What glows in black holes?

We've all heard of these mysterious objects capable of entrapping anything – even light.

Dr. Agnieszka Janiuk

Centre of Theoretical Physics, Polish Academy of Sciences, Warsaw

Black holes are the final stage in the evolution of massive stars, when the thermal pressure of matter can no longer counterbalance the star's own gravitational field after its nuclear fuel runs out. Such objects collapse in on themselves under their own mass. If the original star was relatively small, it could become a white dwarf or a neutron star: then the final collapse is stopped by the formation of degenerate electron gas pressurized to vast densities (in a white dwarf) or superdense matter consisting of degenerated neutrons (in a neutron star). These types of compact objects can exist indefinitely while they cool. However, the situation is very different for objects which start off being massive.

Research into stellar evolution indicates that stars with a mass just over eight times greater than our Sun explode as supernovae near the end of their existence to form neutron stars or black holes. The latter are formed when the star's nucleus is too massive to create a stable configuration from neutron matter; the exact details depend on the matter equation of state and aren't fully understood, but we do know that the minimal mass required is no more than around two or three times that of the Sun's.

On the other hand, we also know that there is an upper limit on a star's mass above which a supernova explosion doesn't leave anything behind. For stars with a mass over a hundred times greater than that of our Sun, the energies of photons emitted during the supernova explosion are so high that they exceed

the limits on the formation of electron/positron pairs. This type of unstable supernova leaves nothing behind. And so, for a black hole to be formed, the mass of the original star must be somewhere between these two bounds.

The enormous surface gravity of black holes means that even light cannot escape due to its finite speed. The upshot is that isolated black holes cannot be observed. (The exception are micro black holes with masses of the order of 1015 g and sizes around a femtometer; they evaporate as part of a process known as Hawking radiation, but that's a topic for another article.) However, the majority of stars in the Universe don't exist in isolation, but rather form a part of binary or multiple systems. It turns out that such systems can survive the death and collapse of one of their components. The remaining companion continues to orbit the center of mass common with the collapsed object, enabling us to learn something about the companion.

In X-ray binaries, a relatively ordinary star – a dwarf or giant – accompanies a black hole. The gravity of the black hole attracts the surface layers of the companion star and the rotation along the system's orbital plane creates a flat, disk-shaped structure. Such an accretion of matter onto the black hole is preceded by a vast increase in the disk matter temperature. This is the result of viscosity, as adjacent rings within disk "rub" against each other as part of differential rotation. The disk reaches such a high temperature that the thermal radiation it emits falls within the X-ray range.

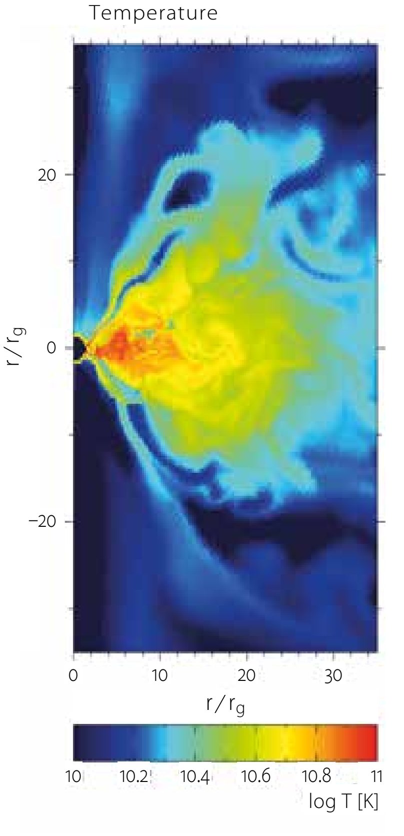
Careful observations

Since Earth's atmosphere doesn't let through radiation in this wavelength range, observing such accretion disks surrounding stellar black holes became possible only with the advent of satellite technologies. The first research satellite dedicated to X-ray astronomy was Uhuru; launched in 1970, it studied binary systems

Dr. Agnieszka Janiuk
Associate Professor at the PAS Centre of Theoretical Physics, leads a team of astrophysicists studying accretion processes and the outflows of matter in the near neighborhood of black holes.

agnes@cft.edu.pl

Simulation results showing the distribution of temperature in the hyperaccretion disk around a black hole, at the base of a jet creating a gamma-ray burst – A. Janiuk (2017, ApJ, 837,39).



and catalogued many remains of supernovae. It also conducted observations of Seyfert galaxies, in which the main source of activity is accretion onto supermassive black holes in their centers, and galaxy clusters in which dispersed hot gas emits high-energy radiation.

Since then, space missions have been providing fresh information about how accretion onto black holes actually takes place and collecting data on distinctive features of the spectral distribution of their radiation and the objects' variability. Many of the radiation sources are transient – they flash in the X-ray spectrum only for a while, before going out. Additionally, bright sources are frequently variable in short timescales, manifesting as regular oscillations around a mean brightness. This is likely linked to various types of viscous and thermal instabilities in the accretion process.

Such systems can also change their spectral state: in accreting black holes and neutron stars, thermal emission from the accretion disk is frequently accompanied by non-thermal components of the spectrum. The latter do not originate from the disk but most likely from a cloud or corona over the disk. Extensive research is being conducted into the relative positions and dynamic and radial feedback between the objects.

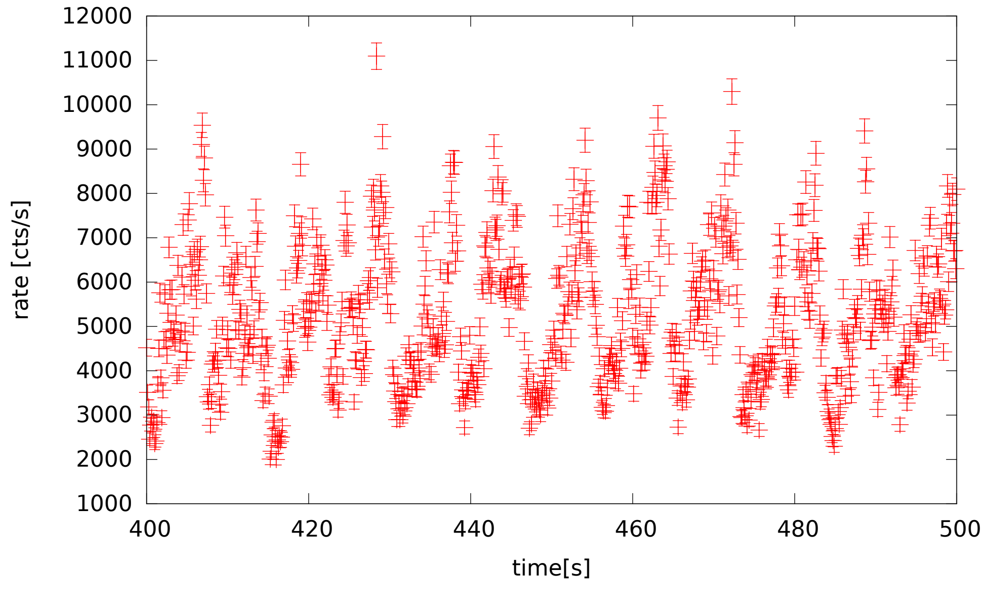
The likely theoretical scenario is as follows: photons with a perfect black-body spectral distribution, emitted from the disk surface, are dispersed in a reverse Compton process by the electrons found in hot plasma of the clouds.

Our understanding of accretion disks is based on the analysis of observations conducted in the X-ray range (disks found in active centers of galaxies and surrounding supermassive black holes are cooler and emit ultraviolet rays) and on theoretical models. The latter have gone far beyond simple, approximate formulas describing the object's structure and assuming its stationary, symmetric nature and hydrostatic balance. This gives us an insight into the disk's structure.

Members of the astrophysics group from the Centre of Theoretical Physics, visiting the Interdisciplinary Modelling Centre at the University of Warsaw. From left: Dr. Szymon Charzyński, Dr. Agnieszka Janiuk, Dr. Petra Sukova; the Okeanos supercomputer in the background.

More advanced modeling includes elements which can only be considered using massive computer simulations. Hydrodynamic equations are non-linear and need to be solved numerically, especially if we allow for the presence of a magnetic field within the disk and if we want to accurately describe the effects linked with the general theory of relativity and powerful gravitational potential. Relativistic magnetohydrodynamics is the best tool for studying the structure and evolution of accretion disks. Computer simulations are the only effective means of studying the extreme accretion disks which surround the black holes that are the sources of gamma-ray bursts (GRBs) reaching Earth. GRBs, first described in the 1960s as temporary bursts of extremely high energy, appear in random locations in the sky, on average every few days. The photon streams registered by gamma detectors, combined with the vast distances to their sources (the distances are assessed by identifying the parent galaxies where the bursts appear), indicate that they are some of the brightest objects in the Universe, with a luminosity several orders of magnitude greater than that of supernovae.

Since the accretion of matter onto a black hole is the most energy-efficient process we know, astron-



Curve showing the short-term variation in the luminosity of a binary X-ray system. Observations from the Rossi X-ray Timing Explorer satellite. X-ray data available from the RXTE archive at heasarc.gsfc.nasa.gov. Data for this object extracted by Mikołaj Grzędzielski.

omers posit that gamma rays must be generated by newly formed black holes, absorbing vast amounts of matter in fractions of a second. Some of the potential gravitational energy of the black hole and its rotational energy are processed during accretion. A GRB is therefore the manifestation of the emission of a narrow jet of plasma ejected perpendicularly to the accretion disk's equatorial plane, along the black hole's rotational axis. The jet becomes transparent and starts emitting photons only at distances in the order of 1013 cm from its base. The disk itself is even more opaque: the matter it comprises is at a high density and temperature, which means photons are constantly undergoing absorption and scattering.

The particles which are able to escape from the disk, taking with them some of the energy and thus cooling the disk, are neutrinos. They are formed during nuclear reactions in the disk's hot plasma – a mixture of free neutrons, protons, electron/positron pairs and nuclei of heavier elements such as helium. However, many are annihilated with their antiparticles (the reactions form neutrinos and antineutrinos), depositing the energy generated during the annihilation process in the jet and increasing its acceleration.

Due to the vast distances, we don't expect jets of neutrinos from GRBs to be significant by the time they reach Earth, although existing neutrino detectors can only provide upper boundaries so far.

Cluster computing

For the reasons outlined above, direct observation of the hyperaccretion disks responsible for GRBs is impossible. We can deduce their properties indirectly by studying jet emissions and measuring their energy levels and temporal variation. These properties should depend on the physical parameters of disk/black hole systems, such as the black hole's mass and rotational speed and the volume of mass accreted in the disk per unit of time.

Magnetic fields are also significant; their geometric configuration and input into the total pressure complete our model. The model is formulated on the basis of the magnetohydrodynamic equations which underline our simulations. These time-consuming calculations are conducted on computer clusters.

My astrophysics team at the PAS Centre of Theoretical Physics has permanent access to a mini-cluster (20 processor cores) which we use to conduct tests. The actual calculations are carried out using the resources of the Interdisciplinary Modelling Centre (IMC) at the University of Warsaw, funded by a computational grant. We mainly use the Cray supercomputer, comprising over 1000 cores, housed at the IMC's new site in Tarchomin near Warsaw.

For example, a model of a magnetized hyperaccretion disk accreting for 0.1 seconds onto a black hole in the center of a GRB, in a two-dimensional simulation with a typical resolution of 256 x 256, takes the computer a few weeks to calculate using ten or so of its nodes. Simulations of accretion onto a black hole in "ordinary" X-ray systems, for now ignoring magnetic fields and complex microphysics resulting from nuclear reactions, take a similar length of time to conduct in three dimensions.

Such simulations enable us to learn about effects which disturb axial symmetry, common in binary systems and in the centers of galaxies, as well as about what really happens in the near neighborhood of black holes.

Agnieszka Janiuk

Further reading:

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Sukova P., Janiuk A. (2016). Non-linear behaviour of XTE J1550–564 during its 1998–1999 outburst, revealed by recurrence analysis, *Astronomy and Astrophysics*, 591, A77.

Sukova P., Charzynski S., Janiuk A. (2017). Transonic structure of slowly rotating accretion flows with shocks around black holes. In: New Frontiers in Black Hole Astrophysics, *Proceedings of the International Astronomical Union, IAU Symposium, Volume 324*, pp. 23–26.