THE ASTROPHYSICAL JOURNAL, 494:L181–L184, 1998 February 20

DYNAMICAL CONSTRAINTS ON ALTERNATIVES TO SUPERMASSIVE BLACK HOLES IN GALACTIC NUCLEI

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Received 1997 October 21; accepted 1997 December 12; published 1998 January 22

ABSTRACT

The compelling dynamical evidence for massive dark objects in galactic nuclei does not uniquely imply massive black holes (BHs). To argue convincingly that these objects are BHs we must rule out alternatives to a BH, and the alternative to a point mass is a cluster of some sort of nonluminous objects, such as a cluster of brown dwarfs or stellar remnants. We use simple physical considerations to derive the maximum possible lifetime of a dark cluster that may consist of any plausible form of nonluminous gravitating objects—from brown dwarfs and very low mass objects of cosmic composition to white dwarfs, neutron stars, and black holes. The lower this limit relative to the galaxy age, the more implausible the cluster hypothesis is, thus arguing for a point mass. A cluster with a lifetime much shorter than 10 Gyr is unacceptable, since observing it at the present epoch would be highly improbable. Since the goal is to rule out a dark cluster by showing that its lifetime must be very short, we make the most generous assumptions possible under the observational constraints to allow for its survival. We find that the lifetime of such a hypothetical cluster must be much shorter than the galaxy age only in the cases of NGC 4258 and our Galaxy, thus strongly arguing for a point mass. In all other galaxies, the case of a massive BH, although compelling, is not yet watertight. We also note that there are two exotic alternatives to a massive BH that cannot be ruled out even in the cases of NGC 4258 and the Galaxy: clusters of elementary particles (e.g., bosons), and clusters of very low mass ($\lesssim 0.04\ M_\odot$) BHs. We point out, however, serious difficulties with these alternatives, and argue that they are highly implausible.

Subject headings: black hole physics — galaxies: kinematics and dynamics — galaxies: nuclei

1. INTRODUCTION

There is now compelling evidence for massive dark objects at the centers of several galaxies (e.g., Kormendy & Richstone 1995, hereafter KR95). The possibility that these are black holes (BHs) fits well into the picture where quasars and AGNs are powered by accretion onto a massive BH, so that dead quasar engines should be hiding in many nearby galaxies. However, as emphasized by KR95, the massive BH picture has become a paradigm, which is a dangerous situation since it is easy to believe that we have proved what we expect to find. High M/L ratios and gas velocities of order $\sim 10^3$ km s^{-1} in galactic centers do not uniquely imply massive BHs. To argue convincingly that these objects are BHs we must rule out alternatives to a BH, and the alternative to a point mass is a cluster of some sort of nonluminous stars, such as a cluster of stellar remnants, brown dwarfs, or very low mass objects. We should not exclude these possibilities even if the formation of such clusters might seem implausible. After all, the physical conditions in galactic centers are much different from those in the solar vicinity, and our understanding of star formation is still limited. We note that the existence of 10^6–$10^{9.5}\ M_\odot$ BHs is still the more exotic of the above interpretations, and its acceptance requires extraordinary evidence.

Dynamical data alone cannot provide a rigorous proof of a massive BH, unless relativistic velocities are detected at a few Schwarzschild radii. They can, however, provide an upper limit to the lifetime of a hypothetical cluster. The lower this limit relative to the galaxy age, the more implausible the cluster hypothesis is, thus arguing for a point mass. A cluster with a lifetime much shorter than ~ 10 Gyr is unacceptable because observing it at the present epoch would be highly improbable. In § 2 we use simple physical considerations to derive the maximum possible lifetime of a dark cluster that may consist of any plausible form of nonluminous gravitating objects—from brown dwarfs and very low mass objects of cosmic composition to stellar remnants. We describe a criterion for ruling out such alternatives to a massive BH and apply it to observed cases. In § 3 we discuss two exotic possibilities that cannot be excluded—clusters of elementary particles and very low mass BHs—and argue that they are highly implausible.

2. LIMITS TO THE LIFETIME OF A DARK CLUSTER

2.1. *Structure and Composition of Dark Clusters*

Since the goal is to rule out a dark cluster by showing that its lifetime must be very short, the cluster must be chosen in the most generous way to allow for its survival. Thus, we shall assume that (1) the cluster is of lowest possible concentration, which would minimize the stellar collision rate; (2) the cluster consists of equal-mass objects, since otherwise mass segregation would accelerate its evolution; and (3) the objects comprising the cluster have zero temperature, thus having the smallest possible radii at a given mass, which would minimize the stellar collision rate. We also assume for simplicity an isotropic velocity distribution.

The least centrally concentrated model for a cluster with a given mass and half-mass radius is a nearly uniform core with the steepest possible density falloff at larger distances. Thus, we shall assume a Plummer model for the cluster structure, which has the steepest asymptotic density profile observed in any astrophysical system,

$$\rho(r) = \rho_0 \left(1 + \frac{r^2}{r_c^2}\right)^{-5/2}, \qquad (1)$$

where $\rho_0 = 3M/4\pi r_c^3$ is the central density, r_c is the core radius, and M is the cluster's total mass. It is useful to replace the two cluster parameters, ρ_0 and r_c, by the cluster's half-mass, $M_h \equiv M/2$, and its half-mass density, ρ_h, which is the mean density within the cluster's half-mass radius, R_h. In the case of a Plummer model we have $R_h = 1.3r_c$ and $\rho_0 = 4.4\rho_h$.

We shall examine all plausible classes of nonluminous objects that may comprise a dark cluster: (1) BHs with $m_* \gtrsim 3\ M_\odot$; (2) neutron stars with $1.4 \lesssim m_* \lesssim 3\ M_\odot$; (3) very low mass objects with $m_* \lesssim 3 \times 10^{-3}\ M_\odot$, where the gravitational forces are small compared to the electrostatic forces, as in planets; and (4) objects with masses in the range $3 \times 10^{-3} \lesssim m_* \lesssim 1.4\ M_\odot$, where gravity is balanced by electron degeneracy pressure. These include brown dwarfs, which are hydrogen rich and thus have masses up to the H-burning mass limit ($\simeq 0.09\ M_\odot$), and white dwarfs that can have any mass within this range. A cluster lifetime depends on the mass and size of the objects comprising it. For white dwarfs at zero temperature we shall assume the mass-radius relation derived by Nauenberg (1972),

$$r_*(m_*) = \frac{1.57 \times 10^9}{\mu} \frac{[1 - (m_*/M_3)^{4/3}]^{1/2}}{(m_*/M_3)^{1/2}}\ \text{cm} \qquad (2)$$

for $3 \times 10^{-3} \lesssim m_* \lesssim 1.4$, where μ is the mean molecular weight and $M_3 \equiv 5.816\mu^{-2}\ M_\odot$ is Chandrasekhar's limit. For cold brown dwarfs and lower mass objects of cosmic composition, we shall assume the mass-radius relation derived by Zapolsky & Salpeter (1969; see also Stevenson 1991),

$$r_*(m_*) = 2.2 \times 10^9 \left(\frac{m_*}{M_\odot}\right)^{-1/3} \times \left[1 + \left(\frac{m_*}{0.0032\ M_\odot}\right)^{-1/2}\right]^{-4/3} \text{cm} \qquad (3)$$

for $m_* \lesssim 0.09$.

2.2. *Cluster Lifetime against Evaporation and Collisions*

Since the case of a BH relies on limits to the lifetime of a cluster, it is better to err on the side of caution and use only simple physical considerations. Thus, we shall examine the cluster lifetime only against the processes of evaporation and physical collisions, and do not take into account processes that are not yet fully understood, such as the post–core-collapse evolution of a cluster. We shall discuss core collapse in § 2.4, and show that including it in the analysis would not have made any qualitative difference in our conclusions.

An upper limit to the lifetime of any bound stellar system is given by its evaporation time. Evaporation is the inevitable, continuous process where stars escape from a stellar-dynamical system due to weak gravitational scattering. The evaporation timescale of a cluster that consists of equal-mass objects is $t_{\rm evap} \approx 300t_{\rm rh}$ (Spitzer & Thuan 1972; Binney & Tremaine 1987, hereafter BT87), where $t_{\rm rh} = [0.14N/\ln(0.4N)](R_h^3/GM)^{1/2}$ is the median relaxation time (Spitzer & Hart 1971; BT87), and $N = M/m_*$ is the number of objects of mass m_* comprising the cluster. In terms of the cluster's half-mass M_h, and half-mass density ρ_h, we obtain for a Plummer model

$$t_{\rm evap} \simeq \frac{4.3 \times 10^4 (M_h/m_*)}{\ln[0.8(M_h/m_*)]} \left(\frac{\rho_h}{10^8\ M_\odot\ \text{pc}^{-3}}\right)^{-1/2} \text{yr.} \qquad (4)$$

The other limit on a cluster lifetime comes from the destruction of the cluster due to physical collisions. The characteristic timescale for each star to physically collide with another, taking gravitational focusing into account, is (BT87)

$$t_{\rm coll} = \left[16\pi^{1/2} n\sigma r_*^2 \left(1 + \frac{Gm_*}{2\sigma^2 r_*}\right)\right]^{-1}, \qquad (5)$$

where n is the number density of objects comprising the cluster and σ is their velocity dispersion.

The evolution of a galactic nucleus driven by collisions has been studied by many authors (e.g., Spitzer & Saslaw 1966; Spitzer & Stone 1967; Colgate 1967; Begelman & Rees 1978), and they all agree that the cluster evolution should accelerate rapidly once the cluster reaches an age of $t_{\rm coll}$. By this time, almost every star will have a collision, and many will have multiple collisions. Stellar debris would settle toward the cluster center, accumulating at the bottom of the cluster potential well, while stars undergo a process of runaway coalescence, leading to a rapid buildup of a very massive object at the cluster center. The most likely end product of this process, which would leave much dark matter behind, is a massive BH.

Substituting $\sigma_0 \simeq [(2\pi/9)G\rho_0 r_c^2]^{1/2} = 2^{-1/4}G^{1/2}M_h^{1/3}\rho_h^{1/6}$ for the central velocity dispersion in a Plummer model and $n = \rho_h/m_*$, equation (5) yields

$$t_{\rm coll}(m_*, r_*) = \left[23.8 G^{1/2} M_h^{1/3} \rho_h^{7/6} \left(\frac{r_*^2}{m_*}\right)\left(1 + \frac{m_*}{2^{1/2}\rho_h^{1/3} M_h^{2/3} r_*}\right)\right]^{-1} \text{s.} \qquad (6)$$

The upper limit on the lifetime of a cluster with a given M_h and ρ_h, which consists of objects of mass m_* and radius r_*, is then

$$\tau(r_*, m_*) = \min[t_{\rm coll}, t_{\rm evap}]. \qquad (7)$$

For every combination of M_h and ρ_h, we examined the entire mass range of every class of nonluminous objects described in § 2.1 and found the maximum possible cluster lifetime $\tau_{\rm max}$, where

$$\tau_{\rm max}(M_h, \rho_h) = \max[\tau(r_*, m_*)]. \qquad (8)$$

Figure 1 presents $\tau_{\rm max}$ for the mass and density ranges found in galactic nuclei. For example, the maximum possible lifetime of a cluster with half-mass of $10^7\ M_\odot$ and half-mass density of $10^9\ M_\odot\ \text{pc}^{-3}$ is $\approx 10^{10}$ yr. We note that for different combinations of cluster mass and density, the cluster lifetime peaks at a different stellar type and stellar mass (e.g., $0.6\ M_\odot$ white dwarfs for $[M_h, \rho_h] = [10^6, 10^{12}]$, $1.4\ M_\odot$ neutron stars for $[10^8, 10^{12}]$, $1.1\ M_\odot$ white dwarfs for $[10^9, 10^8]$, and $0.004\ M_\odot$ brown dwarfs for $[10^6, 10^5]$). In most parts of the examined parameter space, the least well-constrained stellar types and masses are 0.1–1 $M_\odot$ white dwarfs and $1.4\ M_\odot$ neutron stars. Note that $\tau_{\rm max}$ increases with mass, which suggests that it should be easier to make a case for less massive BHs than for heavier ones. However, it is generally more difficult to place a stringent constraint on a cluster density in the case of lower mass objects due to the limited angular resolution of the observations.

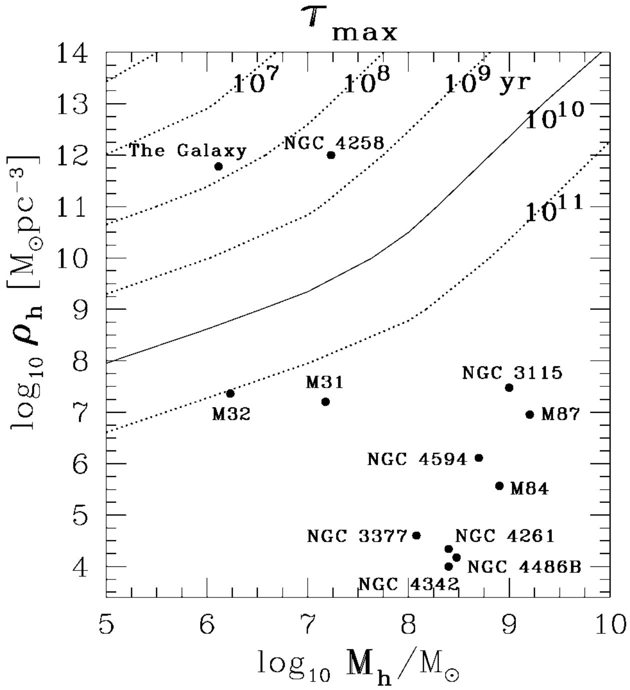

FIG. 1.—Maximum possible lifetime of a dark cluster with half-mass M_h and half-mass density ρ_h, against the processes of evaporation and destruction due to physical collisions. These clusters may consist of any plausible form of nonluminous objects (§ 2.1). The points present the current data for most of the observed BH candidates (Table 1). We see that the lifetime of such hypothetical clusters must be much shorter than 10 Gyr only in the cases of NGC 4258 and our Galaxy, thus strongly arguing for a point mass. In the case of M87, for example, which contains the most massive central object yet detected, the dynamical constraints on alternatives to a BH are very weak (see text).

2.3. *Implications for the Observed Dark Objects*

Observations provide dynamical evidence for large amounts of dark mass within small regions at the centers of several galaxies. The size of these regions is usually determined either by the angular resolution of the observations or by the inner edge of an observed rotating disk. The radius of that region provides the most conservative estimate for the half-mass radius of a central dark cluster; assuming smaller scales for R_h would imply higher densities and thus more rapid cluster evolution. Therefore, we identify the detected mass and mean mass density within that central region as M_h and ρ_h of the hypothetical cluster, respectively. Figure 1 presents the current data for the observed BH candidates (Table 1).

TABLE 1

HALF-MASS OF A HYPOTHETICAL DARK CLUSTER

Galaxy	M_h ($M_\odot$)	R_h (pc)	ρ_h ($M_\odot$ pc^{-3})	References
NGC 3115	1×10^9	2	3×10^7	1
NGC 3377	1.2×10^8	9	4×10^4	2
NGC 4258	1.7×10^7	0.016	1×10^{12}	3
NGC 4261	2.5×10^8	14	2.2×10^4	4
NGC 4342	2.5×10^8	18	1×10^4	5
NGC 4486B	3×10^8	17	1.5×10^4	6
NGC 4594	5×10^8	4.5	1.3×10^6	7
M31	1.5×10^7	0.6	1.6×10^7	8
M32	1.7×10^6	0.26	2.3×10^7	9
M84	8×10^8	8	3.7×10^5	10
M87	1.6×10^9	3.5	9×10^6	11
The Galaxy	1.3×10^6	0.008	6×10^{11}	

NOTE.—The half-mass, $M_h = M_\bullet/2$, of a hypothetical dark cluster, the current upper limit to its half-mass radius, R_h, and the lower limit to its half-mass density, $\rho_h = (3M_h/4\pi R_h^3)$, for the observed BH candidates. The limit on ρ_h at the center of our Galaxy is based on the nearest star to Sgr A* with a measured proper motion (Eckart & Genzel 1997).

REFERENCES.—(1) Kormendy et al. 1996a; (2) Kormendy et al. 1998; (3) Maoz 1995; (4) Ferrarese, Ford, & Jaffe 1996; (5) van den Bosch & Jaffe 1997; (6) Kormendy et al. 1997; (7) Kormendy et al. 1996b; (8) KR95; (9) van der Marel et al. 1998; (10) Bower et al. 1998; (11) Marconi et al. 1998.

We find that the lifetime of a hypothetical central cluster must be much shorter than the galaxy age only in the cases of NGC 4258 and the Galaxy, thus strongly arguing for a point mass. In all other galaxies, we currently cannot completely rule out the possibility of a central dark cluster. It is interesting to notice that in M87, for example, which contains the most massive dark object yet detected ($M_\bullet \approx 3 \times 10^9\ M_\odot$), the dynamical constraints on a central cluster are very weak. It would require observations with nearly 3 orders of magnitude better angular resolution in order to raise the limit on the central density to a point where a dark cluster is safely ruled out in that galaxy. On the other hand, an improvement of less than one order of magnitude in resolution would make it possible to confidently exclude a dark cluster in M32, assuming that the inferred amount of dark mass within the unresolved central region in that galaxy does not drop significantly with increasing resolution.

2.4. *Core-collapsed Dark Clusters*

Dark clusters must undergo core collapse at a finite age, during which the core radius shrinks almost to zero and the central density increases enormously. For a Plummer model of equal-mass objects, core collapse will occur at $t \approx 16t_{\rm rh}$ (Cohen 1980; BT87; Quinlan 1996), where $t_{\rm rh}$ is the median relaxation time defined in § 2.2. Core collapse is not necessarily catastrophic for the cluster as a whole, but it is certainly possible that it may lead to the formation of a BH at the cluster center.

However, since the mass enclosed within the core drops significantly during the collapse, the BH mass will be a very small fraction of the dark cluster mass. The post-collapse evolution of a cluster and the growth rate of a seed BH depend on complicated processes such as binary interactions and stellar mass loss (e.g., Ostriker 1985; Goodman 1993). Since the effect of these processes on the post-collapse cluster evolution are not yet fully understood, we could not include the timescale for core collapse as a limit on the cluster lifetime.

Yet, let us suppose that future investigations would reveal that a BH that contains a significant fraction of the cluster mass must form shortly after a core collapses. Since $16t_{\rm rh}$ is shorter than $t_{\rm evap}$ by a factor of ~ 20 (eq. [4]), we can expect $\tau_{\rm max}$ (eq. [8]) to be shorter by up to the same factor, depending exactly on whether the cluster lifetime is more strongly constrained by collisions or by evaporation. Replacing $t_{\rm evap}$ by $16t_{\rm rh}$ in equation (7), we find that $\tau_{\rm max}$ drops by a factor of nearly 20 in the case of M87, but it decreases only by a factor of 4 to 9×10^{10} and 3×10^{10} yr in the cases of M31 and M32, respectively. The latter result is consistent with the findings of previous investigations of the central objects in M31 and M32 (Goodman & Mok Lee 1989; Richstone, Bower, & Dressler 1990). In any case, we see that it is possible that all the hypothetical dark clusters that are located below the 10 Gyr curve in Figure 1 have not yet undergone core collapse.

3. DISCUSSION

The main results of this investigation are summarized in the abstract, so we avoid redundancy here. We note that there are two exotic alternatives to a massive BH that cannot be safely ruled out even in the cases of NGC 4258 and the Galaxy: clusters of elementary particles and very low mass BHs. Physical collisions do not affect the evolution of a cluster that consists of BHs, and the evaporation timescale can be made arbitrarily long by giving the BHs an arbitrarily small mass. The lifetime of such clusters could exceed 10 Gyr if $m_{\rm BH} < 0.04\ M_\odot$ in the case of NGC 4258, and if $m_{\rm BH} < 0.005\ M_\odot$ in the case of the Galaxy (eq. [4]). The most serious difficulty with such an alternative to a massive BH is that low-mass BHs cannot form in stellar evolution. They may form in the early universe, assuming inflationary cosmology (Garcia-Bellido, Linde, & Wands 1996; Yokoyama 1997). We also note that the mass range of $10^{-8} \lesssim m_{\rm BH} \lesssim 0.03\ M_\odot$ BHs is ruled out by gravitational microlensing experiments (Alcock et al. 1997), if we assume that the same hypothetical BH population comprises both the central dark cluster and the Galactic dark halo.

Collisions and evaporation arguments cannot rule out a massive cluster of elementary particles either. We can only note that particles that may comprise a dark cluster cannot be muon or electron neutrinos of nonzero rest mass, or any other hypothetical noninteracting Maxwell-Boltzmann particles, since their fine-grained phase-space density would be enormously higher than that allowed by cosmological models (see Tremaine & Gunn 1979). These particles could be bosons, for example, where the equilibrium phase-space density does not have a maximum. The most serious difficulty with such an alternative to a massive BH is that it is very difficult to imagine a process of (inverse) mass segregation, where 10^6–$10^{9.5}\ M_\odot$ of *collisionless* gas of elementary particles could dissipate a large fraction of its energy and evolve toward an extremely dense configuration. We conclude that clusters of very low mass BHs and elementary particles cannot be ruled out, but their existence is highly implausible.

Finally, we note that (1) better theoretical understanding of cluster evolution may make it possible to tighten some of the limits derived in this paper in the future; (2) the constraint on the density of a dark object at the center of our Galaxy may be significantly stronger than that used in the present study (see Genzel et al. 1997); and (3) all the arguments presented in this investigation rely on the assumption that we do not live in a very special epoch.

I thank Reinhard Genzel for stimulating discussions, and John Kormendy for useful comments.

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