The formation of ultra-compact binaries in globular clusters

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Evolution of a 1–$M_\odot$ star

“The Eggleton code”

Van der Sluys, 2006
Evolution of a binary star

Van der Sluys, 2006
Low-mass X-ray binaries

Mechanism

- Low-mass star transfers mass to neutron star or black hole
- Gravitational acceleration causes X-rays:
  \[ L_x \approx \frac{GM_{\text{ns}}}{R_{\text{ns}}} \dot{M}_{\text{tr}} \]
- Optical radiation comes from reprocessed X-rays in accretion disk

BinSim

BinSim, R. Hynes, LSU
**The X-ray sky**

**X-ray binaries**
- Bright X-ray sources: in galactic plane, concentrated towards galactic centre
- 13 bright X-ray sources in globular clusters
- Binaries with $P_{\text{orb}} \lesssim 60$ min are called *ultra-compact*

**Ariel V X-ray map of the sky**

**XRBs are over-abundant in GCs:**
- 1 in $10^9$ stars in galaxy is XRB
- 1 in $10^6$ stars in globular clusters is XRB
M 15/NGC 7078 – Chandra

M 15

X-ray sources in M 15

White & Angelini, 2001
Identification of sources: Cees Bassa

ESO & Chandra

- Pointing of a telescope has limited accuracy (∼ 1′′)
- Identification with optical star requires maximum accuracy
- This is done in four steps:
- Step 1: find stars from astrometric catalogue (i.e. with very accurate positions) in ESO 2.2m Wide Field Camera image and use this to position WFC image

NGC 6752, ESO 2.2m
Identification of sources: Cees Bassa

ESO & Chandra

- Step 2: compare positions of stars in HST image with those of WFC image
- Thus: get accurate positions of HST stars
- Step 3: find stars in error circles of Chandra X-ray sources where error is comprised of
  - absolute accuracy
  - astrometric catalogue
  - transfer WFC to catalogue
  - transfer HST to WFC
  - accuracy of X-ray position

NGC 6752, HST
Identification of sources: Cees Bassa

ESO & Chandra

Step 4: compare colours of stars within error circles with normal cluster stars and select deviants

NGC 6752

Figure caption

Left: colour of the star (X-axis) as a function of brightness (Y-axis). Circles surround stars from within error boxes

Right: Hα emission as function of brightness
M 15/NGC 7078 – HST

Optical counterparts

White & Angelini, 2001; Guhathakurta, 1996
Introduction  

Observations  

Magnetic capture  

Direct collisions  

Conclusions

Direct period measurement

Magnitude modulation

Period for M 15-X2

Dieball et al.:  
- FUV study (less crowding)  
- Magnitude modulation: 0.06m  
- > 3000 cycles  
- Period: 22.6 min.

Dieball et al., 2005
Optical vs. X-ray flux

- Optical flux from reprocessed X-rays in disk
- Scales with X-ray flux and size of disk
- Hence, $f_{\text{opt}} / f_X \propto R_{\text{disk}} \propto a_{\text{orb}}$

Van Paradijs & McClintock, 1994

Verbunt & Lewin, 2006, in "Compact Stellar X-ray Sources"
Indirect period indication

**Burst maximum**

- Maximum luminosity during burst is Eddington luminosity:
  \[ L_{\text{Edd}} = \frac{4\pi cGM}{\sigma_T} \]

- Electron scattering cross section depends on hydrogen content:
  \[ \sigma_T = 0.2 \left(1 + X\right) \text{ cm}^2 \text{ g}^{-1} \]

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Kuulkers et al., 2003
Indirect period indication

X-ray spectrum

- Temperature $T_0$ of the seed photons comes from a Compton model
- Temperature $T_{\text{in}}$ is observed from the inner disk
- Ultracompacts show $T_0 \sim T_{\text{in}}$

![Graph](Adapted from Sidoli et al., 2001)
# X-ray sources in globular clusters

## Known period information

<table>
<thead>
<tr>
<th>Cluster</th>
<th>Position</th>
<th>( P_{\text{orb}} )</th>
<th>Indirect indication</th>
<th>X-spect.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>low ( f_{\text{opt}}/f_x )</td>
<td>burst max.</td>
</tr>
<tr>
<td>NGC 1851</td>
<td>0512–40</td>
<td>?</td>
<td>U</td>
<td>U</td>
</tr>
<tr>
<td>NGC 6440</td>
<td>1745–20</td>
<td>8.7 hr</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>NGC 6441</td>
<td>1746–37</td>
<td>5.7 hr</td>
<td>—</td>
<td>N</td>
</tr>
<tr>
<td>NGC 6624</td>
<td>1820–30</td>
<td>11.4 min</td>
<td>U</td>
<td>U</td>
</tr>
<tr>
<td>NGC 6652</td>
<td>1836–33</td>
<td>?</td>
<td>U</td>
<td>U</td>
</tr>
<tr>
<td>NGC 6712</td>
<td>1850–09</td>
<td>21/13 min</td>
<td>U</td>
<td>U</td>
</tr>
<tr>
<td>NGC 7078</td>
<td>2127+12b</td>
<td>17.1 hr</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>NGC 7078</td>
<td>2127+12a</td>
<td>22.6 min</td>
<td>—</td>
<td>U</td>
</tr>
<tr>
<td>Terzan 1</td>
<td>1732–30</td>
<td>?</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Terzan 2</td>
<td>1724–31</td>
<td>?</td>
<td>—</td>
<td>U</td>
</tr>
<tr>
<td>Terzan 5</td>
<td>1745–25</td>
<td>?</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Terzan 6</td>
<td>1751–31</td>
<td>12.4 hr</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Liller 1</td>
<td>1730–33</td>
<td>?</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

- Up to 6 of the 13 X-ray binaries in globular clusters are ultra-compact!
- 11-min system has negative \( \dot{P} \)
Scenario 1: Magnetic braking

Magnetic wind

- Rotating stars can have magnetic fields
- Evolved stars can have strong winds
- Stellar wind follows magnetic-field lines
- Star loses angular momentum efficiently
- Tidal coupling causes orbit to shrink in case of a binary
Magnetic capture

Scenario
- Low-mass donor
- Mass transfer starts after main sequence
- Lose angular momentum through MB
- Minimum period can be as low as 5 min.
- Period derivative can be negative

Example

Podsiadlowski et al., 2002
Magnetic capture

Plotting with BinSim
We can feed the output of the binary-evolution code into BinSim

Example model

$Z = 0.01, 1.1 M_\odot, P_1 = 0.85 \text{ d};$ animation with BinSim
Binary-evolution models

We calculated grids of models with a neutron star of 1.4 M_☉ and a main-sequence donor star.

Initial parameters

- M_i: 0.7 – 1.5 M_☉, with Δ M_i = 0.1 M_☉
- P_i: 0.35 – 2.5 d, with Δ P_i = 0.25, 0.05 of 0.01 d
- Z: 0.0001, 0.002, 0.01 and 0.02
- Magnetic-braking prescriptions:
  2. Reduced Verbunt & Zwaan
  3. Sills et al., 2000 (saturated)
  4. No MB, gravitational waves only
Binary-evolution models

**Behaviour**
- Models with low $P_i$ converge and rebound at $P_{\text{orb}} \sim 70$ min
- Models with high $P_i$ diverge
- Narrow range of $P_i$ leads to ultra-short period

Example for $Z = 0.01, 1.1 M_\odot$

Van der Sluys, Verbunt & Pols, 2005a
Creating a population

1. Start with the calculated grid

![Graph showing population growth over time](image-url)
Creating a population

2. Pick a random $P_i$
Creating a population

3. Select the bracketing tracks

![Graph showing the selection of bracketing tracks over time](image)
Creating a population

4. Interpolate the track for the selected $P_i$
Creating a population

5. Pick a random moment in time, $10 \text{ Gyr} < t < 13 \text{ Gyr}$
Creating a population

6. Find the orbital period $P$ at that moment
Results for a given donor mass

- Generate $10^6$ systems
- Some artefacts at long periods
- Short-period distribution is representative

$Z = 0.01, 1.1 \, M_\odot, 10^6$ binaries

Van der Sluys, Verbunt & Pols, 2005a
Statistics: compare initial-mass functions

Combining distributions for all masses

- Complete grid has $10^7$ systems
- Exact IMF unimportant
- Mass grid not too coarse

$Z = 0.01, 10^7$ binaries

Van der Sluys, Verbunt & Pols, 2005a
Statistics: compare metallicities

Effect of metallicity

- $Z$ has influence, but not dramatic
- Very low $Z$ produces no systems with $P_{\text{orb}} < 20$ min
- Each 11-min binary should have 10-100 20-min counterparts

Van der Sluys, Verbunt & Pols, 2005a
Statistics: compare magnetic-braking strengths

Reducing magnetic braking
- Lower period limit increases
- Unrealistically strong MB needed to get systems below 20 min

Van der Sluys, Verbunt & Pols, 2005b
**Statistics: compare magnetic-braking prescriptions**

**Different MB ‘law’**
- Use more realistic, saturated MB
- Lower limit for saturated MB similar to that for no MB
- No systems below $\sim 70$ min

$Z = 0.01$, $10^7$ binaries

Gravitational Waves
Sills et al. 2000
Verbunt & Zwaan 1981

Van der Sluys, Verbunt & Pols, 2005b
Conclusions

The magnetic-capture scenario cannot produce a sufficient number of ultra-compact X-ray binaries, because

- The initial-period range is very narrow
- The initial-mass range is narrow
- Evolution at ultra-short period is fast
- Often, $P_{\text{min}}$ is reached after a Hubble time
- Magnetic braking must be unrealistically strong
Scenario 2: Direct collisions

Star collisions occur in GCs

- Star density up to $10^6$ times higher than in solar neighbourhood
- Probability of collisions $10^{12}$ times higher
- Direct collisions most likely for subgiants
- Binary with NS and core of subgiant is formed
Scenario 2: Direct collisions

After the collision

- A NS-WD binary is formed
- Gravitational radiation shrinks the orbit
- Orbital period increases as soon as mass transfer starts
- Observed X-ray binaries should always have positive $\dot{P}$

The 11-min system has a measured $\dot{P}/P = -1.8 \pm 0.3 \times 10^{-15} \text{s}^{-1}$
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Van der Klis et al., 1993
Scenario 2: Direct collisions

- Open/closed symbols: 0.8, 0.9 $M_\odot$ star
- Triangles, squares and circles show how far star was evolved
- Symbol size scales with collision probability
- Dashed lines for $1.4 + 0.25 M_\odot$
- Hashed area for $M_{\text{tot}} \pm 0.2 M_\odot$

Lombardi et al., 2006
Conclusions

**Magnetic capture**
- Magnetic capture produces too few ultra-compact X-ray binaries
- More realistic, weaker magnetic-braking laws predict no UCXBs at all
- Magnetic capture cannot explain the observations

**Stellar collisions**
- (Sub)giant collides with neutron star and forms NS-WD binary
- Gravitational waves cause orbital shrinkage until mass transfer starts
- \( \dot{P} \) must be positive
- Measured negative \( \dot{P} \) should then be explained by acceleration