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BLACK HOLE DEMOGRAPHY

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Abstract. Several hundred black hole (BH) candidates have been discovered up to now. Statistical investigations of relativistic objects have been carried out. Neutron stars (NS) and stellar-mass BHs presumably have a bimodal distribution over their masses in contrast with distribution of CO-core masses of massive stars being progenitors of relativistic objects. Masses of supermassive BHs in galactic nuclei correlate with the luminosity of the galactic bulge as well as with the bulge velocity dispersion. Correlation between rotational velocity of a galaxy and the mass of its central supermassive BH is investigated by direct comparison of an observed rotational velocity of the galaxy with the dynamically determined mass of the central supermassive BH.

1. INTRODUCTION

A great progress made in BH observations has iniciated a new branch of astrophysics, BH demography, which provides statistical investigations of basic properties of these extreme objects.

A number of BHs have been discovered during the past decade:

1. 20 stellar-mass BHs in X-ray binary systems;
2. 300 supermassive BHs in galactic nuclei;
3. 3 single stellar-mass BHs discovered due to microlensing effects.

Methods and results of BH investigations are described in recent reviews (see the papers by Charles, 2001; Novikov and Frolov, 2001; Cherepashchuk, 2003; and references therein).

Note that a possibility to observe accreting BHs was first pointed out by Zeldovich (1964) and Salpeter (1964).

2. STELLAR-MASS BLACK HOLES

Stellar-mass BHs are identified from the motion of optical stars in X-ray binary systems (see e.g. Webster and Murdin, 1972; Luytyj et al., 1973) as well as from microlensing effects (Mao et al., 2002; Benett et al., 2002). The radial velocity curve of an optical star in an X-ray binary allows one to determine the mass function, $f_v(m)$. The BH mass, m_x, is calculated using the formula

$$m_x = f_v(m)\left(1+\frac{1}{q}\right)^2 \frac{1}{sin^3 i} \tag{1}$$

where $q = m_x/m_v$ is the mass ratio of the components (m_x being the mass of a relativistic object, and m_v, the mass of an optical star), i is the inclination of the orbital plane. The parameter i can be determined from optical variability of the X-ray binary caused by tidal deformation of the optical star (ellipticity effect). Besides, the parameter i may be determined from orbital variability of absorption lines in the spectrum of the optical star (Antokhina, Cherepashchuk, and Shimanskii, 2005; Abubekerov, Antokhina and Cherepashchuk, 2004). The mass ratio, q, is determined from rotational broadening of absorption lines in the spectrum of the optical star (Wade and Horne, 1988; Shahbaz, 2003).

Since the mass of the dark body responsible for the gravitational lensing is proportional to the square root of the microlensing effect duration, observations of long-term microlensing events allow one to discover single BHs of stellar masses (Mao et al., 2002; Benett et al., 2002).

Comparison of the masses of stellar-mass BHs and those of NSs with the masses of the companion stars in close binary systems is presented in Fig. 1.

There is no correlation between masses of relativistic objects and those of companion stars in binary systems: BHs and NSs occur in binary systems both with high-mass and low-mass companions. In this sense, close binary systems with relativistic components are similar to classic close binaries where all possible combinations of components occur (Martynov, 1972). The masses of all measured X-ray and radio pulsars, as well as the mass of an X-ray burster of the first kind, do not exceed $3M_\odot$, the absolute upper limit of the NS mass being in full accordance with Einstein General Relativity. At the same time, none of the 18 massive ($m_x > 3M_\odot$) compact X-ray sources in close binary systems (BH candidates) show the phenomenon of radiopulsar, X-ray pulsar, or X-ray burster of the first kind, again with full consistency with Einstein General Relativity prediction. Three X-ray binaries with BHs (XN Sco 1994, SAXJ 1819.3-2525, XTEJ 1118+480) show signatures of supernova explosion; in XN Sco 1994, high peculiar velocity of the system's barycenter, $V_{pec} = (-114 \pm 19)$ km $\cdot$ s^{-1}, is observed (Brandt et al., 1995) and enhanced abundance of α-elements O, Si, Mg is found in the optical star spectrum (Israelian et al., 1999). This evidences the supernova explosion which led to the optical star enrichment of the α-elements and the high system's barycenter velocity. The optical star in SAXJ 1819.3-2525 also demonstrates an overabundance of α-elements evidencing the supernova explosion. XTEJ 1118+480 is located at a very high altitude over the Galactic plane, $z = 1.7$ kpc (Wagner et al., 2001), and has a large peculiar space velocity of the barycenter

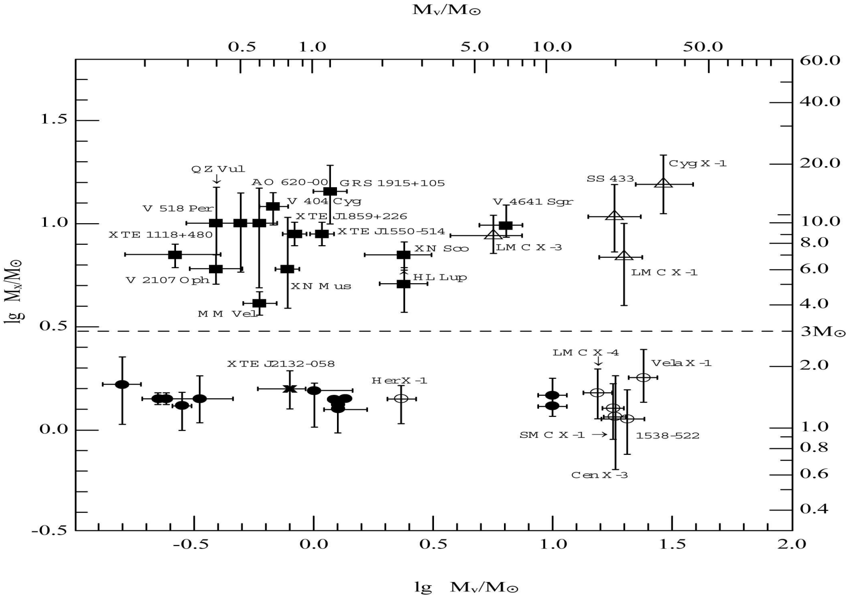

Figure 1: The dependence of masses, M_x, of NSs (circles and crosses) and BHs (triangles and squares) on the companion masses, M_v, in binary systems (masses are in solar units $M_\odot$). The filled circles correspond to radio pulsars, the open circles, to X-ray pulsars, and the cross stands for the NS in X-ray nova XTEJ 2132-058 (X-ray burster of the first kind). The filled squares correspond to BHs in X-ray novae and the open triangles, to BHs in persistent X-ray binaries with massive O-B companions.

of 145 km $\cdot$ s^{-1} (Mirabel et al., 2001), which also can indicate a supernova explosion occurred in the past that gave a high initial space velocity to the system.

In systems GRS 1915+105, SAXJ 1819.3-2525, GRO 1655-40 (XN Sco, 1994), and 1E1740.7-2942, relativistic collimated jets with velocities $v \geq 0.92$c and apparent superluminal plasma clouds were discovered during X-ray outbursts (see e.g. Mirabel et al., 1992). X-ray binary systems with collimated relativistic jets are commonly called microquasars (see reviews in Proceedings of the conferences: Castro-Tirado et al., 2001, Carramiñana et al., 2001).

Observational facts on BH rotation in X-ray binaries based, in particular, on the analysis of the accreting disk X-ray luminosity, are given in the papers (Greiner et al., 2001; Zhang et al., 1997). Accretion disks corotating with a spinning BH penetrate much closer to the BH than for Schwarzchild BHs since the radius of the last marginally stable orbit for a rotating BH is smaller than for a non-rotating one. So the luminosity and the temperature of the thermal X-ray component from a rotating accreting BH must be higher. This is observed for two transient BH X-ray binaries, microquasars GRS 1915+105 and GROJ 1655-40, which most probably contain rapidly rotating BHs (Greiner et al., 2001; Zhang et al., 1997).

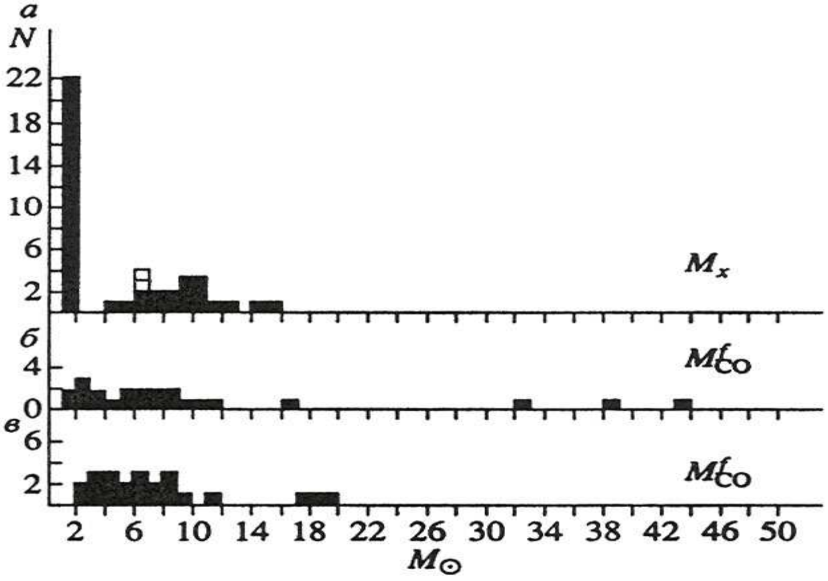

Figure 2: At the bottom, histograms of distributions of the final masses of carbon-oxygen cores M^f_{CO} for 23 Wolf-Rayet stars with known masses are given (the middle plot corresponds to the case $\alpha = 1$ in the relation $\dot{M} = KM^{\alpha}_{WR}$, the bottom plot to the case $\alpha = 2$). In the upper plot, the histogram of the M_x-mass distribution for relativistic objects in binaries is shown (masses M^f_{CO} and M_x are in solar units ($M_\odot$)). Open squares correspond to single BHs with mass determination due to microlensing effects. The high peak at $(1-2)M_\odot$ corresponds to a NS. The distributions of M^f_{CO} are continuous while the distribution for M_x is bimodal with a gap at $M_x = (1{-}2)M_\odot$.

In Fig. 2 a mass distribution of relativistic objects and CO-cores of Wolf- Rayet stars in binary systems is presented. Open squares correspond to single BHs discovered due to microlensing events. As seen from Fig. 2, distribution of relativistic objects is bimodal (Bailyn et al., 1998; Cherepashchuk, 1998).

Masses of 19 NSs lie within narrow limits $m_{NS} = (1-2)M_\odot$ with the mean NS mass $\bar{m}_{NS} = (1.35 \pm 0.15)M_\odot$.

The measured masses of 18 BHs fall within the range $(\ 4-15)M_\odot$. The mean BH mass derived from observations is $\bar{m}_{BH} \approx 8M_\odot$. No NS or BH have been found up to now within the mass range $m_x = (2{-}4)M_\odot$. In contrast with the bimodal distribution of relativistic objects, the distribution of CO-cores of Wolf-Rayet stars at the end of their evolution in binary systems (Cherepashchuk, 2001) is continuous. Wolf-Rayet stars in close binary systems can be considered as progenitors of relativistic objects because a massive star in a close binary always rapidly loses its hydrogen envelope due to mass exchange and forms a Wolf-Rayet star. Collapse of the CO-core of a Wolf-Rayet star leads to the Ibc type supernova explosion and formation of a relativistic object.

Thus, (see Fig. 2), the relativistic object mass distribution is bimodal in spite of its progenitor's masses (CO-cores of Wolf-Rayet stars at the end of their evolution) being continuous. If this result is confirmed by further investigations it will need a special interpretation.

3. SUPERMASSIVE BHs IN GALACTIC NUCLEI

Masses of supermassive BHs in the nuclei of galaxies are measured from observations of gaseous clouds or stars located near the BH. Motion of gas and stars near the nucleus is assumed to be controlled by its gravity field (Woltjer, 1959; Dibai, 1980). In this case the virial relation $v^2 \sim r^{-1}$ should exist between the velocities v of stars or gaseous clouds surrounding the nucleus and the distance r to the nucleus. Hence the estimate of the nucleus mass m_x can be obtained:

$$m_x = \frac{\eta v^2 r}{G} \tag{2}$$

where $\eta = 1 - 3$ depending on an assumed kinematic model for the motion of test bodies around the galactic nucleus (BH candidate). Modern observational facilities (the Hubble Space Telescope, the largest ground-based new generation telescopes equipped with compensation systems for atmospheric distortions, intercontinental radio interferometers for observations of cosmic megamasers, etc.) in many cases allow one to see directly the gas (and in the case of our Galaxy center, individual stars too) moving near the nucleus (see e.g. Ford et al., 1994; Schödel et al., 2002). So the mass of the galactic nucleus is uniqely found by directly applying the Newton's gravity law and from a relation like Eqn (2). Note that characteristic distances from the galactic center to the test bodies are much more than the gravitational radius, so the newtonian law is well applied for the mass determination of the central supermassive BH.

If a circumnuclear gas-dust disk is unavailable for direct imaging and studies, another method is used based on statistical examinations of stellar kinematics in central parts of the galaxy, which is mainly determined by gravitational interaction with the nucleus (see e.g. Kormendy and Richstone, 1995).

In active galactic nuclei, where powerful broad emission lines are observed, the mass of the nucleus can be estimated using Eqn (2). Velocities v of gas clouds forming the broad emission line component are derived from the half-width of this broad component. The distance r from the gas clouds to the nucleus center can be estimated by observing the time delay Δt between the rapid variability of the broad emission line component relative to that of the continuum spectrum, $r \simeq c\Delta t$ (so-called "reverberation mapping method", see e.g. Blanford and McKee 1982, Antokhin and Bochkarev 1983). The delay of rapid variability in emission lines relative to continuum in nuclei of Seyfert galaxies was discovered by Cherepashchuk and Lyutyj (1973).

Note that the first estimate of the masses of active galactic nuclei (quasars) was done by Zeldovich and Novikov (1964) by method based on the hypothesis that the bolometric luminosity of the nucleus is close to the Eddington limit.

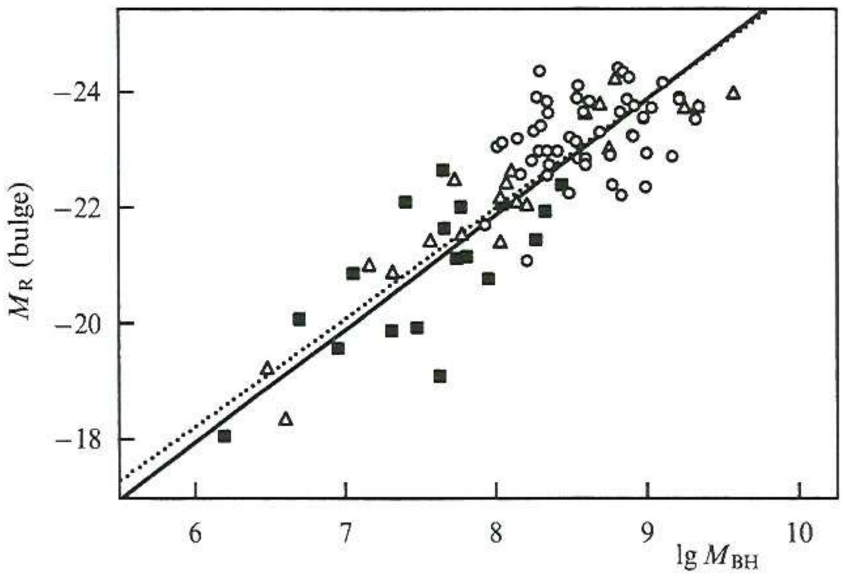

Figure 3: The absolute stellar R-magnitude of the bulge proportional to its mass as a function of the central BH mass for a set of 90 galaxies of different types (from McLure and Dunlop, 2002): open triangles are normal galaxies, filled squares stand for type I Seyfert galaxies, open circles for quasars. Here M_{BH} is given in solar mass $M_\odot$ units.

A high number of measured masses for supermassive BHs in galactic nuclei allows one to develop their demographic (statistical) investigations. In recent years, a lot of papers have appeared on this subject (see e.g. reviews by Ho, 1999 and Kormendy, 2001). Let us briefly describe the most important results.

1. There is a correlation between the supermassive BH mass and the bulge mass (or the bulge luminosity) of a galaxy (see Fig. 3): the central BH mass increases with the bulge mass M_{bulge}, $M_{BH} \simeq 0.0012 M_{bulge}$ (McLure and Dunlop, 2002).

   The presence of such a correlation puts serious constraints on the formation mechanism of supermassive BHs. In particular, the model of mass growth of a supermassive BH due to accretion and coalescence in the hierarchical models of galactic formation appears quite probable (Cattaneo et al., 1999).

2. The supermassive BH mass M_{BH} correlates with the velocity dispersion of stars populating the bulge inside its effective radius, σ_{eff}, average- weighted over the luminosity; the BH mass increases as $\sim \sigma_{eff}^4$ (Tremaine et al., 2002):

$$\lg \frac{M_{BH}}{M_\odot} = (8.13 \pm 0.06) + (4.02 \pm 0.32) \lg \frac{\sigma_{eff}}{200\ \mathrm{km} \cdot \mathrm{s}^{-1}}$$

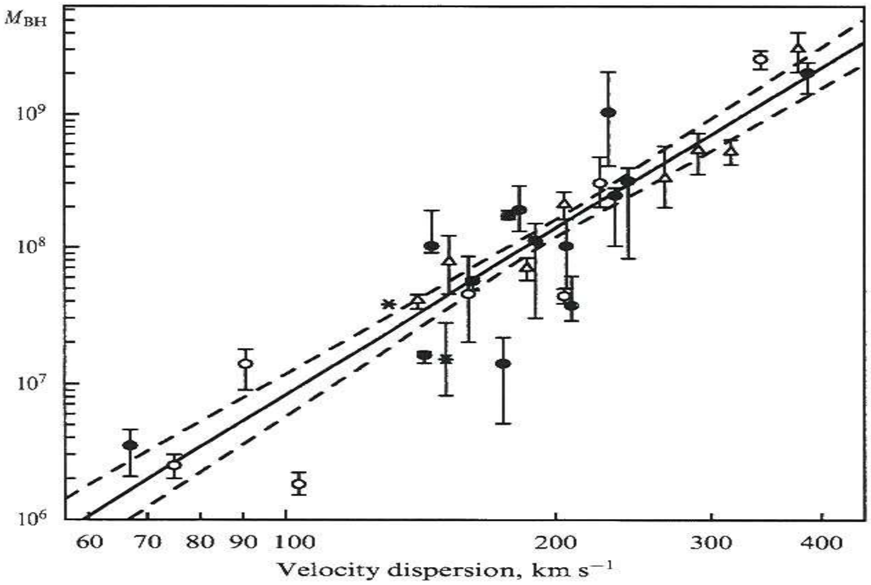

Figure 4: The BH mass (in solar units) in the nucleus of a galaxy as a function of the velocity dispersion of stars in its bulge (from Tremaine et al., (2002)).

This correlation is presented in Fig. 4.

3. The supermassive BH mass does not correlate with the galactic disk luminosities (Kormendy, 2001).

4. For active galactic nuclei there is a correlation between the central BH mass and the visual ($\lambda = 5100$ Å) luminosity L_v of the nucleus (Wandel et al., 1999):

$$\lg \frac{M_{BH}}{M_\odot} = (0.77 \pm 0.07) \lg L_{44} + (7.92 \pm 0.04)$$

   where $L_{44} = L_v/10^{44}$ erg $\cdot$ s^{-1}.

5. Correlation between maximum rotational velocity of a galaxy, V_m, and the mass of the central supermassive BH has been suggested recently on the basis of correlations between M_{BH} and velocity dispersion of stars in the bulge, σ_{eff}, as well as between V_m and σ_{eff} (Baes et al., 2003). This correlation suggests a very important correlation between the mass of the central supermassive BH and the mass of the galactic halo consisting of dark matter. Recently this correlation was checked by Zasov et al. (2005) by direct comparison of observed maximum rotational velocities for $\sim$ 40 galaxies and the mass of central supermassive BH M_{BH} (see Fig. 5).

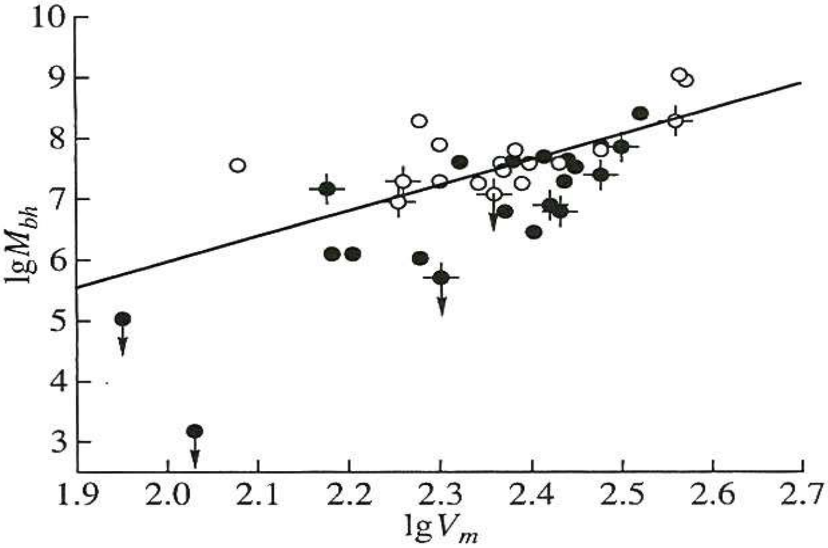

Figure 5: Supermassive BH masses (in solar units) plotted against the maximum observed rotational velocity of galaxies. The open symbols correspond to early-type S0-Sab galaxies (with big bulges). The crosses mark galaxies with disk inclination $i < 40^o$, for which the direct estimates of V_m are least reliable. The line shows the dependence found by Baes et al. (2003) on indirect estimates of V_m.

> Correlation $M_{BH} - V_m$ is confirmed but the dispersion of points in this direct correlation is higher than in the earlier result (Baes et al., 2003). A new result was obtained by Zasov et al. (2005): for a fixed V_m the value of M_{BH} is higher for the galaxies with higher bulges. Therefore, it is clear that the dependence is two-parametric: M_{BH} correlates with the mass of the galactic halo as well as with the bulge mass (see Fig. 6).
>
> For a fixed mass of the galactic halo the mass of the central supermassive BH increases with galactic bulge mass. This result allows us to suggest that both the dark matter of the galactic halo and the barionic matter of the bulge are responsible for the formation, growth, and evolution of the central supermassive BH (see e.g. Il'in, Zybin and Gurevich, 2004).

4. CONCLUSION

Recent progress in stellar-mass BH investigations as well in studies of supermassive BHs allows one to provide detailed demographic analyses of BHs in the Universe. Comparison of basic properties of observed BHs with the properties of stars and galaxies imposes significant constraints on the formation and growing mechanisms

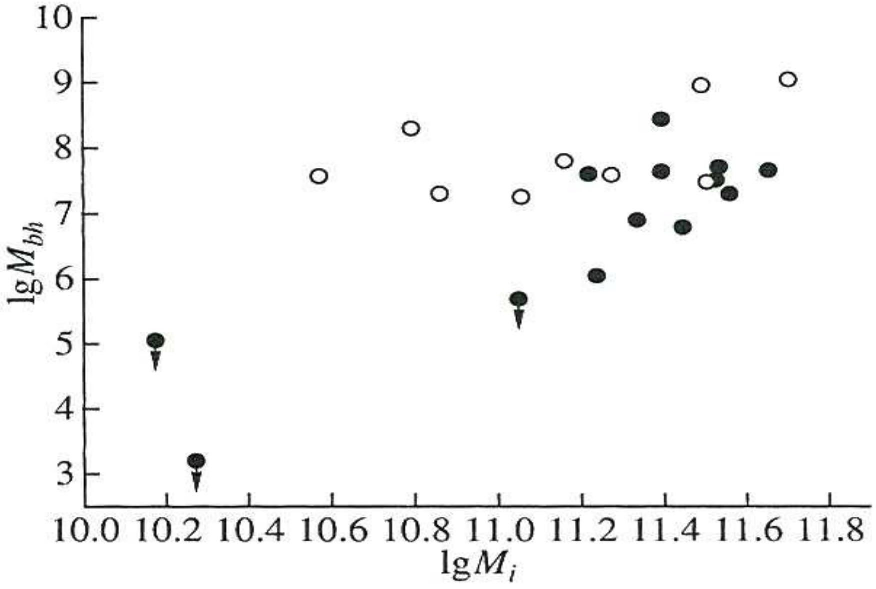

Figure 6: Supermassive BH masses (in solar units) plotted against the indicative masses of the galaxies, $M_i = V_m^2 R_{25}/G$, containing basically dark matter of the galactic halo. The open circles correspond to early-type S0-Sab galaxies (with big bulges).

for BHs of different masses. Further observational investigations of BHs seem to be very promising. New perspectives for observations of single stellar-mass BHs open thanks to discovery of the three BHs from examinations of gravitational microlensing events (Benett et al., 2002; Mao et al., 2002). It is interesting to note that further observations of microlensing events would allow us to distinguish a BH from a wormhole predicted by Einstein General Relativity. In the recent paper by Bogdanov and Cherepashchuk (2002) a possibility to detect wormholes from the gravitational microlensing events is demonstrated.

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