X-Ray Binaries and the Current Dynamical States of Galactic Globular Clusters

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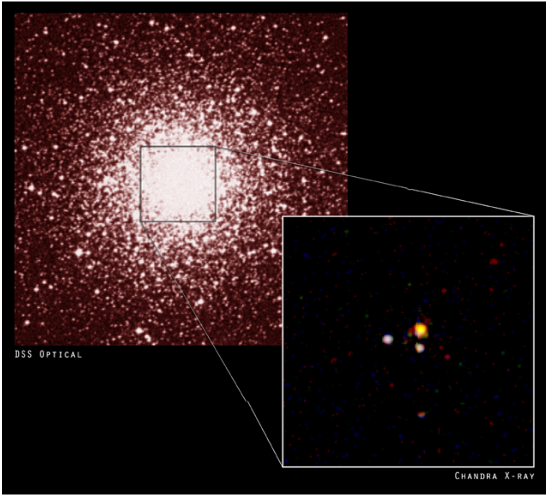
NGC 7099 in Optical and X-Ray



Cohn, Lugger, et al.

Globular clusters look very different in optical and X-ray, and are overabundant in bright X-ray sources relative to the Galactic disk population (by unit mass).

An Overabundance of X-Ray Sources

- Globular clusters have been known for over 30 years to be overabundant in X-ray sources relative to the Galactic disk population, by unit mass. Clark 1975; Katz 1975
- Their X-ray populations include low-mass X-ray binaries (LMXBs), cataclysmic variables (CVs), millisecond pulsars (MSPs), and active binaries (ABs).
- It was quickly realized that the overabundance should be caused by the enhanced rate of dynamical encounters of binaries in the dense cluster cores. Verbunt & Hut 1987
- Recent work has quantitatively confirmed this prediction, with the number of X-ray sources with $L_X \gtrsim 4 \times 10^{30}\,\mathrm{erg/s}$ in a cluster scaling almost linearly with its "encounter frequency" Γ. Pooley, et al. 2003

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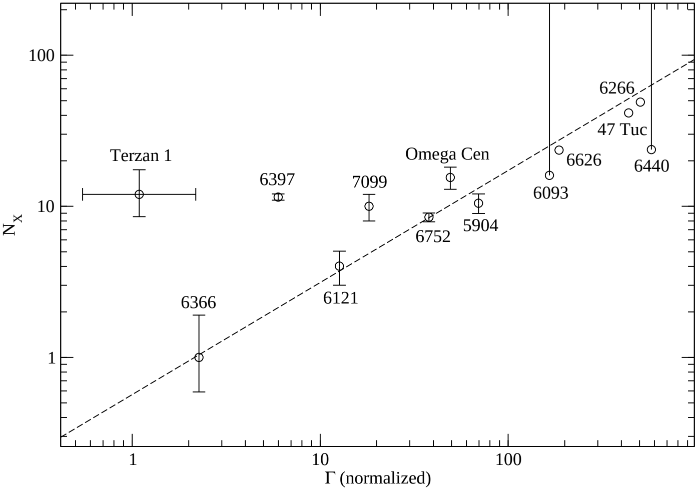
N_X vs. Γ: Three Outliers Are Core-Collapsed Clusters



Pooley, et al. 2003, Lugger, et al. 2007 (NGC 7099), Cackett, et al. 2006 (Terzan 1)

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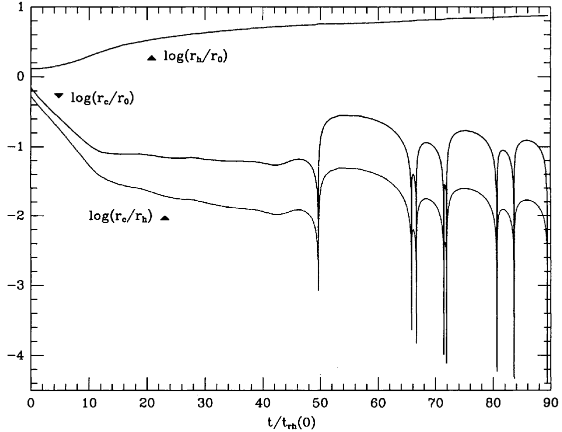
Three Phases of Cluster Evolution



Gao, et al. 1991

Clusters go through: 1) "core contraction", 2) "binary burning" (where binary interactions support core against collapse, analogously to nuclear fusion in main-sequence stars), and 3) "gravothermal oscillations."

Theory Converges on the Binary-Burning Heating Rate

- Since the binary-burning phase is so long-lived, it is widely believed that most globular clusters should currently be in this phase.
- Recently, two independent and very different numerical methods have been used to study cluster properties in the binary-burning phase. Remarkably they agree very well in the value of r_c/r_h predicted during the binary-burning phase.
  Heggie, et al. 2006; Fregeau & Rasio 2007
- The new results show that previous numerical estimates of r_c/r_h are too large by a factor of $\gtrsim 10$, implying that the $\sim 80\%$ of clusters that previously agreed with theory in r_c/r_h no longer do.

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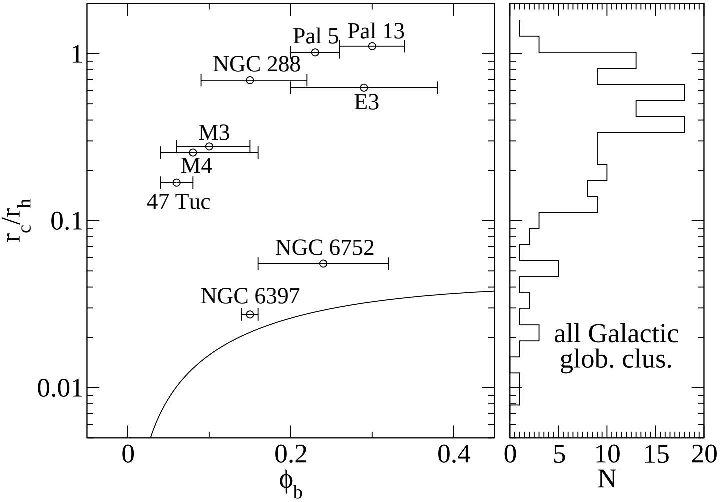
Discrepancy Between Theory and Observations



Fregeau & Heinke

Possible Resolutions of the Discrepancy

- Most clusters could contain central IMBHs, which would act as negative energy sinks Trenti 2006, Miocchi 2007, and/or affect the binary population. Trenti, et al. 2007
- Clusters could simply have "non-traditional" initial conditions: very high or low initial densities, or very large initial binary fractions Fregeau, et al. 2007; or large rates of mass segregation of compact remnants (for young clusters) Merritt, et al. 2004.
- Evaporation of the stellar mass black hole subsystem (for young clusters). Mackey, et al. 2007
- Enhanced stellar evolution mass loss via physical stellar collisions. Chatterjee, et al. (in prep)
- Or, most clusters could simply not be in the binary-burning phase...

The Standard Γ: $N_X \propto dN_{\rm int}/dt$

- If X-ray binaries are dynamically formed, the number in a given cluster should scale with the binary interaction rate.
  Verbunt & Hut 1987
- General interaction rate for two species:

$$\Gamma \equiv \frac{dN_{\rm int}}{dt} = \iint n_1 n_2 \sigma_{12} \left|\mathbf{v}_{12}\right| f(\mathbf{v}_{12}) d^3\mathbf{v}_{12}\, d^3\mathbf{r}$$

- Approximate form:

$$\frac{dN_{\rm int}}{dt} \propto \rho_c^2 r_c^3 / v_\sigma$$

- Approximate form implicitly assumes that binary fraction is constant among all clusters, all interactions are in core, compact object fraction is constant among all clusters, etc.
- Most importantly, this form also represents the *current* interaction rate.

Lifetimes of X-ray Binaries

- X-ray binaries are known to have finite visible lifetimes.
- For LMXBs, the lifetime can vary from $\sim 10^5$ to $10^7\,\mathrm{yr}$ for red giant donors, to $\sim 1\,\mathrm{Gyr}$ for main-sequence companions, to a few Gyr for ultracompacts. Ivanova, et al. 2006
- For CVs, the lifetime is roughly $\sim 1\,\mathrm{Gyr}$. Ivanova, et al. 2006
- Additionally, the strong interaction that places a binary on the path to becoming an observable X-ray source can have occurred several Gyr before mass transfer starts. Ivanova, et al. 2006, 2007

A New Γ: $N_X \propto N_{\rm int}$

- The number of visible X-ray sources should scale with the integrated number of interactions in the recent past.
- General interaction number for two species:

$$\Gamma \equiv N_{\rm int} = \iiint n_1 n_2 \sigma_{12} \left|\mathbf{v}_{12}\right| f(\mathbf{v}_{12}) d^3\mathbf{v}_{12}\, d^3\mathbf{r}\, dt\,.$$

- This can be simplified as with the standard Γ, but keeping important factors and allowing for time evolution of core quantities:

$$N_{\rm int} = f_b f_{\rm co} \frac{81\sqrt{2}a}{4Gm} \int_{t_0-\tau}^{t_0} v_\sigma^3 r_c^{-1}\, dt\,.$$

- This form makes most of the same assumptions as the standard Γ, but allows the properties of the core to vary with time, and leaves τ, the X-ray source lifetime plus lag time, as a parameter.

Three Phases of Cluster Evolution

- The three different phases of cluster evolution can be substituted into our new Γ.
- We exclude the gravothermal oscillation phase, since in this phase a cluster should have a core binary fraction of essentially zero, while all clusters for which it's measured show evidence for larger binary fractions.
- In the binary-burning phase the core properties are taken to be constant.
- For the core contraction phase we use simple self-similar collapse theory, in conjunction with the results of N-body simulations that show nearly universal behavior for many different binary fractions. Hurley 2007

Binary-Burning vs. Core-Contracting

- The result is
$$\frac{N_{\mathrm{int,bb}}}{N_{\mathrm{int,cc}}} = \frac{2.835\tau}{t_0}\left(1-\left(1+9\tau/t_0\right)^{-0.315}\right)^{-1}$$
- This expression has a minimum value of 1 for $\tau = 0$, and a maximum of 5.5 for $\tau = t_0$.
- For the canonical value of $\tau = 4\,\mathrm{Gyr}$ with $t_0 = 13\,\mathrm{Gyr}$, the value is 2.6.
- Interestingly, the only three clusters that are observed to be core collapsed are the only three that are observed to have a significant overabundance in N_X, from ~ 2 for M 80, to ~ 5 for NGC 6397, to ~ 10 for Terzan 1 (whose Γ value is rather uncertain, coincidentally).
- This suggests that the core-collapsed clusters are still in the binary-burning phase while the rest are still in core contraction.

A Confluence of Results Into a Self-Consistent Picture

1. The core-collapsed clusters in the sample have an overabundance of X-ray sources by a factor of ~ 2 to ~ 10.
2. A more refined version of Γ shows that a cluster in the binary-burning phase should have ~ 3 times more X-ray sources than if it were in the core contraction phase.
3. A comparison of observations with recent theory suggests that only core-collapsed clusters agree with predictions for cluster structural parameters in the binary-burning phase.

- It appears that only the $\sim 20\%$ of clusters observed to be core-collapsed are in the binary-burning phase, while the rest are still in core contraction.

Implications

- Many population studies assume constant core properties throughout cluster lifetimes. The numbers of dynamically-formed sources (e.g., blue stragglers, tidal capture binaries) can be scaled, but when feedback is important or the properties of the cluster itself are of interest (e.g., core binary fraction) a simple scaling may not work.
- Clusters with different initial conditions tend to approach common values of structural properties in the binary burning phase. Thus properties of observed clusters may be more strongly dependent on their initial conditions.
- Perhaps most anticlimactically, the many proposed explanations for cluster core energy sources are not needed, including intermediate-mass black holes, and non-traditional initial conditions.

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