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Accretion signatures of intermediate mass black holes in globular clusters

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Abstract. The first indicators of the existence of stellar mass black holes and supermassive black holes came not from direct dynamical evidence but from accretion and associated jet production, respectively. In this article, I review the methodology associated with searches for intermediate mass black holes in globular clusters, as well as the observational results of such searches. At the present time, there is no strong evidence for accretion from intermediate mass black holes in globular clusters, and, in some cases, the inferred upper limits are at odds with the results inferred from dynamical studies. I will discuss possible explanations for these discrepancies. Finally, I will also discuss the case of HLX-1, which does show strong evidence for being an accreting intermediate mass black hole, but which is more likely to be in a young dense star cluster than a *bona fide* globular cluster.

Key words. Accretion, accretion disks –globular clusters: general – Stars: black holes

1. Introduction

At a few points in time, there have been serious discussions about whether globular clusters contain intermediate mass black holes. In the 1970s, with the discovery of X-ray emission from several globular clusters (Clark 1975), it was proposed that there were intermediate mass black holes in the clusters accreting from the intracluster medium (Silk & Arons 1975). Shortly after this discovery, Newell et al. (1976) reported dynamical evidence for an excess central mass in M15, although shortly after that, it was shown that mass segregation could lead to an excess of stellar remnants which would lead to a sharp enhancement of mass-to-light ratio without the presence of an intermediate mass black hole (Illingworth & King 1977). Additionally, the globular cluster X-ray sources all showed Type I X-ray bursts (first discovered in Cen X-4 by Belian et al. 1972). After a consensus developed that the Type I bursts were due to thermonuclear runaway on the surface of a neutron star (e.g. Woosley & Taam 1976), discussions of the X-rays coming from black holes fell out of favor. As a result of the lack of need for intermediate mass black holes to explain either the dynamics or the X-rays, interest in intermediate mass black hole models. The topic has received new interest with better data from Hubble and larger ground-based telescopes, and better modelling. The status of dynamical searches for intermediate mass black holes will be reviewed in an article by Eva Noyola in this volume.

2. Accretion signatures

Early in the Chandra era, a few attempts were made to find evidence for accreting intermediate mass black holes from X-ray measurements (Grindlay et al. 2001; Ho et al. 2003). More recently, work has focused on searches for radio emission from these objects, making use of the fundamental plane of black hole activity (Maccarone 2004).

2.1. Superiority of radio constraints over X-ray constraints

There are several key reasons why the radio-based searches are superior. First, because radio emission falls off more slowly than X-ray emission, searches based on radio emission are more sensitive to faint objects than searches based on X-ray emission. Secondly, if a source is detected, the number of potentially confusing sources that would be expected in the radio is much smaller than that expected in the X-rays; only background active galactic nuclei could be reasonably expected to produce strong radio emission without strong X-ray emission, while X-ray surveys can be confused by accreting compact objects of all types, and even coronally active binary stars.

3. Key parameters for predicting radio emission

The radio emission expected from an accreting black hole depends on: the mass of the black hole; the density of the interstellar medium; the accretion efficiency (i.e. how effective the object is at capturing mass); the radiative efficiency (i.e. how efficient the systems is at converting gravitational potential energy into radiation); and a relation between the radio luminosity and the bolometric or X-ray power.

3.1. Interstellar medium

A few approaches have been used to study the interstellar medium in globular clusters. Searches for free-free emission from a group of clusters have not yielded detections (Knapp et al. 1996). These upper limits indicate that not all of the stellar mass loss is retained in clusters, but are not particularly contraining beyond that. More recently, in a few clusters, Freire et al. (2001) showed that the gas density can be estimated by comparing the dispersion measures of pulsars with their accelerations, finding good agreement with predictions from Pfahl & Rappaport (2001) that gas densities of ~ 0.2 cm^{-3} are typical.

3.2. Capture rate

Our group's work has generally used a simple prescription in which a fraction of the Bondi-Hoyle accretion rate is accreted by the putative black hole. We have typically used a value of 3%, a typical value for the behavior of supermassive black holes accreting from the interstellar medium in elliptical galaxies (Pellegrini 2005). Groups more focused on interpreting X-ray signatures have typically used the full Bondi-Hoyle rate (e.g. Grindlay et al. 2001), which is why they often get apparently similar upper masses on the possible black holes in globular clusters despite the fact that the radio techniques are more sensitive. Intermediate rates are predicted by detailed numerical calculations (Pepe & Pellizza 2013).

3.3. Conversion of accretion rates into observables

We assume an advection dominated accretion flow model for the conversion of accretion rate into X-ray power, as have other groups. In such scenarioes, $L_X \propto \dot{m}^2$ below 2% of the Eddington luminosity where sources make transitions (Maccarone 2003) from thermal accretion disks which agree well with the predictions of the thin accretion disk models, to low/hard states in which the prevailing view is that the emission is dominated by a two temperature accretion flow (Ichimaru 1077).

We have then assumed that the relation between X-ray and radio power follows an empirically derived relationship where $L_X \propto M^{0.6} L_R^{0.6-0.7}$ (e.g. Merloni et al. 2003). This "fundamental plane" was established empirically after being predicted (Heinz & Sunyaev

2003) on the basis of models of compact conical jets which have flat spectra below a particular cutoff frequency due to synchrotron self-absorption. Reconciling these models with the $L_R \propto L_X^{0.6-0.7}$ relation requires an additional assumption of radiatively inefficient accretion, so our scenario is self-consistent.

4. Results

Most of the observations of the observations of globular clusters in the radio have yielded non-detections. By now, published upper limits exist for about 15 clusters (e.g. Maccarone & Servillat 2008; Strader et al. 2012), and our group has data on a total of 50 clusters now. Data reduction is mostly complete on this sample, and no evidence is found for intermediate mass black holes in the clusters. Notably, this sample includes new data on two clusters, 47 Tuc, and Omega Cen, for which there had been 2.5σ flux density excesses in previous maps (Lu & Kong 2011). The upper limits are typically below the claimed detection levels of the dynamical studies, even if we assume relatively conservative values for the prescriptions for estimating what the black hole masses should be. Furthermore, since the expected radio luminosity is a strong function of the black hole mass, rather substantial uncertainties in the other parameters lead to rather smaller errors in the upper limit on the black hole mass.

There is one other object which merits mention, which is not in the Milky Way: G1, in M31. This cluster has one of the strongest claims for having a dynamically confirmed black hole (Gebhardt et al. 2002). It also shows substantial X-ray emission, at a level that could be explained by accretion onto a central black hole, or by a X-ray binaries in the cluster (Pooley & Rappaport 2006). The object has been the subject of one radio detection (Ulvestad et al. 2007), but also the subject of multiple upper limits in the radio that are well deeper than the detection (Miller-Jones et al. 2012). Given the lack of steady radio emission, it seems unlikely that the radio emission comes from an intermediate mass black hole. Two alternative scenarios are reasonably likely: first, the one radio detection may have been spurious, especially since it was obtained during the period of time when the VLA had a hybrid set-up with both old receivers and newly upgraded Jansky VLA receiver. The alternative is that the radio emission seen was from a stellar mass black hole X-ray binary transient in G1. It would also be expected that such an event would produce a radio signature similar to the one reported, while not producing strong enough X-ray emission to trigger all-sky instruments, and the high collision rate in G1 makes such an event reasonably likely.

5. Possibilities for brighter accreting IMBHs in globular clusters and elsewhere

The discussion above is focused largely on faint accreting intermediate mass black holes, and is written largely from the perspective of what can be done in the Milky Way and very nearby galaxies. Alternatively, intermediate mass black holes could be extremely bright in the X-rays. This could happen through tidal capture of a companion star (Portegies Zwart et al. 2004), or through tidal disruption of a star making a fly-by. Predictions for rates of such events are very sensitive to numbers which are not well known, including the fraction of clusters with black holes, the masses of those black holes, and the densities of the central regions of those clusters (e.g. Baumgardt et al. 2004). At the present time, one globular cluster object is consistent with being a horizontal branch star disrupted by a $\sim 100 M_\odot$ black hole (Clausen et al. 2012), but alternative explanations exist (Maccarone & Warner 2011), and the question of why a horizontal branch star would be the first discovered tidal disruption event when these stars are both rarer and smaller than main sequence stars remains.

The object known as HLX-1, in the galaxy ESO 243-49, is an extremely strong candidate intermediate mass black hole. The original base of evidence for its being intermediate mass is its extremely high X-ray luminosity, which sometimes exceeds 10^{42} erg/sec (Farrell et al. 2009). One of the core issues for searches for intermediate mass black holes in globular clusters in other galaxies is that it can be rather difficult to establish the mass of the black hole. A variety of scenarios have been put forward by which stellar mass black holes may have luminosities well in excess of the Eddington rate. However, empirically, the ultraluminous X-ray sources which are widely suspected of being super- Eddington stellar mass black holes have characteristic temperatures which decrease when X-ray luminosity increases (Kajava & Poutanen 2009) while stellar mass black holes at lower Eddington fractions which show thermal components see their temperatures increase as luminosity increases, as does HLX-1 (Godet et al. 2009). This object is thus an outstanding candidate for being an intermediate mass black hole, probably accreting from a companion star in a highly eccentric orbit. It is not, on the other hand, likely to be in a globular cluster (Farrell et al. 2012). Still its formation scenario, especially if it is located in a young analog of a globular cluster, may be relevant for understanding how intermediate mass black holes might form in clusters.

6. Conclusions

At the present time, accretion searches have not provided any evidence for intermediate mass black holes. The number of searches done has now reached a level where it can reasonably be concluded that black holes of at least 1000 $M_{\odot}$ objects are not common in globular clusters. At the same time, some rather clear evidence is starting to develop from the case of HLX-1 that intermediate mass black holes can be produced in nature, so additional searches for them, perhaps in a broader range of cluster environments, are well-motivated.

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