been applied to a sample of 6300 nearest galaxies with radial velocities < 3000 km s^{-1}, concentrated within the Local Supercluster volume. As a result, 840 groups were selected that comprise 55% of the total number of galaxies in the volume. The typical characteristics of these groups are listed in Table 1. The mean crossing time of the groups does not exceed 10% of the Hubble time $1/H$. The mean virial-mass-to-luminosity ratio weakly depends on the group size and is $\sim 30 M_{\odot}/L_{\odot}$. The last value is consistent with the above total mass estimates for the Local Group and M81 group, which makes our system a typical representative of galactic groups.

7. Conclusion

A great number of possible candidates have been put forward to explain the nature of dark matter. They include: dwarf stars, black holes, molecular gas clouds, neutrinos, axions, gravitinos, etc.; see [26, 27] for reviews of various hypotheses and their observational tests. As can be seen from the last two rows of Table 1, the dark-to-visible mass ratio for single galaxies, pairs, and groups is DM/LM = 2 – 3, and only in rich clusters — dense 'knots' of the large-scale structure — this ratio increases by more than an order of magnitude. The total contribution of galaxies, pairs, and groups to the integral matter density (15% + 6% + 27%) is approximately the same as that of rich clusters (52%). Possibly, we are observing two types of dark matter that have essentially different spatial distributions: compact, dark shells of individual galaxies and vast reservoirs filling the volumes of rich clusters.

It should be stressed here that there exist a strict relation between the luminosity of a galaxy and the amplitude of its internal motions (Tully – Fisher relation for spirals, Faber – Jackson relation for E and S0 galaxies), with a dispersion of only 15 – 20%. This means that unseen masses of galaxies are 'sewed' to their visible masses in a surprisingly stable proportion spanning a luminosity range of more than three orders of magnitude.

In recent years observational evidence has emerged [28] favoring the cosmological significance of vacuum, which appears as a universal repulsion force (the famous λ term in the Einstein equation). It cannot be ruled out that, in terms of vacuum cosmology, the problem of dark matter in the Universe will look essentially different.

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Searches for black holes: the recent data

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1. Itroduction

Black holes are predicted by Einstein's General Relativity (GR) theory. A black hole (BH) represents a space – time region for which the parabolic velocity is equal to the speed of light $c = 300\,000$ km s^{-1}. The characteristic size of a BH is determined by the gravitational radius $r_g = 2GM/c^2$. It amounts to $r_g = 30$ km for $M = 10\,M_{\odot}$ and 20 a.u. for $M = 10^9\,M_{\odot}$. The BH event-horizon radius is $r_h = r_g$ for a non-rotating (Schwarzschild) BH and $r_h < r_g$ for a rotating one. For a BH that formed in our epoch, the event horizon has not yet formed, so these are collapsing objects ('virtual' BHs).

From the astronomical point of view, in order for an object to be recognized as a BH, its mass should be measured and its size should not exceed r_g. Also, it is necessary to obtain observational evidence for the object having a 'virtual' event horizon. BH masses are reliably measured by the surrounding gas and star motions. Since $r \gg r_g$, in most cases using the Newtonian gravity law is sufficient.

BH radii are very difficult to measure. So far only very rough ($r < 10 r_g$) indirect estimates have been used: study of the X-ray luminosity due to accretion of matter onto a BH, fast time variability analysis, spectral line profile investigations, etc. No sufficient observational criteria for a BH have been found as yet, but all the necessary conditions are met.

There are 3 known types of BHs:

(1) Stellar mass BHs with $M = 3 - 50\,M_{\odot}$. The stellar evolution ends in the formation of a white dwarf (if the stellar core mass $M_c \leqslant 1.2\,M_{\odot}$), a neutron star (NS) (if $M_c < 3\,M_{\odot}$), or a BH (if $M_c \geqslant 3\,M_{\odot}$).

(2) Supermassive BHs in galactic nuclei ($M = 10^6 - 10^{10}\,M_{\odot}$).

(3) Primordial BHs generated at the early stages of evolution of the Universe. As yet, very little is known about them from the observational point of view.

The existence of intermediate-mass BHs with $M = 10^2 - 10^4\,M_{\odot}$ located in the near-nuclear regions of galaxies (at a mean distance of ~ 390 pc from the nucleus) has been widely discussed in recent years.

Observational studies of BHs proceed in two directions:

(1) Searching for massive compact objects – BH candidates. Here much progress has been made, and the number of them approaches 100.

(2) Looking for sufficient criteria for the BH candidates discovered to be real BHs. Many difficulties have been met on this avenue, but there is some progress and great hopes for future space X-ray, interferometric, and gravitational wave experiments.

2. Black hole mass determination

Galactic nuclei. In many cases, modern observational facilities allow direct measurements of gas and stellar motions around a BH (at distances $r \sim 10^4 - 10^5 r_g$). Therefore, the BH mass can be uniquely derived from the Newton gravity attraction law: $M_{BH} = rv^2/G$, where v is the velocity of the gas or stars, and r is the corresponding distance to the BH.

X-ray binary stars. In this case, the components are not separately visible, only the radial-velocity and light curves of the system can be measured. Assuming a point-like optical-star model and using the Newton gravity law, from the radial-velocity curve one can obtain the mass function of the optical star: $f_v(M) = M_x^3 \sin^3 i/(M_x + M_v)^2$, where M_x is the BH mass, and M_v is the optical star mass. The mass function $f_v(M)$ sets an absolute lower limit on the BH mass: $M_x > f_v(M)$. The effects of the optical star not being point-like, of its pear-like shape, and its X-ray heating-up are negligibly small for a mass ratio $q = M_x/M_v > 5$ (the case of transient X-ray binaries — X-ray novae). The BH mass can be expressed through the mass function: $M_x = f_v(M)[1 + (1/q)]^2(1/\sin^3 i)$. Since the components are not visible separately, there are two free parameters, q and i — the mass ratio and the inclination of the orbital plane of the binary system to the plane of the sky. The parameter i can be found from the analysis of the optical light curve of the system, which is mainly determined by the optical star ellipticity. The parameter q can be determined from the rotational broadening of absorption lines in the optical star spectrum (the star is not point-like and fills its Roche lobe). There are also some additional constraints allowing independent checks of the BH mass obtained from the mass function, such as data on X-ray eclipses, the distance to the system, the optical-star mass M_v estimated from its spectral class and luminosity class, and the orbital variability of absorption line profiles in the optical star spectrum.

3. Black hole radius determination

There are several means to determine the radius of a BH.

(1) From the X-ray luminosity and spectrum. The accretion X-ray energy release is $L_x = 0.057\,\dot{M}c^2$ for a Schwarzschild BH and $L_x = 0.42\,\dot{M}c^2$ for a Kerr BH. In X-ray binaries $L_x = 10^{36} - 10^{39}$ erg s^{-1}, which implies that the object is compact. However, the accretion rate $\dot{M}$ is not known precisely. In addition, in the theory of advection-dominated accretion disks, L_x is small even for a known $\dot{M}$, since the main energy released in accretion is carried by hot ions, which rapidly disappear under the BH event horizon.

(2) From the minimal time scale Δt of the X-ray flux variability. For example, for Cyg X-1 $\Delta t = 10^{-3}$ s, $r < c\Delta t = 300$ km $= 10 r_g$.

(3) From direct observations of BH surroundings in galactic nuclei using high-angular-resolution techniques. So far only weak restrictions are known: $r < 10^4 r_g$. The estimates will be improved in future with the use of space-based interferometers.

(4) From the width Δv of the FeXXV, FeXXVI emission line profiles at ~ 6.4 keV: $\Delta v \approx 100\,000$ km s^{-1}. The redshift of the broad line component corresponds to $r \sim 6 - 10 r_g$.

Additionally, in accordance with GR predictions, all known BH candidates of stellar masses do not exhibit X-ray-pulsar or type-I X-ray-burster phenomena, which are typical of accreting NSs. The spectral and time behavior of accreting NSs and BHs are systematically different.

4. Black hole masses in X-ray binaries.

At present, there are 15 known massive ($M_x > 3\,M_\odot$) compact ($r < 10 r_g$) X-ray sources in close binary systems (BH candidates): $M_x = 4 - 15\,M_\odot$. Among them, four reside in massive X-ray binaries with hot massive O – B or WR stars as secondary companions. These are systems Cyg X-1, LMC X-3, LMC X-1, and Cyg X-3. Eleven are known in transient X-ray binaries (X-ray novae), which have cold low-massive A – M stars as secondary companions. These include the systems AO620-00, GS2023 + 338, GRS1124-68, GS2000 + 25, GROJ0422 + 32, GROJ1655-40, H1705-250, 4U1543-47, GRS1009-45, SAXJ1819.3-2525, and XTE1118 + 480. No X-ray pulsars or type-I X-ray bursters, which would indicate an accreting NS, are found among them, in full agreement with GR predictions. The mean BH mass is $\bar{M}_x = 8 - 10\,M_\odot$. The masses of 18 X-ray and radio pulsars and one type-I X-ray burster (all NSs) in binary systems, in accordance with GR, do not exceed $3\,M_\odot$ and lie within narrow limits $M_{NS} = 1 - 2\,M_\odot$.

The mass distribution of relativistic objects is bimodal: the mean NS mass is $\bar{M}_{NS} = (1.35 \pm 0.15)\,M_\odot$ and the mean BH mass is $\bar{M}_{BH} = 8 - 10\,M_\odot$. Neither NS nor BH have been observed within the mass range $2 - 4\,M_\odot$.

Wolf – Rayet (WR) stars are progenitors of relativistic objects in close binary systems. They are bared helium cores of massive stars that have lost their extended hydrogen envelopes in the course of the mass exchange in binary systems. Mass determinations have been made for 24 WR stars in WR + O systems. WR masses are distributed continuously over a broad interval $M_{WR} = 5 - 55\,M_\odot$. With due account for radial stellar-wind mass losses, the masses M_{CO}^f of carbon-oxygen cores of WR stars at the end of their evolution can be calculated. They lie in a wide range, $M_{CO}^f = (1-2) - (20-44)\,M_\odot$, and are also continuously distributed. The mean value $M_{CO}^f = 7 - 10\,M_\odot$ is close to the mean BH mass $\bar{M}_{BH} = 8 - 10\,M_\odot$.

The difference in mass distributions of relativistic objects and CO cores of massive stars at the end of their evolution allows us to suppose that not only the pre-supernova mass determines the nature of the relativistic object (NS, BH), but also other pre-supernova parameters, such as rotation, magnetic field, etc., play a role. NSs and BHs in X-ray binaries differ not only in their masses but also in their observational appearances, as predicted by GR. This lends more credibility to our assurance that stellar-mass BHs really exist.

5. Black hole masses in galactic nuclei

Mass determinations have been made for more than 60 supermassive ($M > 10^6\,M_\odot$), compact ($r < 10 r_g$), and in most cases dark (mass-to-luminosity ratio $M/L > 100$) bodies residing in galactic nuclei: $M = 10^6 - 10^{10}\,M_\odot$. About 20 masses of Active Galactic Nuclei were derived from the time retardation effect in rapidly varying emission lines with respect to the continuum (the so-called reverberation mapping method). The retardation times measured in different galaxies fall within the range $\Delta t = 5 - 80$ days. The distance from the BH to the emitting line gas clouds is $r = c\Delta t$. The characteristic velocity of the gas clouds motion $\bar{v}$ can be determined from the Doppler line widths. Then the BH mass is $M = \eta\,\bar{v}^2 r/G = 10^7 - 10^8\,M_\odot$, where the parameter $\eta = 1 - 3$ takes into account the character of motion of gas clouds around the BH ($\eta = 1$ for circular motions).

High angular resolution observations of the central regions (nuclei) of many galaxies (M87, NGC4621, NGC7052, etc.) made with the Hubble Space Telescope allowed measurements of the rotational velocity distribution of the central gas structures and mass determination of the underlying BH: $M = 10^8 - 10^9\, M_\odot$.

Very-long-baseline interferometric observations (VLBI) of maser sources in near-nuclear regions permitted reliable BH-mass determinations in the case of NGC4258 ($M = 3.9 \times 10^7\, M_\odot$) and in five other galaxies.

Measurements of the velocities and accelerations of individual stars near the center of our Galaxy allowed their orbits to be determined at distances $r < 0.005$ pc ($\cong 10^4 r_g$) from the central BH. Its mass, as derived from the distribution of individual star velocities in our Galaxy, is $2.6 \times 10^6\, M_\odot$. An independent estimate, based on the accelerations of individual stars, yields a BH mass of $3 \times 10^6\, M_\odot$.

The X-ray luminosity of the Galactic center is very low ($L_x = 10^{37}$ erg s^{-1}) and is $\sim 10^{-8}$ of the critical Eddington luminosity. Using data for ~ 45 galaxies, a correlation has been found between the mass of the galactic bulge and that of the central BH: $M_{\rm BH} \cong (0.2\% - 0.5\%) M_{\rm bulge}$.

In two cases (our Galaxy and galaxy NGC4258), the observed matter density inside the measured nuclear region of the galaxy ($r < 0.005$ pc $\cong 1.5 \times 10^{16}$ cm $\cong 10^4 r_g$ for $M = 10^6\, M_\odot$) is $\rho > 10^{12} - 10^{13}\, M_\odot/\text{pc}^3 = 10^{-10} - 10^{-9}$ g cm^{-3} (in the solar neighborhood $\rho \approx 0.1\, M_\odot/\text{pc}^3$, in the most dense stellar clusters $\rho \sim 10^5\, M_\odot/\text{pc}^3$). At $\rho > 10^{12} - 10^{13}\, M_\odot/\text{pc}^3$, the characteristic time scale of evaporation of individual dark bodies is $T_{\rm dyn} < 10^8 - 10^7$ yr for galactic ages of $\sim 10^{10}$ yr. So massive dark bodies in the nuclei of our Galaxy and NGC4258 must be single compact objects.

The width and profile of the X-ray line FeXXV at 6.4 keV in the spectra of some galactic nuclei correspond to hot-gas ($T \cong 10^7$ K) velocities of $V_{\rm rot} = 100\,000$ km s^{-1} at distances of $r = (3-6) r_g$.

All these data strengthen our assurance of the existence of supermassive BH in galactic nuclei.

6. Prospects for finding sufficient criteria of BH existence

In future, the following experiments are envisaged which will provide sufficient criteria of BH existence.

(1) Space-based radio and X-ray interferometers with an angular resolution of $10^{-6} - 10^{-7}$ arcsec. These facilities will provide a possibility to directly observe processes near the event horizon, which has an angular size of $\sim 10^{-6}$ arcsec in nearby galactic nuclei.

(2) Gravitational wave bursts from binary BH mergings.

(3) Detection of a radio pulsar in a binary system with a BH (one pulsar in pair with a BH is expected per ~ 1000 single pulsars).

(4) Detailed studies of X-ray line profiles and rapid variability of X-ray fluxes from accreting BHs.

(5) Studying the gravitational microlensing of galactic nuclei by stars in intervening galaxies — gravitational lenses (angular resolution of up to 10^{-6} arcsec).

(6) Routine accumulation of reliable mass estimations of BH candidates and statistical comparisons of the observed NS and BH properties.

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Superfluidity in neutron stars

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1. Introduction

Neutron stars (NSs) are the most compact of all stars. Their masses are around $1.4\, M_\odot$, where $M_\odot$ is the solar mass, and their radii are about 10 km. Accordingly, the mean density of the NS matter is a few times ρ_0, where $\rho_0 = 2.8 \times 10^{14}$ g cm^{-3} is the density of the matter in atomic nuclei. Atomic nuclei are almost incompressible in laboratory conditions. NSs are often called natural laboratories of supranuclear-density matter.

According to current views [1], a NS consists of four main layers. The outer layer, which extends to a density of 4×10^{11} g cm^{-3}, is *the outer crust*, which consists of degenerate electrons (e) and ions (nuclei). Deeper, to $\sim 0.5\,\rho_0$, there is the *inner crust*, composed of nuclei, electrons, and free neutrons (n). Further, to $\sim 2\rho_0$, there is the *outer core* containing a Fermi liquid of neutrons with a small admixture of degenerate electrons and protons (p) and, possibly, muons. Finally, the NS central region constitutes the *inner core*, whose composition is largely unknown. A reliable theory of the superdense NS matter is still absent. The main difficulty is in the description of strong interactions of various particles accounting for many-body effects. Instead of a strict theory, there are many different theoretical models. Some models predict the appearance of hyperons in the NS cores, while others predict either pion or kaon condensation or the appearance of light, almost free quarks (u, d, and s). One cannot exclude mixtures of different phases, for instance, hyperons and quarks. Some models give a fairly stiff equation of state and, therefore, rather high maximum allowed masses of NSs, $(2-3)\, M_\odot$. According to other theories, the equation of state is moderate or soft, and the maximum masses are lower, $(1.5-2)\, M_\odot$. The nature of matter in the NS cores is the main mystery of NSs. Its solution would be of fundamental importance for physics and astrophysics.

Let us mention a hypothesis of Witten [2], according to which a plasma of almost free quarks is the most stable state of matter not only at high pressures but also at zero pressure. If so, instead of NSs, so-called *strange stars* should exist, almost fully composed of quark matter of density $\gtrsim \rho_0$.

NSs are observed in all ranges of the electromagnetic spectrum, from radio to hard gamma rays. They may be either isolated objects or components of binary systems. They manifest themselves as radio and X-ray pulsars, X-ray bursters, X-ray transients, soft-gamma repeaters, or anomalous X-ray pulsars. The birth of NSs in supernova explosions leads to powerful neutrino outbursts. NSs may be powerful sources of gravitational radiation.

2. Superfluid gaps

One of the main features of NSs is *superfluidity* of the baryon component of their matter. It is believed that superfluidity is produced by Cooper pairing of baryons with opposite momenta under the action of the attractive part of the strong interaction of particles. Superfluidity is switched on as the temperature T falls below a critical temperature, T_c, leading to the appearance of a gap Δ in the baryon dispersion relation near the Fermi level. The gap