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Searching for intermediate mass black holes in globular clusters with the Very Large Telescope

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Abstract. The exact shape of the velocity dispersion profile $\sigma(r)$ in the central regions of globular clusters is one of the best indicators of the possible presence of an intermediate-mass black hole (IMBH). In principle, this could be measured from the radial velocities (V_r) of individual stars, and also as the line broadening in integrated light spectra. In practice, the case of NGC 6388 shows that these two methodologies can provide opposite conclusions about the presence of an IMBH. Here we present the first results of an ESO Large Programme running at the Very Large Telescope, that uses Adaptive Optics assisted Integral Field Spectroscopy to acquire spectra of dozens individual stars in the innermost cluster regions (over arcsecond scales) to firmly assess the possible presence of an IMBH.

Key words. globular clusters: general – Stars: kinematics and dynamics – Techniques: spectroscopic – methods: observational

1. Introduction

The discovery of intermediate mass ($10^3 - 10^4 M_\odot$) black holes (IMBHs) would have a dramatic impact on a number of open problems, ranging from the formation of supermassive BHs and their co-evolution with galaxies, to the origin of the ultraluminous X-ray sources in nearby galaxies, up to the detection of gravitational waves (e.g. Gebhardt et al. 2005). However, the evidences gathered so far in support of the existence of IMBHs are inconclusive and controversial (see references in Kirsten & Vlemmings 2012). Galactic globular clusters (GCs) are thought to be the best places where to search for these elusive objects. In fact, the extrapolation of the "Magorrian relation" (Magorrian et al. 1998) down to the IMBH masses naturally leads to the GC mass regime. Moreover, numerical simulations have shown that the cores of GCs are the ideal habitat for the formation of IMBHs (e.g., Portegies Zwart et al. 2004; Giersz et al. 2015).

For these reasons, the recent years have seen an increasing number of works dedicated to the search for IMBHs in GCs, exploiting all the proposed observational channels, ranging from the detection of X-ray and radio emission (see refs. in Strader et al. 2012), to the detailed study of the cluster structure, especially in terms of the shape of the density and velocity dispersion (VD) profiles (e.g., Lützgendorf et al. 2011, 2012, 2013). In particular, in the presence of an IMBH, a power-law density profile $\Sigma_*(r) \propto r^\alpha$ with a slope $\alpha \sim -0.3$ (significantly shallower than the one expected in a post-core collapse system: $\alpha \sim -0.7$) and a cuspy VD profile are expected in the innermost cluster regions (e.g., Baumgardt et al. 2005; Miocchi

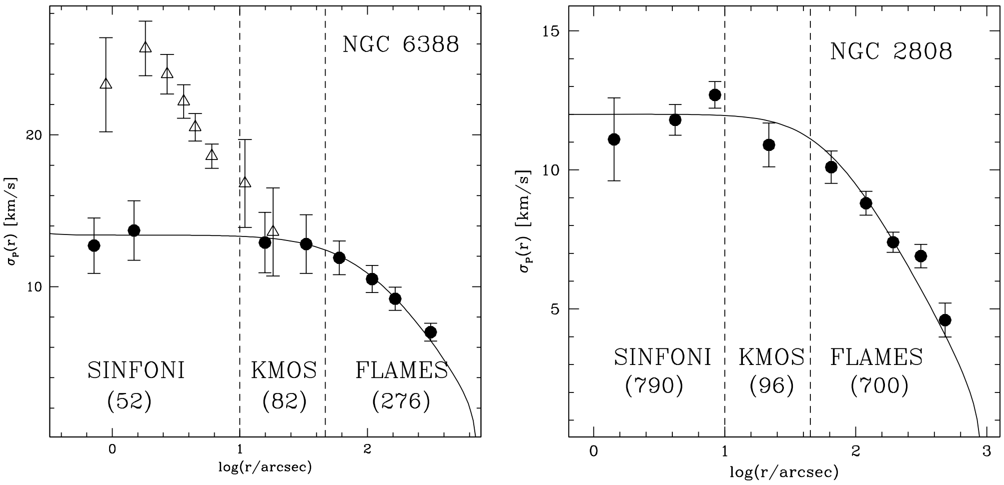

Fig. 1. VD profiles of NGC 6388 and NGC 2808 obtained from the RVs of individual stars (circles), measured following our multi-instrument approach: SINFONI+KMOS+FLAMES. The number of individual spectra measured with each instrument is labelled within brackets. In the case of NGC 6388 the empty triangles show the VD profile obtained from integrated light spectra (Lützgendorf et al. 2011).

2007). In spite of such an effort, however, no firm conclusions could be drawn to date. This is because the predictions about the X-ray and radio emission are quite uncertain, and the precise determination of the density and (especially) the VD profiles is very challenging in the highly crowded central regions of GCs. In addition, different methodologies to measure the VD can bring to incompatible results. In fact, in principle, for gas-free and resolved-star populations as Galactic GCs are, VD and rotation can be obtained both from the measure of the stellar line-of-sight (los) velocity (through spectroscopy) and from the velocity components on the plane of the sky (from internal proper motions, PMs). In practice, however, this is very challenging. In fact, accurate PM measurements require high-precision photometry and astrometry on quite long time baselines and they just started to be feasible, mainly thanks to the combination of multi-epoch HST observations and the improved techniques of data analysis (Anderson & van der Marel 2010; Bellini et al. 2014; Watkins et al. 2015). On the other hand, the standard approach commonly used in extra-Galactic astronomy (i.e. measuring the line broadening and Doppler shift from integrated light spectra) can be prone to a severe "shot noise bias" in the case of resolved stellar populations, since the spectra can be dominated by the light of just a few bright stars (e.g. Dubath et al. 1997). The alternative approach is to measure the dispersion about the mean of the radial velocities (RVs) of statistically significant samples of individual stars. This is safe from obvious biases, but it is observationally very challenging, especially in the highly crowded GC centres, requiring multi-object and spatially resolved spectroscopy.

2. The project

In the context of a comprehensive approach to the understanding of the internal cluster dynamics, we are leading two Large Programmes at the ESO Very Large Telescope (193.D-0232 and 195.D-0750, PI: Ferraro, for a total of 300 hours of observing time). The methodology that we follow consists in a coordinated use of the last generation spectrographs to sample the entire radial extension of GCs: (*i*) Adaptive Optics (AO) Integral Field Spectroscopy (IFS) to acquire spectra of dozens individual stars in the innermost cluster regions (arcsecond

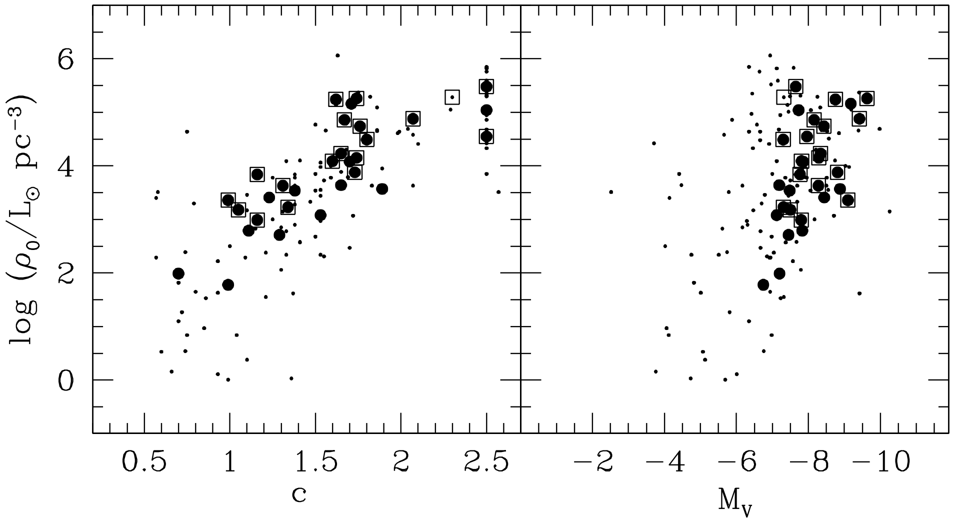

Fig. 2. Distribution of the target globular clusters in the planes of central density versus concentration parameter (*left*) and central density versus absolute total magnitude (*right*). The small dots correspond to the entire Galactic population (from Harris 1996, 2010 version), the filled circles mark our KMOS+FLAMES targets, the empty squares highlight the GCs for which we are collecting SINFONI observations.

scale) by using the near-infrared spectrograph SINFONI, (*ii*) seeing-limited IFS for the intermediate radial range (tens of arcsecond scale) by using the near-infrared spectrograph KMOS, and (*iii*) wide-field multi-object spectroscopy for the most external regions (from one to tens arcminute scales) by using the spectrograph FLAMES. We use IFS in a non-conventional mode, by extracting spectra only from those "pixels" (spaxels) illuminated by individual, resolved stars (which are instead rejected in the classical integrated-light approach). This methodology has been found to be the most suitable to properly explore the central region of GCs and search for the IMBH signature.

The pilot projects In fact, we tested this idea with two pilot projects on high-density GCs (NGC 6388 and NGC 2808), and the obtained results (Lanzoni et al. 2013; Lapenna et al. 2015) fully demonstrate the success of such a multi-instrument approach and the indubitable superiority of the individual RV diagnostics. In particular, in the first pilot project we observed NGC 6388, a cluster suspected to harbour an IMBH (Lanzoni et al. 2007; Lützgendorf et al. 2011). The results obtained in this high-density cluster (with core radius $r_c = 7.2''$ and central luminosity density $\log \rho_0 = 5.37$ in $L_\odot/\mathrm{pc}^3$) demonstrated the revolutionary potentiality of diffraction-limited IFS: the AO-corrected SINFONI observations attained an angular resolution comparable to that of HST, thus allowing us to extract individual spectra for 52 resolved stars within only $2''$ from the centre, in just one pointing. The resulting VD profile (solid circles in Fig. 1a) reveals a centrally flat behaviour with a value of $\sim$ 13 km/s. This profile and the observed density distribution are best-fitted by a model with no central IMBH. Instead, the VD profile obtained from the line broadening of integrated light spectra shows a steep inner cusp with a central value of $\sim$ 25 km/s (empty triangles in Fig. 1a), suggesting that a $\sim 2 \times 10^4 M_\odot$ IMBH is hidden in this cluster (Lützgendorf et al. 2011). Such a discrepancy is due to the shot noise bias produced by 3 very bright stars with opposite RV (see Fig.12 in Lanzoni et al. 2013), which artificially broaden the spectral lines and bring to a severe overestimate of the central VD. These results clearly demonstrate that the safest way to determine the los VD in Galactic GCs is from individual star RVs. Our multi-instrument approach has been even more effective in NGC 2808 (r_c = 15″, $\log \rho_o = 4.7$), where we have been able to measure more than 1600 individual RVs in total (see Fig. 1b; Ferraro et al. 2016, in preparation). In particular, thanks to a mosaic of seven SINFONI pointings, we measured the RV of more than 800 individual stars within only 10″ from the centre of this high-density cluster! This is indeed a major, unprecedented achievement, the VD profile of no other Galactic GC was obtained at such a level of accuracy: the time is ripe for a revolutionary advancement in the field of GC internal dynamics.

The sample A sample of 36 GCs (see Fig. 2) representative of the overall Galactic population has been selected to properly encompass (i) the cluster dynamically-sensitive parameter space (they span a large range of central densities and a factor of three in the concentration parameter), (ii) different stages of dynamical evolution (Ferraro et al. 2012); the sample includes both post- and pre- core-collapse GCs, with the core relaxation time spanning almost three orders of magnitude, and (iii) different environmental conditions (they are distributed at different heights on the Galactic plane, thus to sample both the bulge/disk and the halo populations ($|z| < 1.5$ kpc, and $1.5 < |z| < 13$, respectively). The selected targets are also more luminous than $M_V = 6.8$ (i.e. populous enough to guarantee large samples of giants for a meaningful determination of the VD), relatively close (within 16 kpc, thus providing spectra with good signal-to-noise ratios for stars down to the sub-giant branch, in reasonable exposure times) and not extremely metal-poor ([Fe/H]> −1.8, thus allowing RV measurements with an accuracy of ∼ 2 km/s also from relatively low-resolution IR spectra).

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