

SHRINKING THE BRANEWORLD: BLACK HOLE IN A GLOBULAR CLUSTER

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ABSTRACT

Large extra dimensions have been proposed as a possible solution to the hierarchy problem in physics. In one of the suggested models, the RS2 braneworld model, black holes may evaporate by Hawking radiation faster than in general relativity, on a timescale that depends on the black hole mass and on the asymptotic radius of curvature of the extra dimensions. Thus the size of the extra dimensions can be constrained by astrophysical observations. Here we point out that the black hole, recently discovered in an extragalactic globular cluster, places the strongest upper limit on the size of the extra dimensions in the RS2 model, $L \lesssim 0.003$ mm. This black hole has the virtues of old age and relatively small mass. The derived upper limit is within an order of magnitude of the absolute limit afforded by astrophysical observations of black holes.

Key words: black hole physics – early universe – galaxies: star clusters

1. INTRODUCTION

A universe with large extra dimensions has been proposed as a possible solution to the hierarchy problem in physics (Arkani-Hamed et al. 1998; Antoniadis et al. 1998; Randall & Sundrum 1999b). If the standard model is restricted to act only on a four-dimensional brane whereas gravity propagates into the five-dimensional bulk, the effective Planck scale in the four-dimensional spacetime can be significantly larger than the electroweak energy scale, in agreement with the experimental requirements. The maximum size of the extra dimensions can be constrained, in general, by verifying Newton’s law of gravity on submillimeter scales in torsion-balance laboratory experiments. Current constraints are as small as $L \lesssim 0.044$ mm (Kapner et al. 2007; Geraci et al. 2008).

The size of the large extra dimensions can also be constrained by a variety of astrophysical tests (see Arkani-Hamed et al. 1998 for discussion). In a particular case of the RS2 braneworld model (Randall & Sundrum 1999a), Emparan et al. (2002) and Tanaka (2003) used the anti-de-Sitter space/conformal field theory (AdS-CFT) correspondence to suggest that black holes would evaporate by Hawking radiation much faster than in classical general relativity, if the higher-dimensional Planck scale is comparable to the electroweak scale. However, this theoretical prediction rests on the validity of the holographic conjecture that a classical five-dimensional black hole solution corresponds to a quantum-corrected four-dimensional black hole. Gregory et al. (2008) argued that this conjecture gives different results in the weak-coupling and strong-coupling limits and therefore requires further study. Further, Fitzpatrick et al. (2006) suggested that a static (non-evaporating) black hole solution exists in the strong-coupling limit. It is not yet resolved whether such a static solution is dynamically stable; if not, the black hole would still decay on a timescale similar to that for the evaporation. Emparan et al. (2003) derived the evaporation timescale to be

$$\tau_{\text{ev}} \simeq 120 \left(\frac{M}{M_{\odot}} \right)^3 \left(\frac{L}{1 \text{ mm}} \right)^{-2} \text{ yr}, \quad (1)$$

where M is the black hole mass and L is the asymptotic radius of curvature of the extra dimensions. If such an accelerated

evaporation is confirmed by further studies, it opens a possibility for constraining L based on astrophysical observations of black holes.

Psaltis (2007) applied this argument to the black hole in the binary system XTE J1118+480 in the Galaxy. The mass of the black hole has been dynamically measured to be $M = 8.5 \pm 0.6 M_{\odot}$, and a lower limit on the age derived from its kinematics and position above the Galactic plane was found to be $\tau_{\text{age}} \gtrsim 1.8 \times 10^7$ yr. Equation (1) and the analysis of measurement uncertainties then constrain the maximum size $L \lesssim 0.08$ mm. Johannsen et al. (2009) further showed that a rapid evaporation of a black hole in a binary system would lead to an orbital period derivative that is potentially measurable. They then used the observed upper bound on the orbital period derivative of the binary that harbors the black hole A0620–00 to reach a similar upper bound on the asymptotic radius of curvature. The same technique was later applied to the binary that harbors the black hole XTE J1118+480 by Johannsen (2009).

In this Letter we discuss how the recent discovery of a black hole in an old globular cluster leads to a much stronger upper bound on the asymptotic radius of curvature of the extra dimensions.

2. AN OLD BLACK HOLE IN A GLOBULAR CLUSTER

Maccarone et al. (2007) reported the discovery of a compact object in a globular cluster RZ2109 located in an elliptical galaxy NGC 4472 in the Virgo cluster of galaxies. The black hole nature of this object was inferred from the strong variability of the high-luminosity (4×10^{39} erg s⁻¹) X-ray source observed with the *XMM-Newton* satellite. Zepf et al. (2008) furthermore showed that the optical spectrum is dominated by a very broad [O III] 5007 Å emission line. They argued that the only extant model able to account for the observations is a $\simeq 10 M_{\odot}$ black hole accreting close to its Eddington limit. We discuss further constraints on the mass in Section 3.2.

The most interesting feature of this observation is that it is the first robust identification of a stellar-mass black hole in a globular cluster. The association with a globular cluster

Table 1
Observations of Black Holes

BH System	$M (M_{\odot})$	Age (yr)	L (mm)
XTE J1118+480	8.5 ± 0.6	$> 10^7$	0.08
A0620-00	10 ± 5	...	0.16
RZ2109	≈ 10	$\approx 10^{10}$	0.003

strongly argues that the black hole is very old. Globular clusters are special stellar systems, which remain gravitationally bound for a Hubble time and contain stars that all formed within a relatively short period of time. Even in the cases of a few of the most massive clusters in the Galaxy, for which detailed color–magnitude diagrams and spectroscopy show evidence of multiple stellar populations, the likely age spread is of the order of 1 Gyr (e.g., Sollima et al. 2005; Villanova et al. 2007; Cassisi et al. 2008). This spread is still an order of magnitude shorter than the cluster age. Based on observations of the main-sequence turnoff point of the cluster stars, the oldest globular clusters in the Galaxy are thought to be approximately 13 Gyr, and none is younger than 7 Gyr (e.g., Krauss & Chaboyer 2003; Sarajedini et al. 2007; Marín-Franch et al. 2009). Age measurements of extragalactic clusters are more uncertain, but both absorption-line spectroscopy (Cohen et al. 2003) and optical and near-infrared photometry (Hempel et al. 2007) studies find that the globular clusters in NGC 4472 are as old as those in the Galaxy. Moreover, an ongoing detailed study of the spectrum of RZ2109 itself confirms its old age (M. Steele et al. 2009, in preparation). Thus a reliable and conservative age estimate of the globular cluster RZ2109 is 10 ± 3 Gyr.

If the black hole is found to be in the globular cluster in the present epoch, its progenitor must have formed with the rest of the stars in the cluster. This is because a globular cluster in a galaxy cannot capture any star that was previously unbound to it (e.g., Mieske & Baumgardt 2007). The cluster gravitational potential is too small compared to the kinetic energy of objects orbiting a large elliptical galaxy such as NGC 4472. A typical velocity dispersion inside globular clusters is ~ 10 km s $^{-1}$, while orbital velocities in elliptical galaxies are in excess of 200 km s $^{-1}$.

The lifetime of a progenitor star that led to the formation of the black hole in a type II supernova explosion is negligibly short. Stellar evolution models for a wide range of progenitor masses indicate main-sequence lifetimes smaller than a few times 10^7 yr. As a result, the age of a $10 M_{\odot}$ black hole in a globular cluster is practically equal to the age of the cluster itself.

Using Equation (1) for the age of 10 Gyr and mass of $10 M_{\odot}$, we obtain an upper bound on the asymptotic radius of curvature of the extra dimensions $L \lesssim 0.003$ mm. This bound is lower by an order of magnitude than previous table-top and astrophysical constraints. Figure 1 and Table 1 summarize the constraints on the maximum size of the extra dimensions from the black hole in RZ2109, the black holes in XTE J1118+480 and A0620-00, and the laboratory measurements. The new limit provided by the black hole in RZ2109 is much smaller than that for XTE J1118+480 because of the crucial difference in the black hole ages. The shaded region shows the expected uncertainty in this limit due to the uncertainties of the black hole mass (between 5 and $20 M_{\odot}$) and its age (between 7 and 13 Gyr). Even for the worst combination of the parameters, the upper bound increases to $L \lesssim 0.01$ mm, which is still an improvement by a factor of $\simeq 5$ from the current laboratory limit.

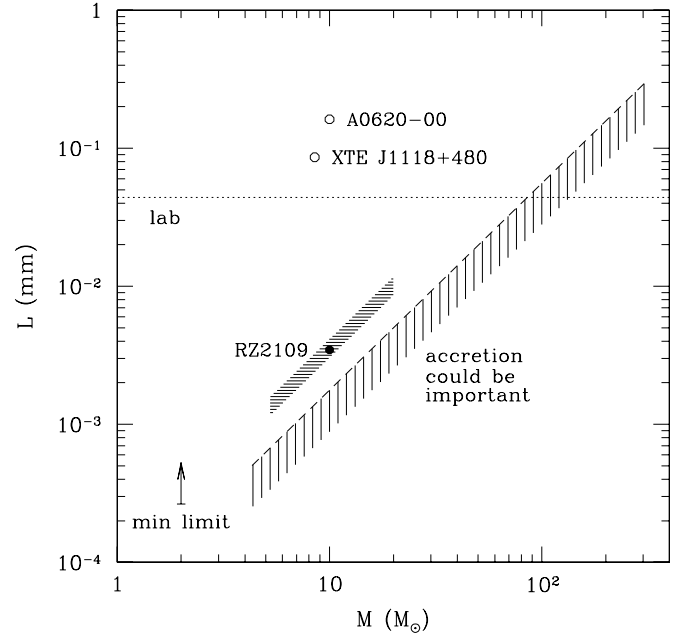


Figure 1. Constraints on the asymptotic radius of curvature of the extra dimensions, L , from the evaporation of black holes of mass M and age τ ($L \propto M^{3/2} \tau^{-1/2}$). Horizontal dotted line shows the current laboratory limit. The filled circle shows the limit obtained in this paper for the black hole in a globular cluster RZ2109. The shaded region indicates the uncertainty range due to the expected uncertainty of black hole mass (from 5 to $20 M_{\odot}$) and its age (from 7 to 13 Gyr). The minimum limit is obtained for the smallest black hole mass ($2 M_{\odot}$) and largest age (13.7 Gyr). The dashed line with a shaded region extending downward shows the range of masses where steady accretion of matter onto the black hole may dominate the evaporation.

3. CAVEATS AND UNCERTAINTIES

3.1. Accretion and Collisions

In this Letter we placed a strong upper bound on the asymptotic radius of curvature of the extra dimensions, by estimating the age and mass of the black hole recently discovered in an extragalactic globular cluster. The only potential caveats to our arguments would appear if the black hole were less massive when it formed and then subsequently merged with other stars or has grown significantly by accretion. While such scenarios are possible in a globular cluster, we argue here that they are unlikely to change our bound.

The black hole mass can change with time because of evaporation, accretion, and collisions with other stars:

$$\frac{dM}{dt} = -\frac{M}{3\tau_{\text{ev}}(M)} + \dot{M}_{\text{acc}} + \dot{M}_{\text{coll}}. \quad (2)$$

The rates of accretion and collisions are likely to be variable in time, but to obtain practical estimates we make the following simplifying assumptions. We take \dot{M}_{coll} to be constant in time and independent of the BH mass. We take the accretion rate to be a constant fraction $f_E \leq 1$ of the Eddington rate,

$$\dot{M}_{\text{acc}} = f_E \frac{M}{t_E}, \quad t_E \approx 4.5 \times 10^7 \left(\frac{\epsilon}{0.1} \right) \text{ yr}, \quad (3)$$

where ϵ is the radiative efficiency of accretion and is typically $\epsilon \approx 0.1$. Thus $\dot{M}_{\text{acc}} \propto M$. With these assumptions the total mass derivative is a monotonic function of the mass:

$$\frac{dM}{dt} = -\text{const} \frac{L^2}{M^2} + \frac{f_E}{t_E} M + \dot{M}_{\text{coll}}, \quad (4)$$

that is dM/dt increases if M increases, and vice versa. So if at one time in the past the derivative was positive the mass will only keep increasing, the rate of evaporation will diminish, and the black hole will survive. Conversely, if the derivative was negative both accretion and collisions will become less important with time, and the black hole will evaporate in a finite amount time similar to $\tau_{\text{ev}}(M)$.

Consider first the case of continuous accretion at a fraction f_E of the Eddington limit. The increase of mass by accretion would overwhelm the evaporation of the black hole if its mass is larger than (Psaltis 2007)

$$M \gtrsim 50 \left(\frac{1}{f_E} \right)^{1/3} \left(\frac{\epsilon}{0.1} \right)^{1/3} \left(\frac{L}{1 \text{ mm}} \right)^{2/3} M_{\odot}. \quad (5)$$

Stellar black holes have a minimum mass $\gtrsim 2 M_{\odot}$, which is an upper limit for a neutron star mass for most proposed equations of state of nuclear matter. We can set an upper bound on the time-averaged value of f_E by requiring that the black hole has increased its mass at most by a factor of $n \lesssim 10$ over its age, τ_{age} . This leads to

$$f_E \lesssim \frac{t_E}{\tau_{\text{age}}} \ln n = 4.5 \times 10^{-3} \ln n \left(\frac{\epsilon}{0.1} \right) \left(\frac{\tau_{\text{age}}}{10 \text{ Gyr}} \right)^{-1}. \quad (6)$$

As a result, the black hole could have accreted only at a fraction of a percent of the Eddington rate over its lifetime. An alternative interpretation is that the black hole could have accreted at the Eddington rate but only for a fraction f_E of its lifetime. In any case, if the observed black hole mass has been gained over time, the condition of Equation (5) must also be satisfied at some earlier time when the mass was lower. In our example the initial mass was M_{obs}/n and hence accretion dominates evaporation at all times if the current mass is higher than

$$M \gtrsim 300 \frac{n}{(\ln n)^{1/3}} \left(\frac{\tau_{\text{age}}}{10 \text{ Gyr}} \right)^{1/3} \left(\frac{L}{1 \text{ mm}} \right)^{2/3} M_{\odot}. \quad (7)$$

The more mass a black hole gained by accretion the stricter is this limit. Figure 1 shows the limit for a black hole that doubled its mass over its lifetime ($n = 2$). This limit comes within a factor of 2 in mass M or size L obtained for RZ2109. Although interestingly close, this limit indicates that steady accretion of matter could not have significantly hampered the evaporation of the black hole.

Consider now the case in which the mass of the black hole has grown after it merged with other stars in the cluster. The increase in mass by a factor of n requires a time-averaged rate of $\dot{M}_{\text{coll}} = M \tau_{\text{age}}^{-1} (1 - 1/n)$. This rate dominates the evaporation rate for

$$M \gtrsim 300 \frac{n}{(n-1)^{1/3}} \left(\frac{\tau_{\text{age}}}{10 \text{ Gyr}} \right)^{1/3} \left(\frac{L}{1 \text{ mm}} \right)^{2/3} M_{\odot}. \quad (8)$$

This equation is essentially the same as Equation (7), except for a factor $(n-1)^{1/3}$ instead of $(\ln n)^{1/3}$. As in the case of accretion, the strictest constraint on the mass occurs at the initial epoch when the black hole mass is the smallest. Therefore, collisions can be important only in the same mass range as steady accretion.

3.2. Mass of the Black Hole in RZ2109

The constraint on L scales with the mass of the black hole in RZ2109. How reliable is our estimate of its mass of $10 M_{\odot}$?

The strong [O III] emission from RZ2109 strengthens the case for a stellar mass black hole in the cluster in three key ways.

First, it dramatically reduces the already low probability that the variable X-ray source in the cluster is a background active galactic nucleus superposed on the globular cluster in the galaxy, by providing strong evidence that there is an unusual feature at the same redshift as the cluster.

Second, the [O III] lines provide evidence against an alternative possibility that the source is an intermediate mass black hole accreting well below its Eddington limit. The luminosity of the [O III] 5007 Å line is about 1.4×10^{37} erg s⁻¹ (Zepf et al. 2008), while the velocity width of the line is about 2000 km s⁻¹. This combination cannot be produced by virial motions around a black hole of less than about $10^4 M_{\odot}$ without invoking a density of oxygen atoms exceeding the critical density for the [O III] line (Zepf et al. 2008), and even at $10^4 M_{\odot}$, considerable fine tuning is needed to have the full volume of the “virial region” at exactly the critical density of the [O III] lines. The most likely situation, then, is that the emission line’s large velocity width comes from a strong wind. While energetically important disk winds have been suggested from sources accreting at low fractions of the Eddington limit (e.g., Blandford & Begelman 1999), only at very high fractions of L_E are winds expected with the mass loss rates needed to produce the observed [O III] emission (e.g., Proga 2007, and references therein). Therefore, the strength and breadth of the [O III] line indicates that the accretor is an object of stellar mass accreting at or slightly above its Eddington luminosity.

Third, the bright [O III] emission presents a strong case that the source is not a neutron star accreting well above its Eddington luminosity. In Maccarone et al. (2007) it was shown that, without beaming, an unphysically high accretion rate would be required to allow for this system to be a super-Eddington neutron star accretor. However, geometric beaming has been suggested as a way to produce the high luminosities seen in some ultraluminous X-ray sources without invoking unphysically high mass transfer rates and without invoking black hole masses in excess of $\sim 20 M_{\odot}$ (e.g., King et al. 2001). The observed [O III] emission is a new argument against significant beaming. The [O III] emission cannot come from a small enough region to be beamed geometrically, and hence must be unbeamed. For the beaming factors of ~ 10 , which would be needed to allow the accretor in RZ2109 to be a neutron star, one would first need to explain an intrinsic luminosity ratio $L_{[\text{O III}]} / L_{\text{bol}} \sim 0.03$, far below what is seen from active galactic nuclei (e.g., Heckman et al. 2005). Also, one would need to explain the lack of any globular clusters with strong, broad [O III] lines but no bright X-ray sources, given that a large number of globular clusters have been searched for emission lines, turning up no other cases of clusters with very broad lines but finding numerous narrow lines typically associated with planetary nebulae (e.g., Minniti & Rejkuba 2002; Brodie et al. 2005; Pierce et al. 2006; Chomiuk et al. 2008).

Thus we conclude that the accretor in RZ2109 is a black hole of $5.3\text{--}20 M_{\odot}$. These limits come from estimating the fraction of the Eddington luminosity that is contributed by the observed X-ray luminosity $L_X \approx 4 \times 10^{39}$ erg s⁻¹, as follows:

$$M \approx 16 \left(\frac{L_E}{L_X} \right) \left(\frac{2}{\mu_e} \right) M_{\odot}, \quad (9)$$

where μ_e is the mean molecular weight per electron. The lack of observed hydrogen Balmer emission from the source (Zepf et al. 2008) indicates that the donor star is likely to be hydrogen poor, which gives $\mu_e \approx 2$. The most likely candidate for such

an object in a globular cluster is a white dwarf. The expected orbital period of the binary system with the observed L_X and M is about 5 minutes (e.g., Bildsten & Deloye 2004). This scenario will be considered in further detail in M. Steele et al. (2009, in preparation). The lack of emission from any element heavier than oxygen is also a strong argument against the possibility of this system being a tidally-induced supernova (suggested by Rosswog et al. 2009).

The lower bound on the mass can be estimated by looking at the degree to which black hole X-ray binaries in the Galaxy can exceed their Eddington luminosities in the absence of beaming effects. In the compilation of Garcia et al. (2003) the only black hole X-ray binary observed at more than three times its Eddington luminosity is V4641 Sgr, which shows highly superluminal proper motions of its jet (Orosz et al. 2001) and hence is likely to be strongly beamed, and which also showed such a high luminosity only for a very short duration, in contrast to the steady high L_X of the source in RZ2109. Thus we can place a lower bound on the black hole mass by taking $L_X \leq 3 L_E$, which gives $M \geq 5.3 M_\odot$.

The upper bound comes from the conservative assumption that the source must be at least at 80% of its Eddington luminosity to be driving a strong wind. Taking $L_X \geq 0.8 L_E$ gives $M \leq 20 M_\odot$, in the case of accretion of hydrogen-free material. Note that if the accreted material is all hydrogen, then $\mu_e = 1$ and the upper bound increases to $40 M_\odot$, but the observed lack of Balmer emission makes the latter case unlikely.

4. SUMMARY

We set the strongest upper limit to date on the asymptotic radius of curvature of the extra dimensions in the RS2 braneworld model, $L \lesssim 0.003$ mm, based on observations of the black hole in a globular cluster RZ2109 in an external galaxy NGC 4472. This limit scales with the age and mass of the black hole, but for all realistic values of these parameters, the robust bound is $L < 0.01$ mm (Figure 1).

The bound can be further reduced if a smaller mass for an old black hole is reliably measured. The absolute minimum is obtained for the smallest black hole mass and oldest age. The smallest stellar black hole mass is expected to be around $2 M_\odot$. The oldest age cannot exceed the age of the universe, 13.7 Gyr. Thus the strongest constraint on L from black hole evaporation is $\sim 3 \times 10^{-4}$ mm. It is shown by the upward arrow in Figure 1. The current constraint derived for the black hole in RZ2109 is within an order of magnitude of this absolute limit afforded by astrophysical observations of black holes.

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