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 $\pm$ 5% inferred with WD sequence fitting** (Renzini et al.'96)

- **Binary fraction 15%$\rightarrow$ 38% in inner core** (Rubenstein & Bailyn '97)

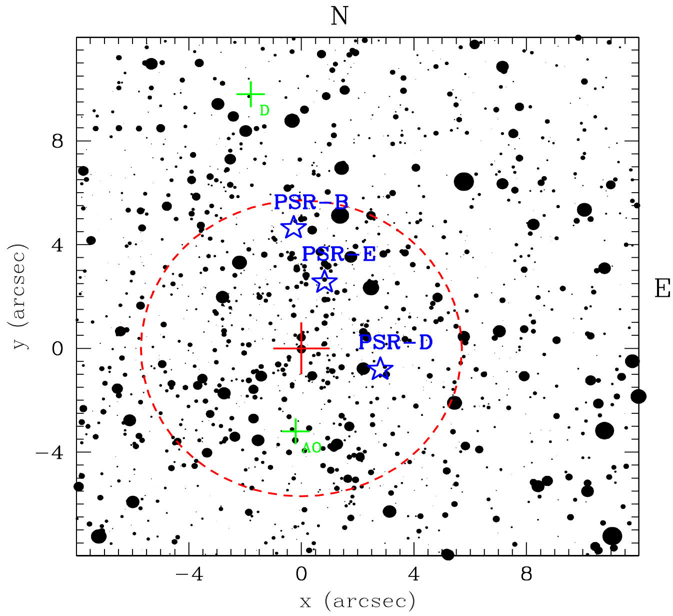
- **Metallicity [Fe/H]=−1.56** (Harris '99)

- **Central velocity dispersion** $2.1 \div 9.7$ **km/s (2σ-interval)** (Dubath, Meylan & Mayor '97)

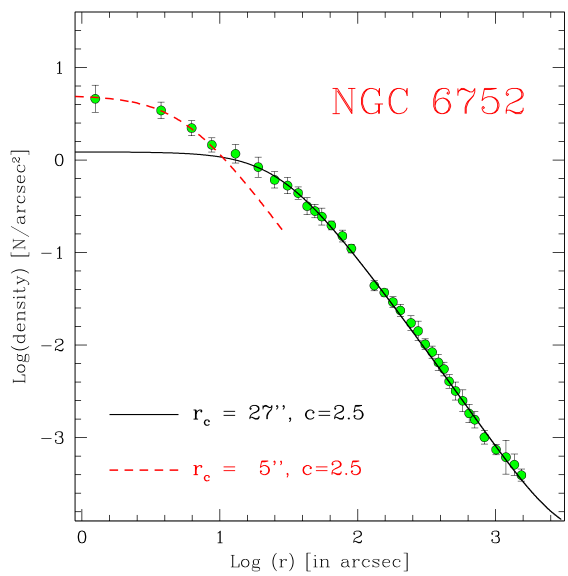
- **4 single millisecond pulsars (P = 8.4 ms, 5.3 ms, 9.0 ms, 4.6 ms) and 1 binary millisecond pulsar (PSR−A with P=3.3 ms, P_b =20.6 hrs and $M_{c,min}$=0.18 $M_\odot$) have been discovered in the cluster** (D'Amico et al. 2002)

... 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)

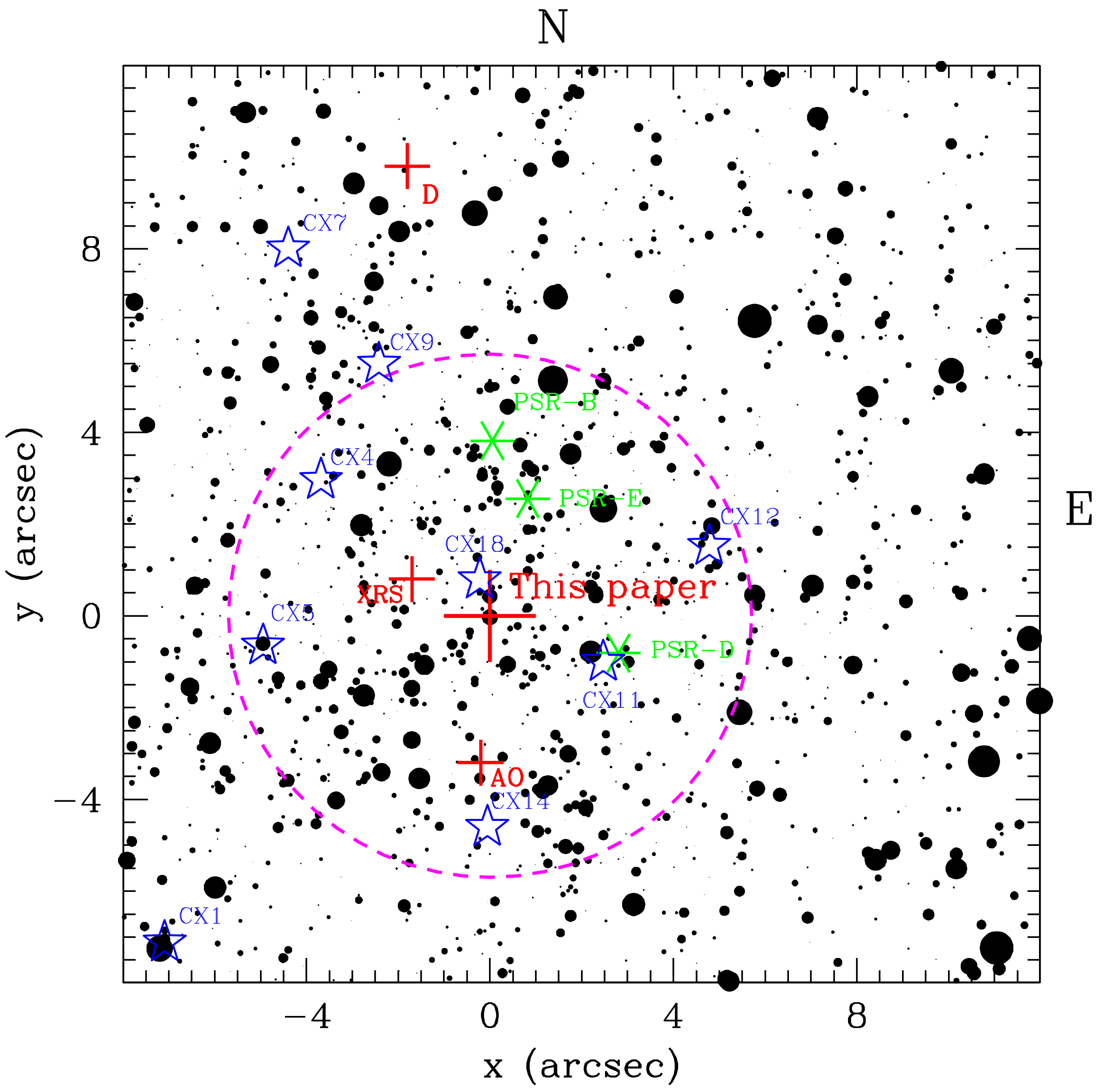


CENTRE OF GRAVITY



STAR DENSITY PROFILE

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)


N
E
y (arcsec)
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PSR−B
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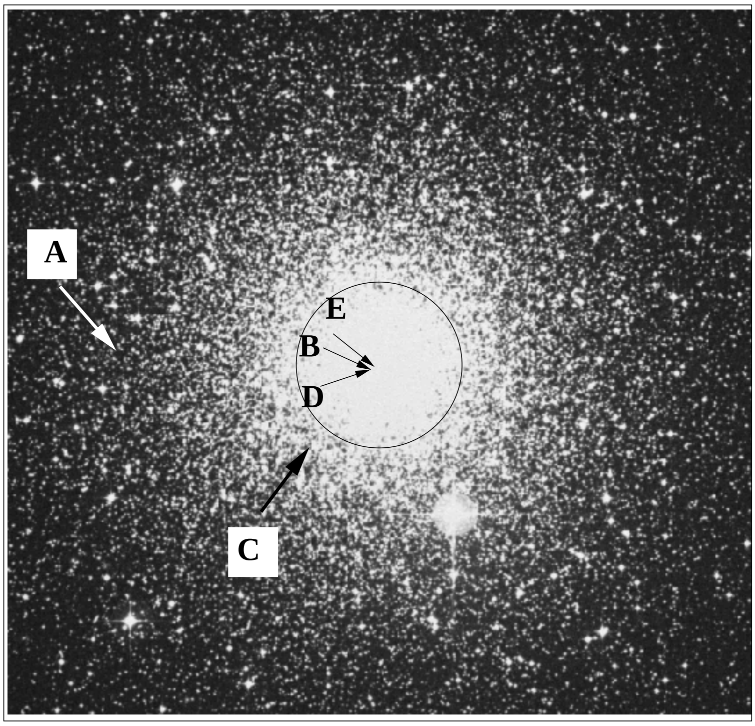
CX18
XRS
This paper
CX5
PSR−D
CX11
AO
CX14
CX1

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 ∼ 74 core radii, equivalent to ∼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 ∼ 0.8 half-mass-radii (Prince at el. 1991)]

- **PSR-C** is located at ∼1.4 half-mass radii from the cluster centre of gravity; it is the most largely offset single pulsar known

$\dot{P}/P \longrightarrow$ ACCELERATIONS

- **PSR-D has the 3rd 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 3rd 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 $\vec{V}_{\rm psr}$, is observed at a telescope to have barycentrized period P given by:

$$P \;=\; [\;1\;+\;\vec{V}_{\rm psr}\cdot\vec{n}/c\;]\;P_o$$

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

$$\frac{\dot{P}}{P} \;=\; \frac{\dot{P}_o}{P_o} \;+\; \frac{V^2_{{\rm psr},\perp}}{cD} \;+\; \frac{\vec{a}_{\rm psr}\cdot\vec{n}}{c}$$

Hence negative $\dot{P}/P$ implies that acceleration $\vec{a}_{\rm psr}$ 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...

Mass-to-Light Ratio estimate

The maximum acceleration $a_{l,max}$ 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)

$$\left|\frac{a_{l,max}(\theta_\perp)}{c}\right| \simeq 1.1 \frac{G}{c} \frac{M_{cyl}(<\theta_\perp)}{\pi D^2 \theta_\perp^2}$$

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

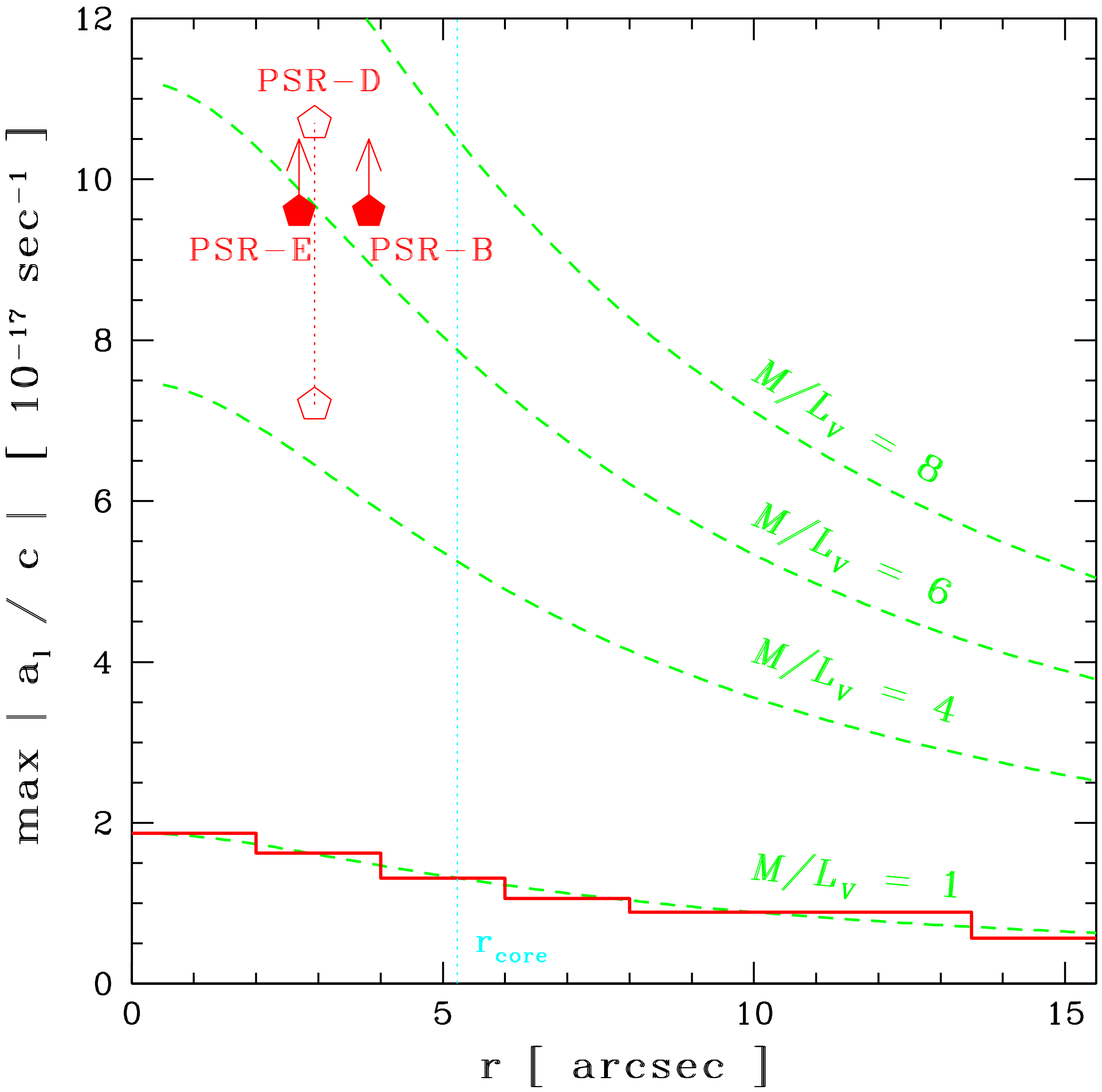
$$\left|\frac{\dot{P}}{P}(\theta_\perp)\right| < \left|\frac{a_{l,max}(\theta_\perp)}{c}\right|$$

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

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

A lower limit to the mass-to-light ratio $\mathcal{M}/\mathcal{L}_V$ in the central region of a globular cluster can be inferred from observation of $\dot{P}/P$ and Σ_V

Combining the new optical data with the results from the timing of the radiopulsars (Ferraro et al. '03, subm)



- The inferred $\mathcal{M}/\mathcal{L}_v \gtrsim 6-7$ is the **highest lower limit on the central mass-to-light ratio** reported for a globular cluster containing pulsars. E.g. $\mathcal{M}/\mathcal{L}_v \gtrsim 3$ for M15 (Phinney '93) and $\mathcal{M}/\mathcal{L}_v \gtrsim 0.7$ 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**

$\longrightarrow$ $\gtrsim 20\%$ 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**

$\longrightarrow$ 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 ~ 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 $\tau_{sn} \lesssim 1$ 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 interaction 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**

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

⇓

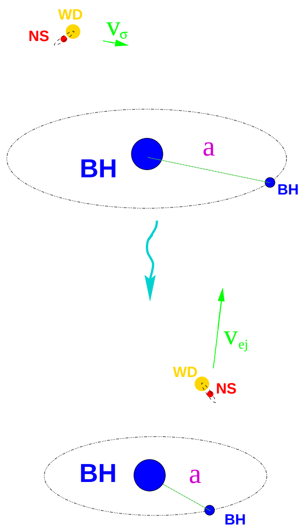
compatible with the lifetime of a BH+BH binary in NGC 6752 if $a_{BH+BH} \gtrsim 0.4$ AU;

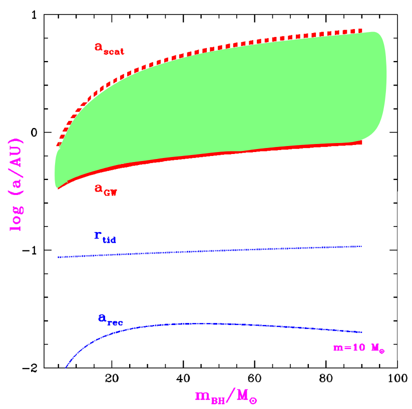
consistent with the energy available for the ejection of PSR−A if $a_{BH+BH} \lesssim 1.3$ AU;

compatible with the dynamical friction time ~ 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 ?

$\Rightarrow$ CENTRAL CLUSTER OF WHITE DWARFS

$\Downarrow$

- OK for explaining MSPs accelerations
- HARDLY accounts for the star density profile
- FAILS in explaining ejection of PSR−A and PSR−C

$\Rightarrow$ CENTRAL CLUSTER OF NEUTRON STARS

$\Downarrow$

- OK for explaining MSPs accelerations
- HARDLY explains ejection of PSR−A and PSR−C
- FAILS in accounting for the star density profile

$\Rightarrow$ SINGLE INTERMEDIATE MASS BH: $\lesssim 500\ M_\odot$

$\Downarrow$

- OK for explaining MSPs accelerations
- OK for accounting for the star density profile
- FAILS in explaining the eccentricity of PSR−A

$\Rightarrow$ BINARY BH OF MODERATE MASS: $\sim 10 \div 100\ M_\odot$

$\Downarrow$

- 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 an other cluster, M15, which has been repeatedly and deeply searched for Black-Hole signatures

$\Downarrow$

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