THE INTERIOR OF BLACK HOLES AND THEIR ASTROPHYSICS

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Abstract.

Gravity warps space and time into a funnel and generates a black hole when a cosmic body undergoes a catastrophic collapse. What can one say about the interior of a black hole? The important point is that inside a black hole the space radial direction becomes time, and time becomes a space direction. The path into the gravitational abyss of the interior of a black hole is a progression in time. There is a peculiar region inside a black hole where some characteristics of the space-time curvature become singular. We call this region singularity. The colossal tidal gravitational forces near singularity modify physical laws. Space and time are not only strongly curved near the singularity, but they split into quanta. The fall into the singularity is unstoppable for a body inside a black hole. This paper also addresses the following questions:

- Can one see what happens inside a black hole?
- Can a falling observer cross the singularity without being crushed?
- Can new baby universes arise inside a black hole?

An answer to all these questions is probably “yes”. We give also a brief review of the modern black hole astrophysics.
1. Introduction

A black hole is perhaps the most fantastic of all conceptions of the human mind. Black holes are neither bodies nor radiation. They are clots of gravity. The study of black hole physics extends our knowledge of the fundamental properties of space and time. Quantum processes occur in the neighborhood of black holes, so that the most intricate structure of the physical vacuum is revealed. Even more powerful (catastrophically powerful) quantum processes take place inside black holes (in the vicinity of the singularity). One can say that black holes are a door to a new, very wide field of study of the physical world. But probably the problems of the internal structure of black holes are a real great challenge.

Inside a black hole the main sights are the singularity.

In this paper we want to outline the recent achievements in our understanding of the nature of the singularity (and beyond) inside a realistic, rotating black hole.

We give also a brief review of some problems of astrophysics of black holes.

For systematic discussion of the problems of the internal structure of black holes see [1-4]. Discussion of the problems of astrophysics of black holes see in [5-10].

2. Interior of Black Holes

The problem of black holes interior was the subject of a very active investigation last decades. There is a great progress in these researches. We know some important properties of the realistic black hole’s interior, but some details and crucial problems are still the subject of much debate.

A very important point for understanding the problem of black hole’s interior is the fact that the path into the gravitational abyss of the interior of a black hole is a progression in time. We recall that inside a spherical hole, for example, the radial coordinate is timelike. It means that the problem of the black hole interior is an evolutionary problem. In this sense it is completely different from a problem of an internal structure of other celestial bodies, stars for example, or planets.

In principle, if we know the conditions on the border of a black hole (on the event horizon), we can integrate the Einstein equations in time and learn the structure of the progressively deeper layers inside the black hole. Conceptually it looks simple, but there are two types of principal difficulties which prevent realizing this idea consistently.

The first difficulty is the following. The internal structure of a generic rotating black hole even soon after its formation depends crucially on the conditions on the event horizon at very distant future of the external ob-
server (formally at the infinite future). This happens because the light-like signal can propagate from the very distant future to those regions inside a black hole which are deep enough in the hole. The limiting light-like signals which propagate from (formally) infinite future of the external observer form a border inside a black hole which is called a Cauchy horizon.

Thus, the structure of the regions inside a black hole depends crucially on the fate of the black hole at infinite future of an external observer. For example, it depends on the final state of the black hole quantum evaporation (because of the Hawking radiation), on possible collisions of the black hole with other black holes, or another bodies, and it depends on the fate of the Universe itself. It is clear that theoreticians feel themselves uncomfortable under such circumstances.

The second serious problem is related to the existence of a singularity inside a black hole. A number of rigorous theorems (see references in [1]) imply that singularities in the structure of spacetime develop inside black holes. Unfortunately these theorems tell us practically nothing about the locations and the nature of the singularities. It is widely believed today that in the singularity inside a realistic black hole the characteristics of the curvature of the spacetime tends to infinity. Close to the singularity, where the curvature of the spacetime approaches the Plank value, the Classical General Relativity is not applicable. We have no a final version of the quantum theory of gravity yet, thus any extension of the discussion of physics in this region would be highly speculative. Fortunately, as we shall see, these singular regions are deep enough in the black hole interior and they are in the future with respect to overlying and preceding layers of the black hole where curvatures are not so high and which can be described by well-established theory.

The first attempts to investigate the interior of a Schwarzschild black hole have been made in the late 70's. It has been demonstrated that in the absence of external perturbations, those regions of the black hole interior which are located long after the black hole formation are virtually free of perturbations, and therefore it can be described by the Schwarzschild geometry for the region with radius less than the gravitational radius. This happens because the gravitational radiation from aspherical initial excitations becomes infinitely diluted as it reaches these regions. But this result is not valid in general case when the angular momentum or the electric charge does not vanish. The reason for that is related to the fact that the topology of the interior of a rotating or/and charged black hole differs drastically from the Schwarzschild one. The key point is that the interior of this black hole possesses a Cauchy horizon. This is a surface of infinite blueshift. Infalling gravitational radiation propagates inside the black hole along paths approaching the generators of the Cauchy horizon, and the energy density
of this radiation will suffer an infinite blueshift as it approaches the Cauchy horizon.

In general the evolution with time into the black hole deeps looks like the following. There is a weak flux of gravitational radiation into a black hole through the horizon because of small perturbations outside of it. When this radiation approaches the Cauchy horizon it suffers an infinite blueshift. The infinitely blueshift radiation together with the radiation scattered by the curvature of spacetime inside the black hole results in a tremendous growth of the black hole internal mass parameter (“mass inflation”, after Poisson and Israel [11]) and finally leads to formation of the curvature singularity of the spacetime along the Cauchy horizon. The infinite tidal gravitational forces arise here. This result was confirmed by considering different models of the ingoing and outgoing fluxes in the interior of charged and rotating black holes. It was shown that the singularity at the Cauchy horizon is quite weak. In particular, the integral of the tidal force in the freely falling reference frame over the proper time remains finite. It means that the infalling object would then experience the finite tidal deformations which (for typical parameters) are even negligible. While an infinite force is extended, it acts only for a very short time. This singularity exists in a black hole at late times from the point of view of an external observer, but the singularity which arises just after the gravitational collapse of a star is much stronger. It seems likely that an observer falling into a black hole with the collapsing star encounters a crushing singularity, but an observer falling in a late times generally reaches a weak singularity.

3. Quantum effects

As we mentioned in Section 2 quantum effects play crucial role in the very vicinity of the singularity. In addition to that the quantum processes probably are important also for the whole structure of a black hole. Indeed, in the previous discussion we emphasized that the internal structure of black holes is a problem of evolution in time starting from boundary conditions on the event horizon for all moments of time up to the infinite future of the external observer.

It is very important to know the boundary conditions up to infinity because we observed that the essential events - mass inflation and singularity formation - happened along the Cauchy horizon which brought information from the infinite future of the external spacetime. However, even an isolated black hole in an asymptotically flat spacetime cannot exist forever. It will evaporate by emitting Hawking quantum radiation. So far we discussed the problem without taking into account this ultimate fate of black holes. Even without going into details it is clear that quantum evaporation of the black
holes is crucial for the whole problem.

What can we say about the general picture of the black hole’s interior accounting for quantum evaporation? To account for the latter process we have to change the boundary conditions on the event horizon as compared to the boundary conditions discussed above. Now they should include the flux of negative energy across the horizon, which is related to the quantum evaporation. The last stage of quantum evaporation, when the mass of the black hole becomes comparable to the Plank mass $m_{Pl} = (\hbar c/G)^{1/2} \approx 2.2 \times 10^{-5} g$, is unknown. At this stage the spacetime curvature near the horizon reaches $l^{-2}_{Pl}$, where $l_{Pl}$ is the Plank length:

$$l_{Pl} = \left( \frac{\hbar c}{G} \right)^{1/2} \approx 1.6 \times 10^{-33} cm.$$

This means that from the point of view of semiclassical physics a singularity arises here. Probably at this stage the black hole has the characteristics of an extreme black hole, when the external event horizon and internal Cauchy horizon coincide.

As for the processes inside a true singularity in the black hole’s interior, they can be treated only in the framework of an unified quantum theory incorporating gravitation, which is unknown.

4. Baby Universes inside a Black Hole?

How the effects of quantum gravity could modify the structure of the spacetime singularity inside the black hole. To analyze this, let us consider a black hole which arises as a result of a spherically symmetric gravitational collapse. We know that the spacetime inside the black hole outside the collapsing matter can be described as an evolution of anisotropic homogeneous three-dimensional space. This metric has the Kasner-type asymptotic behavior near the singularity: the contraction of space in two directions is accompanied by expansion in the third direction. The curvature invariant $R^2 = R_{\alpha\beta\gamma\delta}R^{\alpha\beta\gamma\delta}$ grows as $R^2 = 48M^2/r^6$, (we use units $c = 1, G = 1$).

Such behavior is a consequence of the classical equations which are valid until the spacetime curvature becomes comparable to the Plank one. Particle creation and vacuum polarization may change this regime. Quite general arguments allow one to suggest that the quantum effects may result in a decrease of the spacetime anisotropy, see references in [1]. Unfortunately, one cannot prove this result rigorously without knowing the physics at Plank scales.

Under these circumstances it is natural to use the following approach. One might assume that the notion of quantum average of a metric $g = \langle \hat{g} \rangle$ is still valid in the regions under consideration, and the average metric $\bar{g}$ obeys some effective equations. We do not know these equations at the moment, but we might assume that these equations and their solutions obey
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some general properties and restrictions. For example, it is natural to require that the effective equations for $g$ in the low curvature limit reduce to the Einstein equations with possible higher-curvature corrections. It is also possible to assume that the future theory of quantum gravity would solve the problems of singularities of classical general relativity. One of the possibilities is that the equations of the complete theory would simply not allow dynamically infinite growth of the curvature, so that the effective curvature $R$ of $g$ is bounded by the value of order $1/l^2$. This limiting curvature principle was proposed by Markov [12], [13]. This principle excludes curvature singularity formation, so that the global properties of the solutions must change.

In the application to the problem of black hole interior the limiting curvature principle means that the singularity which, according to the classical theory exists inside a black hole, must be removed in the complete quantum theory. We cannot hope to derive this result without knowledge of the theory, but we may at least discuss and classify possibilities. Such approach is a natural first step, and it was used in a number of publications. We discuss here a singularity-free model of a black hole interior proposed by Frolov, Markov, and Mukhanov [14, 15]. According to this FMM-model, inside a black hole there exists a closed Universe instead of a singularity. It is assumed that the transition between Schwarzschild and de Sitter regimes is so fast that the transition region can be approximated by a thin spacelike shell. The presented model can be considered as “the creation of a universe in the laboratory”. One of the assumptions of FMM and other similar models is that a “phase transition” to the de Sitter-like phase takes place at a homogeneous spacelike surface $r = r_0$. The presence of perturbations and quantum fluctuations, growing as $r \to 0$, could spoil the homogeneity. The bubbles of the new de Sitter-like phase could be formed independently at point separated by spacelike distances. For these reasons, one could expect that different parts of a black hole interior, can create spatially disconnected worlds.

5. Can one see what happens inside a Black Hole?

Is it possible for a distant observer to receive information about the interior of a black hole? Strictly speaking, this is forbidden by the very definition of a black hole. What we have in mind in asking this question is the following. Suppose there exists a stationary or static black hole. Can we, by using some device, get information about the region lying inside the apparent horizon?

Certainly it is possible if one is allowed to violate the weak energy condition. For example, if one sends into a black hole some amount of
"matter" of negative mass, the surface of black hole shrinks, and some of the rays which previously were trapped inside the black hole would be able to leave it. If the decrease of the black hole mass during this process is small, then only a very narrow region lying directly inside the horizon of the former black hole becomes visible.

In order to be able to get information from regions not close the apparent horizon but deep inside an original black hole, one needs to change drastically the parameters of the black hole or even completely destroy it. A formal solution corresponding to such a destruction can be obtained if one considers a spherically symmetric collapse of negative mass into a black hole. The black hole destruction occurs when the negative mass of the collapsing matter becomes equal to the original mass of the black hole. In such a case an external observer can see some region close to the singularity. But even in this case the four-dimensional region of the black hole interior which becomes visible has a four-dimensional spacetime volume of order $M^4$. It is much smaller than four-volume of the black hole interior, which remains invisible and which is of order $M^3T$, where $T$ is the time interval between the black hole formation and its destruction (we assume $T \gg M$). The price paid for the possibility of seeing even this small part of the depths of the black hole is its complete destruction.

Does this mean that it is impossible to see what happens inside the apparent horizon without a destructive intervention? We show that such a possibility exists (Frolov and Novikov [16, 17]). In particular, we discuss a gedanken experiment which demonstrates that traversable wormholes (if only they exist) can be used to get information from the interior of a black hole practically without changing its gravitational field. Namely, we assume that there exist a traversable wormhole, and its mouths are freely falling into a black hole. If one of the mouths crosses the gravitational radius earlier than the other, then rays passing through the first mouth can escape from the region lying inside the gravitational radius. Such rays would go through the wormhole and enter the outside region through the second mouth, see details in [1].

6. Astrophysics of Black Holes

The observational evidence at present is that black holes do exist in the Universe. Thus the singularities of spacetime which we discussed in the previous sections are real things.

A review of the black holes astrophysics we gave in [8]. Here we will give some additional remarks.

First of all we remind that modern astrophysics deals with two types of black holes in the universe.
(1) **Stellar black holes**, i.e. black holes of stellar masses that were born when massive stars died.

(2) **Supermassive black holes** with masses up to $10^9 M_\odot$ and very recently (September 2002) some information appeared about possible discovery of the black holes of intermediate masses: $(4 \times 10^3 - 2 \times 10^4)$ solar masses in global cluster.

We start from the remarks concerning stellar black holes.

As we described in [8] very massive stars at the very end of their evolution probably turn into black holes. The evolution of stars in close binary systems differs from the evolution of solitary stars because of mass transfer from one star to another. The conclusions about masses of black hole progenitor in this case could be essentially different. In particular, a black hole can be produced in the binary where originally, besides a normal star, there was a neutron star. A black hole can be formed as a result of the flux of matter from the star companion onto the neutron star, which finally makes the mass of the latter greater than the neutron mass limit (which is probably $M_\odot \approx 3 M_\odot$).

Nowadays it is believed that Wolf-Rayet (WR) binaries may be progenitors of the binary systems with relativistic objects (neutron stars and black holes).

Wolf-Rayet stars are believed to be hot massive stars that are close to the end of their nuclear burning phase. Formation of neutron stars and black holes in close binary systems is going through the WR stage of initially more massive stars in the binary systems.

Recently Cherepashchuk [6] has analyzed the observed properties of Wolf-Rayet stars and relativistic objects in close binary systems. He calculated the final masses $M_{CO}^f$ for the carbon-oxygen cores of WR + O binaries taking into account the radial loss of matter via stellar wind, which depends on the mass of star. The analysis includes new data on the clumpy structure of WR winds, which appreciably decreases the required mass-loss rates $\dot{M}_{WR}$ for the WR stars, (see Fig.1, top and bottom panels). The masses $M_{CO}^f$ lie in the range $(1 - 2)M_\odot - (20 - 44)M_\odot$ and have a continuous distribution. The masses of the relativistic objects $M_x$ are $1 - 20 M_\odot$ and have a bimodal distribution: the mean masses for neutron stars and black holes are $1.35 \pm 0.15 M_\odot$ and $8 - 10 M_\odot$ respectively, with a gap from $2 - 4 M_\odot$ in which no neutron stars and black holes are observed in close binaries, (see Fig.1, middle panel). The mean final CO-core mass is $\overline{M}_{CO}^f = 7.4 - 10.3 M_\odot$, close to the mean mass for the black holes. This suggests that it is not only the mass of the progenitor that determines the nature of the relativistic object, but other parameters as well - rotation, magnetic field, etc.

Now some remarks concerning supermassive black holes.

At the beginning we will remind some facts.
About one percent of all galactic nuclei eject radio-emitting plasma and gas clouds, and are themselves powerful sources of radiation in the radio, infrared, and especially, the “hard” (soft wavelength) ultraviolet, X-ray and gamma regions of the spectrum. The full luminosity of the nucleus reaches in some cases $L \approx 10^{47}$ erg/s. This is millions of times greater than the luminosity of the nuclei of more quite galaxies, such as ours. These objects were called active galactic nuclei (AGN). Practically all the energy of activity and of the giant jets released by galaxies originates from the centers of their nuclei.

Quasars form a special subclass of AGN. Their characteristic property is that their total energy release is hundreds of times greater than the combined radiation of all the stars in a large galaxy. At the same time the average linear dimensions of the radiating regions are small: a mere one-hundred-millionth of the linear size of a galaxy. Quasars are the most powerful energy sources registered in the Universe to date. What processes are responsible for the extraordinary outbursts of energy from AGN and quasars?

At the beginning of 1980s a paradigm was established in which AGN are powered by black holes accreting gas stars [18].

Clearly, the processes taking place in quasars and other galactic nuclei are still a mystery in many respects. But the suggestion that we are witnessing the work of a supermassive black hole with an accretion disk seems rather plausible. Rees (1990) advocates a hypothesis that the massive black holes are not only in the active galactic nuclei but, also in the centers of “normal” galaxies (including nearby galaxies and our own Milky Way). They are quiescent because they now starved of fuel (gas). Observations show that galactic nuclei were more active in the past. Thus, “dead quasars” (massive black holes without fuel) should be common at the present epoch.

How can this black holes be detected? It has been pointed out that holes produce cusp-like gravitational potentials and hence they should produce cuspy-like density distributions of the stars in the central regions of galaxies. Some authors have argued that the brightness profiles of the central regions of particular galaxies imply that they contain black holes. However the arguments based only on surface brightness profiles are inconclusive. The point is that a high central number density of stars in a core with small radius can be the consequence of dissipation, and a cusp-like profile can be the result of anisotropy of the velocity dispersion of stars. Thus these properties taken alone are not sufficient evidence for the presence of a black hole.

The reliable way to detect black holes in the galactic nuclei is analogous to the case of black holes in binaries. Namely, one must prove that there is a large dark mass in a small volume, and that it can be nothing but a
Figure 1. Distribution of the final masses $M_{CO}$ for two different versions of the theory (see details in [6]), top and bottom panels; and distribution of the masses of the relativistic objects $M_x$, middle panel. According to [6].

black hole. In order to obtain such a proof we can use arguments based on both stellar kinematics and surface photometry of the galactic nuclei.

If the distribution of the mass $M$ and the luminosity $L$ as functions of the radius are known we can determine the mass-to-light ratio $M/L$ (in solar units) as a function of radius. This ratio is well known for different types of stellar populations. As a rule this ratio is between 1 and 10 for elliptical galaxies and globular cluster (old stellar population dominates there). If for some galaxy the ratio $M/L$ is almost constant at rather large radii (and has a “normal” value between 1 and 10) but rises rapidly toward
values much larger than 10 as one approaches the galactic center, then this is the evidence for a central dark object (probably a black hole).

The technique described above has been used to search for black holes in galactic nuclei. Another possibility is to observe rotational velocities of gas in the vicinity of the galactic center.

The modern search techniques and results for the ground-based detections see in [19] and [20].

Here we discuss the results from Hubble Space Telescope (Kormendy and Gebhardt [7]). According to [7], dynamical black hole (BH) detections are available for at least 37 galaxies (see Table 1). Their conclusions are the following.

(1) BH mass correlates with the luminosity of the bulge component of the host galaxy, albeit with considerable scatter. The median BH mass fraction is 0.13% of the mass of the bulge.

(2) BH mass correlates with the mean velocity dispersion of the bulge inside its effective radius, i.e., with how strongly the bulge stars are gravitationally bound to each other. For the best mass determinations, the scatter is consistent with the measurement errors.

(3) BH mass correlates with luminosity of the high-density central component in disk galaxies independent of whether this is a real bulge (a mini-elliptical, believed to form via a merger-induced dissipative collapse and starburst) or a “pseudobulge” (believed to form by inward transport of disk material).

(4) BH mass does not correlate with the luminosity of galaxy disks. If pure disks contain BHs (and active nuclei imply that some do), then their masses are much smaller than 0.13% of the mass of the disk.

We conclude that present observations show no dependence of BH mass on the details of whether BH feeding happens rapidly during a collapse or slowly via secular evolution of the disk. The above results increasingly support the hypothesis that the major events that form a bulge or elliptical galaxy and the main growth phases of its BH - when it shone like a quasar - were the same events.

In the future we expect the most fundamental progress in the work on the black holes astrophysics from gravitational wave astronomy.

7. Probing black holes with gravitational waves

Observations of stellar and massive black holes in optics and X-and γ-rays do not provide us with direct information about spacetime regions close to a black hole, since the radiation is generated in regions far from horizon. To explore the region close to the horizon in detail may well require using a new information channel in astrophysics - gravitational waves. With the
construction of new gravitational wave observatories this option becomes very important.

Among the most promising sources of gravitational waves which can be observed by the gravity wave detectors are astrophysical compact binaries. Three types of compact binaries are mainly discussed: neutron star - neutron star (NS/NS) binaries, neutron star - black hole (NS/BH) binaries, and black hole - black hole (BH/BH) binaries. Because of the emission of gravitational waves at some stage of their evolution, compact binaries enter the inspiral phase which ends with a coalescence. During these final stages of the binary system evolution they emit powerful gravitational waves.

An international network of ground-based gravitational wave detectors is now under construction. It includes two detectors of the American Laser Interferometer Gravitational-wave Observatory (LIGO) [21], the French/Italian 3-kilometer-long arms interferometer VIRGO near Pisa (Italy) [22], and the British/German 600-meter interferometer GEO-600 near Hannover (Germany) [23].

The LIGO detector, which is now under construction, consists of two vacuum facilities with two 4-km-long orthogonal arms. One of these detectors is in Hanford (state Washington) and the other in Livingston (state Louisiana). Their coincident operation will start in 2002. Gravitational waves coming from far-distant sources effectively change the relative length of the arms, which can be measured by the phase shift between two lasers beams in the two orthogonal arms. With expected accuracies of the arm-length difference $\Delta L \sim 10^{-16}$ cm, the expected sensitivity of the detector would be $\Delta L/l \sim 10^{-21} - 10^{-22}$. This sensitivity will be achieved in LIGO within the frequency range from 40 to 120 Hz. The efficiency of LIGO is effectively reduced by photon counting statistic (‘shot noise’) at higher frequency and by seismic noise at lower frequency. The LIGO facilities are designed to house many successive generations of upgraded interferometers. The second generation, LIGO II, is planned to start to be designed in 2005, and to be observing before 2007. Working in the same frequency range, it will have an approximately two orders of magnitude higher sensitivity. Table 2 gives the limiting distances up to which the LIGO detectors would be able to observe different types of binaries.

Black hole binary evolution and its emitted gravitational waveforms can be divided into the following three stages: inspiral, coalescence, and ringdown. The inspiral epoch for a BH/BH binary requires post-Newtonian expansions for its understanding and is qualitatively the same as for other compact binaries. Gravitational radiation during coalescence and ringdown epochs contains information which allows the BH/BH case to be singled out. Supercomputer simulations are required to determine the dynamics of two merging black holes and to produce templates which can be used to
decode the information encoded in emitted gravitational waves. The ring-
down epoch is much better understood. At this stage, two initial black holes
form a new final one, which is in a very excited state. Its further evolution
involves a decay of these excitations. These excitations are a nonlinear su-
perposition of quasi-normal modes. The decay of the quasi-normal modes
produces a characteristic ‘ringing’ in the gravitational waveforms.

Gravitational waves emitted at the stages of BH/BH coalescence and
ringdown carry information about the highly nonlinear, large-amplitude dy-
namics of spacetime curvature, and for this reason the study of these signals
tests Einstein gravitational equations in their full complexity. Table 3 gives
an estimate of the amplitude signal-to-noise (S/N) ratio for coalescences at
a 1000-Mpc distance for two black holes of equal mass.

The time- and length-scales for double black-hole dynamics (including
the gravitational radiation from such systems) are proportional to the to-
tal mass. Other parameters (such as the black hole mass ratio, black hole
angular momentum and so on) enter through dimensionless combinations.
The total number of cycles spent in the LIGO/VIRGO band for a BH/BH
of $10 M_{\odot}$ is about 600. These detectors will be able to detect and study
gravitational waves emitted during last few minutes of their evolution for
black hole binaries with a total mass of up to $10^3 M_{\odot}$. For larger masses, a
gravitational wave detector must have a much lower frequency band. Fu-
ture space-based gravitational wave interferometers will work in this band.
LISA is an example of such a project.

The Laser Interferometer Space Antenna (LISA) consists of 3 spacecraft
flying $5 \times 10^6$ km apart in the shape of an equilateral triangle. The center
of the triangle will be at the ecliptic plane at the same distance from the Sun
as the Earth and $20^\circ$ behind the Earth on the orbit. The three spacecraft
will act as a giant interferometer measuring distortions in space caused by
gravitational waves. This project was proposed in 1993 by the United States
and European scientists as a joint NASA/ESA (National Aeronautics and
Space Administration/European Space Agency) mission. If approved, the
project will start in 2005 with a launch planned around 2010 [24].

The frequency band of LISA covers $10^{-4} - 1Hz$, that is 10,000 times
lower than the frequency band of LIGO/VIRGO. Its sensitivity in this
frequency band will be at the level of $10^{-23}$. LISA will be able to register
gravitational waves emitted by BH/BH binaries for a total mass in the
range $10^3 M_{\odot} - 10^8 M_{\odot}$ (massive and supermassive black holes), away from
each other by a distance corresponding to redshifts of $z \sim 3000$. Since it
is very unlikely that massive and supermassive black holes form so early
(until they are primordial), this means that LISA will be able to observe
practically all coalescing black hole binaries in the visible universe within
this range of mass.
For a discussion of gravitational-wave radiation from colliding black holes it is very important to know how many BH/BH binaries exist in the universe. Unfortunately, this is not known. The scatter between the most optimistic and most pessimistic estimates is quite wide. However, for BH/BH binaries with a total mass of $5 - 50 M_\odot$ that are created from main-sequence progenitors, one can expect a coalescence rate in our Galaxy of 1 per 1-30 million years [25-27]. If these estimates are correct, LIGO/VIRGO will see one coalescence per year for such binaries up to the distance of 300-900 Mpc. The event rate for supermassive black hole coalescences is much more uncertain - from 0.1 to 1000 per year. But even for the pessimistic rate value, LISA will be able to observe 3 BH/BH binaries with a total mass of $3,000 - 10^5 M_\odot$ that are 30 years away from their final coalescence [27,28]. For all details see [29].

To summarize, there is a good chance that in the near future gravitational waves from coalescing black holes will be observed and, hence, for the first time we shall be able to probe almost directly our theoretical predictions concerning black holes.

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TABLE 1. Census of Supermassive Black Holes (2001 March), according to [7].

| Galaxy       | Type | $M_{B,\text{bulge}}$ | $M_{BH}(M_{\text{low}}, M_{\text{high}})$ | $\sigma_e$ | D   | $r_{cusp}$ |
|--------------|------|-----------------|---------------------------------|----------|------|--------------|
|              |      | $M_\odot$       | $\text{km/sec}$ | Mpc       | arcsec |              |
| Galaxy Sbc  | -17.65 | 2.6 (2.4 - 2.8) e6 | 75 | 0.008 | 51.40 |
| M31 Sb      | -19.00 | 4.5 (2.0 - 8.5) e7 | 160 | 0.76  | 2.06  |
| M32 E2      | -15.83 | 3.9 (3.1 - 4.7) e6 | 75 | 0.81  | 0.76  |
| M81 Sb      | -18.16 | 6.8 (5.5 - 7.5) e7 | 143 | 3.9   | 0.76  |
| NGC 821 E4  | -20.41 | 3.9 (2.4 - 5.6) e7 | 209 | 24.1  | 0.03  |
| NGC 1023 S0 | -18.40 | 4.4 (3.8 - 5.0) e7 | 205 | 11.4  | 0.08  |
| NGC 2778 E2 | -18.59 | 1.3 (0.5 - 2.9) e7 | 175 | 22.9  | 0.02  |
| NGC 3115 S0 | -20.21 | 1.0 (0.4 - 2.0) e9 | 230 | 9.7   | 1.73  |
| NGC 3377 E5 | -19.05 | 1.1 (0.6 - 2.5) e8 | 145 | 11.2  | 0.42  |
| NGC 3379 E1 | -19.94 | 1.0 (0.5 - 1.6) e8 | 206 | 10.6  | 0.20  |
| NGC 3384 S0 | -18.99 | 1.4 (1.0 - 1.9) e7 | 143 | 11.6  | 0.05  |
| NGC 3608 E2 | -19.86 | 1.1 (0.8 - 2.5) e8 | 182 | 23.0  | 0.13  |
| NGC 4291 E2 | -19.63 | 1.9 (0.8 - 3.2) e8 | 242 | 26.2  | 0.11  |
| NGC 4342 S0 | -17.04 | 3.0 (2.0 - 4.7) e8 | 225 | 15.3  | 0.34  |
| NGC 4473 E5 | -19.89 | 0.8 (0.4 - 1.8) e8 | 190 | 15.7  | 0.13  |
| NGC 4486B E1 | -16.77 | 5.0 (0.2 - 9.9) e8 | 185 | 16.1  | 0.81  |
| NGC 4564 E3 | -18.92 | 5.7 (4.0 - 7.0) e7 | 162 | 15.0  | 0.13  |
| NGC 4594 Sa | -21.35 | 1.0 (0.3 - 2.0) e9 | 240 | 9.8   | 1.58  |
| NGC 4649 E1 | -21.30 | 2.0 (1.0 - 2.5) e9 | 375 | 16.8  | 0.75  |
| NGC 4697 E4 | -20.24 | 1.7 (1.4 - 1.9) e8 | 177 | 11.7  | 0.41  |
| NGC 4742 E4 | -18.94 | 1.4 (0.9 - 1.8) e7 | 90  | 15.5  | 0.10  |
| NGC 5845 E  | -18.72 | 2.9 (0.2 - 4.6) e8 | 234 | 25.9  | 0.18  |
| NGC 7457 S0 | -17.69 | 3.6 (2.5 - 4.5) e6 | 67  | 13.2  | 0.05  |
| NGC 2787 SB0 | -17.28 | 4.1 (3.6 - 4.5) e7 | 185 | 7.5   | 0.14  |
| NGC 3245 S0 | -19.65 | 2.1 (1.6 - 2.6) e8 | 205 | 20.9  | 0.21  |
| NGC 4261 E2 | -21.09 | 5.2 (4.1 - 6.2) e8 | 315 | 31.6  | 0.15  |
| NGC 4374 E1 | -21.36 | 4.3 (2.6 - 7.5) e8 | 296 | 18.4  | 0.24  |
| NGC 4459 SA0 | -19.15 | 7.0 (5.7 - 8.3) e7 | 167 | 16.1  | 0.14  |
| M87 E0      | -21.53 | 3.0 (2.0 - 4.0) e9 | 375 | 16.1  | 1.18  |
| NGC 4596 SB0 | -19.48 | 0.8 (0.5 - 1.2) e8 | 136 | 16.8  | 0.22  |
| NGC 5128 S0 | -20.80 | 2.4 (0.7 - 6.0) e8 | 150 | 4.2   | 2.26  |
| NGC 6251 E2 | -21.81 | 6.0 (2.0 - 8.0) e8 | 290 | 106   | 0.06  |
| NGC 7052 E4 | -21.31 | 3.3 (2.0 - 5.6) e8 | 266 | 58.7  | 0.07  |
| IC 1459 E3  | -21.39 | 2.0 (1.2 - 5.7) e8 | 323 | 29.2  | 0.06  |

Notes - BH detections are based on stellar dynamics (top group), ionized gas dynamics (middle) and maser dynamics (bottom). Column 3 is the B-band absolute magnitude of the bulge part of the galaxy. Column 4 is the BH mass $M_{BH}$ with error bars ($M_{\text{low}}, M_{\text{high}}$). Column 5 is the galaxy’s velocity dispersion (see Figure 1). Column 6 is the distance (Tonry et al. 2001). Column 7 is the radius of the sphere of influence of the BH.
TABLE 2. List of the sources detectable by LIGO I and LIGO II. Neutron stars are assumed to have mass $1.4M_\odot$, and black holes are assumed to have mass $10M_\odot$. Data from Ref.[21].

| Systems               | Distance for LIGO I | Distance for LIGO II |
|-----------------------|---------------------|----------------------|
| Inspiral NS/NS binaries | 20 Mpc              | 450 Mpc              |
| Inspiral NS/BH binaries | 40 Mpc              | 1000 Mpc             |
| Inspiral BH/BH binaries | 100 Mpc             | 2000 Mpc             |

TABLE 3. Amplitude signal-to-noise (S/N) ratio for coalescences at 1000-Mpc distance for two black holes of equal mass. Data from Ref. [21].

| BH/BH coalescences | S/N for LIGO I | S/N for LIGO II |
|--------------------|----------------|-----------------|
| $10M_\odot/10M_\odot$ | 0.5            | 10              |
| $25M_\odot/25M_\odot$ | 2              | 30              |
| $100M_\odot/100M_\odot$ | 4              | 90              |