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IMBHs in globular clusters: accretion rate correlations with cluster parameters

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Abstract. The existence of intermediate-mass black holes (10^2–$10^3 M_\odot$) is still a matter of debate. However, since their presence in globular clusters could impact on our knowledge of these systems, IMBHs deserve a detailed study of their detection mechanisms. One of these mechanisms is the detection of the emission due to the accretion of the surrounding media. In this work we present a simple numerical model to estimate the accretion rate onto IMBHs at the centre of GCs in order to find correlations between this and the cluster parameters. Our model includes the gravitational potential of the cluster and the constant injection of gas by the red giants in the cluster. We find that, if IMBHs are actually present at the centres of GCs they would be more easily detectable in more massive clusters with large values of the stellar velocity dispersion.

Key words. accretion – black hole physics – globular clusters: general

1. Introduction

Observational and theoretical works have suggested the existence of intermediate-mass (10^2–$10^3 M_\odot$) black holes (IMBHs). Some of these works are directly connected with globular clusters (GCs). For example, Miller & Hamilton (2002) proposed a formation scenario in which stellar-mass black holes merge to form an IMBH in GCs. On the other hand, Portegies Zwart et al. (2004) suggested that runaway collisions of massive stars can lead to the formation of IMBHs at the center of these stellar systems.

Soon afterwards, many attempts of detecting IMBHs in GCs have been made. Noyola et al. (2008) measured the surface brightness profile of ω Cen, which shows a central cusp consistent with the presence of a 4000 $M_\odot$IMBH. McLaughlin et al. (2006) fitted the proper motion profiles of 47 Tuc obtaining a mass estimate of 1000–1500 $M_\odot$. Lastly, Gebhardt et al. (2002) combined kinematic and photmetric data of G1 and estimate the mass of its putative IMBH in $2 \times 10^4 M_\odot$. In addition to these works, Miocchi (2007) suggested that the presence of IMBHs could explain the blue stragglers population in GCs, as a consequence of the tidal stripping of nearby stars by the black hole. Hence, studying the presence of IMBHs in GCs seems a relevant task in order to understand the stellar population and evolution of these systems.

One way to detect IMBHs is via their emission in the X-ray band due to the accretion of the surrouding media. Although with low densities, Freire (2001) reported the detection of

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ionized gas in 47 Tuc which makes this scenario possible. Accordingly, Maccarone (2004) estimated the accretion rate onto IMBHs assuming the standard model for spherical accretion (Bondi & Hoyle 1944) and the measured density of 47 Tuc for all the clusters they analize. Moreover, the author need to assume that the accretion rate is only a fraction of the Bondi-Hoyle rate in order to match the non-detections of X-ray central sources in GCs. However, a few years later, Nucita et al. (2008) reported the detection of an X-ray source coincident with the GC centre. This could suggest that the accretion process might change from one GC to another. Despite this, Bondi & Hoyle (1944) model has been extensively used for IMBH mass estimations by authors who performed X-ray surveys (Servillat et al. 2008; Cseh et al. 2010; Lu & Kong 2011). It is worth pointing out that all these attepmts yielded to upper limits for the X-ray luminosity and, hence, for the IMBH mass.
In this work we present an overall description of a numerical model for the gas dynamics in GCs with an IMBH at its centre (for further details see Pepe et al. 2013). In Section 2 we briefly describe the model. In Section 3 we present a summary of our main results and a brief discussion. Finally, in Section 4 we present our conclusions.

2. Model description

In order to study the gas dynamics in the GC environment, we included in the standard fluid equations the gravitational pull of the stars in the GC and the constant injection of gas by the red giants. Assuming that these stars follow the stellar mass distribution and that they all eject the same amount of matter in similar intervals of time, the density of gas injected results proportional to the stellar distribution ρ^*. This distribution is described by the model developed by Miocchi (2007), which consists of a King model (King 1966) plus an IMBH at the centre of the GC. Following Scott & Rose (1975) we assume the gas to be an ideal, isothermic gas with spherical symmetry in a steady state. So, the dynamics of the gas is described by the continuity and Euler equations. The former is

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

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 $\alpha = 10^{-11}$ (Scott & Rose 1975; Priestley et al. 2011; Knapp 1996). Euler's equation is

$$\rho u\frac{du}{dr} = -\frac{k_{\rm B}T}{\mu}\frac{d\rho}{dr} - \frac{GM(r)\rho}{r^2} - \alpha u\rho^*, \tag{2}$$

where G is the gravitational constant, $k_{\rm B}$ is Boltzmann's constant, μ is the mean molecular mass of the ICM, and $M(r)$ the sum of the stellar mass $M^*(r)$ inside radius r and the central IMBH mass $M_{\rm BH}$. It is assumed here that the material is injected with null velocity in the flow.

These equations can be simplified introducing the variable $\tilde{q} = q/\alpha$, where $q = \rho u r^2$ is the bulk flow. This way, we can solve the equations independently of α. However, α must be known to calculate the density and the accretion rate. To perform the integration we define adimensional variables $\xi = r r_0^{-1}$, $\psi = u\sigma^{-1}$, $\omega = \tilde{q}(\rho_0 r_0^3)^{-1}$, $\Omega^*(\xi) = M^*(r)(4\pi\rho_0 r_0^3)^{-1}$, $\Omega_{\rm BH} = M_{\rm BH}(4\pi\rho_0 r_0^3)^{-1}$, and $\Omega(\xi) = \Omega^*(\xi) + \Omega_{\rm BH}$, where r_0 is the King radius, ρ_0 is the cluster central density, and $\sigma^2 = 4\pi G\rho_0 r_0^2/9$ is the velocity dispersion parameter. With these definitions and, after integrating Eqn. 1, the equations that describe the flow dynamics are

$$\omega = \Omega^*(\xi) + \omega_0, \tag{3}$$

$$\frac{d\psi}{d\xi} = \frac{\psi}{\psi^2 - \psi_{\rm s}^2}\left(\frac{2\psi_{\rm s}^2}{\xi} - \frac{d\omega}{d\xi}\frac{(\psi_{\rm s}^2 + \psi^2)}{\omega} - \frac{9\Omega(\xi)}{\xi^2}\right) \tag{4}$$

It is worth pointing out that the integration constant ω_0 is proportional to the accretion rate of the black hole.

Eqns. 3 and 4 were integrated assuming boundary conditions compatible with our problem. Far away from the acretting black hole, the velocity of the flow must be positive as

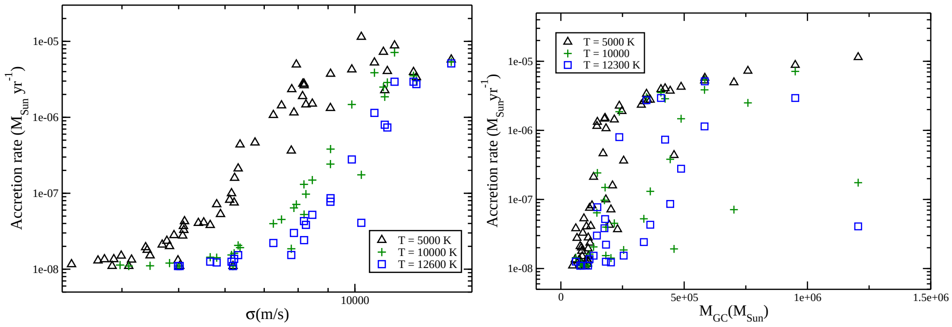

Fig. 1. Left panel: Accretion rate vs globular cluster velocity dispersion (σ). Right panel: Accretion rate vs GC mass. In both cases three different temperatures are shown: 5000K (triangles), 10000K (plus signs) and 12300 K (squares) and a $1000M_{\odot}$IMBH is assumed.

there is no matter source outside the cluster. On the other hand, on the black hole surface, matter can only fall inwards as there is no pressure gradient that supports the gravitational pull of the black hole and the cluster. As a direct consecuence, there exists a stagnation radius ξ_{st} at which $u = 0$. Evaluating Eqn. 3 at the stagnation radius gives

$$\Omega^*(\xi_{st}) = -\omega_0, \tag{5}$$

which means that all the matter ejected by the red giants inside ξ_{st} is acretted by the IMBH and hence, we can obtain an estimation of the accretion rate.

3. Results

We present in this section a summary of our results and a brief discussion. For an extensive discussion and all the correspoding plots please refer to Pepe et al. (2013). We applied the model presented in Section 2 for a set of four GCs (NGC 7078, Liller 1, NGC 6626 and NGC 5139) which span the concentration range of Milky Way GCs. Since the hydrodynamical variables are scaled with the cluster parameters, the relevant variables related to the gas temperature and black hole mass are c_s^2/σ^2 and Ω_{BH}, respectively. We find that the accretion rate decreases for increasing temperature, which can be explained in terms of the gas energetics: as the gas gets hotter, it has more energy to escape from the gravitational pull of the system and the stagnation radius moves inwards, resulting in a lower accretion rate. We also find an abrupt decrease of the accretion rate at $c_s^2/\sigma^2 \sim 1$, as a result of the same behavior for r_{st}, leading to two possible accretion rate regimes. For small values of $c_s^2/\sigma^2 (< 1)$ we find the system in a high-accretion rate regime (HAR) while for large values (> 1) we obtain an accretion rate value up to 2 orders of magnitude lower (low-accretion rate regime, LAR). Consequently, those GCs with higher values of σ will be more likely to be in a HAR for the range of temperatures expected for GCs (5000K – 15000K; Scott & Rose 1975; Priestley et al. 2011).

We also study the dependence with the black hole mass (Ω_{BH}). In this case, the scaling paramters (ρ_0, r_0) cover a narrow range of values and Ω_{BH} does not vary significantly from cluster to cluster (at a fixed M_{BH}) for the range of masses of IMBHs ($100M_{\odot}$– $10000M_{\odot}$). However, we find two different behaviours depending on the accretion rate regime. If the GC is in a HAR regime there is no dependence of the accretion rate on the black hole mass since r_{st} is located in the outer parts of the cluster which are not influenced by the IMBH. On the other hand, if the GC is in a LAR regime the stagnation radius is located in the very inner parts of the GC and its location depends on the black hole mass. In this case, the accretion rate scales as M_{BH}^2, like in Bondi & Hoyle (1944) model.

Since we find that in some cases there is a dependence of the accretion rate with the cluster properties, we applied our model to the whole list of GCs in the Harris (1996) catalogue with well established parameters in order to construct the flow models. In some cases, the models were discarded because the IMBH mass was similar to the cluster mass, while in others no stagnation radius was found for the hottest temperatures (the ICM escapes completely as a wind). We found no trend for the accretion rate $\dot{M}$ with r_0 or ρ_0, but a clear correlation with the cluster mass $M_{\rm GC}$ and velocity dispersion parameter σ. In the left panel of Fig. 1, we show the accretion rate vs the velocity dispersion of the cluster for different values of the gas temperature and a conservative value of $1000 M_{\odot}$for the IMBH mass. This correlation is a consequence of the strong dependence of the accretion rate on gas temperature: for a fixed T, as σ increases c_s^2/σ^2 decreases and we approach the HAR regime, while for lower values of σ we reach the LAR regime. In the right panel of Fig. 1 we show the dependence of the accretion rate on the GC mass. A trend of increasing accretion rate with the cluster mass can also be seen for high accretion rates. This is explained by the fact that these clusters are accreting in the HAR regime, for which the stagnation radius is well outside the cluster core and hence encloses almost the whole cluster stellar mass. As $\dot{M}$ is proportional to the stellar mass inside $r_{\rm st}$, the correlation with $M_{\rm GC}$ arises.

4. Conclusions

We presented in this work a simple model for the accretion onto an IMBH at the centre of a GC. We aimed at refining the predictions for the accretion rate, improving the hydrodinamical model for the gas. We studied the effects of adding the gravitational pull of the cluster and the injection of gas by the red giants and found that the accretion flow differs cualitatively from the standard Bondi-Hoyle model. A stagnation radius develops, whose location determines the value of the accretion rate, dividing the clusters in two groups according to their accretion rate value: low- and high-accretion regime. As discussed extensively in Pepe et al. (2013), the estimated accretion rate values yield to an overestimation of the X-ray luminosity and, therefore, can not be used to estimate the IMBH mass. For this reason, different improvements of the model (such as the relaxation of the isothermal hypothesis) are currently being made. Nonetheless, the relation between the accretion rate and the cluster dispersion velocity suggest that, if IMBHs are actually present at the centre of GCs, they would be more easily detectable in more massive GCs with high velocity dispersions.

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