Open Clusters:

$N$-body models ...

Jarrod Hurley

April, 2009
**NBODY4/6 software**

- includes stellar evolution
  - fitted formulae as opposed to “live” or tables
  - rapid updating of $M$, $R$ etc. for all stellar types and metallicities
  - done in step with dynamics

- and a binary evolution algorithm
  - tidal evolution, magnetic braking, gravitational radiation, wind accretion, mass-transfer, common-envelope, mergers

- and as much realism as possible
  - perturbed orbits (hardening & break-up), chaotic orbits, exchanges, triple & higher-order subsystems, collisions, etc.
  - … regularization techniques
  - + Hermite integration with GRAPE
  - + block time-step algorithm
  - + external tidal field …

(Aarseth 1999, PASP, 111, 1333
Hurley et al. 2001, MN, 323, 630)
Simulation of a Rich Open Cluster

Initial Conditions

- 12,000 single stars (0.1 - 50 M\(\odot\))
- 12,000 binaries (\(a\): flat-log, \(e\): thermal, \(q\): uniform)
- solar metallicity (\(Z = 0.02\))

- Plummer sphere in virial equilibrium
- circular orbit at \(R_{gc} = 8\) kpc
  - \(M \sim 18700\) M\(\odot\)
  - tidal radius 32 pc
  - \(T_{rh} \sim 400\) Myr
  - \(\sigma \sim 3\) km/s
  - \(n_c \sim 200\) stars/pc\(^3\)
  - 6-7 Gyr lifetime
  - 4-5 weeks of GRAPE-6 cpu
M67 at 4 Gyr?

- solar metallicity ✓
- 50% binaries ✓
- $N \sim 2000$ and $1300 \, M_\odot$ luminous mass ✓
- tidal radius 15pc ✓
- half-mass radius 2.5pc ✓
- core radius 0.6pc ✓
- 29 blue stragglers
- $N_{bs}/N_{ms,2TO} \sim 0.15$
- centralized population
- half in binaries
- 29 blue stragglers
- \( \frac{N_{bs}}{N_{ms,2TO}} \sim 0.15 \)
- centralized population
- half in binaries

4d, \( e=0.2 \)
846d, \( e=0.5 \)
1003d, \( e=0.3 \)
1221d, \( e=0.1 \)
- 29 blue stragglers
- \( N_{bs}/N_{ms,2TO} \sim 0.15 \)
- centralized population
- half in binaries

- 25 blue stragglers
- \( N_{bs}/N_{ms,2TO} = 0.18 \)
- centralized population
- half in binaries
- 29 blue stragglers
- $N_{bs}/N_{ms,2TO} \sim 0.15$
- centralized population
- half in binaries

- 25 blue stragglers
- $N_{bs}/N_{ms,2TO} = 0.18$
- centralized population
- half in binaries

15 via dynamics
M67 Observed CMD

- 29 blue stragglers
- $N_{bs}/N_{ms,2TO} \sim 0.15$
- centralized population
- half in binaries

N-body Model CMD

- 25 blue stragglers
- $N_{bs}/N_{ms,2TO} = 0.18$
- centralized population
- half in binaries

- triples
- exchanges
- collisions
- hardening

15 via dynamics
all observed orbital configurations
all observed orbital configurations

\[ P_{\text{circ}} \sim 7-8 \text{d (binary evolution)} \quad \text{cf. } \sim 12 \text{d observed} \]

\[ \Rightarrow \text{same or slightly less for M67 simulation} \]

\[ \Rightarrow \text{increase for } 100k \text{ simulations?} \]
Binding Energy Distribution of Binaries

N-body

Field
Binding Energy Distribution of Binaries

- **Primordial Binaries**
- **BSE Binaries 4 Gyr**

![Graph showing binding energy distribution with logarithmic scales for different types of binaries.](image-url)
Binding Energy Distribution of Binaries

- Primordial Binaries
- BSE Binaries 4 Gyr
- NB4 Binaries 4 Gyr
Binding Energy Distribution of Binaries

- Primordial binaries
- BSE binaries 4 Gyr
- NB4 binaries 15 Gyr

100k, 5% simulation
Core

(a) perturbed disruption
exchange disruption

(b) mergers/collisions
binary escape
SN disruption

$N_{a,0} = 12000$
$N_{b,0} = 12000$
Where are the binaries?
White dwarf fractions $\rightarrow$ kicks?

- 28000 stars, 40% binaries
- 20000 stars, 10% binaries
- 28000 stars, 0% binaries

M67 observed $\sim 0.1 < 0$
Binary Effects on Evolution
Binary Effects on Evolution