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SEARCH FOR ISOLATED BLACK HOLES: PAST, PRESENT, FUTURE

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Abstract. The critical property of a black hole is the presence of an event horizon. It may be detected only by means of a detailed study of the emission features of its surroundings. The temporal resolution of such observations has to be comparable to r_g/c, which is in the 10^{-6}–10 s range, depending on the mass of the black hole. At SAO RAS we have developed the MANIA hardware and software complex, based on the panoramic photon counter, and we use it in observations on the 6 m telescope for searching and investigating the optical variability of various astronomical objects on time scales of 10^{-6}–10^{3} s. We present here the hardware and methods used for these photometric, spectroscopic and polarimetric observations, together with the principles and criteria for object selection. The list of objects includes objects with featureless optical spectra (DC white dwarfs, blazars) and long microlensing events.

Keywords: black holes, accretion, observations.

1. Accretion onto isolated stellar-mass black holes

Even though more than 60 years have passed since the theoretical prediction of black holes as astrophysical objects [1], in a certain sense they still have not been discovered.

The features of a black hole — the compactness (the size for mass M is close to the Schwarzschild radius $r_g = \frac{2GM}{c^2}$) and mass larger than $3M_\odot$ — are necessary but not sufficient features. The key property of a black hole is the presence of an event horizon instead of a usual surface. It is necessary to detect and study the emission generated very close to an event horizon to decide whether the horizon is present in a given compact and massive object.

This is a very complicated task that cannot be easily performed in X-ray binaries and AGNs due to the high accretion rate and, consequently, the high optical depth of the accreting gas. At the same time, single stellar-mass black holes which accrete an interstellar medium of low density (10^{-2}–1 cm^{-3}) are the ideal case for detecting and studying an event horizon [2].

The analysis of existing data on possible black hole masses and velocities in comparison with the interstellar medium structure shows that in the majority of cases in the Galaxy (> 90%) the dimensionless accretion rate $\dot{m} = \dot{M}c^2/L_{edd}$ can not exceed 10^{-6}–10^{-7} [3]. For typical interstellar medium inhomogeneity the captured specific angular momentum is smaller than that on the BH last stable orbit, and the accretion is always spherically-symmetric [4, 5]. The only possible exception is the case of a slowly-moving ($V < 10$ km/s) black hole in cold dense clouds of interstellar hydrogen ($n \sim 10^2$–10^5 cm^{-3}, $T \sim 10^2$ K), where the accretion may become disk-like and the accretion rate is high enough to provide luminosities up to 10^{38}–10^{40} erg/s.

The plasma in the accretion flow is collisionless all the way down to the event horizon, and the continuity of the flow is provided by the magnetic field. Correct treatment of adiabatic heating, the major accretion flow heating mechanism in spherically-symmetric accretion flow, shows that it is 25 % more efficient than the flow for ideal gas[3]. Due to it the plasma temperature in the accretion flow grows much faster and the electrons become relativistic earlier – the radius where electrons become relativistic $R_{rel} = r_{rel}/r_g \approx 6000$, in contrast to $R_{rel} \approx 1300$ in [6] and $R_{rel} \approx 200$ in [7]. The accretion flow is much hotter, and our estimation of "thermal" luminosity

$$L = \eta \dot{M} c^2 = 9.6 \cdot 10^{33} M_{10}^3 n_1^2 (V^2 + c_s^2)_{16}^{-3} \text{ erg/s} \quad (1)$$

is significantly higher than the estimates derived by Ipser & Price [7]

$$L_{\text{IP}} = 1.6 \cdot 10^{32} M_{10}^3 n_1^2 (V^2 + c_s^2)_{16}^{-3} \text{ erg/s} \quad (2)$$

and by Bisnovatyi-Kogan & Ruzmaikin [6]

$$L_{\text{BKR}} = 2 \cdot 10^{33} M_{10}^3 n_1^2 (V^2 + c_s^2)_{16}^{-3} \text{ erg/s}, \quad (3)$$

while the optical spectrum shape is nearly the same (see Fig. 1). The efficiency of accretion as a function of accretion rate is shown in Fig. 4.

Correct treatment of the magnetic field behaviour in accretion flow is an extremely complicated task (see, for example, [8] and references therein). The basis of our analysis is the assumption of energy equipartition in the accretion flow (Shvartsman's theorem, see [2]) which determines the radial dependencies of both infall velocity and magnetic field strength. A direct consequence of this assumption is the necessity of magnetic energy dissipation at the rate defined as the difference between the rates of magnetic energy

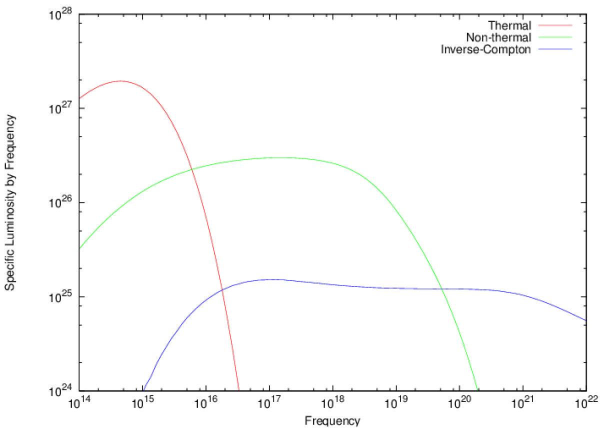

FIGURE 1. Decomposition of a single black hole (with the mass $10\,M_{\odot}$) emission spectrum into thermal and nonthermal parts. The accretion rate is $1.4 \cdot 10^{10}$ g/s, which corresponds to $\dot{m} = 10^{-8}$.

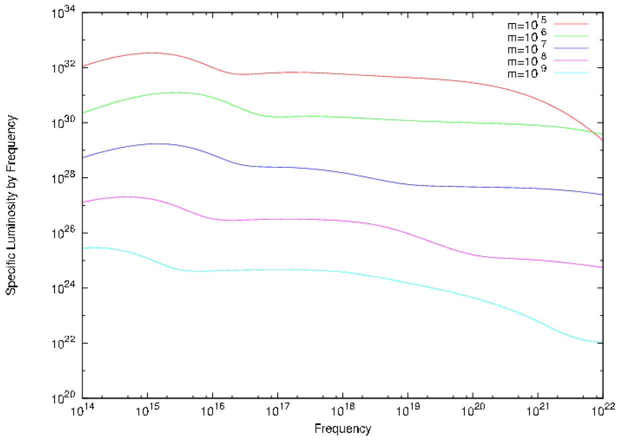

FIGURE 2. Spectra of the accretion flow onto the $10\,M_{\odot}$ black hole for the various accretion rates.

increase for a purely frozen-in magnetic field and the rate for equipartition [6].

In the accretion models proposed earlier this dissipation runs continuously[9] in the turbulent flow and its mechanism is not examined in detail. We considered conversion of the magnetic energy in the discrete turbulent current sheets [10] as a mechanism providing such dissipation, and studied the observational consequences of this process. These include the generation of various modes of plasma oscillations (ion-acoustic and Lengmur plasmons mostly) and the acceleration of electrons, which is very important for the observational appearances of the whole accretion flow. The beams of the accelerated electrons emit their energy due to the motion in the magnetic field and generate an additional nonthermal component in addition to synchrotron emission of thermal particles (see Figs. 1 and 2).

A large fraction of black hole emission is generated inside the $2r_g$ sphere, and so carries information about the physical conditions of space-time very close to the event horizon.

An important property of nonthermal emission is its flaring nature — the electron ejection process is discrete, and the typical light curve of a single beam is shown in Fig. 3. The light curve of each flare has a stage of fast intensity increase and a sharp cut-off, and its shape reflects the properties of the magnetic field and space-time near the horizon. A study of these flares in black hole emission therefore provides a way to probe extreme space-time regions directly very close to the horizon.

2. OBSERVATIONAL APPEARANCE OF AN ISOLATED BLACK HOLE

The black hole at a 100 pc distance (a sphere with this radius must contain several tens of such objects, see [11]) looks like a 15–25$^{\mathrm{m}}$ optical object (due to the "thermal" spectral component) with a strongly variable counterpart in high-energy spectral bands ("nonthermal" component) [3]. The hard emission consists of flares, the majority of which are generated inside a $5r_g$ distance from the BH. These events have durations of $\sim r_g/c$ ($\sim 10^{-4}$ s), a rate of 10^3–10^4 flares per second, and an amplitude of 2–6 %. The BH variable X-ray emission can be detected by modern space-borne telescopes.

The optical emission consists of a quasi-stationary "thermal" part and a low-frequency tail of nonthermal flaring emission. The rate and duration of optical flares are the same as X-ray flares, while their amplitudes are significantly smaller. Indeed, the contribution of the nonthermal component to the optical emission is approximately $2 \cdot 10^{-2}$ for $\dot{m} = 10^{-8}$–10^{-6}, so the mean amplitudes of optical flares are 0.04–0.12 %, while the peak amplitudes may be 1.5-2 times higher and may reach 0.2 %. Certainly, it is nearly impossible to detect such single flares, but their collective power reaches 18–24$^{\mathrm{m}}$ and may therefore be detected in observations with high time resolution ($< 10^{-4}$ s) by large optical telescopes[3].

Of course, the variability of the BH emission is related not only to the electron acceleration processes described here. Additional variability may be result from plasma oscillations from various kinds, or other types of instabilities. The time scale of such variability may be from r_g/c till r_c/c (where $r_c = \frac{2GM}{V^2+c_s^2}$ is the gas capture radius [12]), i.e., from microseconds till years.

3. THE SEARCH FOR ISOLATED STELLAR MASS BLACK HOLES IN THE OPTICAL BAND

The most striking property of the accretion flow onto a single black hole is its inhomogeneity — the clots of plasma act as probes testing the space-time properties near the horizon. The characteristic timescale of emission variability is $\tau_v \sim r_g/c \sim 10^{-4}$–$10^{-5}$ s and this short stochastic variability may be considered as a distinctive property of a black hole as the smallest

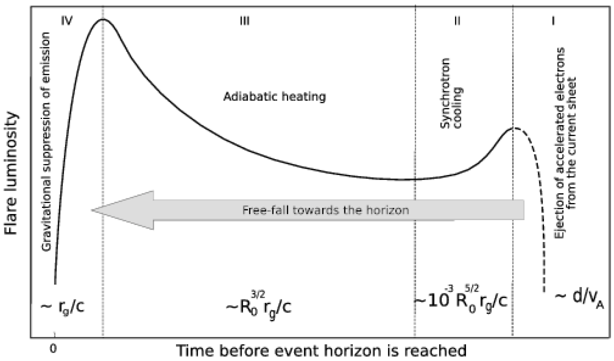

Figure 3. Internal structure of a flare as a reflection of the electron cloud evolution. The prevailing physical mechanisms defining the observed emission are denoted and typical durations of the stages are shown.

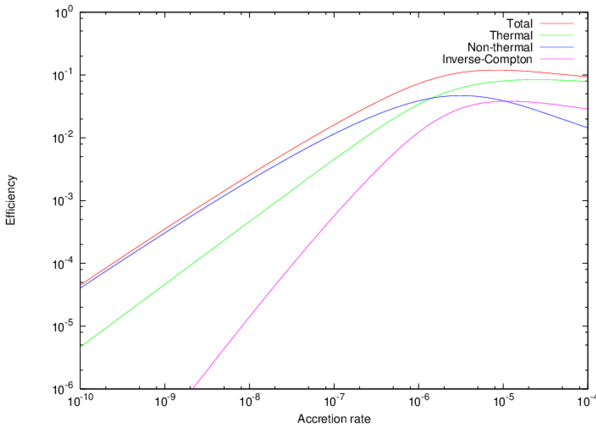

Figure 4. Efficiencies of the synchrotron emission of thermal and non-thermal electron components of the accretion flow.

possible physical object with a given mass. Its parameters — spectra, energy distribution and light curves – carry important information on space-time properties of the horizon [3].

The general observational appearance of a single stellar-mass black hole at typical interstellar medium densities — its brightness and featureless optical spectrum — is the same as other optical objects without spectral lines — DC-dwarfs and ROCOSes (Radio Objects with Continuous Optical Spectra, a subclass of blazars) [13]. The suggestion that isolated BHs can be among them forms the basis of the observational programme in search of isolated stellar-mass black holes — MANIA (Multichannel Analysis of Nanosecond Intensity Alterations). It uses photometric observations of candidate objects with high time resolution, special hardware and data analysis methods [14, 15], and is based on the fact that fast variability is the critical property of isolated black hole emission.

In observations of 40 DC-dwarfs and ROCOSes using the 6-meter telescope of the Special Astrophysical Observatory and the standard high time resolution photometer based on photomultipliers, only upper limits for variability levels of 20–5 % on the timescales of 10^{-6}–10 s respectively were obtained, i.e., BHs were not detected [15–17].

In the new stage of the MANIA experiment, since the end of 1990s, we have developed the multichannel panoramic spectro-polarimeter (MPPP) based on the position-sensitive detector (PSD) with 1 µs time resolution ([18, 19]). Such detectors use the set of microchannel plates (MCP) for electron multiplication and a multi-electrode collector to determine the incoming photon position. The PSD used in our observations has the following parameters: quantum efficiency of 10 % in the 3700–7500 A range (S20 photocathode), MCP stack gain of 10^6, spatial resolution of 70 µm (0.21″ for the 6 m telescope), 700 ns time resolution, $7 \cdot 10^4$ pixels with 22 mm working diameter, and 200–500 counts/s detector noise. The "Quantochron 4-480" spectal time-code convertor with 30 ns time resolution and 10^6 counts/s maximal count rate is used as an acquisition system. This equipment allows us to study 20–22^{m} objects for 1-hour exposure (under good weather conditions) with microsecond temporal resolution [20, 21].

In recent years, the population of objects with featureless optical spectra and without known localizations has been extended by means of the cross-correlation of surveys of various wave bands (from radio to gamma) and follow-up spectroscopic observations [13, 22]. These objects are the major targets of a new stage of the MANIA experiment.

In addition, some evidence has recently appeared that the isolated stellar mass black holes may be among the unidentified gamma-ray sources [23, 24].

Another large class of candidate objects for isolated black holes are those where independent estimation of the mass is possible, e.g., long-lasting MACHO microlensing events [25]. Another possibility is a black hole in a binary system with a white dwarf (though, strictly speaking, this type of black hole is not isolated, it accretes from interstellar gas only, and therefore may be considered in the same way). This type of binary may be detected by means of its periodic brightness amplification on the tens of seconds time scale due to gravitational microlensing [26]. By using the technical equipment of SDSS (23^{m} limit in a 6-square-degree field), roughly 15 such objects may be detected in the course of 5 years. It is clear that in such a system it is easy to estimate the mass of the black hole.

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