Astrophysical Black Holes

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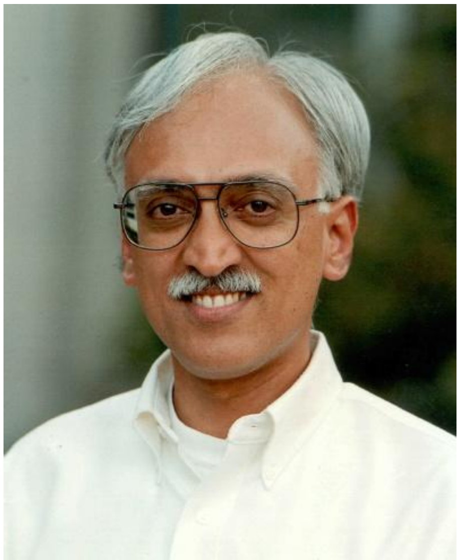
Sitting in the quiet corner office at the Center for Astrophysics in Cambridge, Massachusetts, high-energy phenomenon is the last thing that comes to mind. However, Prof. Ramesh Narayan, Thomas Dudley Cabot Professor of the Natural Sciences, Harvard University, whose office we are sitting in, happens to be one of the co discoverers of a holy grail of theoretical Physics, the conclusive evidence for the existence of the most extreme object in classical Physics, the Black Hole.



Prof. Ramesh Narayan, Thomas Dudley Cabot Professor of Natural Sciences

Prof. Narayan is the world's leading expert on accretion processes around astrophysical black holes. The interesting thing about astrophysical black holes is that, in spite of what all Physicists remember most about them, their “blackness", the *Event Horizon* shrouding the singularity in the metric, in reality they are among the most luminous objects in nature. The intense gravitational field around the Black Hole gathers any gaseous material around it in a rotating disk circulating around it. The viscosity of the gas (as well as other dynamical instabilities) enables it to lose angular momentum and fall in. These dissipative processes result in heating and lights up the gas like beacons that are visible straight across the Universe. By studying these bright sources we can figure out information on the gravitational engines in their center, the target of Prof. Narayan's research.

Astrophysics of Black Holes

Astrophysical Black Holes are very massive objects with masses ranging from several to 10^9 times the mass of the Sun (M_{sun}, 1.99×10^{33} gm). They are observed in the galaxy (mostly as binary systems) and also as “massive” black holes in the centers of galaxies. Our own Galaxy is presumed to have a black hole in its center. This macroscopic scale means that these objects are well described by classical General Relativity. This makes them a beautifully simple problem. They are the perfect elementary particles described purely by three parameters, their mass (M), spin (a_*, defined so that the black hole's angular momentum is $a_* GM^2/c$) and charge. However in the astrophysical context, it is very hard to see how a black hole would be able to retain its charge. The surrounding plasma would rapidly neutralize it. This means astrophysical black holes are fully described by just two numbers, its mass and a_*, the latter being a number between 0 (non-spinning black hole) and 1 (a maximally spinning black hole).

Estimating mass of a black hole is a requirement for identifying black hole candidates. The prescription for finding these objects is straightforward. Find a compact object of mass in excess of about $3\,M_{\rm sun}$. This object is most likely a black hole. Using the equation of state of matter at nuclear density and general relativity it is possible to show that the maximum mass a neutron star can have is between 2-3 $M_{\rm sun}$. This argument follows similar techniques used by Prof. S. Chandrasekhar to determine the maximum mass of a white dwarf, in which case the star is supported by relativistic electron gas pressure.

The masses of black holes of stellar mass can be measured if they are in a binary system with an observed companion. Let $P_{\rm orb}$ be the period of the orbit and $K_c = v\sin i$ the line of sight Doppler velocity. Here *i* is the angle of inclination of the perpendicular to the plane of the orbit to the line of sight. Then the "mass function," $f(M)$, of the black hole candidate is given by:

$$f(M) \equiv \frac{K_c^3 P_{\rm orb}}{2\pi \mathrm{G}} = \frac{M\sin^3 i}{(1+{}^{M_c}\!/_{M})^2}$$

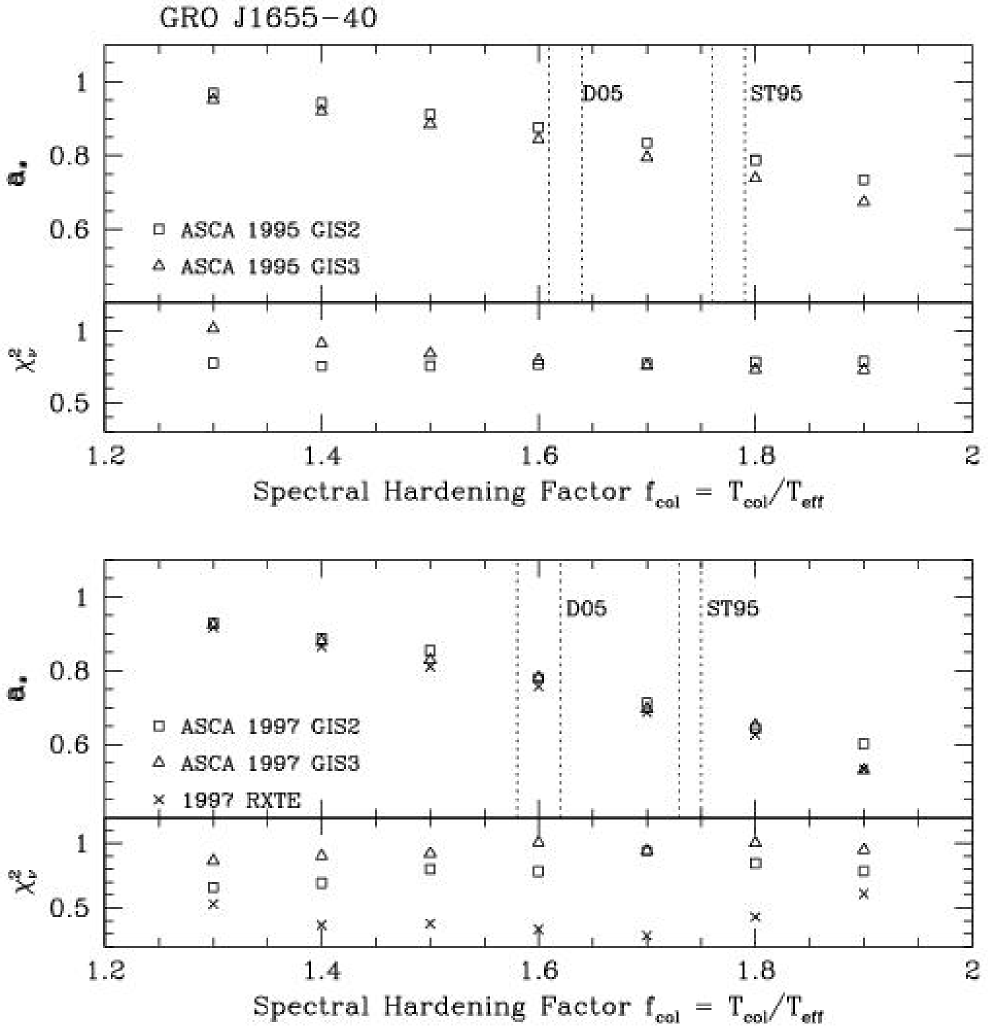
Here *M* is the mass of the black hole and M_c is the mass of the companion. As can be seen we need independent estimates for M_c and *i* to get an estimate for *M*. It is possible to get an estimate of M_c from the color (a measure of surface temperature and age) of the companion. And one can estimate *i* from the light curve of the binary. But these estimates have some errors in them which allow us to place bounds on the mass of the candidate *M* rather than measure it exactly. Regardless if *M* is required to be above $3\,M_{\rm sun}$ the object is a good black hole candidate.

Massive black holes in centers of galaxies are identified either through orbits of stars nearby, or through observations of the orbital motion of gas distributed in disks around the black hole candidates. These measurements result in a large range of black hole candidate masses, from $3\times10^6 M_{\rm sun}$ for our own galaxy (presumed to be the radio source Sagittarius A*) to up to $10^{9.5} M_{\rm sun}$ in active galactic nuclei.

In addition to these there are hints of intermediate mass black holes falling in between these two populations with masses around $10^3 - 10^4 M_{\rm sun}$ from ultra-luminous X-ray sources observed in nearby galaxies.

Spins of Black holes

As mentioned before astrophysical black holes are characterized completely by their masses and spins. Just as with their mass, it is possible to estimate their spins dynamically. Obviously the spins of black holes do not have any gravitational effect in the Newtonian approximation. However in a general relativistic framework the spin of the black hole has a dynamical effect on the orbits around it. One particularly important effect is the existence of an innermost stable orbit (whose radius is signified as $R_{\rm ISCO}$). For a non-spinning black hole $R_{\rm ISCO} = 6GM/c^2$ where as for a maximally spinning black hole, $R_{\rm ISCO} = GM/c^2$ if the orbit is co rotating with the black hole and $R_{\rm ISCO} = 9GM/c^2$ if it is counter-rotating.



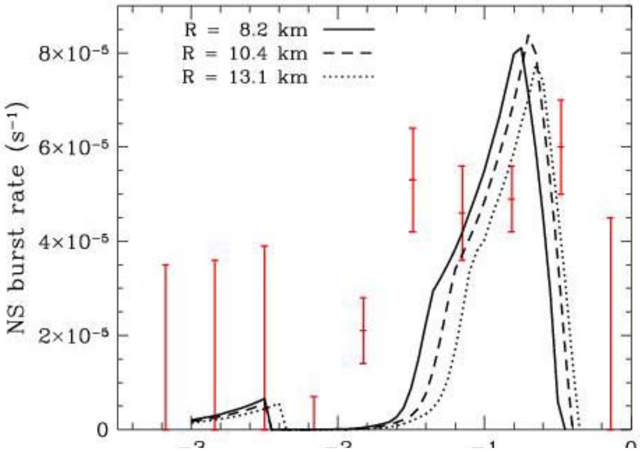
Measured values of spin parameter, a_*, as a function of the spectral hardening factor f_{col}

In a recent paper [Shafee et. al (2005)], Prof. Narayan and collaborators were able to estimate the spins of stellar mass black holes. This was done by fitting the X-ray thermal continuum spectra from two black hole binary candidates with a fully relativistic model of a thin accretion disk around a Kerr black hole. This model includes all relativistic effects such as frame-dragging, gravitational redshift, and bending of light by the gravity of the black hole. It also includes effects of the disk of gas on the light as well. Additionally to measure the spin, it is necessary to know the mass M of the black hole candidate, the inclination i of the orbit and the distance D to the system. For this reason two candidates were picked with measured distances, masses and inclination and observed with two satellites; the Advanced Satellite for Cosmology and Astrophysics (*ASCA*) and the Rossi X-ray Timing Explorer (*RXTE*). There is still one parameter that is unknown, f_{col}, the spectral hardening factor, which is a measure of the deviation of the radiation from its assumed black body spectrum. Fitting the spin-factor a_* while holding f_{col} fixed results in a very good fit. This means that the data itself doesn't constrain f_{col}, but it is possible to constrain it from theoretical models. Figure 2 shows that most likely values for a_* for the two candidates lie in the range of $\approx 0.7 - 0.8$ for the object J1655 and $\approx 0.7 - 0.8$ for U1543.

One very interesting conclusion that can be drawn is that this spin very likely refers to the natal spin of the (putative) black hole. It is possible to estimate an upper bound to the age of the binary system from the nature of the companion star. This age is too short a time for the black hole to be able to pick up the observed spin from accreting material (which falls in with angular momentum that is deposited to the black hole).

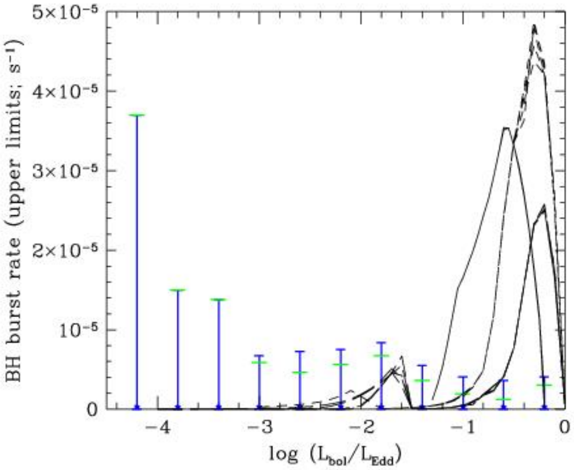
The Event Horizon

Notice that we've being referring to these objects as candidate (or putative) black holes. Is it possible to have direct proof that these are indeed black holes? The proof would be in observing the event horizon. Prof. Narayan and collaborators have poured in considerable energy in being able to do just this. If these compact objects were indeed neutron stars instead of black holes, they would have some hard surface (rather than the event horizon). This would have a dramatic effect on the material falling in. A hard surface means that matter would collect, slowly increasing its density and temperature, until it could ignite in what is known as a *Type I* X-ray burst. Prof. Narayan and collaborators have been able to show that these bursts are an inevitable consequence of the accumulation of matter that is rich in H and He onto the dense and hot surface of a neutron star, or whatever the compact object (that does not have an event horizon) is presumed to be. They performed a survey [Remillard et al. (2005)] of these *Type I* bursts in black hole candidates and black hole binary groups versus neutron stars. The results are summarized in the figures. As is clear from the figures, the theoretical models fit the neutron star data quite well. That is, they show *Type I* X-ray bursts at the rate and luminosity the models predict. The black hole candidates on the other show no burst activity. This is consistent with them not having a hard surface.



Average burst rates for neutron star systems. The lines are models and points are measurements from the survey with their 1 σ error bars. The models are consistent with the data

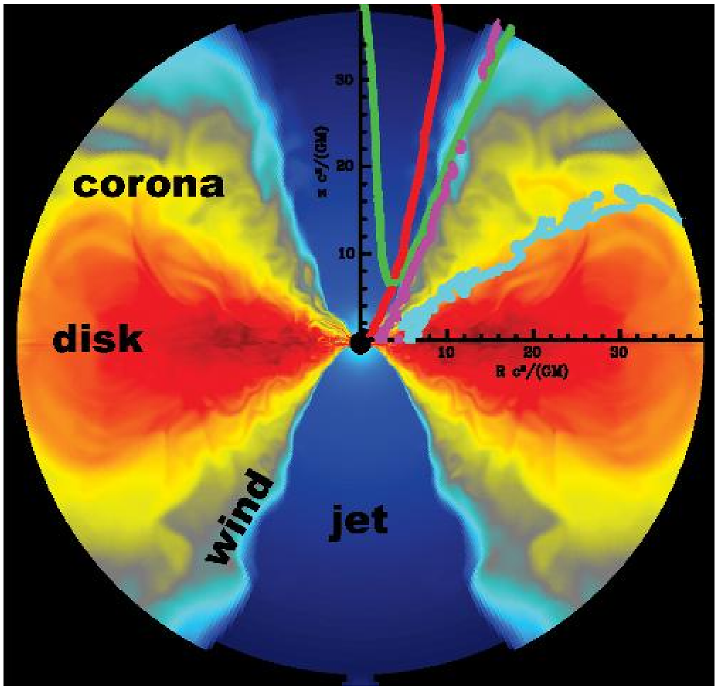
This is quite possibly best evidence for the reality of the most extreme phenomenon in classical physics; the proof of the existence of event horizons around black holes. It is hard to imagine a more dramatic demonstration of predictions made by theoretical physics.



Average burst rates for black hole candidate systems. As for the neutron stars the lines are models and points are measurements from the survey with their 1σ error bars. The models are completely inconsistent with the data.

What Next?

Momentous as this may be, all this is only a start. There remain many difficult problems relating to astrophysical black holes. One of the more interesting of which is jets of material emanating from them. Astrophysical black holes with significant accretion always seem to display spectacular jets. This has often been described as inevitable as accreting material spirals into the central black hole. Jets are the ``obvious" way for this material to lose angular momentum. A small amount of material carries away the angular momentum in jets, collimated and powered by magnetic fields. However in reality things are not so obvious. Dr. McKinney, a collaborator of Prof. Narayan, has written a parallel, fully relativistic magneto-hydrodynamics code which can simulate the accretion on to a black hole. The results of these simulations do indeed display jets as shown in the figure, but these jets are by no means inevitable. Their appearance is a function of several things, not least of which is the spin parameter of the black hole.



Simulation of a disk around a black hole and its jet. The color displays the density of material. Red is the highest density and blue-black is lowest. The cyan line marks where gas pressure dominates magnetic pressure. The purple line is where the gas pressure equals the magnetic pressure. The red line is where magnetic energy equals rest mass energy. Most of the corona and jet is unbound and outgoing

Prof. Narayan and his collaborators are launching a program of observation where they will survey black hole candidates measuring their spins and jet activity. By observing the correlation of the characteristics of the black holes and its environs, they hope to constrain theoretical models to be able to say exactly what goes on with the material in its rush to self-destruction on to the event horizon of the black hole.

Conclusions

From its very beginning theoretical Physics has used Astrophysics as a testing ground. This has not changed over the years. If anything theoretical Physics has become even more reliant on Astrophysics to find and test its predictions. Fortunately for us, the Universe is extremely large, extremely old and extremely diverse. We can take heart from knowing that Prof. Narayan's heroic efforts to lift the veil from one of the most bizarre phenomena in the Universe is but a scraping of the surface of what theoretical physics says is possible. Astrophysics is ready to reveal its riches to the enterprising Physicist willing to foray into it.

Bibliography

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