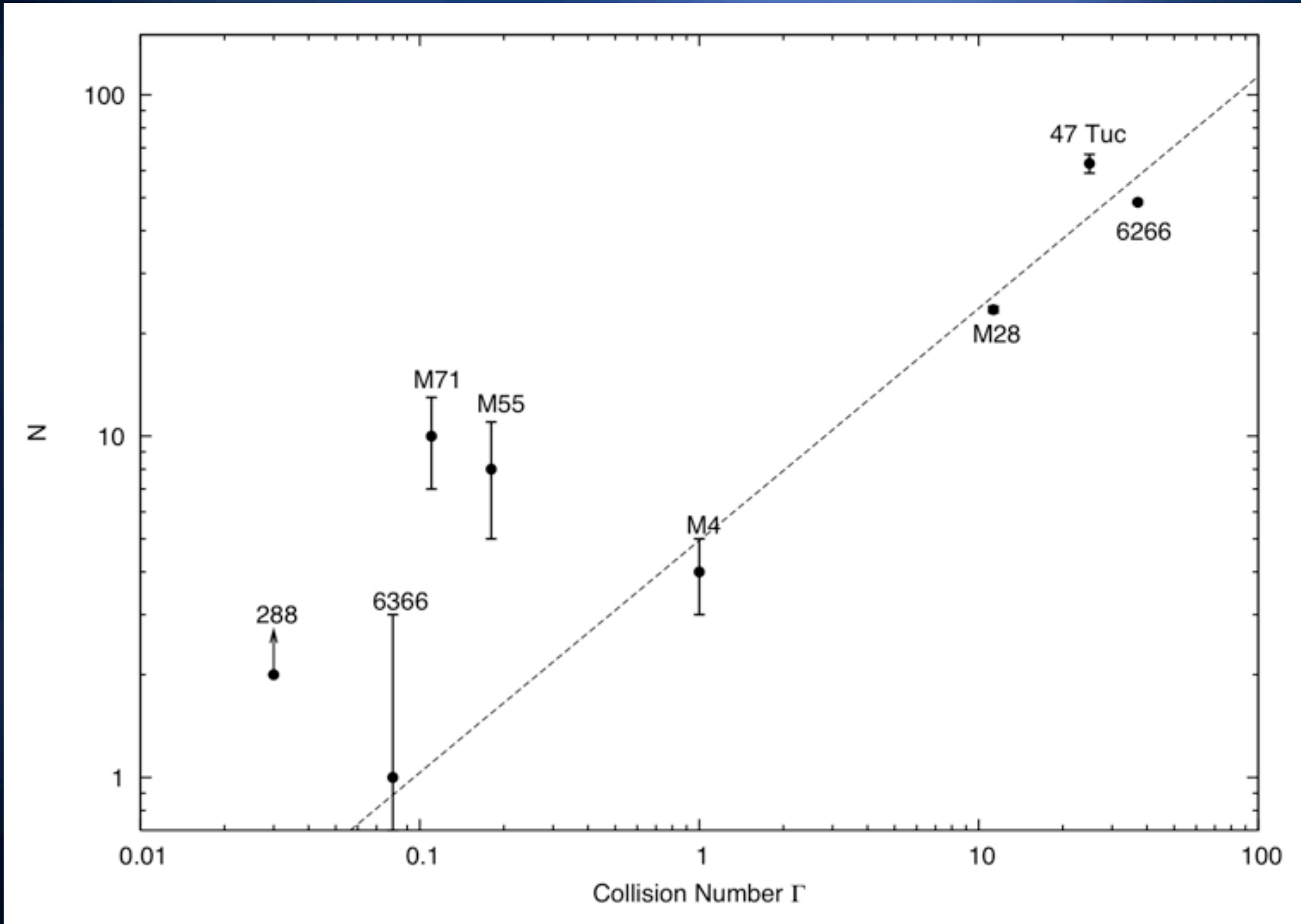
- Pooley et al. (2003) has quantitatively studied the relationship between the number of X-ray sources in each cluster and properties of the cluster itself by using Chandra observations. They found the strongest correlation between the encounter frequency and the number of X-ray sources within the half-mass radius of the globular cluster.

Summary and Discussion

- In a globular cluster, binary systems may change due to their internal evolution and/or due to external encounters. The over-abundance of bright X-ray binaries in globular clusters is the consequence of stellar encounters. These mechanisms, i.e. tidal capture or exchange encounter, scale with the encounter rate in a globular cluster

$$\Gamma \propto \int \frac{n_1 n_2 R}{v} \mathrm{d}V \propto \frac{\rho_0^2 r_c^3}{v} \propto r_c^2 \, \rho_0^{1.5} \equiv \Gamma'$$

Summary and Discussion



Number of observed cluster X-ray sources with Lx ≥ 4x10^{30} erg/s vs. the collision number Γ.

Summary and Discussion

- As suggested by Verbunt (2002), ABs are most likely primordial binaries, and their numbers should scale with the cluster mass. Following Kong et al. (2006), we calculated the half masses with

$$M_h \propto 10^{-0.4Mv}$$

by assuming the visual mass-to-light ratio is the same for all clusters listed in the table.

Summary and Discussion

- It is now thought that X-ray binary systems in dense globular clusters are created principally through exchange interactions between primordial binaries and other stars. On the other hand, in low-density globular clusters a large part of X-ray binaries are believed to be primordial in origin.
- The number of X-ray faint sources with $L_{X,0.5\text{-}6keV} > 4\times10^{30}$ ergs/sec found in M71 is higher than the predicted value on the basis of either the collision frequency or the half mass. We suggest that those CVs and ABs in M71 are primordial in origin.
- The X-ray overabundance of low-density clusters like M71 can be explained that fewer primordial binaries may have been destroyed through binary interactions.
- Study of other low-density globular clusters will help us better understand their evolution and dynamics.