The Search for Intermediate-mass Black Holes in Globular Clusters

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Intermediate-mass black holes (IMBHs) fill the gap between supermassive and stellar-mass black holes and they could act as seeds for the rapid growth of supermassive black holes in early galaxy formation. Runaway collisions of massive stars in young and dense stellar clusters could have formed IMBHs that are still present in the centres of globular clusters. We have resolved the central dynamics of a number of globular clusters in our Galaxy using the FLAMES integral-field spectrograph at the VLT. Combining these data with photometry from HST and comparing them to analytic models, we can detect the rise in the velocity dispersion profile that indicates a central black hole. Our homogeneous sample of globular cluster integral-field spectroscopy allows a direct comparison between clusters with and without an IMBH.

The missing link?

Black holes have fascinated humanity for almost three centuries. Objects of pure gravity forming singularities in spacetime were first postulated by John Michell in 1783 and still seem enigmatic to physicists today, fuelling a strong drive to understand their nature, growth and evolution on all scales. Supermassive black holes (SMBHs) have masses from a million up to several billions of solar masses and are situated in the centres of massive galaxies. When a SMBH accretes the surrounding material it emits tremendous amounts of energy. This energy can be observed at all wavelengths and is detectable at large distances. The most active galaxies are quasars and have been a puzzle to astronomers since their discovery in the early 1960s. Their presence at large redshifts indicates that they existed at a time when the Universe was only one billion years old or less, at a very early stage of structure formation (Fan, 2006) when the first galaxies were just forming. How could a black hole with a mass of a billion or more solar masses have formed so early in the history of the Universe, when galaxies were not yet fully evolved?

Black holes can grow in two ways: through the accretion of surrounding material and by merging with other black holes. Even if a black hole accretes at the highest possible rate (the Eddington rate) for a billion years, it would not reach one million solar masses if it started with a one solar mass seed. Observations have also shown that SHMBs do not constantly accrete at the efficiency of the Eddington rate. Thus, the preferred process to explain the rapid growth of SMBHs is through the merger of smaller seed black holes of intermediate mass (between 100 and 10 000 solar masses, e.g., Ebisuzaki et al., 2001).

Numerical simulations have shown that intermediate-mass black holes can form in runaway mergers of stars in a dense environment, such as young star clusters. Also, ultraluminous X-ray sources at off-centre positions in galaxies provide strong evidence of massive black holes in stellar clusters (e.g., Soria et al., 2011). The globular clusters observed today are as old as their host galaxy: could they have delivered seed black holes, the missing link, in the crucial early stage of galaxy formation?

A further motivation for studying IMBHs is that observations have shown a correlation between the masses of SMBHs and the velocity dispersion of their host galaxies (see Figure 1 and e.g., Ferrarese & Merritt, 2000; and Gebhardt et al., 2000). Extrapolating this relation to the mass ranges of IMBHs yields a velocity dispersion of between 10 and 20 km/s, such as those observed from the stars in globular clusters. The origin and interpretation of this relation is still under debate and it is not known whether it

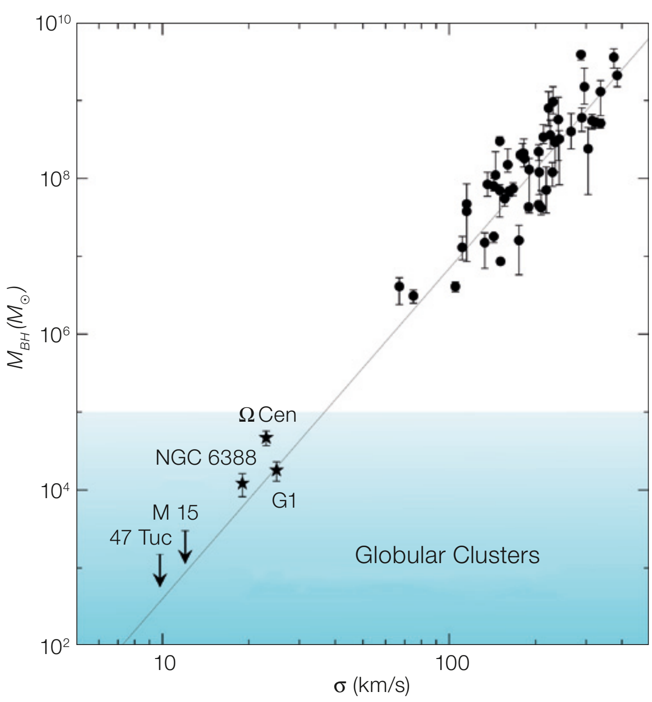

Figure 1. The M_{BH}– σ relation for supermassive black holes in galaxies is shown. Globular clusters and dwarf galaxies lie at the extrapolation of the relation towards lower black hole masses. The points for a few globular clusters are plotted.

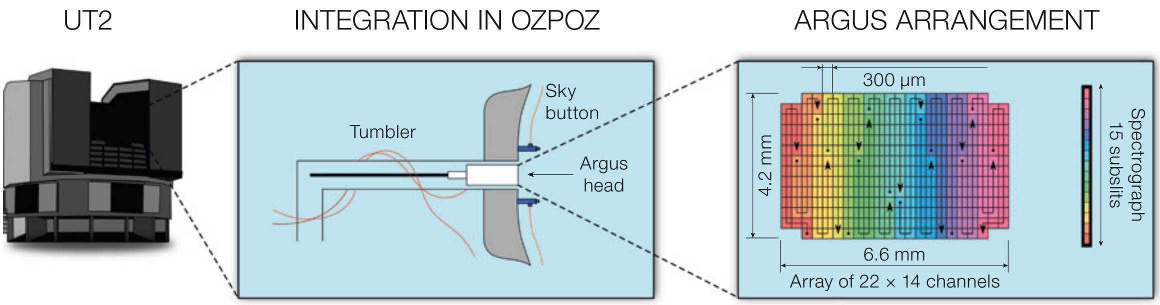

Figure 2. A schematic of the VLT FLAMES ARGUS integral field unit in the Ozpoz fibre positioner is shown (centre). The ARGUS fibre geometry and the allocation of fibres into sub-slits feeding the GIRAFFE spectrometer is shown at right.

truly holds at the lower mass end. The study of IMBHs and their environments might shed light on many astrophysical problems, helping us to develop a better understanding of black hole formation and galaxy evolution.

The idea that IMBHs might exist in globular clusters was first proposed decades ago. Many observational attempts to find direct evidence of a black hole in globular clusters have followed. However, most studies have only observed the light profiles in the centre of the clusters and compared these with models. A central black hole does produce a prominent cusp in the surface brightness profile of a globular cluster (Bahcall & Wolf, 1976; Baumgardt et al., 2005), but this signature can be confused with the one expected from a core-collapse process. For this reason, it is crucial to study the kinematic profile in addition to the light profile.

Our group set out to search for the kinematic signatures of intermediate-mass black holes in Galactic globular clusters by trying to understand which of our observed globular clusters host an intermediate-mass black hole at their centre and which do not. With a sample of ten clusters, our goal is to understand whether the presence of an IMBH correlates with any of the cluster properties.

Mapping the integrated light

A central black hole in a dense stellar system, such as a globular cluster, affects the velocities of its surrounding stars. As an additional gravitational potential it causes the stars in its vicinity to move faster than expected from the gravitational potential of the cluster itself. Measuring this difference provides an estimate of the mass of the possible black hole. Obtaining velocities and velocity dispersions in the centres of globular clusters, however, is very difficult due to the high stellar densities in these regions. Resolving individual stars in the centre and measuring spectra with ground-based telescopes requires adaptive optics, extraordinary weather conditions and time-consuming observations. For these reasons we used a different method — integrated light measurements (Noyola, 2010; Lützgendorf, 2011).

We used the large integral field unit ARGUS, a mode of the FLAMES facility mounted on Unit Telescope 2 of the Very Large Telescope (VLT). Figure 2 shows schematically the properties of the instrument. ARGUS consists of a 22 × 14 array of microlenses (called spaxels for **spa**tial pi**xels**) with a sampling of 0.52 arcseconds per microlens and a total aperture of 11.5 by 7.3 arcseconds on the sky; this field allows the core of a globular cluster to be covered in a few pointings. A more detailed description of FLAMES and the ARGUS mode can be found in Pasquini (2002) and Kaufer (2003). For the observations the GIRAFFE spectrograph was set to the low spectral resolution mode LR8 (coverage 820–940 nm at a spectral resolution of 10 400) and the ARGUS unit was pointed to different positions, each of them containing three exposures of 600 s with 0.5 arcsecond dithering, to cover the entire core radius. The position angle of the long axis of the integral field unit was varied from 0 to 135 degrees in order to achieve maximum coverage of the cluster centre.

Figure 3 shows the combined pointings from the ARGUS observations of the cluster NGC 2808 together with the reconstructed field of view on the Hubble Space Telescope (HST) image. The HST images were obtained with the Wide Field and Planetary Camera 2 (WFPC2) in the *I*-band (F814W) filter in May 1998 (GO-6804, PI: F. Fusi Pecci) and retrieved from the European HST archive. The choice of filter is related to our spectral observations, which are obtained in the wavelength range of the calcium triplet, a prominent absorption feature around 860 nm and ideally suited to the measurement of radial velocities. By measuring the relative shift of the calcium triplet through absorption line fitting, we obtained a velocity for each spectrum. The final velocity map for NGC 2808 is also shown in Figure 3. Velocity maps are instructive to look at and good for identifying suspicious features, but in order to compare our data to model predictions we need the velocity dispersion profile. It is the velocity dispersion σ, or the second moment of the velocity (the quadratic sum of the expectation value of the velocity and the velocity dispersion), which holds information about the mass distribution.

In order to derive a velocity dispersion profile, we used radial bins around the centre of the cluster and combined all the spectra included in each bin. The absorption lines of the resulting spectra are broadened due to the different velocities of the individual stars contributing to the spaxels. Measuring the width of these lines yields the velocity dispersion for each bin, thus a velocity dispersion profile as a function of radius. Great care is taken to measure the true velocity dispersion and not artefacts of the instrument, the data reduction or the data combination process.

Black hole hunting

A black hole is suspected when we see a difference between the measured ve-

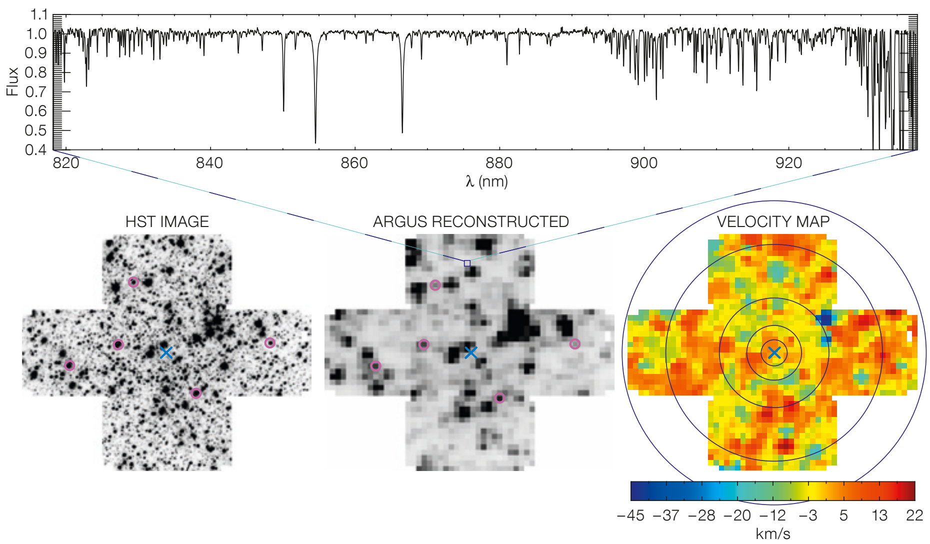

Figure 3. The process of deriving a velocity dispersion profile with integral-field spectroscopy is illustrated. Shown are the field of view on the HST image (left panel), the ARGUS reconstructed pointing (middle panel), a datacube with each spaxel (spatial element) being a spectrum in the calcium triplet region (shown above), and the resulting velocity map (right panel). The circles indicate the bins applied to derive the velocity dispersion profile.

locities and the expected velocities from the gravitational potential of the cluster derived from its light distribution only. In order to determine these expected velocities, we needed an estimate of the stellar density in the cluster. This is done by taking images from HST and measuring the surface brightness profile. We determined the photometric centre of the cluster by measuring the symmetry point of the spatial distribution of the stars. Using colour–magnitude diagrams, we also identified the stars which do not belong to the cluster.

In addition to the VLT and HST observations, data from other instruments are required for kinematic measurements of outer regions that are too faint to be studied using integrated light. In order to detect a black hole, only the innermost points are critical, but in order to understand the global dynamics of the cluster and to determine its mass, the entire velocity dispersion profile is needed. The outer kinematics can be obtained through the measurement of individual stars, since the density of stars is lower than in the centre. The instruments we used to obtain the outer kinematics are the Rutgers Fabry Perot on the Blanco 4-metre telescope at Cerro Tololo Inter-American Observatory (CTIO) and multi-object spectrographs such as FLAMES/Medusa. A Fabry Perot instrument can also operate as an integral field unit: narrow wavelength band, wide-field images at a series of different wavelength steps are recorded. This results in a set of images with high spatial resolution from which the stellar absorption line features can be extracted by combining the photometry of the objects from each wavelength bin (Gebhardt et al., 1992).

After deriving the full kinematic and photometric profiles, the information is fed into models. We use different kinds of models. The first and the simplest kind are analytical Jeans models. The models take the surface brightness profile, deproject it into a three-dimensional density profile and predict a velocity dispersion profile. The latter is then compared to the actual measured velocity dispersion profile. We study the variations of the model when including the additional gravitational potential of a black hole into the equations. By trying different black hole

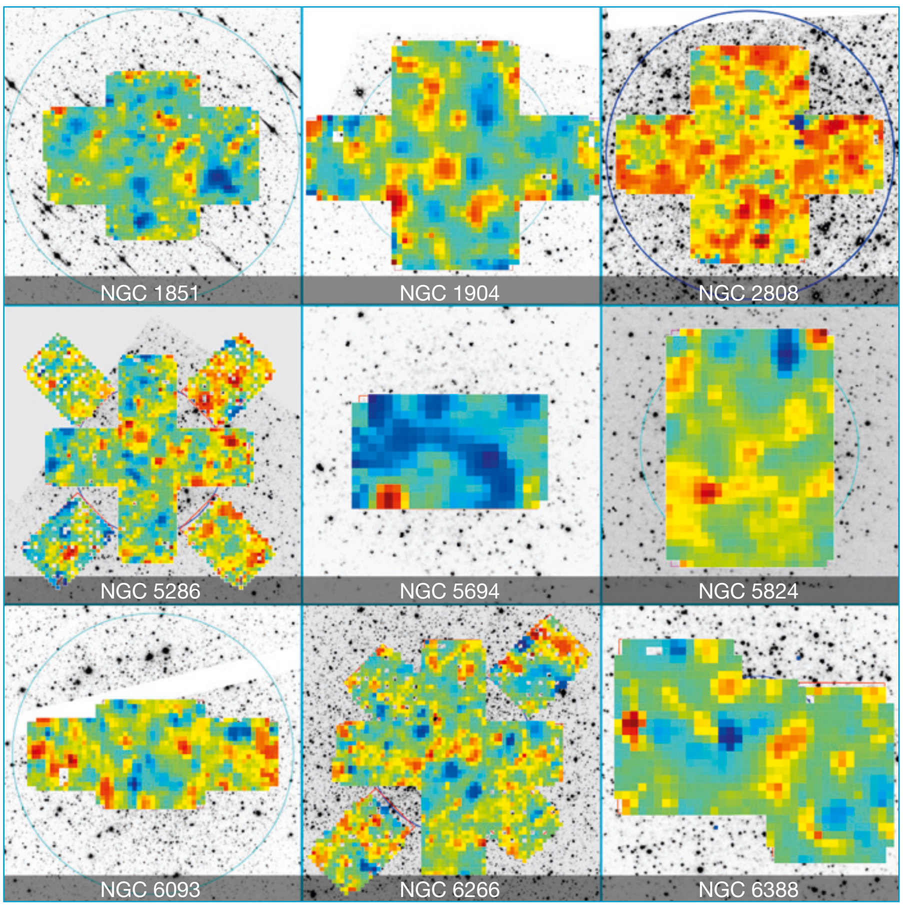

Figure 4. Velocity maps of all the Galactic globular clusters of our sample (except Omega Centauri) are shown superposed on HST images.

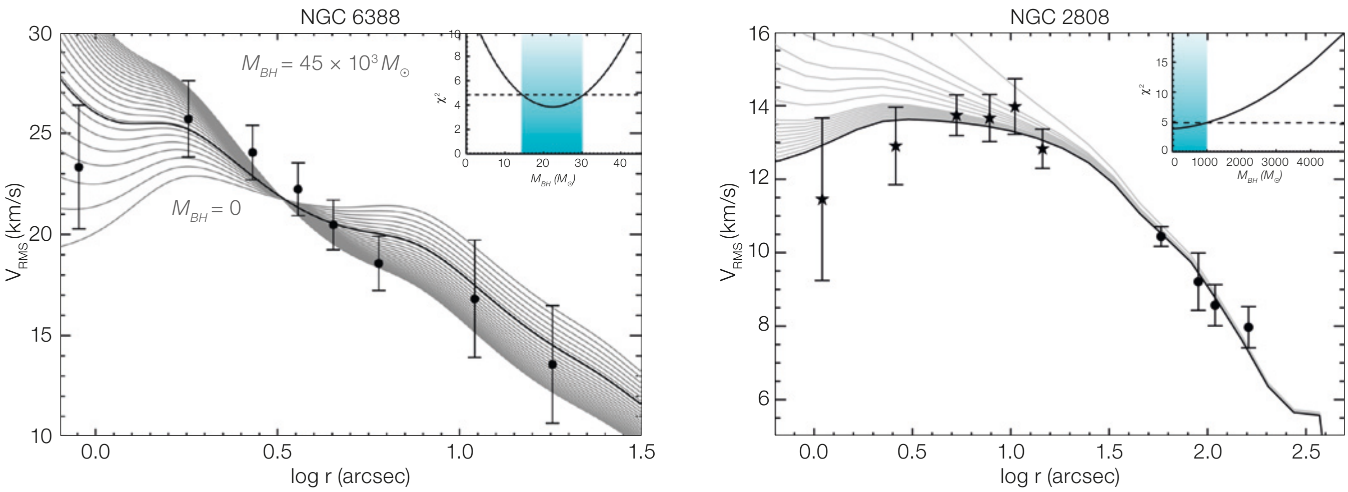

Figure 5. The velocity dispersion profiles of the globular clusters NGC 6388 and NGC 2808 are shown. Overplotted are a set of Jeans models with different black hole masses (grey lines) and the best-fit model (black line). In the corner of each plot the variation of χ^2 of the fit as a function of black-hole mass is shown. The shaded area marks the region for $\Delta\chi^2 < 1$, and thus the 1σ error on the black hole mass. While for NGC 2808 the profile is rather flat and does not require a black hole, NGC 6388 has a steeper profile and a best-fit model with a ~ 17 000 $M_\odot$ black hole (Lützgendorf et al., 2011, Lützgendorf et al., 2012, in prep.).

masses, we find which model fits our data best. Figure 5 shows the entire velocity dispersion profile for two examples: NGC 2808 and NGC 6388 with a set of Jeans models overplotted. A central black hole causes a rise in the velocity dispersion profile. In the case of NGC 2808 no black hole is needed in order to explain the observed data but in the case of NGC 6388 the profile shows a clear rise, making this cluster an excellent candidate for hosting an intermediate-mass black hole.

In addition to these analytical models, N-body simulations are employed in order to reproduce the observations (Jalali et al., 2011). This approach is crucial in order to exclude alternative scenarios which could cause a kinematic signature similar to a black hole, such as a cluster of dark remnants (e.g., neutron stars). N-body simulations are ideally suited for globular clusters since their kinematics are only determined by the motions of their stars/particles. Assuming certain initial conditions, the stars are distributed in space according to a mass function (i.e., luminosities) and are assigned velocities. Then, the system evolves by letting the particles interact gravitationally. By following the evolution of this cluster over a lifetime (~ 12 Gyr), we studied its evolution in detail and compared the final state with the observations. By changing the initial conditions, we found the simulations which fitted the observed data best and learnt about the intrinsic properties of the globular clusters and their black holes, such as mass-to-light ratio variations and the anisotropy in the cluster.

Black hole or no black hole?

Our sample, so far, includes ten Galactic globular clusters observed in 2010 and 2011, including the pilot project target Omega Centauri. All of them have been analysed and velocity maps have been computed (see Figure 4 for all the clusters except Omega Centauri). Modelling all the clusters, however, is not straightforward as each cluster shows peculiarities: some show very shallow kinematic profiles, while others seem to have multiple centres — one photometric and one kinematic.

However, for most of the clusters we are confident that we can determine from the central kinematics whether they are likely to host an intermediate-mass black hole or not and that good constraints on their masses can be provided. The two examples in Figure 5 show that in the case of NGC 6388 a model with a black hole of ~ 17 000 $M_\odot$ is needed to reproduce the data, while the velocity dispersion profile in the core of NGC 2808 is rather flat and an IMBH larger than ~ 1000 $M_\odot$ is excluded. Among all our candidates we find clusters like NGC 2808 as well as clusters where the central points of the velocity dispersion profile are rising just as in NGC 6388 and Omega Centauri.

After finalising the analysis and the modelling of all the clusters in our sample, we will be able to start correlating the presence and mass of an IMBH with the cluster properties. We will also be able to set the selection criteria for further studies and use our experience and expertise to extend the search for IMBHs to more distant objects and larger samples. This strategy will advance our knowledge of globular cluster formation and evolution and bring us closer to an understanding of black hole growth and galaxy formation.

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