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Black-Hole Astrophysics*

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Abstract

Black-hole astrophysics is not just the investigation of yet another, even if extremely remarkable type of celestial body, but a test of the correctness of our understanding of the very properties of space and time in very strong gravitational fields. Physicists' excitement at this new prospect for testing theories of fundamental processes is matched by that of astronomers at the possibility to discover and study a new and dramatically different kind of astronomical object. Here we review the currently known ways that black holes can be identified by their effects on their neighborhood — since, of course, the hole itself does not yield any direct evidence of its existence or information about its properties. The two most important empirical considerations are determination of masses, or lower limits thereof, of unseen companions in binary star systems, and measurement of luminosity fluctuations on very short time scales.

1. Black-Hole Theory

The reader is no doubt familiar with the fundamental physical considerations by which the attractive nature of the self-gravity of spatially distributed matter inevitably leads to the possibility of collapse to a singularity (see e.g., Chapter 33 of [?]). This section outlines the reasoning behind the belief that black holes have indeed been produced in three different locations, and then summarize the ways in which it is thought these objects might reveal themselves.

1.1 Overview

In order for black holes to become an astronomical as well as a physical reality, evidence that Nature can and has produced this state must be obtained. The current situation is much as it was with neutron stars, after physicists had established their theoretical possibility, while Baade and Zwicky ([?]) were arguing that supernovae were the furnaces in which these strange objects could be produced, but before the discovery of pulsars led to the universally accepted conclusion that the Galaxy is littered with neutron stars.

There are three types of black holes:

TYPE	MASS ($M_\odot$)	LOCATION
Dead stars	> 3.2	Throughout galaxies
Supermassive	$> 10^6$	Galaxy centers
Primordial	$> 5 \times 10^{-19}$	Throughout Universe?

The first kind of black hole is the inevitable end-product of the evolution of a sufficiently massive ordinary star (greater than about 30 $M_\odot$). Section **??** contains some considerations that lead to this conclusion (plus similar remarks about the other kinds of black holes). Estimates of the black-hole birth rate, based on stellar evolution and related considerations, are on the order of 0.003/year for main sequence stars of mass $M > 30M_\odot$; the rate scales as $M^{-1.4}$. Summing these rates, we find that there should be roughly 10^7 to 10^8 black holes in the Galaxy. This may be an overestimate, as there may be significant mass loss by massive stars in the course of their evolution (up to 50%, [?]).

1.2 Black-Hole Formation

Each of the three types of black holes listed above originates in a very different way.

Stellar-Mass Black Holes

All sufficiently massive stars are thought to evolve into black holes. The maximum mass of a neutron star is the well-known Rhoades and Ruffini limit of $3.2M_\odot$ [?]. Steady or catastrophic mass loss can possibly intervene in some cases, allowing stars that initially exceed this limit to evolve to a final state other than a black hole. Estimates for the minimum mass of stars that cannot escape evolution into black holes are in the tens of solar masses (10 according to [?], 30 according to [?], 50 according to [?] and [?]).

Stars of initial mass in a range $\sim 10-30M_\odot$ often make use of the neutron-star final state available to them, as we know from the many pulsars in the Galaxy. The theory of supernovae indicates that there is probably no way that black holes of masses $\leq 1M_\odot$ can be formed. But an alternative scenario involves ordinary stellar evolution to a neutron-star, followed by gradual accretion of matter to the point where the neutron currently known star mass limit is exceeded.

Those stars which are formed in a binary system and evolve into the black-hole state (before the companion has time to evolve to its final state) are the best candidates for detection, through their influence on the companion. In particular, the quest for binary stars with unseen companions deduced to be more massive than the Rhoades and Ruffini limit has been a major research thrust (see Section **??**). It should be kept in mind that this approach automatically excludes detection of black holes that are less massive than this limit, as well as those that are simply not in binaries.

The evolutionary scenario of massive binary systems predicts the existence of a subclass of binary radio pulsars consisting of a neutron star and a black hole, with a density of ~ 1 per 1000 single pulsars ([**?**]) . In such systems, the mass of the unseen companion would be > 3–$4M_\odot$, and the pulsars themselves would be similar to standard isolated ones. The recently discovered binary 1-s pulsar PSR B0042-73=PSR J0045-7319 in the Small Magellanic Cloud, with a massive companion in a highly elongated (eccentricity $e = 0.8$) 51-day orbit ([**?**]) may be the first such black hole/pulsar. The paradox that the first pulsar discovered in the SMC proved to be in a binary system can be naturally understood if its companion actually is a 10–$30M_\odot$ black hole, as illustrated in [**?**], with calculations of the evolution of radio pulsars after a star formation burst.

Supermassive Black Holes

It is not yet known how supermassive black holes form, although a great deal has been written on this subject. One consideration discussed recently by Haehnelt and Rees ([**?**]) is that, in most hierarchical models for formation of structure in the Universe, the build-up of structures of galactic size occurs at a time similar to the peak of the quasar activity. They argue that the timescale for the formation of a black hole in a newly forming dark matter halo is short, and that there need not be a time lag between the formation of a protogalaxy and the "switching on" of a quasar. If a density concentration of the order of $10^8 M_\odot$ occurs in a region 1 pc across, they conclude that it will have no non-relativistic equilibrium state that can be supported for long, and will collapse to a supermassive black hole.

Another approach taken by Quinlan and Shapiro ([**?**]) is to start from an assumed dense cluster of stars in a galactic nucleus and follow the build-up of $100M_\odot$ or larger-seed black holes by collisions.

Further growth to a supermassive black hole is possible via several mechanisms, including feeding of the black hole by tidal disruption of stars, pre-existing gas, and gas from solar winds ([**?**, **?**, **?**]).

Alternate ways of forming seed black holes of perhaps 10^5 to $10^7 M_\odot$ have been investigated recently. Umemura, Loeb, and Turner ([**?**]) include inverse Compton coupling with the microwave background at redshifts above roughly 160 to dissipate angular momentum from partially ionized density fluctuations near the Jeans mass, allowing them to collapse. Eisenstein and Loeb ([**?**]) consider the statistical distribution of tidal torques for density fluctuations in different regions of protogalaxies; they find that the number of such regions that will have low angular momentum, and thus be able to collapse rapidly, is large. The estimated density of massive black holes formed by such collapses is comparable with or larger than the density of bright galaxies.

It is also of interest to consider ways in which binaries containing massive black holes with masses in the range of roughly 10^4 to $10^8 M_\odot$ may have formed. The possibility of detecting gravitational wave signals from such objects is discussed in the chapter of this volume for **Group G3**. It is generally believed that mergers of pre-galactic structures occurred frequently at earlier times, and binary black holes could result if black holes had already formed in each of two merging structures. Studies to investigate the conditions under which the black holes will spiral together in less than a Hubble time are in progress. Another possibility is that a compact star in the density cusp around a massive black hole will become so tightly bound that it will lose a few percent of its rest energy by gravitational radiation before it plunges in. Observations of gravitational wave signals from sources involving massive black holes would give information about the demographics of such objects and about their surroundings.

Primordial Black Holes

Members of this last class of black holes form from primordial density perturbations, either directly, through bubble collisions, or from the collapse of cosmic loops. These black holes will evaporate in

$$\tau = 10^{10} \left(\frac{M}{10^{15}\mathrm{gm}} \right)^3 \text{ years} . \tag{1}$$

1.3 Indirect Observations of Black Holes

The current challenge is to find incontrovertible observational evidence of black holes. This is difficult because of the well-known facts concerning the inability of radiation, or information of any kind, to escape from within the Schwarzschild radius of a black hole. Nevertheless a number of viable proposals have been put forth to detect and characterize black holes through the behavior of matter in their vicinity. Two effects that have been examined so far are the orbital motion of a star around a black hole (see Section **??**), and luminosity variations on the short time scales associated with material orbiting just outside the Schwarzschild radius and/or falling into the black hole (see Section **??**).

For example, basic physical considerations ([**?**], [**?**]) indicate that matter in the vicinity of a black hole will form into a disk, which gradually feeds material into the central maw. In the meantime, however, the hot gas in the disk will radiate energy that readily escapes the system and can reach an observer. This release of energy can be extremely efficient, as the potential energy that can be released, or "binding energy," is $0.057Mc^2$ for a nonrotating black hole and $0.42Mc^2$ for a maximally rotating black hole. The material can come from a companion star in the case of binary systems (stellar wind or Roche lobe overflow), or from material surrounding the galactic nucleus in the case of supermassive black holes. The resulting luminosity is on the order of

$$L_{nr} \approx (3 \times 10^{36}\text{ergs/sec})\ \frac{\dot{M}}{10^{-9} M_\odot/\text{year}} \tag{2}$$

for a nonrotating black hole, or about 10 times more for rotating black holes. Section **??** gives more detail about the structure of disks around black holes.

A second approach is to try to sense the gravitational potential of unseen black holes in galaxies, by observing brightness and radial velocity profiles in the central regions of galaxies (see Section **??**).

In the case of black holes that happen to be in binary systems, it should be possible to deduce the presence of a black-hole companion by studying the motion of the visible component of the system. Further, one can hope to weigh the black hole, although in practice one determines only the *optical-mass function*, which provides a lower limit on the mass (see Section **??** below).

2. Observations

This section reviews the ways in which optical, x-ray, and γ-ray observations are being used to probe the Universe for the presence of black holes.

2.1 Optical Observations

Historically, optical observations of x-ray sources have led to the identification of most of the currently viable black-hole candidates.

Dynamical Measurements of Binary Systems

In view of the notion that black holes are the natural end-product of stellar evolution, it is reasonable to expect that many such objects will be members of binary systems, in which the other star has not yet evolved into its final state. This is fortunate, because a binary system is an ideal place to seek the effects of the gravitational field of an otherwise unseeable black hole. The basic idea is to try to find evidence for the presence of a star that should be visible were it an ordinary star, but which is not seen.

To rule out the possibility that the unseen star is a neutron star, it is necessary to show it to have a mass larger than the theoretical upper limit for neutron star masses, namely about 3 $M_\odot$. So the observational problem becomes that of establishing a large lower limit on the mass of unseen binary companions, as was firstly proposed by Zel'dovich in 1965 [**?**]. (Naturally this method cannot be effective at the detection of black holes that happen to have masses less than this limit.)

As is known from classical binary star studies, if one can measure the period and inclination of a binary orbit, plus the radial-velocity amplitudes due to the orbital motion of each star, then the sum of the two masses is determined. Various other considerations can lead to estimates of the mass ratio, and thence of the individual masses. The motion of a black hole cannot be directly observed. (However, it can be inferred by observations of radial velocity lines in the surrounding accretion disk). It turns out that what is determined from observations of the motion of a visible star of mass M_{opt} in the presence of an unseen companion of mass M_X is the *optical mass function*:

$$f(M) = \frac{(M_X sin\ i)^3}{(M_X + M_{opt})^2} = \frac{PK_{opt}^3}{2\pi G}, \tag{3}$$

where P is the orbital period, K_{opt} is the semi-amplitude of the optical radial velocity variation, i is the orbital inclination angle, and G is the gravitational constant. This observable provides a lower limit on M_X, because no matter what M_{opt} or the inclination are, it is always true that

$$M_X \geq f(M). \tag{4}$$

The main observational uncertainty comes from the radial velocity amplitude, K_{opt}, which can be affected by x-ray heating, tidal distortion, non-synchronous rotation of the companion, and spectral contamination due to the surrounding gas and disk. On the other hand, P is most often known more accurately than is G!

If the lower limit (**??**) is not good enough, then it may be possible to provide an actual estimate of M_X by determining the approximate value of M_{opt} and i, but there are almost always rather large uncertainties in these values.

The best cases for the existence of stellar-mass black holes at present are the binary x-ray sources ([**?**]). The presence of a large (10^{38} ergs/sec) and rapidly variable x-ray source implies the presence of an object at least as dense and massive as a neutron star. In many cases the optical mass function and additional data imply that the unseen mass $M_X > 3.2\ M_\odot$, the limit necessary to establish that the star should have collapsed to a black hole. It is important that a system not exhibit bursts or pulsations, which are tell-tale signs that the star is a neutron star. Appendix A contains a list of black-hole candidates, most of which are the kind of system just described.

Cygnus X-1 is the best-studied case and considered by some to be the best hope for conclusively establishing the existence of a black hole. The optical companion has been identified, and detailed studies of the millisecond variability of the x-ray emission from this system provides some further positive evidence (Section **??**; [**?**, **?**, **?**, **?**]).

Two systems in the Large Magellanic Cloud are also good black-hole candidates. LMC X-1 may be similar to Cyg X-1, in that its companion is more massive than the unseen object, but uncertainty of the identification of the companion star and the presence of a surrounding nebula of ionized gas provide complications. ([**?**, **?**]). LMC X-3 is interesting in that the x-ray star is more massive than its optical companion. No "normal" star can hide in this system, as it would outshine the companion, which is a B star ([**?**, **?**, **?**, **?**, **?**, **?**, **?**]).

There is a class of objects called *x-ray transients* – detected only a small fraction of the time that their position has been observed by one or another x-ray telescope. In some cases the presence of short time-scale bursts or pulsations implies that the compact star is a neutron star, but otherwise it is possible that the x-ray source is a black hole. The systems A0620-00, Nova Muscae 1991, and V404 Cyg are examples of such. There is a considerable body of observational evidence on these cases (for A0620-00: [**?**, **?**, **?**, **?**, **?**, **?**, **?**, **?**]; for Nova Muscae 1991: [**?**, **?**, **?**, **?**]); for V 404 Cygni: [**?**, **?**]).

In summary, there are six good candidates for binary systems containing stellar mass black holes, as shown in Figure 1, based on [**?**]. Three systems (Cyg X-1, LMC X-1, and LMC X-3) are persistent x-ray emitters with massive ($> 5M_\odot$) companions. Three systems (A0620-00, Nova Muscae 1991, and V404 Cyg) are transient x-ray sources with low mass ($<\ 3\ M_\odot$) companions and bright accretion disks. The actual mass determinations are uncertain, and depend sensitively on the assumed relationship between mass and luminosity, the fraction of the Roche lobe which is filled, the assumption of synchronism of the stellar rotation, the contribution of the disk and gas to the optical luminosity of the system, and the details of the stellar evolutionary history of the system.

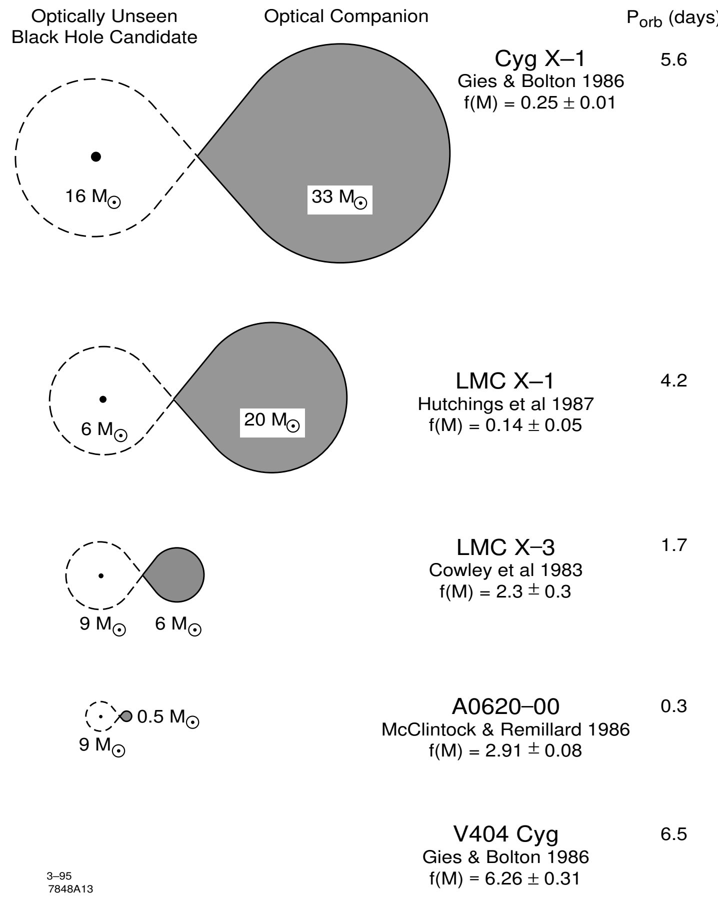

Figure 1: Sketches of the orbital configurations for six of the leading black-hole candidates.

Kinematics of Galaxy Cores

As mentioned earlier (Section **??**) the gravity of unseen black holes in galaxies will produce central cusps in the distribution of mass, characteristic features in radial velocities of stars near the singular nucleus, and perhaps other observable effects. Figure 2 reveals details of both a brightness cusp and large, asymmetric Doppler shifts near the center of M 87. These Hubble Space Telescope (HST) ([**?**, **?**]) observations of unprecedented spatial resolution provide perhaps the strongest evidence at present in favor of the existence of supermassive black holes in at least some nuclei of ordinary galaxies— i.e., those that are not currently violently active.

There are also observations of brightness cusps and increased velocity dispersion at the centers of other relatively nearby galaxies. One important case is M 32, where HST observations of the brightness cusp ([**?**]) can be interpreted most easily as due to a $3 \times 10^6 M_\odot$ black hole. M 31 is more complicated because it shows two cusps ([**?**]), but is consistent with the existence of either one or two massive black holes. Since M 32 and M 31 are both in the Local Group, and since there are only four spirals or ellipticals other than the Milky Way which are as luminous as M 32, the statistics are of strong interest. If it turns out that both of these galaxies do indeed contain massive black holes, this would suggest that a substantial fraction of all ellipticals and spirals above a certain size may contain such objects.

Another important source of observational information concerning the amount of matter in massive black holes comes from the integrated light of quasars ([**?**, **?**]). From the amount of matter that has to have been fed in to produce the light, at least 3×10^{-5} of all the baryons in the universe are contained in massive black holes.

2.2 X-ray Observations

This section reviews the x-ray observations that contribute evidence for the existence of stellar-mass black holes. Good references for this material are [**?**, **?**]. It is clear that there is no clean division based on wavelength. x-ray observations are important in interpreting the optical data on binary systems, as discussed in the previous subsection.

Here we concentrate on the evidence provided more or less directly by the x-ray variability and spectral data. A large amount of observational and theoretical work has led to the standard model for binary x-ray sources, in which mass flows from one star and accretes onto the other, which is presumed to be a compact star with a deep gravitational potential well. Figure 3, adapted from Figure 25.2 of [**?**], shows such an effective potential for the motion of a test particle in the Schwarzschild geometry of a concentrated mass.

In most cases the gas forms a repository in the form of a flat disk centered on the compact star, but may also flow more or less directly onto it. This process yields irregular luminosity fluctuations associated with the unsteadiness of the flow of gas onto the disk, the inhomogeneity of the disk itself, and perhaps most important the disordered way in which the gas at the inner edge of the accretion disk falls into the compact central object. While some of the variability and spectral properties of these accretion systems may be independent of the nature of the compact star, there is good reason to hope that distinctive features can be found that will serve to identify it—as a black hole, neutron star, or white dwarf.

The primary observational handle on this kind of system is through measurements of the time variability of the emission, presumably connected with the unstable, turbulent flow patterns described just above, and its spectrum—which, by virtue of the high temperatures generated by the dissipative processes in the disk, is concentrated in the x-ray part of the spectrum. Figure 4(a) is a cartoon of this kind of accretion flow for a neutron star system, but could just as well depict that for a black hole. Figure 4(b) is a similar sketch of a possible scenario for accretion and the formation of jets in active galactic nuclei, or AGNs (see Section **??**).

As described in Section (**??**), complete dynamical models of accretion disks are now being constructed, and comparison of detailed predictions with high-quality observations will be possible in the foreseeable future.

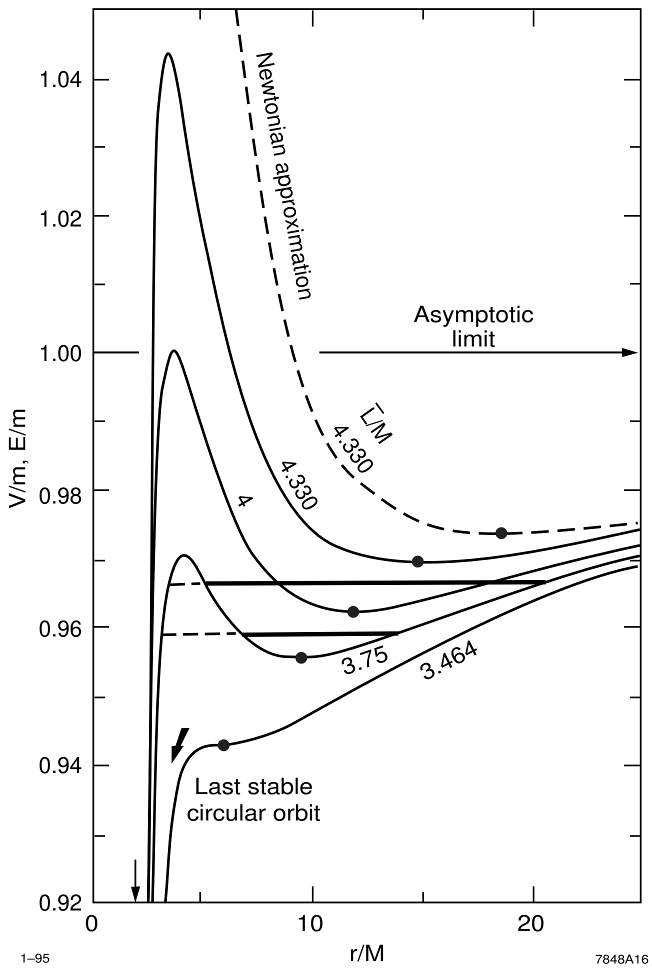

Figure 3: Plot of the effective potential for the motion of a test particle around a nonrotating black hole.

2.3 γ-Ray Observations

The Burst and Transient Source Experiment (BATSE) of GRO was designed to obtain light curves and spectral information about the so-called γ-ray bursts that had been discovered earlier by the Vela nuclear surveillance satellites, as well as any other transitory sources of γ-ray radiation.

Since BATSE continuously monitors the whole sky, it provides reasonably accurate ($\sim$0.2 deg) positional data as bright sources pass behind the limb of Earth and allows investigation of spectral and temporal changes in the detected sources. The BATSE Occultation Team ([**?**, **?**]) has used the long-term light curves and spectral information provided by this technique to study black hole

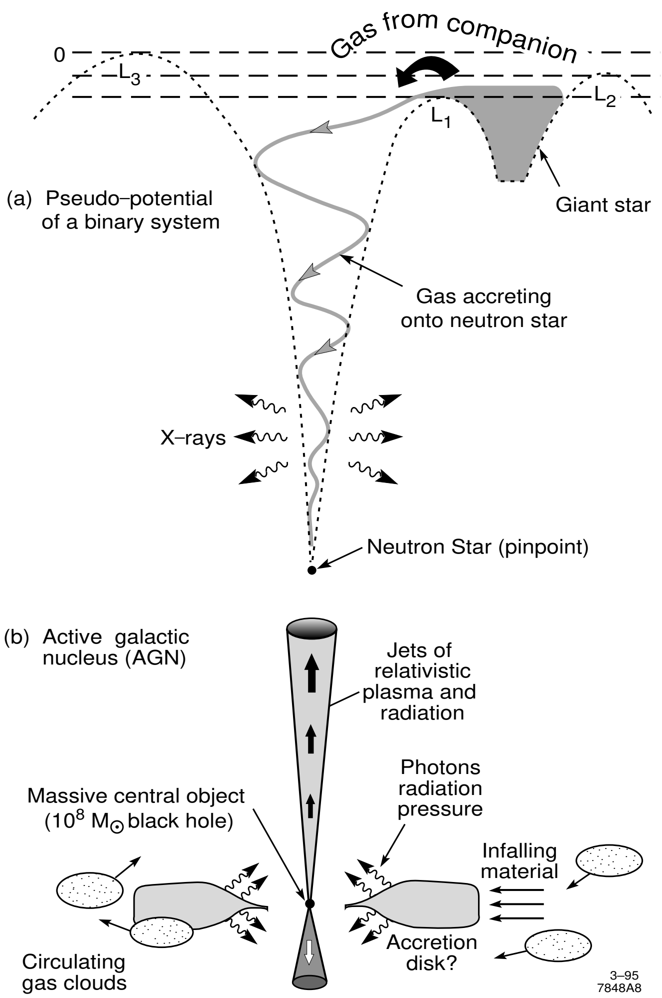

Figure 4: (a) Sketch of the potential due to an ordinary giant star and a companion neutron star, showing how gas from the giant falls into the well around the compact neutron star, emitting x-rays. (b) Sketch of the accretion disk and jet emanating from the nucleus of an active galaxy.

candidates over the whole sky. The results are limited to relatively bright objects, and there is potential for source confusion.

These observations are important because they provide information about aspects of black-hole candidates that are not well understood, and in particular, the hard x-ray and gamma-ray emission in the ~10-keV to 1-MeV energy range. It is not certain where the high-energy emission originates, but generally it is thought that optically thin regions are responsible, either in the disk, such as in the inner region close to the black hole, or nearby, as in a disk corona or in cooling clouds. The extreme spectral variation within a single source and large changes in luminosity (4 or more orders of magnitude) strongly suggest that we may be dealing with more than one emission region.

The greatest success in describing the high-energy spectrum of black-hole candidates has been achieved by invoking inverse Compton scattering of soft photons in hot-electron plasmas [?]. This model has worked well for Cygnus X-1, and can describe the complex changes in the high-energy portion of the spectrum [?]. Broad-band spectra of Cygnus X-1, including soft x-rays, however, show that relativistic corrections should be incorporated into the Comptonization model. A more general analytical form has been developed recently by Titarchuk [?].

The spectral behavior in "persistent" black-hole sources, such as the appearance and evolution of the spectra, and the transitions between the so-called high and low states, are also present in the black-hole candidates which are transient x-ray sources. This is a comforting observation, in that there is significant overlap between the black-hole candidates deduced from optical studies as described in Section ??, and those solely identified on the basis of their broad-band x-ray behavior (see Appendix A) regardless of their persistent or transient nature. So far, however, it has been a difficult task to relate our standard physical and geometric picture of x-ray binary sources to the sudden appearance of the high-energy emission and the variable behavior observed in the growing database of transients. It is presumed that the transient outbursts are due to instabilities in the mass transfer or in the accretion disk itself, but a complete understanding of these systems remains as a future goal.

BATSE and the other GRO instruments are collecting observational data that is starting to elucidate these matters. We now summarize some of the empirical results on the light curves and spectra of the black-hole candidates that have been observed so far.

The ultrasoft or soft x-ray transients, sometimes called x-ray novae because of the resemblance of their light curves to those of classical novae, usually have a fast rise of about 1–7 days in the hard x-ray band. The spectral evolution and light curves vary from source to source; Nova Persei 1992 had an exponentially decreasing x-ray intensity following the primary maximum, with a time constant of approximately 40 days, and persisted in hard x-rays for nearly 8 months–see Figure 5. In contrast, the x-ray emission from Nova Ophiuchi 1993 (also shown in Fig. 5) had a very slow decay (time constant in excess of 300 days) for about three months, then decreased rapidly over a period of one week to being nearly undetectable with BATSE. Long-lived secondary maxima in x-ray emission (lasting several weeks to months) have appeared in several of the nova transients, such as Nova Muscae 1991, Nova Persei 1992 (the secondary peak of the latter also decayed exponentially), and most recently in X-ray Nova Ophiuchi 1993. There may be subtle spectral changes associated with these secondary maxima, but the

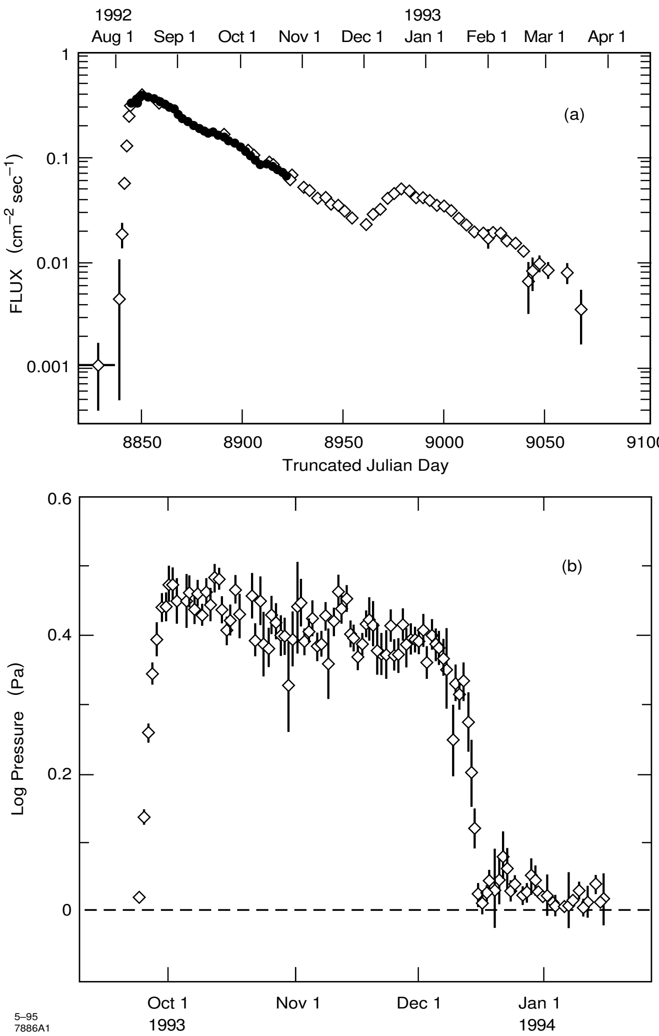

Figure 5: Light curves for (a) Nova Persei (= GRO J0422+32) and (b) Nova Ophiuchi (= GRO J1719-24 = GRS 1716 - 249).

changes occur over long periods of time and will have to be studied further. Other objects such as Nova Vel 1993 and 4U 1543-47 had rather short-lived primary maxima, with time constants on the order of 2 to 10 days, and spectra that first soften, then harden much as with Nova Persei 1992.

Other transients with notably hard spectra that resemble those of the stronger black-hole candidates, such as GX 339-4 and GRS 1915+105, do not exhibit the fast rise to maximum intensity of the x-ray novae. It is not known what causes this difference in the appearance of the light curves. The hard-state outbursts of GX 339-4 observed by BATSE in 1991, 1992, and 1993–94 are very similar in intensity, duration and intervals, which suggest an underlying "clock" governing when outbursts may occur. GRS 1915+105, first becoming visible in BATSE data in May 1992, is extremely variable and has been visible in hard x-rays for over two years. It has also been recently identified with the source of superluminal matter ejection (apparent velocity exceeding the speed of light) as observed in high-resolution radio interferometry measurements [**?**]. This is the first galactic source of its kind to exhibit superluminal motion in jets similar to those well-known in active galaxies and quasars. In contrast to the bright x-ray novae, which may have outburst repetition rates of one per decade or even lower, GX 339-4 and GRS 1915+105 seem to have higher "duty" cycles, and may help us to understand better the driving mechanism behind the transient behavior.

EGRET Observations

The Energetic Gamma Ray Experiment Telescope (EGRET) on the Compton Gamma Ray Observatory has the highest energy band of all the GRO instruments ($> 50MeV$), and can localize a strong point source to 5 to 10 arcminutes. We now summarize what has been learned with this instrument about the spectra and time dependence of active galactic nuclei (AGN).

Curiously, many nearby active galaxies, including Seyferts and some prominent blazars, have not been detected at all in high-energy γ-rays. Of the extragalactic sources which are detected, most are quasars and five are BL Lacertae objects. They lie at a wide range of distances, with redshifts from 0.03 to 2.17.

In many of these sources the energy in the γ-ray band, say above 100 MeV, is much larger than the total energy received in all lower bands—and ranges from 10^{44} to 10^{49} ergs/s. This range corresponds to possibilities for the geometry of the emission—principally, whether or not the source is beamed. The spectra in the EGRET energy range are generally well-represented by power laws, with photon-spectral indices ranging from -1.6 to -2.6. In some cases there is a suggestion of steepening of the spectrum at the highest energies observed.

Many of the sources exhibit variability, with the γ-ray flux varying by a factor of 3 in a few days in some cases. The most dramatic case of such variability is 3C 279, which displays enormous changes in luminosity, in intervals possibly as short as a few days.

There are a variety of models for the emission of GeV radiation, most of which postulate the presence of a supermassive black hole at the center of the active nucleus. The emission mechanisms invoked include synchrotron self-Compton, inverse Compton scattering off external low-energy photon sources, and cascades initiated by electrons, protons, or heavy nuclei.

3. Interpretation of Observations

This section describes several of the crucial issues connected with the interpretation of astronomical observations of systems possibly containing black holes.

3.1 Differentiation Between Black Holes and Neutron Stars

One of the key observational difficulties is the possibility that objects suspected as black holes from considerations summarized in Section **??** above, may in fact be neutron stars, and vice versa. In binary star accretion systems, direct observations of the compact component are hindered by the presence of the other star and the disk. The gravitational fields produced by a black hole and a neutron star of the same masses are largely indistinguishable at the distances at which the companion and the disk lie from the center of the compact object. The optical-mass function can be used to identify black holes that greatly exceed the theoretical mass limits (see Section **??**), but the case of smaller masses is much more difficult.

This section outlines, for the best black-hole candidates and firmly identified neutron stars, some observed characteristics that may serve as definitive (or at lease useful) discriminants between these two kinds of compact stars. These considerations are useful to the extent that there is a plausible theoretical explanation of the observed phenomenology, based on known physical properties of these two types of star.

Currently we find clues to the identity of the compact star in gross features of the time-dependence of the radiation from the system: bursts, pulses, quasi-periodic oscillations (QPOs), and transient flares, to name the most important ones.

Type I x-ray bursts seem to be positive proof that the object is a neutron star, but not all neutron stars exhibit them. Similarly, neutron stars can be pulsars, but black holes cannot. While the electrodynamics of a rotating black hole embedded in a messy magnetized plasma environment is not rigorously understood—nor is that of an ordinary neutron-star pulsar—it seems unlikely that a black hole can function as a pulsar.

The phenomenology of QPOs is rich in features that are probably diagnostic of details in the accretion flows (see, e.g., [**?**]). However, in the absence of more definitive observational studies and detailed dynamical models of the accretion process (see Section **??**), QPOs are not yet definitive diagnostics.

The phenomenon of a *superhump*, a bright extension of the normal dwarf-nova-like outburst behavior ([**?**]), is thought to be due to a temporary enhancement of the accretion (and therefore luminosity) due to a tidal instability. Theory indicates that superhumps are easily produced by massive black holes, but are difficult for neutron stars. Superhumps have been definitely been observed in Nova Muscae [**?**] and probably in A 0620-00 [**?**].

Both neutron stars and black holes exhibit transient outbursts, but it may be possible to discriminate between them based on the recurrence times or other phenomena connected with the details of instabilities occurring within accretion disks. An interesting result from spectral studies such as Tanaka (1992) is the indication that the radius of the inner edge of the accretion disk is a constant, independent of the x-ray luminosity of the system, at about $3R_S$, three Schwarzschild radii. This can be associated with the last stable orbit around a black hole (see Section **??** and Figure 3).

Let us turn now to the phenomenology of the radiation spectrum. The indication from various studies is that the spectral signature of a black hole consists of the combination of an ultra-soft spectral component plus a power law, while that of a neutron star is a hard thermal spectrum, commonly assumed to be a Comptonized-thermal spectrum. This picture is a simplification in a number of ways. Some black-hole candidates (e.g., V 404 Cyg and Nova Persei 1992 = J 0422 + 32) have no soft component, and some neutron stars have power laws extending to > 100 keV, but only when the x-ray luminosity is below what may be a critical value, on the order of 10^{36-37} ergs/s ([**?**]). Figure 6 presents a summary comparison of the spectral (and timing) characteristics of various systems.

An important question is: what is needed if these important but mostly phenomenological and inconclusive considerations are to become definitive identity tests? The answer, we feel, is observations with broad coverage of wavelength (radio to γ-ray) and time variability (μ-second to decades), coupled with theoretical understanding of the physics of the accretion and radiation processes.

3.2 Wavelet Methods for Analysis of Timing Data

One of the features of the luminosity time series from most x-ray sources, including both the black-hole candidates and neutron-star accretion sources such as the low-mass X-ray binaries (LMXB's) is the presence of fluctuations on time scales that span a large range. Indeed, fluctuations are seen from the shortest time scales permitted by the observational time resolution, up to the longest time intervals over which the data are obtained (up to 10's of hours of continuous exposure, or the much longer intervals corresponding to the history of X-ray astronomy as an observational science). Hence we really have only limits on the total extent of the range of time scales.

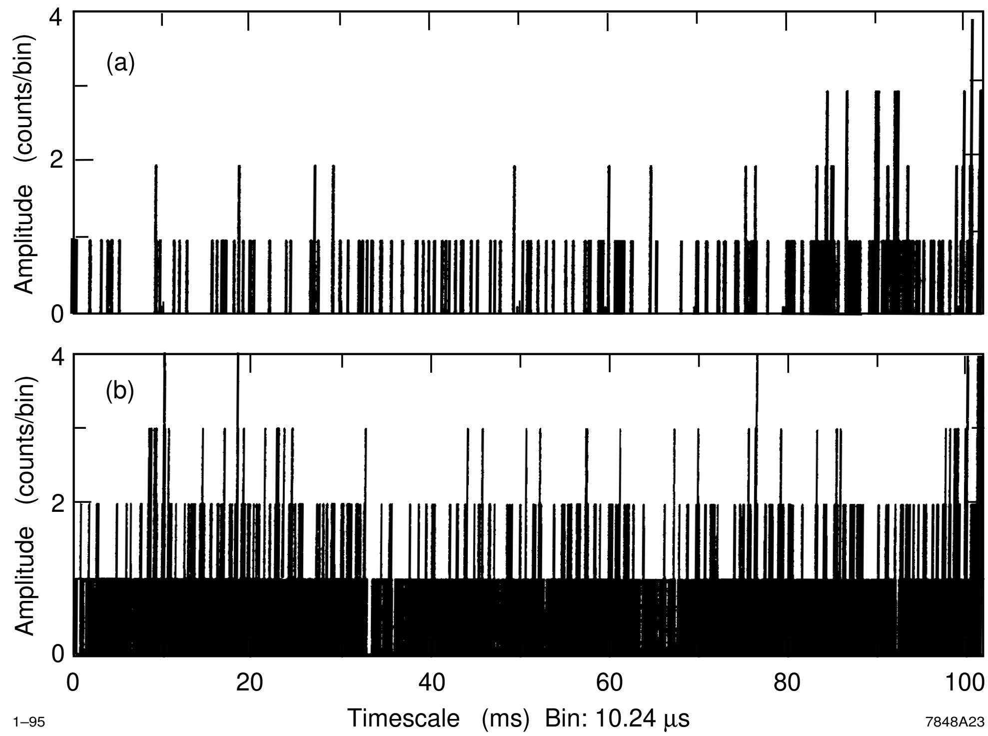

Figure 6: Table illustrating the characteristic spectral and power-spectral differences that differentiate black-hole candidates, low-mass x-ray binaries, and high-mass x-ray binaries.

The techniques of *multiresolution analysis*, and especially the special case of *wavelets*, are perfect tools for studying such data, as well as for representing solutions to the physical equations describing the dynamic evolution of the accretion process. This is because a wavelet basis forms a hierarchy of scales, with each scale level differing from its neighbors by factors of two. In particular, given a specific choice for the *mother wavelet* $\psi(t)$, the basis comprises this set of functions

$$\psi_{s,l}(t) = 2^{-\frac{s}{2}} \psi\left(\frac{t}{2^s} - l\right) \ , \tag{5}$$

where s is the *scale index* and l is the *location index.* Note that the width of the function $\psi_{s,l}(t)$ is proportional to 2^s; in data analysis applications the scale index s varies over a range of values so that the shortest scale is on the order of the interval between samples, and the longest scale is on the order of the total interval over which the data is sampled.

The representation of data, or of a function, as a linear superposition of the functions in the wavelet basis takes the form

$$X(t) = \sum_{s,l} c_{s,l} \psi_{s,l}(t) \ , \tag{6}$$

where the

$$c_{s,l} = \int X(t) \psi_{s,l}(t) dt \ , \tag{7}$$

are the wavelet coefficients of $X(t)$ with respect to the wavelets $\psi_{s,l}(t)$.

There are several key points. First, the wavelets are localized functions. They are non-zero only over a finite subrange of the total time interval over which the observations extend. This allows easy representation of localized features—jumps, discontinuities, or bumps in the data. Compare against the situation with Fourier components, where local features require the superposition and delicate cancellation of the completely global basis functions.

Second, the scales of the wavelets extend over the complete range—from the smallest scale (the sampling interval) to the largest (the sample range), and they do so in a convenient time-scale hierarchy in which the levels differ by a factor of two. Wavelets are thus perfect for representing data (or functions) that are *self-similar* (sometimes called *scaling* or *fractal*). This multi-scale feature can be achieved in Fourier representations by using a logarithmic frequency scale—but the weighting that wavelets naturally apply to the levels in their dyadic hierarchy often turns out to be more suitable to the signal-to-noise present in the time-series data.

Finally, there is a simple relationship between the size of the wavelet coefficients and the smoothness of the function they represent through Eq. (**??**). Basically, if you diminish the absolute value of some of the wavelet coefficients, you are guaranteed that the resulting function $X(t)$ will be smoother than it was. (The relationship between smoothness and the size of the expansion coefficients does not hold in Fourier analysis.) The practical result of this is a cornucopia of denoising and smoothing algorithms based on truncation or "shrinkage" of the wavelet coefficients ([**?**]). A *denoising* procedure is a way of correcting data for the presence of noise of known or assumed character. Wavelet denoising methods are particularly good at removing noise without smoothing out edges, bumps, or other localized features in the data.

A simple tool that has proven useful in analyzing stochastic data from x-ray sources ([**?**]) is the wavelet analog of the power spectrum, sometimes called the *scalegram*. If the $C_{s,l}$ are the wavelet coefficients of some discrete data X_n, defined much as in Eq. (**??**) for a continuous function $X(t)$, then the scalegram of these data is defined to be

$$V^X(s) = \frac{S}{N}\sum_l (C_{s,l})^2, \tag{8}$$

where the l-sum is over the allowed values at scale s.

The scalegram can be easily corrected for the Poisson noise present in x-ray data, as in any photon counting data. A simple computation shows that the scalegram of time-series data subject to an additive normally distributed observational noise of variance σ_R (usually zero in x-ray astronomy), plus Poisson noise (due to the statistics of counting a finite number of photons), satisfies

$$E[V^{X_{obs}}(s)] = V^{X_{true}}(s) + \sum_n X_n^{true} H_j(n) + \sigma_R^2 \ ; \tag{9}$$

$H_j(n)$ depends on the wavelet used, and is just $\frac{1}{N}$ (independent of both n and j) for the Haar wavelet. Thus the scalegram of x-ray data can be corrected for counting statistics simply by subtracting the mean count rate—a very good estimate for the correction term in this equation.

Further, the scalegram can be evaluated for time series data that are arbitrarily spaced in time, including point process data (e.g., for such data as the arrival times of individual photons).

Putting all of these features together, the scalegram and related tools seem to be very well-suited for studying fluctuations of x-ray sources on the shortest possible time scales. This is the kind of information that is needed for identification and characterization of black-hole accretion. The next section discusses the attempt to analyze HEAO data on Cygnus X-1 for this very signature.

3.3 Millisecond Time Variability in Cygnus X-1

The accretion of matter onto black holes is almost certain to be accompanied by rapid and violent fluctuations in luminosity. Although no definitive and reliable theoretical models of the accretion process yet exist—see Section (**??**)— the expectation is that there will be fluctuations on a broad range of time scales, all the way down to the approximate-millisecond scale associated with the dynamical time expected for accretion onto the black hole itself (millisecond). In addition, if the luminosity comes from blobs of gas that are in orbits around the central black hole, one would expect the power spectrum to contain these orbital frequencies. This would then lead to a truncated "chirp" signal— the frequency rising as the blob spirals into the maw, but abruptly cut off as it passes through the last such stable orbit.

An attempt to study the short-time scale behavior of a black-hole candidate has already been made ([**?**]—see also earlier work in [**?**, **?**, **?**]), for the bright x-ray source Cygnus X-1. Meekins et al., (in [**?**]) constructed a special algorithm to deal with the problem that variability on longer time scales voids the assumption that the short-time-scale fluctuations are a constant-mean Poisson process. In effect, fluctuations on longer time scales may leak into the measured power at shorter time scales. These authors constructed an "equivalent power" from the comparison of the actual and expected χ-squared values. Figure 7 shows their plot of this power as a function of time scale. Note that there is strong evidence for a cutoff in the power at around 1 ms, in qualitative agreement with the picture described above.

As described above, in Section (**??**), wavelet techniques in general, and the scalegram in particular, are likely to be of great use in this kind of problem. Scargle, in unpublished work carried out at this workshop, demonstrated such an approach using synthetic data generated to be much like the actual Cygnus X-1 data analyzed by Meekins et al., in terms of its signal-to-noise, sampling, etc. The data consisted of a chirp signal as described above, truncated at the frequency corresponding to the 1 millisecond cutoff found by Meekins et al., and then made noisy by sampling it as a (Poisson-distributed) photon process with the same mean

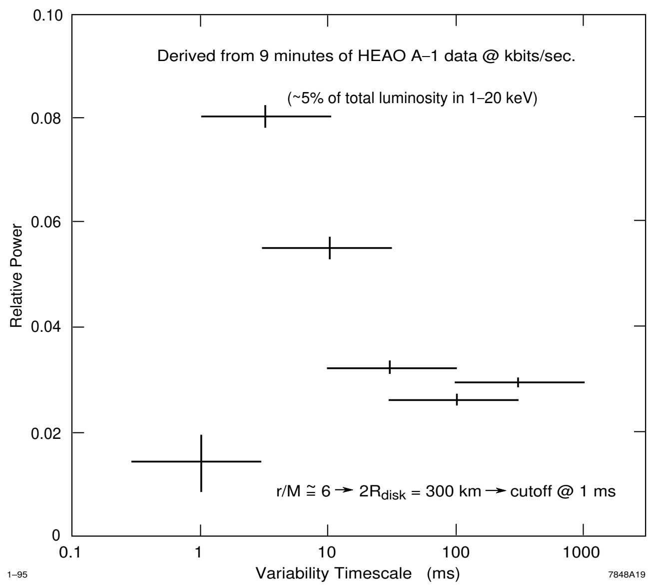

Figure 7: Plot of the power (derived from a χ-squared analysis by Meekins and coworkers, from special high-time resolution data on Cyg X-1 by HEAO). This analysis shows that the intrinsic variability of this black-hole candidate extends down to a few ms, but then cuts off at around 1 ms—as expected from the accretion of blobs into a black hole.

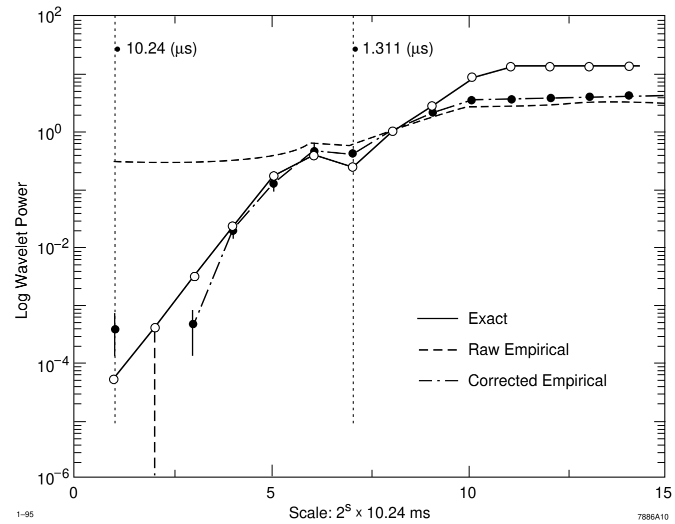

Figure 8: Plot of the wavelet power vs. time scale index, or *scalegram*, for synthetic data with the same signal-to-noise as the Meekins et al. data for Cyg X-1 discussed in the caption to Fig. 7. The synthetic data consisted of randomly occurring chirp signals—cutoff at frequencies above about 1 kHz (time scale = 1.311 ms), to mimic a signal like that possibly present in Cyg X-1. The scalegram shows a steep cutoff starting at about this cutoff (1 ms) and extending down to possibly on the order of 10 μ sec. The solid line with open circles is the scalegram of the known chirp signal, the dashed line is that of the synthetic noisy data, and the solid line with filled circles is this empirical scalegram corrected for the presence of Poisson noise in the data.

arrival rate as in the actual observations. Figure 8 shows that the scalegram not only senses the cutoff at around 1 millisecond, but also faithfully tracks the known ("true") scalegram of the underlying process for time scales at least an order of magnitude smaller.

In the near future we plan to reanalyze this HEAO data [obtained on May 7, 1978 with the NRL Large-Area Sky Survey instrument (A-1)] with the scalegram technique. These and other new techniques will be used to probe the short-time scale variability of the black-hole candidates that will be observed by new x-ray timing experiments—see Section **??**.

3.4 Models of Accretion Disks

It is clear from our discussions of the observational issues that future progress in the search for black holes will be based on improved theoretical understanding of both the structure and time-variability of accretion, directly and via disks, onto compact objects. We need to study the differences between accretion onto black holes, neutron stars, and white dwarfs.

As with stellar structure, the starting point is the merging of a body of observational data relevant to the physical conditions (spatial distribution, temperature, large scale motions, and ionization/excitation of the gas) with mathematical representation of the relevant fundamental physical laws.

An understanding of the average, or time-independent, equilibrium configuration of the accretion systems begins with the structure equations:

1. Hydrostatic equilibrium in the vertical direction
2. Conservation of angular momentum
3. Energy balance: Bremsstrahlung and Comptonized Bremsstrahlung cooling, and energy exchange between protons and electrons
4. Pair Balance
5. Pressure = f(temperature)

Theoretical analysis of accretion disks by solving such structure equations is a problem of current interest (see [**?**, **?**] for overviews, and [**?**, **?**, **?**, **?**, **?**, **?**, **?**, **?**, **?**, **?**, **?**, **?**, **?**] for detailed results).

Thermal instabilities have been found in a number of cases (e.g., because the ionization of hydrogen causes a very sensitive dependence of opacity on temperature at $T \sim 6,000K$). The resulting instability modulates the x-ray flux from the inner disk. Scargle and co-workers [**?**] have developed a simple dynamic model, called the "dripping handrail," for accretion that produces both quasi-periodic oscillations and low-frequency noise as different aspects of the same physical process. They arbitrarily assumed the existence of a density threshold that may be produced by the kind of instability just discussed, or the basic orbital instability close to the central black hole. Mineshige and co-workers ([**?**, **?**]) have similarly developed dynamic models based on the so-called sandpile models of self-organized criticality, which has many of the same properties as the dripping handrail. In particular, both these models explain the apparently stochastic behavior of the system as intrinsic to its dynamics, without the need to postulate the existence of some kind of random process—such as a random accretion rate.

4. The Future: New Missions

Since x-ray time-series data is so important for probing black-hole candidates, more data with better signal-to-noise and time resolution is needed. Fortunately, two future space missions should provide such "timing" data in the next few years.

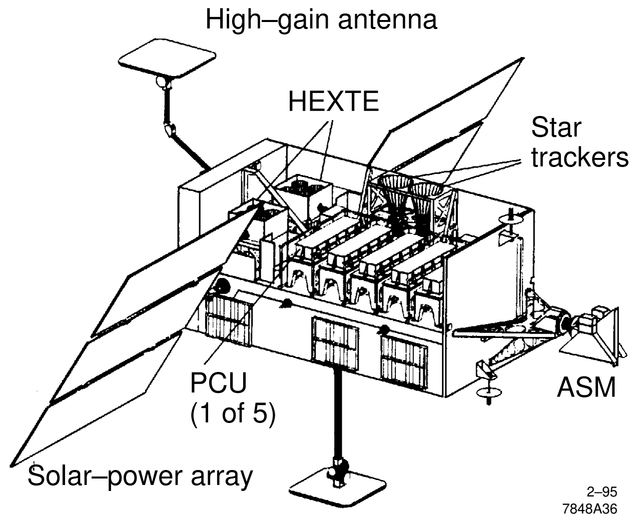

Figure 9: NASA's X-Ray Timing Explorer Satellite (XTE).

4.1 X-Ray Timing Explorer

The X-Ray Timing Explorer (XTE) shown in Figure 9 has been designed to study many of the problems decribed in this report. XTE is a NASA mission scheduled to be launched in late 1995. The instruments on XTE are a collaboration of Goddard Space Flight Center, Massachusetts Institute of Technology, and University of California San Diego. It will make pointed observations with both large-, medium-, and high-energy detectors (2 keV–200 keV), and scanning observations with a smaller all-sky monitor. The pointed observations will be selected by NASA peer review from proposals submitted in response to a NASA Research Announcement. The large-detector area, data acquisition, and telemetry have been specifically designed for high-resolution timing and high x-ray photon count rates.

XTE will have the following scheduling features for scientific reasons: sources more than 30^o off the ecliptic can be observed at any time. Time-constrained observations will be supported, e.g., in order to observe objects at specific epochs, to allow participation in collaborative multi-wavelength observations, and for repeated observations. There will be provision to monitor given sets of objects, such as active galactic nuclei or Be binaries, with short observations. Transients will be observable with the pointed detectors within seven hours of detection by the all-sky monitor or notification from another observatory.

Studies to be carried out by XTE include the nature of black holes (including those that may be in active galactic nuclei), neutron stars, and white dwarfs—their interactions with their environs, the systems in which they are formed,Fappen and their ultimate fates. Objectives will include, where appropriate, interior composition and properties, and relationships between magnetic and rotation axes. Of special interest are radiation generation mechanisms, disk and wind instabilities, x-ray transients, end points of binary system evolution, and formation of the x-ray background due to cosmologically distributed active galactic nuclei.

For more details about XTE see the World Wide Web at this URL:

http://heasarc.gsfc.nasa.gov/0/docs/xte/xte.html

or contact the Project Scientist Jean Swank at this Internet address:

swank@lheavx.gsfc.nasa.gov.

4.2 USA

The Unconventional Stellar Aspect (USA) depicted in Figure 10 has also been designed to study problems described in this report. A collaboration of the Naval Research Laboratory and Stanford University scientists, with representation also from NASA-Ames, Sonoma State University, the University of Oregon, the University of Washington, the University of Calgary, and Saddleback College, USA is scheduled for launch on the ARGOS satellite in early 1996. It is designed to make long, pointed observations of selected sources, with emphasis on lower x-ray energies. USA's 1 keV–30 keV energy range extends that of XTE toward low energies, where for many sources the count rates are larger. These instruments, as well as the data acquisition and telemetry systems, have been specifically designed for high-resolution timing—with a "workhorse" mode having 4-μs time resolution and 16 channels of energy resolution—and high x-ray photon counts.

The scientific goals of USA include many of the same as listed above for XTE, but USA will be used in a largely different observation mode—namely dedicating large amounts of observing time to a few important objects. This will allow the elucidation of these black hole and neutron star accretion systems, and is scientifically complementary to the planned functioning of XTE as a general purpose x-ray timing observatory, to be used by guest investigators in a great variety of observing programs.

For more details about USA see the World Wide Web at this URL:

http://xweb.nrl.navy.mil/www_hertz/ usa.html

or contact the Project Scientist Kent Wood at this Internet address:

wood@ssd0.nrl.navy.mil.

4.3 Prospects for the Future

The developments summarized above lead to the conclusion that identification of black holes with a great degree of certainty is not far off. The observational case for many or all of the binary black-hole candidates listed in Appendix A is growing stronger as the data accumulate, in most cases. One must keep in mind, however, the caution provided by the failed black-hole candidates in Appendix B.

Theoretical understanding of the physical conditions and processes in accretion systems connected with black holes and other compact stars has also progressed.

In addition to improved optical, x-ray, and gamma-ray observations, gravitational wave detectors may give new information on black holes (see Chapter G-3). If ground-based detectors being built in the US and Europe reach their full sensitivity, which is well beyond the expected initial sensitivity, coalescence signals for neutron-star, black-hole binaries would be observable well beyond the Virgo cluster. A laser interferometer space antenna, such as the one being considered by the European Space Agency, would be able to look for and study signals from several types of sources involving massive black holes.

Acknowledgments

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