X-RAY SOURCES AND THEIR OPTICAL COUNTERPARTS IN THE GALACTIC GLOBULAR CLUSTER M12 (NGC 6218)

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2008.11.21
• Scientific Purpose
• Our target -- M12
• Data Analysis
• Source identification
• Discussion
Scientific Purpose

- To know the population and their formation mechanism of X-ray sources in globular clusters.
- To help construct the dynamical evolution scenarios of those X-ray sources and globular clusters.
- Different X-ray sources in globular clusters

- Low-mass X-ray binaries (LMXBs)
- gLMXBs
- Millisecond Pulsars (MSPs)
- Cataclysmic Variables (CVs)
- Active binaries (ABs)


Fig. 8.1. Various types of X-ray sources in globular clusters; sg, ms, wd, and ns stand for subgiant, main-sequence star, white dwarf, and neutron star, respectively. From top to bottom: luminous low-mass X-ray binary, low-luminosity low-mass X-ray binary, recycled radio pulsar (here with a white dwarf companion), cataclysmic variable, and magnetically active binary. $L_{\text{sd}}$ stands for spin-down luminosity. Approximate maximum luminosities (in the 0.5–4.5 keV range) are indicated on the right. The low-mass X-ray binaries harboring a neutron star are referred to as LMXB$_{\text{NS}}$; when they harbor a back hole, we refer to them as LMXB$_{\text{BH}}$, and we refer to both groups together as LMXB.
Different formation channels for the X-ray sources:

- **Dynamical origin**
  - Tidal capture
  - Close encounter (exchange companion)

- **Primordial origin**

The correlation between the number of X-ray sources and the encounter rate $\Gamma$ (dynamical origin) and the mass $M_h$ of globular clusters (primordial origin).
- Different formation channels for the X-ray sources

- Number of globular cluster X-ray sources with $L_X \geq 4 \times 10^{30}$ erg s$^{-1}$ vs. the encounter rate $\Gamma$ of the cluster (a revised version of Fig. 2 of Pooley et al. 2003). Most sources are CVs. In general, the number scales quite well with $\Gamma$, indicating that CVs in globular clusters are formed via close encounters. $\Gamma$ is normalized such that M4 (NGC6121) = 1. It is also clear from the diagram that the low density cluster, NGC288, has an overabundance of low-luminosity X-ray sources.
\[ \Gamma(M12) \equiv \rho_0^{1.5} r_c^2 = 0.41 \]
OUR TARGET -- M12

- R.A. = 16h47m14.5s
  Decl. = -01°56'52" (J2000.0)
- 4.9 kpc from Sun
- $r_c = 0.72$ arcmin
  $r_h = 2.16$ arcmin
- $\log \rho_0 = 3.23$
- $\Gamma = 0.41$
- $N_H = 1.0E+21$
- $M_V = -7.32$
Chandra X-ray Observatory
- high resolution and high sensitivity.
- M 12 was observed by Chandra ACIS-S on 2004 July 17 for about 27 ks.
- SOURCE DETECTION

- wavedetect in CIAO 3.4

- 4 bands:
  0.3-7.0 keV
  0.3-1.0 keV (soft)
  1.0-2.0 keV (medium)
  2.0-7.0 keV (hard)

- Total 20 sources are detected and 6 of them are inside the half-mass radius $r_h$. 
- BACKGROUND ESTIMATION

- Derived from the log N - log S relation in the Chandra Deep Field Survey-South (Giacconi et al. 2001)

- 16-22 sources are background objects in the ACIS-S3 chip; 3-5 sources are estimated to be backgrounds within the half-mass radius of M12.
We have performed astrometry correction for the positions determined by wavdetect listed in the table. The R.A. and Decl. was corrected by −0.05” and −0.09” respectively. The position uncertainties are also given by wavdetect and in units of arcseconds. The unabsorbed flux is derived assuming a power-law model with $N_H = 1.0E+20 \text{ cm}^{-2}$ and a photon index of 2.
Left: The color-color diagram of x-ray sources in NGC 6218. The number represents the source number within the half-mass radius. The lines are the hardness ratios predicted from thermal bremsstrahlung (TB) model and power law (PL) model with different column density. From top to bottom is PL with photon index 1, PL with photon index 2, PL with photon index 3, and TB with temperature 1keV. The column density from left to right is $1E+20$, $1E+21$, $5E+21$, and $1E+22$.

Right: The color-magnitude diagram of x-ray sources in NGC 6218. Sources inside the half-mass radius are marked with error bars.
- Spectral fitting of CX4 and CX9 and light curve of CX4

### Spectral Fits of the Brightest Sources

<table>
<thead>
<tr>
<th></th>
<th>Model$^a$</th>
<th>$N_H^b$</th>
<th>kT/$\alpha$</th>
<th>$\chi^2$/dof</th>
<th>$f_{0.3-7}^c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CX4</td>
<td>TB</td>
<td>1.78±0.90</td>
<td>3.08±1.18</td>
<td>1.67/12</td>
<td>5.17</td>
</tr>
<tr>
<td></td>
<td>PL</td>
<td>3.14±1.27</td>
<td>2.25±0.33</td>
<td>1.55/12</td>
<td>5.32</td>
</tr>
<tr>
<td>CX19</td>
<td>TB</td>
<td>1.65±1.05</td>
<td>12.14±12.65</td>
<td>1.53/11</td>
<td>6.84</td>
</tr>
<tr>
<td></td>
<td>PL</td>
<td>2.07±1.07</td>
<td>1.53±0.30</td>
<td>1.53/11</td>
<td>6.98</td>
</tr>
</tbody>
</table>

**NOTES.** — All quoted uncertainties are 90\%.

$^a$ TB: thermal bremsstrahlung; PL: power-law.

$^b$ in units of $10^{21}$ cm$^{-2}$

$^c$ 0.3–7 keV unabsorbed flux in units of $10^{-14}$ ergs cm$^{-2}$ s$^{-1}$.
- Why We Need Optical Observation?

- Most Chandra sources do not have enough photon counts to perform meaningful spectral fitting.

- Optical observation can provide us with more information about the Chandra X-ray sources and then help us to identify them.
Hubble Space Telescope (HST)

- M12 was observed with HST Advanced Camera for Survey (ACS) for three filters: F435W (B_435), F625W (r_625), and F658W (H_α_658)
- photometry: dolphot

Color-magnitude diagrams (CMDs) of HST ACS observation of M12. The number represents the X-ray source number within the half-mass radius.
In order to find optical counterparts of the X-ray sources, we need to perform astrometry improvement.

Relative astrometry:
- put the X-ray and optical images on the same image frame and coordinate system individually
- use UCAC2 catalog and ESO 2.2m WFI image as referenced image frame
- **ASTROMETRY**

- **Position error circle**
  - the quadratic sum of
    1) the position uncertainty of the X-ray sources (given by wavdetect)
    2) the uncertainty of the astrometry in the WFI and HST image alignment (UCAC2 to HST astrometry and WFI to HST astrometry)
    3) the uncertainty of the Chandra X-ray image boresight correction (Chandra to WFI astrometry)
  - $1\sigma$ position error varies from 0.2” to 0.5” for the 20 X-ray sources

- We took all the HST sources inside the 95% confidence position error circle, which is $\sim 2.48\sigma$
FIG. 5. — $5'' \times 5''$ finding Charts for the X-ray sources inside the HST ACS field of view. The 95% error circles of X-ray sources have been laid on the charts. The optical counterpart candidates are marked with letters.
We identified the optical counterparts to the 5 X-ray sources inside the FOV of HST ACS based on:
1) X-ray luminosity
2) X-ray spectrum (if available)
3) optical spectrum (CMD)
4) X-ray to optical flux ratio $f_x/f_{opt}$
SOURCE IDENTIFICATION


SOURCE IDENTIFICATION

- SOURCE IDENTIFICATION OF CX4

- CX4 $L_x \sim 2E+32$ ergs/s
- Hard X-ray color of CX4
- 4b shows $H_\alpha$ emission
- The relatively high $f_x/f_{opt}$
- Both 4a and 4b are identified as CVs
- Source Identification of CX7

- $\text{CX7 } L_x \sim 1 \times 10^{31} \text{ ergs/s}$

- Relatively hard X-ray color of CX7

- 7c: blue and some $H_\alpha$ emission $\Rightarrow$ CV

- 7a & 7b: on the main-sequence and low $f_x/f_{opt}$ $\Rightarrow$ both ABs
### Optical Counterparts to Chandra X-ray Sources

<table>
<thead>
<tr>
<th>CX</th>
<th>Δ R.A. (arcsec)</th>
<th>Δ Decl. (arcsec)</th>
<th>$B_{435}$</th>
<th>$r_{625}$</th>
<th>Hα$_{658}$</th>
<th>$f_X/f_r^a$</th>
<th>Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>3a</td>
<td>0.15</td>
<td>-0.08</td>
<td>24.511 ± 0.025</td>
<td>22.289 ± 0.022</td>
<td>21.871 ± 0.039</td>
<td>0.573</td>
<td>AGN</td>
</tr>
<tr>
<td>3b</td>
<td>0.18</td>
<td>0.66</td>
<td>19.809 ± 0.002</td>
<td>18.532 ± 0.003</td>
<td>18.213 ± 0.005</td>
<td>0.018</td>
<td>AB</td>
</tr>
<tr>
<td>3c</td>
<td>-0.20</td>
<td>0.37</td>
<td>26.090 ± 0.080</td>
<td>23.769 ± 0.064</td>
<td>23.321 ± 0.120</td>
<td>2.298</td>
<td>AGN</td>
</tr>
<tr>
<td>4a</td>
<td>-0.20</td>
<td>0.16</td>
<td>21.147 ± 0.004</td>
<td>19.855 ± 0.006</td>
<td>19.566 ± 0.010</td>
<td>3.151</td>
<td>CV</td>
</tr>
<tr>
<td>4b</td>
<td>-0.47</td>
<td>-0.01</td>
<td>21.603 ± 0.005</td>
<td>20.184 ± 0.007</td>
<td>19.479 ± 0.009</td>
<td>4.266</td>
<td>CV</td>
</tr>
<tr>
<td>6a</td>
<td>-0.27</td>
<td>0.48</td>
<td>24.885 ± 0.032</td>
<td>22.758 ± 0.030</td>
<td>22.669 ± 0.067</td>
<td>1.375</td>
<td>CV/AGN</td>
</tr>
<tr>
<td>6b</td>
<td>-0.27</td>
<td>0.19</td>
<td>27.031 ± 0.159</td>
<td>25.736 ± 0.365</td>
<td>25.796 ± 0.938</td>
<td>12.703</td>
<td>AGN</td>
</tr>
<tr>
<td>7a</td>
<td>0.11</td>
<td>0.06</td>
<td>19.112 ± 0.001</td>
<td>18.091 ± 0.002</td>
<td>17.854 ± 0.004</td>
<td>0.032</td>
<td>AB</td>
</tr>
<tr>
<td>7b</td>
<td>0.03</td>
<td>0.42</td>
<td>18.884 ± 0.001</td>
<td>17.606 ± 0.002</td>
<td>17.351 ± 0.003</td>
<td>0.021</td>
<td>AB</td>
</tr>
<tr>
<td>7c</td>
<td>0.15</td>
<td>0.29</td>
<td>20.216 ± 0.003</td>
<td>19.746 ± 0.006</td>
<td>19.258 ± 0.009</td>
<td>0.149</td>
<td>CV</td>
</tr>
<tr>
<td>9a</td>
<td>0.18</td>
<td>-0.02</td>
<td>22.534 ± 0.008</td>
<td>20.859 ± 0.010</td>
<td>20.537 ± 0.017</td>
<td>0.205</td>
<td>CV</td>
</tr>
<tr>
<td>9b</td>
<td>-0.12</td>
<td>0.10</td>
<td>19.750 ± 0.002</td>
<td>18.626 ± 0.003</td>
<td>18.385 ± 0.005</td>
<td>0.026</td>
<td>AB</td>
</tr>
</tbody>
</table>
We identified 3-5 optical counterparts of Chandra X-ray sources inside the HST ACS field of view, which is an overabundance if the number of X-ray sources scales with the encounter rate $\Gamma$.

If the number of X-ray sources scales with the mass (inside the half-mass radius) $M_h = 10^{-0.4 M_V}$, then 6 X-ray sources related to M12 are predicted, which is over-estimated comparing to the observation.
Bassa et al. (2008) suggest a X-ray source number dependence on the collision number and the mass that \( N = 1.2 \Gamma_{(M4)} + 1.1M_{h(M4)} \). 2 X-ray sources are expected for M12. So we suggest that \( M_{h} \) may have more dependence.

M12 core density is slightly lower than M4. The close encounters may still have its importance in producing low luminosity X-ray sources, while the overabundance of X-ray sources reveals the evidence of primordial origin which is a more probable channel for M12 to manufacture those X-ray sources.
THANK YOU!!