

Black hole event horizons and advection-dominated accretion

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While the widely accepted theory of black holes has long predicted that they should be black because they are surrounded by an 'event horizon' (a one-way membrane from which nothing, not even light can escape), direct evidence for this event horizon has been very difficult to obtain. A felicitous union of new observations and new theory has now provided evidence that black holes are what their name implies: black holes in space.

OBSERVATIONAL evidence for the existence of black holes has accumulated very rapidly in the past few years¹⁻³. This evidence has been in the form of discoveries of super-compact, massive objects, which have masses and densities too high to resist collapse under their own gravitational attraction. However, the proof that these objects are black holes is somewhat indirect: they are considered black holes because, by process of elimination, they can be nothing else. But now a team of researchers lead by Ramesh Narayan at the Harvard-Smithsonian Center for Astrophysics has found evidence that some of these objects are actually vacuuming up large quantities of mass and energy. This is the first evidence that black holes are actually what their name implies, 'black holes' in space⁴.

The observational part of this story starts with the discovery of Cyg X-1, a bright X-ray star in the constellation Cygnus. The evidence strongly suggests that Cyg X-1 contains a ~ 15 solar mass black hole¹. However, the case is not airtight—there are marginally viable models of Cyg X-1 that do not require a black hole^{5,6} (but see ref 7). A different sort of black hole binary literally burst on the scene in 1975, with the discovery of a new X-ray source in the constellation Monoceros⁸. The new source was given the designation A0620-00 after its astronomical co-ordinates. Within a week this 'X-ray nova' had grown to become the brightest object in the X-ray sky. X-ray satellites pin-pointed the position of the new source, allowing ground-based optical telescopes to identify a variable star as the source of the enormous X-ray outburst. Over the next several months the X-ray and optical outburst faded away to pre-outburst (quiescent) levels.

At its peak, the X-ray output of A0620-00 was nearly 10^5 times greater than the total output of our sun at all wavelengths. This prodigious X-ray luminosity is a sure sign that matter is accreting onto a very compact

object. This X-ray nova was almost certainly a new member of the class of a few dozen previously known X-ray binaries, in which a compact star pulls matter off a nearby companion star. As the mass accretes onto the compact object, it is heated (by internal friction) to enormous temperatures, causing up to 10% of the mass in the accretion flow to be converted into X-rays.

In 1986, Jeff McClintock and Ron Remillard found that the compact star in A0620-00 must weigh more than 3 solar masses⁹. This mass measurement is very secure, relying only on the measurement of the binary star systems orbital period and velocity, and application of Kepler's laws of orbital mechanics. Straightforward theoretical arguments tell us that any compact star more massive than 3 solar masses must collapse to a black hole¹⁰. Thus A0620-00 became the first member of a new class of X-ray binary known as Black-Hole X-ray Novae, or BHXN.

For more than a decade, A0620-00 was not only the first member of the BHXN class—it was also the only member! That situation has changed dramatically in the last few years. Recently five more BHXN have been found, all containing collapsed objects more massive than 3 solar masses. This surge in the number of BHXN is due to the recent launching of several X-ray All Sky Monitors (ASMs), including the ones on Japan's GINGA satellite and NASA's Compton Gamma Ray Observatory. The ASMs are small X-ray telescopes that continuously scan the entire sky for X-ray sources. Once or twice per year the telescopes find a new, tremendously bright X-ray nova. At optical wavelengths, these nova also brighten substantially, but even at their brightest they are relatively innocuous stars—they would not draw attention to themselves unless the X-ray all sky monitors were there to discover them. Because the arguments are so straightforward, many astronomers feel that these six BHXN are the most secure black hole candidates known.

The theoretical part of the story starts with a study of accretion that Ramesh Narayan and Insu Yi¹¹ (now

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at Princeton) first published in 1994. The standard model of accretion in astrophysical systems is the thin disk model¹². In this model, the accreted matter forms a geometrically thin disk as it spirals inwards. As the matter flows towards the central star, it releases gravitational energy, which is converted to heat and immediately radiated away. The theory of thin disks is well developed, and the observational evidence for these disks in many binary star systems is irrefutable.

Narayan and Yi found that the thin disk is a special case of the general theoretical solution to the dynamical accretion equations. Another possible solution is one in which the gas does not immediately radiate away the gravitational energy released by accretion, but instead stores the energy as heat and 'advects' this energy towards the central star. In this case the in-falling matter forms a two-temperature plasma and the flow is nearly spherical. Most of the heat is carried by the protons, and a small amount leaks to the electrons. This small amount is radiated away, but most (99% or more) of the heat is carried directly to the central star. These flows have become known as Advection-Dominated Accretion Flows, or ADAFs. Narayan and Yi's solution to the accretion equations implied that ADAFs would only form at relatively low accretion rates, and that at high rates accretion would take place via the traditional thin disk. A second group¹³ independently discovered the same ADAF solutions to the accretion equations at about the same time as Narayan and Yi. An important fundamental difference between ADAF and thin disk accretion becomes very obvious if the accreting object is a black hole – if the flow is an ADAF the accretion energy would simply disappear once it got to the event horizon of the black hole, whereas a thin disk would radiate away about 10% of the rest mass energy on the way down to the black hole. The event horizon is the imaginary spherical surface surrounding the black hole at a radius of $R \sim 3 \text{ km } M_{\text{BH}}$ (where M_{BH} is the black hole mass in solar units) through which matter and energy can enter but never leave.

X-ray nova are a great testing ground for the ADAF theory. During the outburst, the accretion rate is high and there is clear evidence for the thin disk. But as the nova decays, the accretion rate falls into the regime where the thin disk should fade away and the ADAF solution should apply. Even before Narayan and Yi's work, there were signs that the thin disk model was having trouble explaining post-outburst (quiescent) observations of A0620-00 made with the Hubble Space Telescope and the ROSAT X-ray observatory¹⁴. These observations seemed to indicate that the inner part (near the black hole) of the thin disk seen in A0620-00 during outburst was gone – or at least very faint. Another mystery was that the Hubble observations showed the outer part of the disk to be rather bright, indicating a

moderate accretion rate. But the ROSAT observations showed very little X-ray emission, indicating that the flow onto the black hole was ~ 1000 times lower. It was as if matter was flowing from the binary companion into the disk, but then getting 'stuck' in the disk and not flowing down towards the black hole.

The new ADAF theory and the mysterious observations of A0620-00 came together beautifully in a paper by Narayan, McClintock and Yi¹⁵ in 1996. The apparent discrepancy between the accretion rate indicated by the outer disk, and that indicated by the X-ray emission is elegantly explained by the ADAF model. As applied to A0620-00, the ADAF model postulates that the outer part of the disk is a normal thin disk, but at some point it gradually becomes a nearly spherical, advection-dominated flow. In this way the low X-ray luminosity is explained (the energy is advected into the black hole), and the rather bright outer disk correctly indicates a rather moderate mass accretion rate. Because the low X-ray luminosity would only occur if the central star was a black hole, this model requires that A0620-00 be a black hole with an event horizon.

Further verification of the ADAF model came with observations of one of the newly discovered BHXN, V404 Cyg. The Japanese/NASA X-ray astronomy satellite ASCA was able to accurately measure the X-ray spectrum of V404 Cyg over a large wavelength range. When the ADAF model was applied to V404 Cyg, Narayan, Barret and McClintock¹⁶ found that the model is able to accurately predict the shape of the X-ray spectrum, and also is consistent with the optical and ultra-violet measurements. In contrast, it is impossible to explain either the X-ray spectrum or the broader wavelength observations with the thin disk model. Figure 1 shows the optical, ultra-violet and X-ray data, along with the best fitting ADAF and thin disk model. A thin-disk model going through the center of the optical and X-ray data over predicts the ultraviolet flux by at least a factor of 10, and predicts a steeply falling X-ray spectrum, contrary to the flat X-ray spectrum actually observed. So we see that the ADAF model is not only able to explain the X-ray luminosity of BHXN, but is also able to explain the observed broad-band spectrum. Because the shape of the emergent spectrum is critically dependent upon the event horizon hiding the energy advected into the black hole, this agreement is further evidence that black holes do have event horizons.

The agreement between the ADAF model spectrum and the observations of V404 Cyg is a somewhat model-dependent confirmation of black-hole event horizons. A model independent test would be considered more rigorous. A nearly model-independent test has been carried out by Narayan, Garcia, and McClintock¹. They made use of the fortuitous fact that nature has kindly provided two 'flavours' of X-ray Novae: some containing black

holes (or at least collapsed objects heavier than 3 solar masses), and some containing neutron stars. If black holes have event horizons, then when they are in quiescence they should be substantially fainter than the neutron star systems—because 99% of the accretion energy will be advected over the edge of the event horizon. In the case of neutron stars, the accretion energy will be released (radiated) when the infalling matter hits the neutron star surface, even if 99% of the energy is stored (advected) in the flow.

Narayan, Garcia and McClintock compared the X-ray luminosities of four BHXN and five neutron star X-ray nova (NSXN). This sample of nine objects includes essentially all the available data on X-ray nova. The NSXN are distinguished from the BHXN by virtue of displaying 'type I' X-ray bursts. These bursts are sudden increases on the luminosity of the neutron star by a factor of ~ 10 , which fade in a few hundred seconds. These bursts are caused by an explosive thermonuclear run-away on the surface of the neutron star, and are an unique and unambiguous indicator of the presence of a neutron star.

The comparison of luminosities is shown graphically in Figure 2. The horizontal axis is the log of the peak outburst luminosity of the X-ray nova. The vertical axis is the log of the quiescent luminosity divided by the

peak outburst luminosity. Several features of the plot are worthy of mention. First, we see that the BHXN and NSXN separate along the horizontal axis—all of the BHXN are more luminous in outburst than the NSXN. This is because all nine systems accrete at close to the Eddington luminosity during outburst, and because the BHXN systems are heavier. The Eddington luminosity is the maximum luminosity which an accretion-powered system can attain, and it is directly proportional to the mass of the accreting object. At the Eddington luminosity the emergent light pushes on the infalling matter with enough force to just balance the gravitational attraction causing the accretion. The neutron stars are ~ 1.4 solar masses, while the BHXN have masses somewhere between 5 and 15 solar masses². The dashed vertical line represents the Eddington limit for a 1.4 solar mass neutron star, and neatly divides the two flavours.

The horizontal axis shows that BHXN are heavier than NSXN, but it does not show that they have event horizons. This is demonstrated in the vertical axis, which shows the Eddington scaled quiescent luminosity. Here we see that all of the BHXN are fainter in quiescence than the NSXN. The dashed horizontal line has no

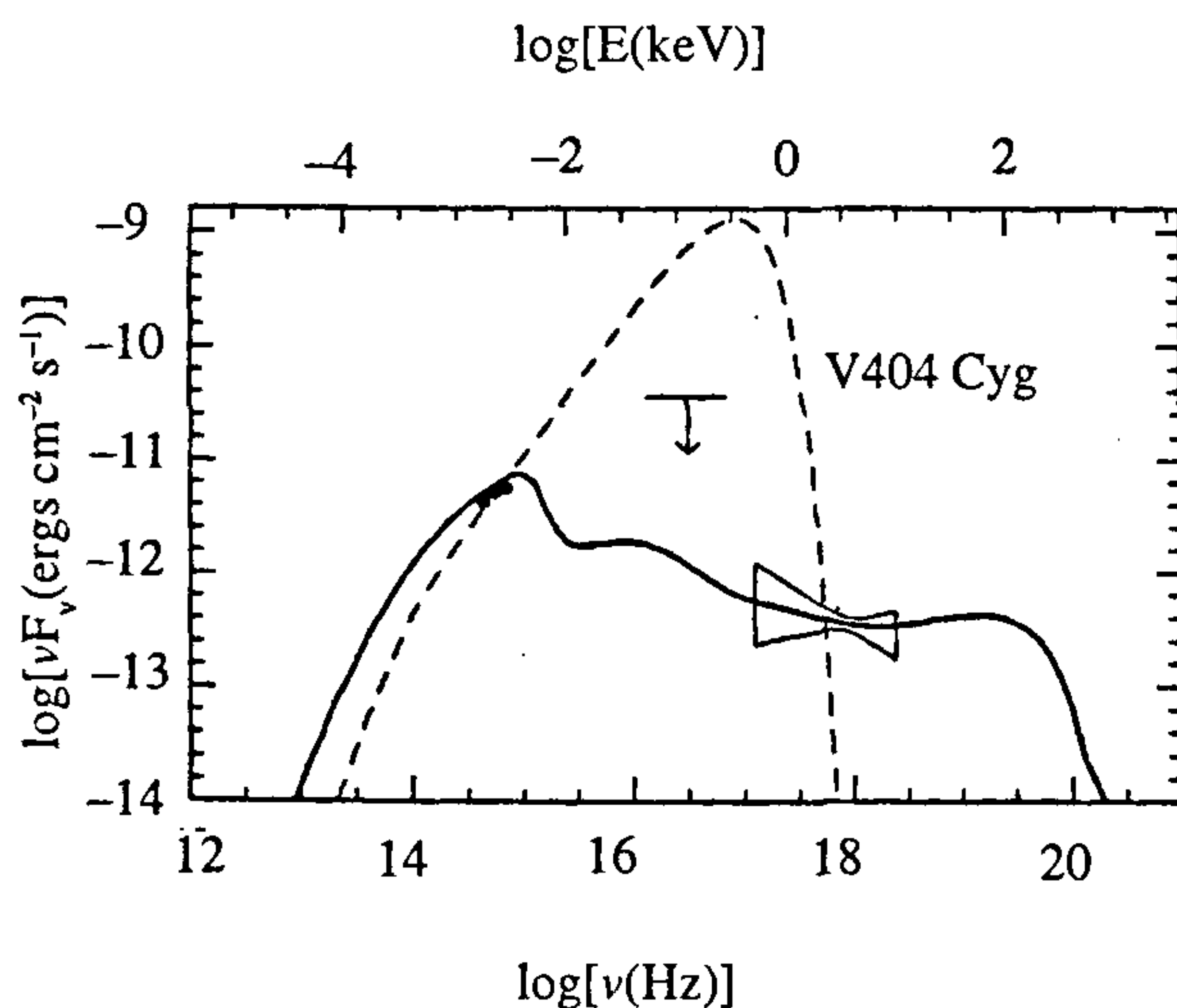


Figure 1. The bow-tie represents the X-ray measurements with the ASCA satellite of the spectrum of the X-ray nova V404 Cyg. The measurements extend from a photon energy of 0.5 to 10 keV, and the upper and lower edges of the bow-tie represent 95% confidence limits on the observed flux. The three dots show the flux in the optical band, and the arrow indicates a 99% confidence upper limit on the extreme ultraviolet flux. The dashed line is the predicted spectrum according to a conventional accretion model, and is a poor fit to the observations. The solid line is the prediction of the ADAF model, which fits the observations very well. In this model, the central star swallows more than 99% of the energy and radiates less than 1%. In order to swallow this much energy without a trace, the star has to be a black hole with an event horizon.

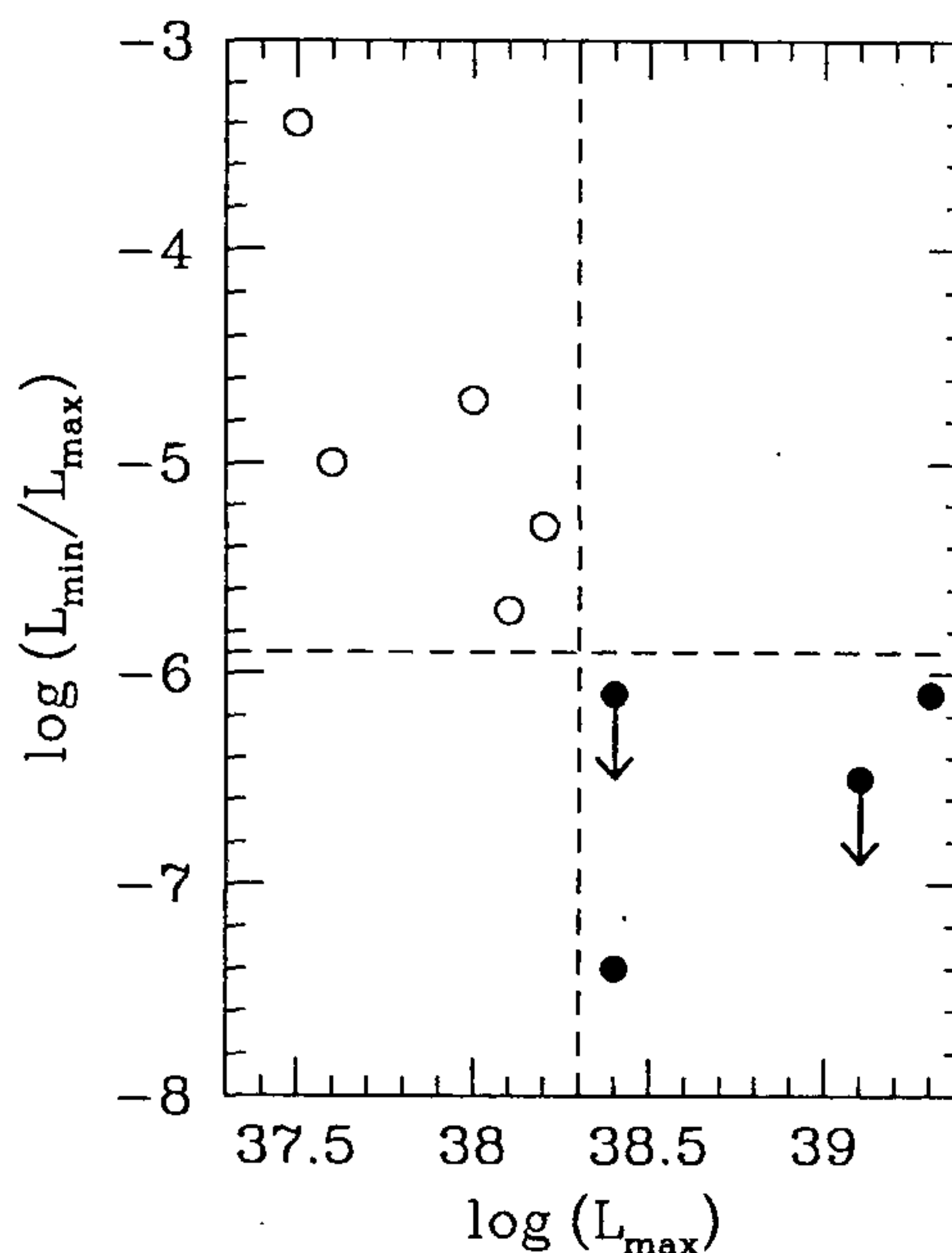


Figure 2. The observations of nine X-ray novae are shown. For each source, the ratio of the minimum to maximum observed X-ray flux is plotted (on a logarithmic scale). The filled circles correspond to black hole candidates. Two of the sources are too dim at flux minimum to be detected with current telescopes. The arrows indicate 99% confidence upper limits for these sources. The open circles correspond to neutron star systems. The clear separation of the black hole candidates from the neutron stars is expected according to the ADAF model, and provides a strong indication that the black hole candidates have event horizons.



Figure 3. An artist's conception (not to scale) of X-ray Nova binary star systems: the top one containing a black hole, and the bottom one containing a neutron star. Because nothing, not even light, can escape the event horizon around the black hole, it appears black. The neutron star does not have an event horizon, and therefore shines brightly. Because these binary star systems are at great distances, they appear as mere points of light even when viewed with the most powerful telescopes. But the difference between the two is still seen, when looked at with X-ray telescopes in earth orbit the neutron stars appear as brighter points than the black holes.

The gravitational tug from the black hole or neutron star is pulling matter off the binary companion on the left. This matter spirals inwards, first forming a disk, and then forming a spherical flow (an ADAF) down towards the central object. When it gets to the center it either silently disappears over the event horizon of the black hole, or violently impacts the surface of the neutron star.

physical significance, it merely shows the dividing line between the BHXN and NSXN. While there is quite a bit of scatter along the vertical axis, the mean Eddington scaled quiescent luminosity for the BHXN is a factor of ~ 100 less than that of the NSXN. Given that we believe the two flavours of X-ray nova have the same average mass accretion rate in quiescence, the fact that the BHXN are fainter indicates that some of the accretion energy is being hidden. More exactly, the fact that the luminosities are a factor of ~ 100 different means that 99% of the accretion luminosity is being hidden! If we

are right that the quiescent mass accretion rates are the same, then the only way the energy can be hidden is if the black holes have event horizons which the energy can hide behind. Furthermore, the large difference in mean Eddington scaled quiescent luminosity indicates that something like advection must be going on – if the thin disk extended all the way down to near the surface of the black holes we would expect only a factor of two difference in quiescent luminosities, because the thin disk radiates nearly all of its accretion energy on the spot (and advects very little of the energy towards the center).

This comparison between BHXN and NSXN is shown in Figure 3. The small, solar type secondary is on the left. A thin stream of mass is pulled off it and into orbit in a thin disk around the central object. The disk extends inwards a short distance, and is then disrupted into a spherical ADAF. The ADAF flows inwards, and (at the top) disappears into the black hole. At the bottom the ADAF is shown striking the surface of the neutron star, where the heat is released and radiated outwards as X-rays. Note that all attempts to adhere to a physically meaningful scale in this figure have been abandoned in order to clearly show the various components of the systems.

Of course there are caveats in this study. Probably the most uncertain assumption is that the NSXN and BHXN accrete at similar Eddington scaled mass accretion rates in quiescence. Certainly this assumption is true in outburst because both classes seem to nearly reach their respective Eddington limits (see Figure 1). It is difficult to measure the quiescent accretion rates in the BHXN in a model independent way, so there is little observational evidence either for or against this assumption. Given what little we do know the assumption seems reasonable, but it is difficult to make a much stronger statement.

The outstanding new feature of this study is that it shows, for the first time, the 'black' nature of black holes. Discoveries of black holes, both those in X-ray binaries and those in the centre of galaxies, have been discoveries of bright objects. When in the center of galaxies, super-massive black holes are the engines that power the brightest objects in the universe, quasars. With the realization that the accretion onto black holes may be advection-dominated at low accretion rates, there will likely be more studies showing the black nature of black holes. Recent surveys of galaxies by HST have shown that most galaxies contain super-massive black holes in their centers¹⁷, but these galaxies are not quasars – they may be fossil quasars now accreting in an advection-dominated mode.

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GENERAL ARTICLES

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MEETINGS/SYMPOSIA/SEMINARS

International Congress on Sustainable Development of Environment and Wild Life (ICSDEWL)

Date: 18-21 December 1997

Place: Ujjain, India

Themes include: Environmental trade; Socio-economic aspects and tribal rights; Sustainable wild life; Tiger project and forest conservation; Ramsar convention; National Agenda-21; National conservation strategy; Biodiversity; Role of National Parks, Zoos and Sanctuaries; Water resources; Wetland management; Renewable energy resources; Environment education and awareness; Human habitat management; Bhopal gas tragedy and public participation in Narmada and other major dam constructions.

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International Conference on Polymer Characterization (6th POLYCHAR)

Date: 7-9 January 1998

Place: Texas, USA

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DAE's Fourth Biennial Trombay Symposium on Radiation and Photochemistry - TSRP-98

Date: 14-19 January 1998

Place: Mumbai

Topics include: Ultrafast processes, dynamics of electron solvation and geminate recombination; Charge, electron and energy transfer processes; Excited states, ionic intermediates and free radical processes; Multiphoton excitation, ionisation and vibrational photochemistry; Gas phase photochemistry and dynamics; Industrial applications of radiation and photochemistry; Phot and radiation chemistry in organized and microheterogeneous media.

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