The formation of ultra-compact binaries in globular clusters

Marc van der Sluys[1]

Frank Verbunt[2], Onno Pols[2]

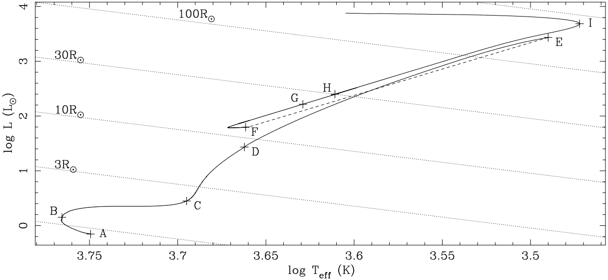
[1] Northwestern University, [2] Utrecht University

Birmingham, October 19, 2007

Outline

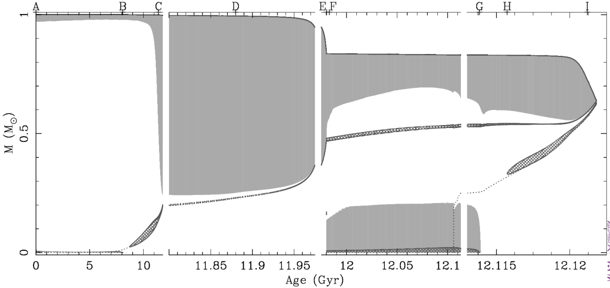
1. Introduction
   - X-ray binaries
2. Observations
   - X-ray binaries in globular clusters
   - Identification of sources
   - Direct period measurement
   - Indirect indication of the period
3. Magnetic capture
   - Magnetic braking
   - Creating a population
   - Statistics
4. Direct collisions
   - Binary formation through stellar collisions
5. Conclusions

Evolution of a 1–$M_\odot$ star

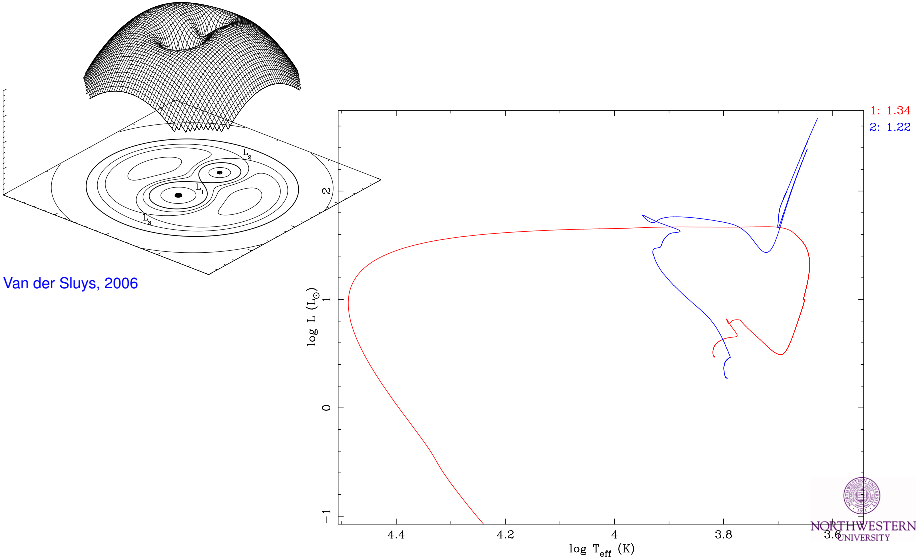


“The Eggleton code”

Van der Sluys, 2006



Evolution of a binary star



Van der Sluys, 2006

Low-mass X-ray binaries

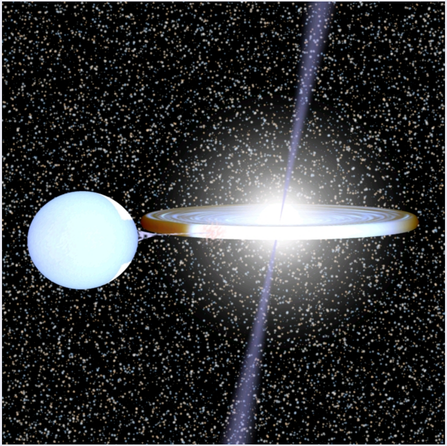
Mechanism

- Low-mass star transfers mass to neutron star or black hole
- Gravitational acceleration causes X-rays:

$$L_{\mathrm{x}} \approx \frac{GM_{\mathrm{ns}}}{R_{\mathrm{ns}}}\dot{M}_{\mathrm{tr}}$$

- Optical radiation comes from reprocessed X-rays in accretion disk

BinSim



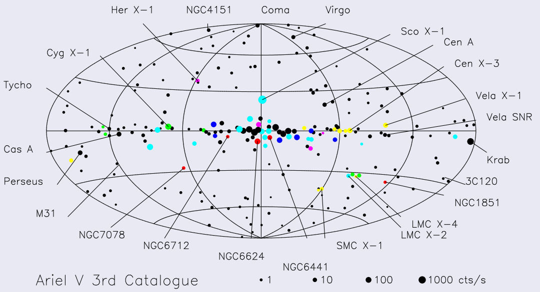
BinSim, R. Hynes, LSU

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 $P_{\mathrm{orb}} \lesssim 60$ min are called *ultra-compact*

Ariel V X-ray map of the sky



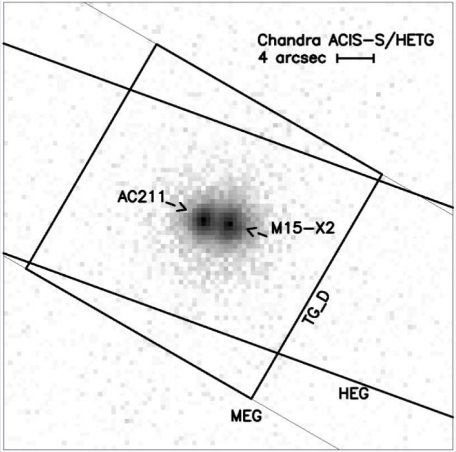
XRBs are over-abundant in GCs:

- 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



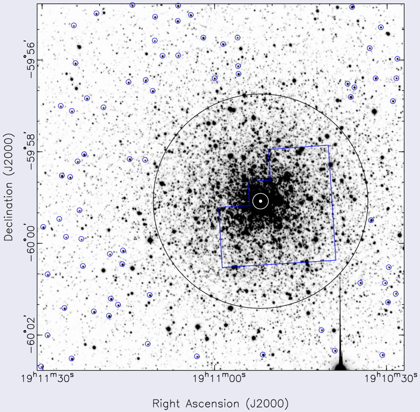
White & Angelini, 2001

Identification of sources: Cees Bassa

ESO & Chandra

- Pointing of a telescope has limited accuracy ($\sim 1''$)
- 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

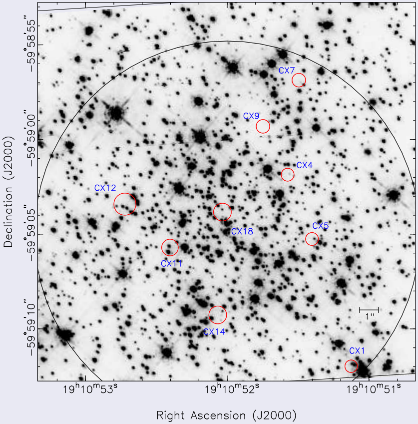


Identification of sources: Cees Bassa

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

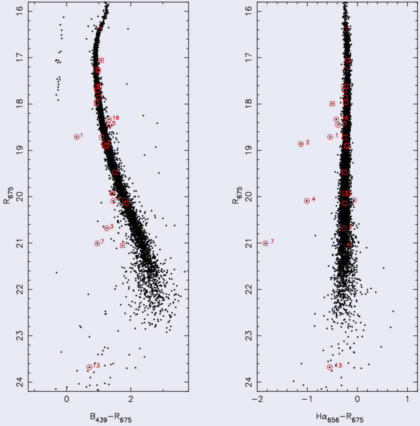
ESO & Chandra

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

Figure caption

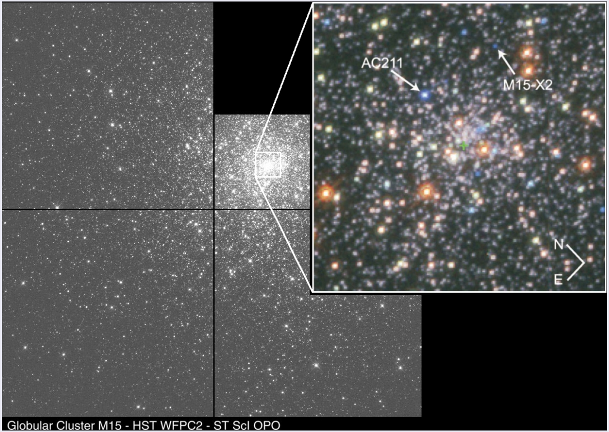
- *Left:* colour of the star (X-axis) as a function of brightness (Y-axis). Circles surround stars from within error boxes
- *Right:* H α emission as function of brightness

NGC 6752



M 15/NGC 7078 – HST

Optical counterparts



White & Angelini, 2001; Guhathakurta, 1996

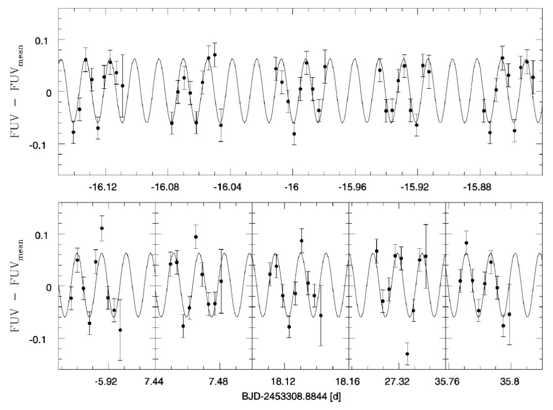
Direct period measurement

Period for M 15-X2

Dieball et al.:

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

Magnitude modulation



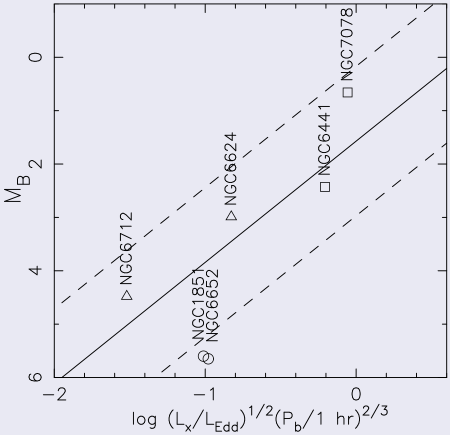
Dieball et al., 2005

Indirect period indication

Optical vs. X-ray flux

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

Van Paradijs & McClintock, 1994



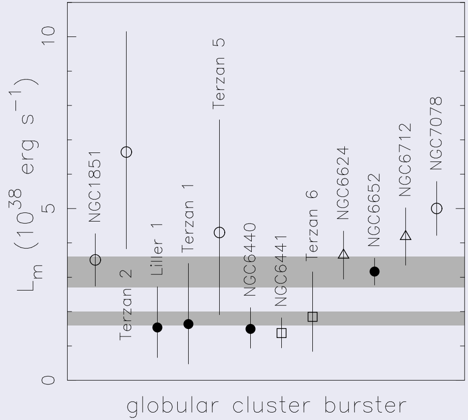
□ normal P △ ultra-short P O unknown P

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

Indirect period indication

Burst maximum

- Maximum luminosity during burst is Eddington luminosity: $L_{\mathrm{Edd}} = \frac{4\pi cGM}{\sigma_{\mathrm{T}}}$
- Electron scattering cross section depends on hydrogen content: $\sigma_{\mathrm{T}} = 0.2\ (1 + X)\ \frac{\mathrm{cm}^2}{\mathrm{g}}$



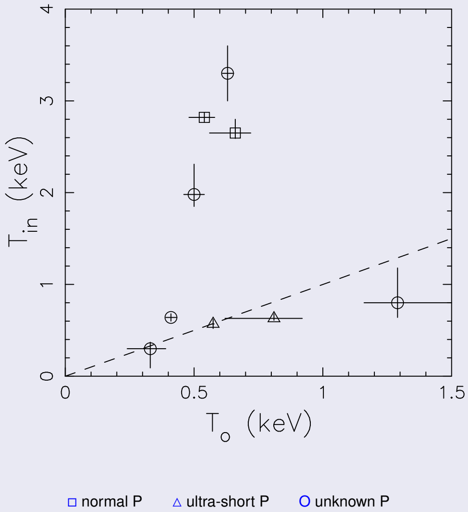
□ normal P △ ultra-short P O unknown P

Kuulkers et al., 2003

Indirect period indication

X-ray spectrum

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



Adapted from Sidoli et al., 2001

X-ray sources in globular clusters

Known period information

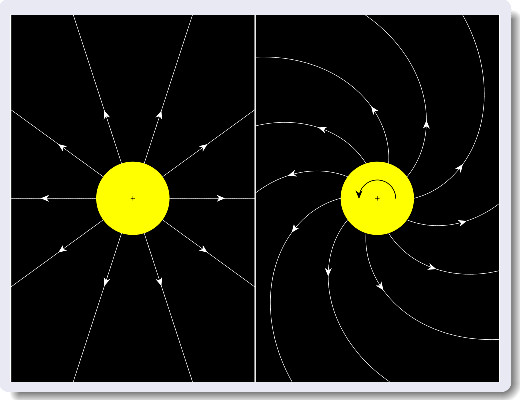
Cluster	Position	P_{orb}	Indirect indication		
			low $f_{\mathrm{opt}}/f_{\mathrm{x}}$	burst max.	X-spect.
NGC 1851	0512–40	?	U	U	U
NGC 6440	1745–20	8.7 hr	—	—	N
NGC 6441	1746–37	5.7 hr	—	N	N
NGC 6624	1820–30	11.4 min	U	U	U
NGC 6652	1836–33	?	U	U	U
NGC 6712	1850–09	21/13 min	U	U	U
NGC 7078	2127+12b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

- 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

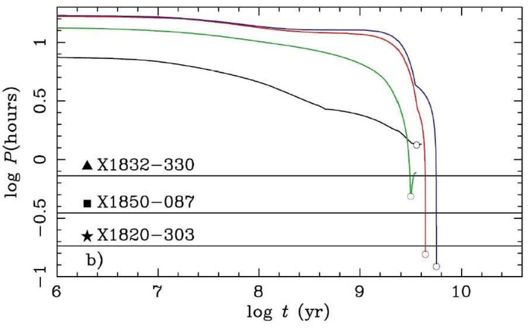


Magnetic capture

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

$Z = 0.01$, $1.1\,M_\odot$, $P_\mathrm{i} = 0.85\,\mathrm{d}$; animation with BinSim

Binary-evolution models

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

Initial parameters

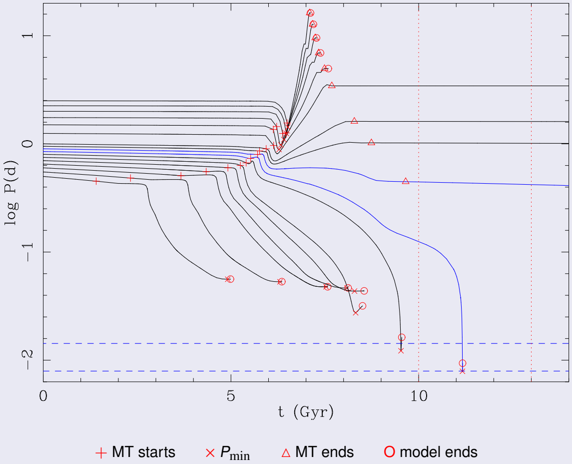
- M_i: 0.7 – 1.5 $M_\odot$, with $\Delta M_\mathrm{i} = 0.1\,M_\odot$
- P_i: 0.35 – 2.5 d, with $\Delta P_\mathrm{i} = 0.25$, 0.05 of 0.01 d
- Z: 0.0001, 0.002, 0.01 and 0.02
- Magnetic-braking prescriptions:
  1. Verbunt & Zwaan, 1981
  2. Reduced Verbunt & Zwaan
  3. Sills et al., 2000 (saturated)
  4. No MB, gravitational waves only

Binary-evolution models

Behaviour

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

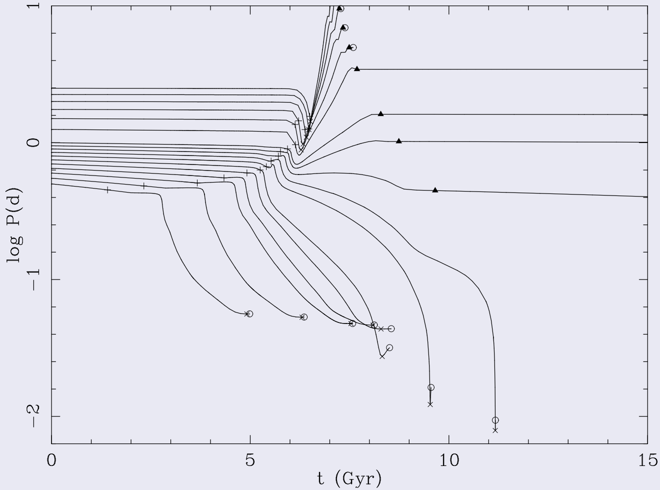
Example for $Z = 0.01$, $1.1\,M_\odot$



Van der Sluys, Verbunt & Pols, 2005a

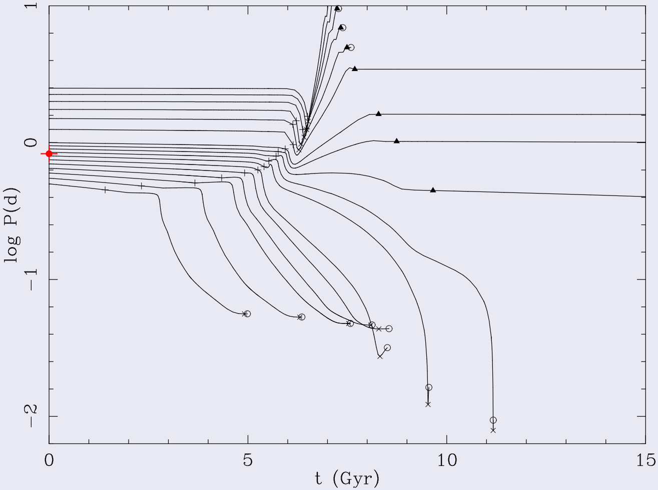
Creating a population

1. Start with the calculated grid



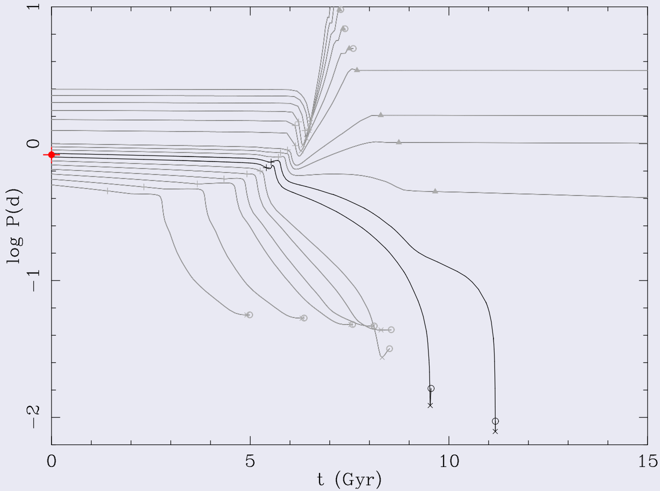
Creating a population

2. Pick a random P_i



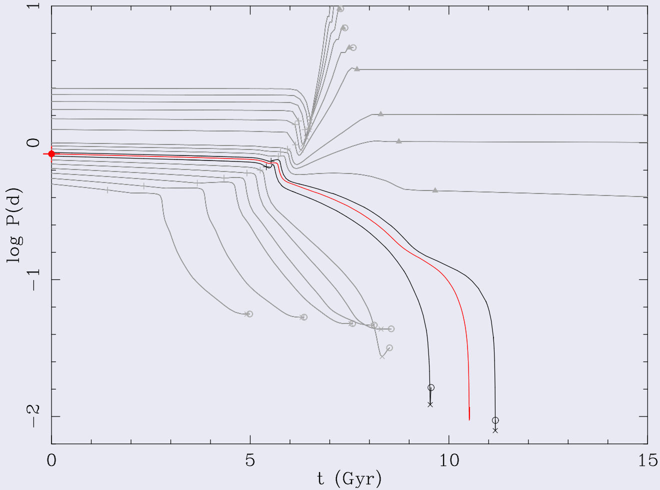
Creating a population

3. Select the bracketing tracks



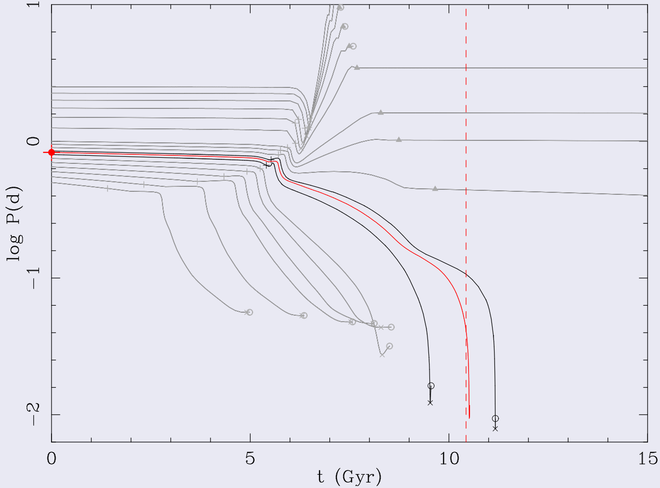
Creating a population

4. Interpolate the track for the selected P_i



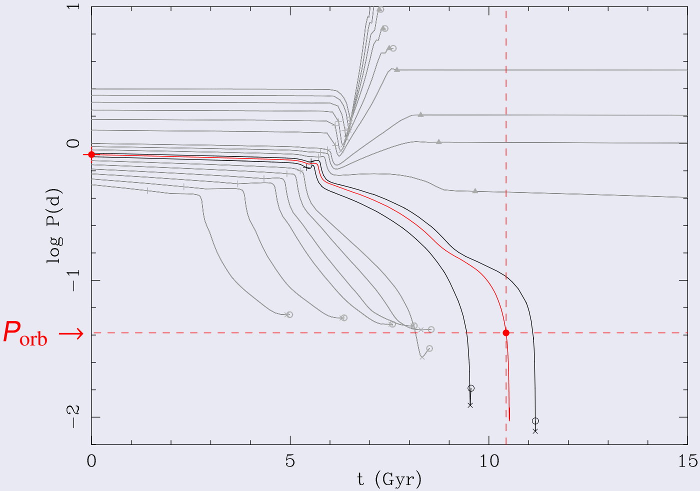
Creating a population

5. Pick a random moment in time, 10 Gyr < t < 13 Gyr



Creating a population

6. Find the orbital period *P* at that moment

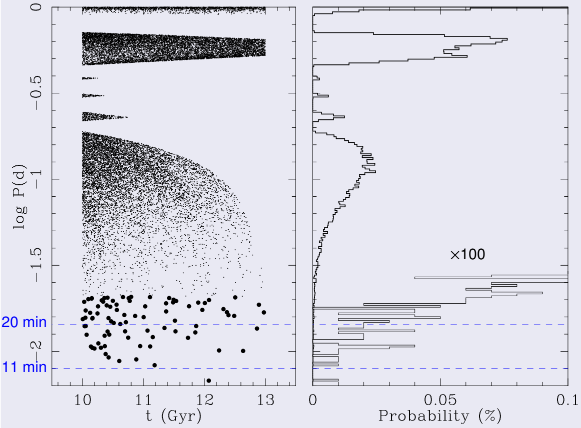


Statistics

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



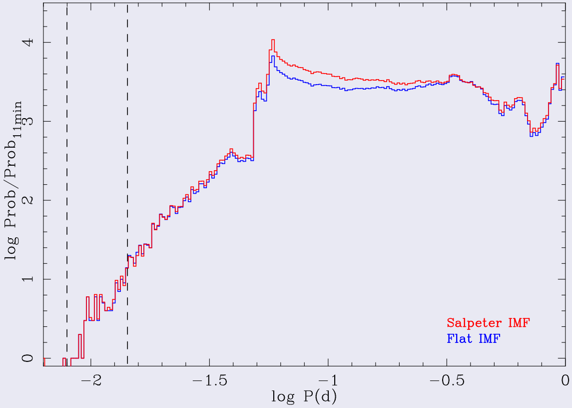
Van der Sluys, Verbunt & Pols, 2005a

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



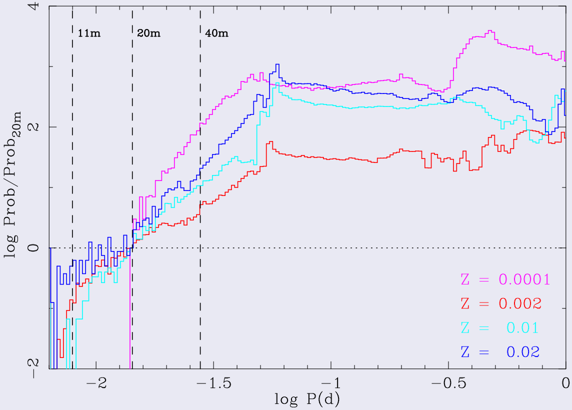
Van der Sluys, Verbunt & Pols, 2005a

Statistics: compare metallicities

Effect of metallicity

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

10^7 binaries



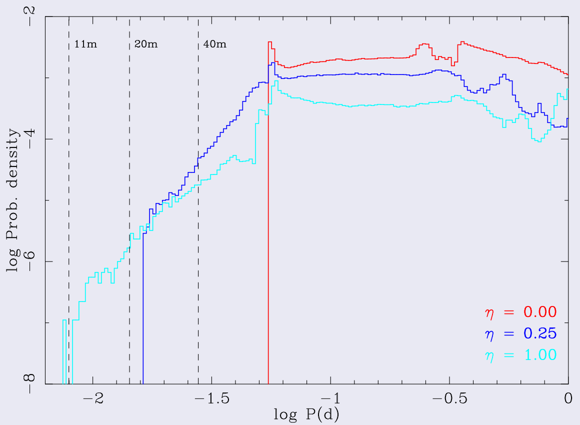
Van der Sluys, Verbunt & Pols, 2005a

Statistics: compare magnetic-braking strengths

Reducing magnetic braking

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

$Z = 0.01$, 10^7 binaries



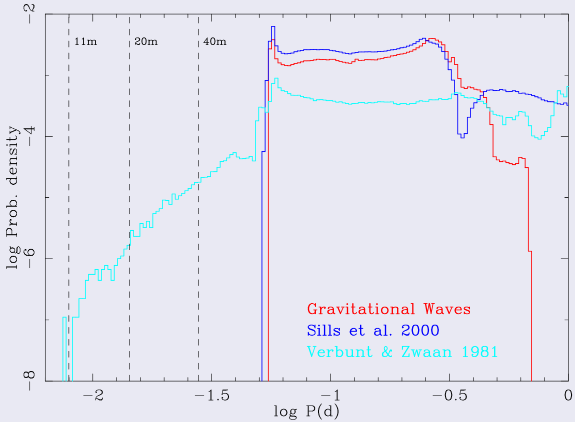
Van der Sluys, Verbunt & Pols, 2005b

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 ~ 70 min

$Z = 0.01$, 10^7 binaries



Van der Sluys, Verbunt & Pols, 2005b

Conclusions

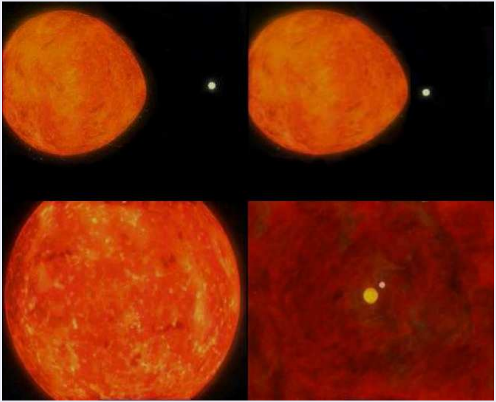
The magnetic-capture scenario cannot produce a sufficient number of ultra-compact X-ray binaries, because

- The initial-period range is very narrow
- The initial-mass range is narrow
- Evolution at ultra-short period is fast
- Often, P_{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



NORTHWESTERN UNIVERSITY

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 $\dot{P}/P = -1.8 \pm 0.3 \times 10^{-15}\mathrm{s}^{-1}$

Scenario 2: Direct collisions

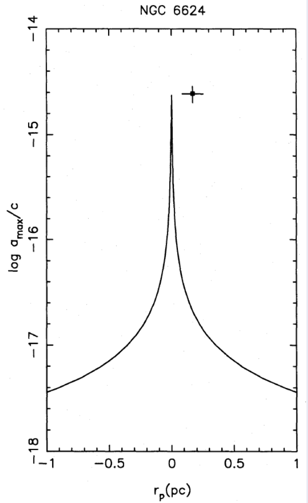
After the collision

- 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 $\dot{P}/P = -1.8 \pm 0.3 \times 10^{-15}\mathrm{s}^{-1}$

Scenario 2: Direct collisions

After the collision

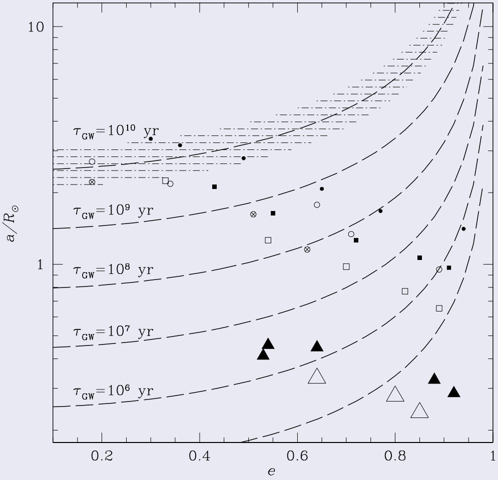
- A NS-WD binary is formed
- Gravitational radiation shrinks the orbit
- Orbital period increases as soon as mass transfer starts
- Observed X-ray binaries should always have positive $\dot{P}$
- The 11-min system has a measured $\dot{P}/P = -1.8 \pm 0.3 \times 10^{-15}\mathrm{s}^{-1}$



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