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Intermediate-mass black holes in Galactic globular clusters

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Abstract. Over the last few years, different observations have suggested the existence of intermediate-mass ($\sim 10^3$ M$_\odot$) black holes in the centers of globular clusters. However, the issue is still a matter of debate, as current observations have alternative explanations. We previously developed a hydrodynamical model for the interstellar medium in these systems to explain the luminosity of the central X-ray source found in NGC 6388, assuming a black hole accreting from the insterstellar medium. Here, we explore the predictions of our model regarding the flow of the interstellar matter in the inner cluster regions and find that the density and velocity profiles could help to determine the presence of a central black hole as well as its mass.

Keywords. ISM: kinematics and dynamics, accretion, accretion disks

1. Introduction

Over the last few years, different observations have suggested the existence of black holes with masses of $10^2 - 10^4$ M$_\odot$, intermediate between the masses of black holes formed by the collapse of high-mass stars and those of the supermassive black holes found in the centers of galaxies (Miocchi 2007). For this reason, they have been called intermediate-mass black holes (IMBHs). First, ultraluminous X-ray sources (ULXs) have been detected in nearby galaxies (Fabbiano 2006). The luminosities of these sources ($L > 10^{40}$ erg s^{-1}) are well in excess of the Eddington luminosity for stellar-mass objects. As this limit is proportional to the accreting object's mass, these luminosities could be interpreted as sub-Eddington emission of more massive objects, i.e., IMBHs. On the other hand, stellar density profiles and stellar dynamics in the centers of globular clusters suggest the presence of central objects with masses in the range of interest (van den Bosch *et al.* 2006; McLaughlin *et al.* 2006; Miocchi 2007; Noyola *et al.* 2008). However, the evidence is not conclusive and there exist alternative models to explain the observations (Fabbiano 2006).

One way to detect black holes is through the emission of matter they accrete, usually observed in X-rays, or that of matter ejected in the form of jets, observed as radio emission. Maccarone *et al.* (2004) investigated this emission, assuming that the IMBHs in globular clusters accrete from the interstellar medium (ISM), but found that neither radio nor X-ray emission could be detected at present. Their model assumes that the ISM density is constant and the accretion proceeds at 0.1% of the Bondi–Hoyle rate. However, an extended X-ray source has been detected in the center of NGC 6388 by Nucita *et al.* (2008), with properties that are consistent with those expected for accretion onto an IMBH. This observation motivated us to develop a hydrodynamical model for the ISM, to explore a more realistic scenario for the accretion onto any possible IMBH (Pepe & Pellizza 2008). We have shown that the accretion regime differs from that of Bondi–Hoyle accretion because of the constant injection of matter by the cluster red giants. We have also shown that the luminosity of the X-ray source in the center of NGC 6388 can be explained by this flow if an efficiency of 1.5×10^{-4}, similar to that found by other authors, is assumed.

The existence of ISM in globular clusters has been demonstrated by several authors (Freire *et al.* 2001; Boyer *et al.* 2006), hence its flow could become a valuable tool to explore the existence of IMBHs. In the present sudy, we explore the predictions of our model regarding the behaviour of observable quantities such as the velocity and density of the ISM in the inner region of the cluster, where the influence of the IMBH is most important. We aim at determining the presence of an IMBH and its mass.

2. The model

To determine the presence of IMBHs in the centers of globular clusters, we studied the dynamics of the ISM using our hydrodynamical model (Pepe & Pellizza 2008). The ISM is generated by mass loss from the red giants in the cluster. The cluster's gravitational field can be described by a King model (King 1966). The values of the model parameters for NGC 6388 were taken from Harris (1996). Following Scott & Rose (1975), we assumed that the ISM is an ideal gas, and that its flow can be considered as steady, spherically symmetric and isothermal. Under these hypotheses, the flow is governed by continuity and Euler's equations. The former is

$$\frac{1}{r^2}\frac{\mathrm{d}}{\mathrm{d}r}(\rho r^2 u) = \alpha\rho^*, \tag{2.1}$$

where r is the radial coordinate, u and ρ the velocity and density of the flow, respectively, and ρ^* is the stellar density. The right-hand side describes the gas injection by the stars at a fractional rate α. Euler's equation is

$$\rho u\frac{\mathrm{d}u}{\mathrm{d}r} = -\frac{k_\mathrm{B}T}{\mu}\frac{\mathrm{d}\rho}{\mathrm{d}r} - \frac{G\rho}{r^2}(M(r) + M_\mathrm{BH}) - \alpha u\rho^*, \tag{2.2}$$

where G is the gravitational constant, k_B is Boltzmann's constant, μ the mean molecular mass, $M(r)$ the stellar mass inside a radius r, and M_BH the central IMBH mass. It is assumed here that the material is injected with zero velocity into the flow. As shown by Pepe & Pellizza (2008), Equations (2.1) and (2.2) can be combined into

$$\frac{\mathrm{d}\psi}{\mathrm{d}\xi} = \frac{\psi}{\psi^2 - \psi_\mathrm{s}^2}\left(\frac{2\psi_\mathrm{s}^2}{\xi} - \frac{\Omega'(\xi)(\psi_\mathrm{s}^2 + \psi^2)}{\Omega(\xi) - \Omega(\xi_\mathrm{st})} - \frac{9(\Omega(\xi) + \Omega_\mathrm{BH})}{\xi^2}\right), \tag{2.3}$$

where the dimensionless variables $\xi = r/r_0$, $\psi = u/\sigma$, $\Omega(\xi) = M(r)/4\pi\rho_0 r_0^3$ and $\Omega_\mathrm{bh} = M_\mathrm{bh}/4\pi\rho_0 r_0^3$ have been introduced. Here, r_0 is the cluster's King radius, ρ_0^* its central density, $\sigma^2 = 4\pi G\rho_0 r_0^2/9$ the velocity dispersion and ψ_s the nondimensional sound speed in the medium. Here, ξ_st is the nondimensional stagnation radius, at which $\psi = 0$. Equation (2.3) was integrated numerically using the algorithm described in Pepe & Pellizza (2008), but extending the integration inwards of the inner sound radius, and for different values of the IMBH mass in the range $10^3 - 10^4$ M$_\odot$. A model with $M_\mathrm{BH} = 0$ was also computed to investigate the properties of the flow in the no-IMBH case.

3. Results

Figure 1 shows the results of integrating Equation (2.3) for different IMBH masses, $M_\mathrm{BH} = 1,\ 3,\ 5,\ 8,\ 10 \times 10^3$ M$_\odot$ and $T = 10^4$ K, for the inner region of the cluster. In Pepe & Pellizza (2008) we showed that when an IMBH is present in the center of a

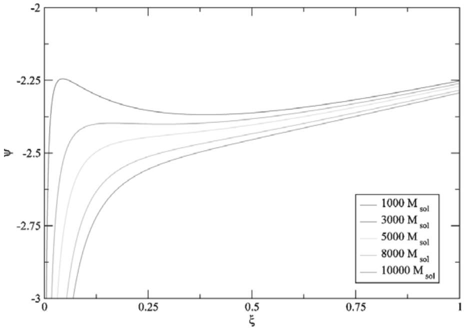

Figure 1. Velocity profile for the ISM in NGC 6388 in the inner region. As the IMBH mass grows, the matter falls faster onto the black hole.

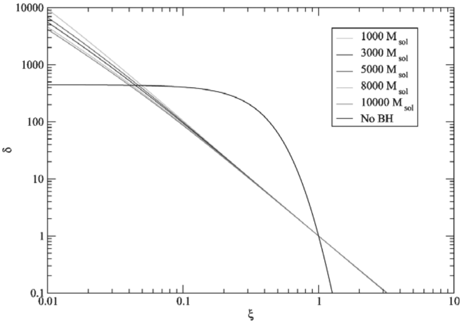

Figure 2. Density profile for the ISM in NGC 6388. The steep profile corresponds to the IMBH case and it differs from the flat profile of the no-IMBH case.

globular cluster, the flow develops a stagnation radius; outside it, the matter is ejected as a wind while inside it is accreted by the black hole. However, no difference could be seen on the cluster scale for different IMBH masses. The behaviour of the flux in the outer regions is mostly determined by the cluster's gravitational pull. Figure 1 shows that in the central region of the cluster the effect of the IMBH becomes observable, as a variation in the velocity profiles with the IMBH mass is observed. The higher the mass, the faster the matter falls onto the IMBH, as one might expect. Figure 2 shows the density profiles for different IMBH masses ($M_{\rm BH} = 0,\ 1,\ 3,\ 5,\ 8,\ 10 \times 10^3\ {\rm M}_\odot$). The density profile changes from flat to steep for $M_{\rm BH} \neq 0$. This could be an observational indicator of the presence of an IMBH in globular clusters with such a density profile. However, varying the IMBH mass produces little change in the density profile.

4. Conclusions

The flow of the interstellar matter ejected by red giants in a globular cluster with a central IMBH was calculated for the cluster inner regions by integration of the hydrodynamic equations in the presence of the cluster and IMBH gravitational fields. We found that the density and velocity profiles of the ISM show differences between the scenarios with and without a IMBH. These could provide a feasible way to observationally determine the presence of such objects in globular clusters. Moreover, if the gas velocity could be measured with the resolution needed, the mass of the IMBH could be estimated. A remarkable fact is that the ISM properties are affected by the presence of the IMBH up to radii comparable to the King radius, while the dynamics of the stars are influenced in a much smaller region.

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