Globular Clusters: Formation, Evolution and the Role of Compact Objects

A relatively massive Black Hole in NGC6752? Clues from pulsar timing

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NGC 6752: generalities

- Distance 4.1 kpc ± 5% inferred with WD sequence fitting (Renzini et al.'96)
- Binary fraction 15% → 38% in inner core (Rubenstein & Bailyn '97)
- Metallicity [Fe/H] = -1.56 (Harris '99)
- Central velocity dispersion 2.1 ± 9.7 km/s (2σ-interval) (Dubath, Meylan & Mayor '97)
- 4 single millisecond pulsars (P = 8.4 ms, 5.3 ms, 9.0 ms, 4.6 ms) and 1 binary millisecond pulsar (PSR-A with P = 3.3 ms, \( P_b = 20.6 \) hrs and \( M_{c,\text{min}} = 0.18 \) M⊙) have been discovered in the cluster (D’Amico et al. 2002)

... moreover, recently ...
...obtained new accurate determinations of the GC center, of the central surface brightness $\Sigma_{v,0}$ and of the star density profile, using HST-WFPC2 images, which allowed to resolve and count the stars even in the inner regions of the cluster (Ferraro et al. '03, subm)

WHENCE a safe classification as core-collapsed cluster and a new determination of the core radius $r_c = 5'' .2$ (corresponding to 0.11 pc) (Ferraro et al. '03, subm)
Results from the timing

ALL the five millisecond pulsars detected in NGC 6752 manifest striking peculiarities – either in LOCATION or in ACCELERATION – with respect to all the other pulsars known in globular cluster (Camilo, this conference)
LOCATIONS

- **PSR-A** is at $\sim 74$ core radii, equivalent to $\sim 3.3$ half-mass radii; the most displaced pulsar detected ever! (D’Amico et al. 2002) [the previous example being PSR B2127+15 in M15 at $\sim 0.8$ half-mass-radii (Prince at el. 1991)]

- **PSR-C** is located at $\sim 1.4$ half-mass radii from the cluster centre of gravity; it is the most largely offset single pulsar known
\[ \dot{P}/P \rightarrow \text{ACCELERATIONS} \]

- **PSR-D** has the 3\textsuperscript{rd} largest \( \dot{P} \) ever observed after PSR B1820–30A in NGC 6624 and PSR B1821–24 in M28

- **PSR-B** and **PSR-E** display the 3\textsuperscript{rd} largest negative \( \dot{P}/P \) after the pulsars A and D in M15

**Where does a negative \( \dot{P}/P \) come from?**

A pulsar located in the direction of the unit vector \( \vec{n} \) with respect to the centre of the solar system, having rest frame spin \( P_o \) and moving with 3-dimensional velocity \( \vec{V}_{\text{psr}} \), is observed at a telescope to have barycentrized period \( P \) given by:

\[
P = \left[ 1 + \vec{V}_{\text{psr}} \cdot \vec{n}/c \right] P_o
\]

Differentiating with respect to time and neglecting \( \mathcal{O}(c^{-2}) \):

\[
\frac{\dot{P}}{P} = \frac{\dot{P}_o}{P_o} + \frac{V_{\text{psr}, \perp}^2}{cD} + \frac{\vec{a}_{\text{psr}} \cdot \vec{n}}{c}
\]

Hence negative \( \dot{P}/P \) implies that acceleration \( \vec{a}_{\text{psr}} \) dominates the period derivative
Origin of the Acceleration

Contributions to $\dot{P}/P$ from centrifugal acceleration (Shklovskii 1970), differential Galactic rotation (Damour & Taylor 1991) and vertical acceleration in the Galactic potential (Kuijken & Gilmore 1989) are all negligible in the case of the cluster NGC 6752

Hence, the acceleration imparted to the pulsars in NGC 6752 can only be due to:

• 1• The overall effects of the **gravitational well** of the Globular Cluster

• 2• The presence of **close perturber(s)** exerting a gravitational pull onto the pulsars

The hypothesis •1• has been routinely applied to many globular clusters hosting millisecond pulsars with negative $\dot{P}/P$

...that allows to estimate the central projected mass–to–light ratio of the Cluster...

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Mass-to-Light Ratio estimate

The maximum acceleration $a_{l,\text{max}}$ experienced by a test particle located at a projected distance $\theta_\perp$ from the centre of a GC can be derived from the following formula, holding to within 10% for all plausible GC models (Phinney 1992)

$$\left| \frac{a_{l,\text{max}}(\theta_\perp)}{c} \right| \approx 1.1 \frac{GM_{\text{cyl}}(<\theta_\perp)}{c} \frac{\pi D^2 \theta^2_\perp}{\pi D^2 \theta^2_\perp}$$

On the other hand, for a MSP displaying negative $\dot{P}/P$

$$\left| \frac{\dot{P}}{P}(\theta_\perp) \right| < \left| \frac{a_{l,\text{max}}(\theta_\perp)}{c} \right|$$

Using $\frac{M}{\mathcal{L}_V}$ and $\Sigma_V$ for converting mass in luminosity, one gets

$$\left| \frac{\dot{P}}{P}(\theta_\perp) \right| < 5.1 \times 10^{-18} \frac{M}{\mathcal{L}_V} \left( \frac{\Sigma_V(<\theta_\perp)}{10^4 \text{ L}_V \Omega \text{pc}^{-2}} \right) \text{ sec}^{-1}$$

A lower limit to the mass-to-light ratio $M/\mathcal{L}_V$ in the central region of a globular cluster can be inferred from observation of $\dot{P}/P$ and $\Sigma_V$
Combining the new optical data with the results from the timing of the radiopulsars (Ferraro et al. ’03, subm)

- The inferred $M/L_v \gtrsim 6 - 7$ is the highest lower limit on the central mass-to-light ratio reported for a globular cluster containing pulsars. E.g. $M/L_v \gtrsim 3$ for M15 (Phinney ’93) and $M/L_v \gtrsim 0.7$ for 47 Tuc (Freire ’03)
Exploring the origin of the high $\mathcal{M}/\mathcal{L}_v$

$\mathcal{M}/\mathcal{L}_v \sim 6$ in the central 0.076 pc of NGC 6752 implies the presence of an extra–amount of $\sim 1000$ M$_{\odot}$ of low-luminosity matter with respect to what seen in a typical core-collapsed cluster

- If the unseen matter is composed by heavy ($\sim 1$ M$_{\odot}$) **WHITE DWARFS**
  
  $\rightarrow$ $\gtrsim 20\%$ of the total population of heavy WDs must be sank in the cluster core for a Salpeter IMF

- If the unseen matter is composed by **NEUTRON STARS**
  
  $\rightarrow$ a NS retention fraction of $\gtrsim 30\%$ is required for a Salpeter IMF

**BUT** the star density profile suggests that the mass of the species dominating the cluster dynamics should be $\sim 0.7$ M$_{\odot}$

- A single (or binary) **BLACK-HOLE** of $\lesssim 500$ M$_{\odot}$ could account for a significant fraction of the unseen matter, without leaving any observable “cusp–like” signature in the available star density profile
Exploring the origin of the displaced position of PSR-A
(Colpi, Possenti & Gualandris 2002)

NO ← A primordial binary born in the cluster halo
      ▼
      only 3 such MSPs expected in all the ∼ 200 GCs !

NO ← A primordial binary born in the cluster core and
ejected due to SN explosion within \( \tau_{sn} \sim 1 \) Gyr since
the cluster formation
      ▼
      the dynamical friction time \( \tau_{df} \sim 1 \) Gyr for a highly
eccentric orbit, thus making impossible the survival of the MSP at the present offset position

NO ← An ejected binary resulting from a scattering inter-
action with a third star in the cluster core
      ▼
      not enough binding energy is available in the binary
system progenitor of the millisecond pulsar in order
to eject it into the cluster outskirts
An ejected binary resulting from an exchange interaction with a third star in the cluster core

uncomfortably long timescale $\gtrsim 20$ Gyr for the occurrence of a suitable event

An ejected binary resulting from a scattering event involving an unequal mass BH+BH binary of total mass $\lesssim 100$ $M_\odot$

compatible with the lifetime of a BH+BH binary in NGC 6752 if $a_{BH+BH} \gtrsim 0.4$ AU;

consistent with the energy available for the ejection of PSR−A if $a_{BH+BH} \gtrsim 1.3$ AU;

compatible with the dynamical friction time $\sim 1$ Gyr;

consistent with the observed very small eccentricity $e \lesssim 10^{-5}$ of the orbit of PSR−A;

consistent with the timescale $\lesssim 2$ Gyr for the occurrence of a suitable event.
Is there a UNIFYING picture for explaining BOTH the strong ACCELERATIONS and the offset POSITIONS of the millisecond pulsars in NGC 6752?
⇒ CENTRAL CLUSTER OF WHITE DWARFS
   ↓
- OK for explaining MSPs accelerations
- HARDLY accounts for the star density profile
- FAILS in explaining ejection of PSR–A and PSR–C

⇒ CENTRAL CLUSTER OF NEUTRON STARS
   ↓
- OK for explaining MSPs accelerations
- HARDLY explains ejection of PSR–A and PSR–C
- FAILS in accounting for the star density profile

⇒ SINGLE INTERMEDIATE MASS BH: $\sim 500 \, M_\odot$
   ↓
- OK for explaining MSPs accelerations
- OK for accounting for the star density profile
- FAILS in explaining the eccentricity of PSR–A

⇒ BINARY BH OF MODERATE MASS: $\sim 10 \pm 100 \, M_\odot$
   ↓
- OK for explaining ejection of PSR–A and PSR–C
- OK for accounting for the star density profile
- HARDLY explains the MSP accelerations

(Colpi, Mapelli & Possenti 2003, in prep)
(Ferraro et al. 2003, subm)
What is occurring to the millisecond pulsars in NGC 6752 is at the same time intriguing and still largely puzzling

NGC 6752 is more than twice closer than another cluster, M15, which has been repeatedly and deeply searched for Black-Hole signatures

NCG 6752 should become a primary target for ultradeep photometry and spectroscopy