A Concise Primer on Stellar-Mass Black Hole Detection

Introduction

Stellar mass black holes were predicted by Oppenheimer and Snyder's 1939 paper detailing the collapse of massive stars, although it wasn't until the 1960's that researchers began the hunt for them in earnest. Nicknamed, "black holes" by Princeton's John Wheeler, these strange objects are highly compact superdense collapsed stars that allow only a small amount of radiation to escape from them and have a mass in excess of three times the mass of the sun[1].

In the past 15 years, a great deal of effort has gone into the detection of these elusive objects by the astronomical community[2]. Although black holes cannot be detected directly, their presence can be inferred by their gravitational influence on nearby stars, by their ability to strongly warp spacetime and by their birth signature.

Astronomers have been able to identify a growing number of likely stellar-mass black holes using a variety of techniques including analysis of X-ray Doppler-shifts, detection of high-speed jets, microlensing, and gamma ray burst study. In this essay, I will briefly outline these techniques.

Black Holes in Binary Systems

Many stars inhabit binary systems in which two stars orbit around their common center of mass. As viewed from Earth, if the plane of the orbit is edge-on (or nearly so), an observer would see a star approaching and then receding as it went around in its orbit. This orbital component of the star's velocity will show up in the spectrum of the star as a periodic shift in the wavelength of known spectral lines. Stars without orbital companions will not show this periodic shift, so any shift is evidence of a gravitationally linked companion. In the case where the companion is not visible, this shift is called a single line spectrum, and may be the only evidence of an invisible companion. Analysis of the magnitude and period of the shift, coupled with mass estimates of the visible star based on its spectral class lead to estimates of the mass of the invisible companion, as well as its orbital characteristics[3].

Figure 1: Binary System Mass Transfer
(http://www.fas.org/irp/imint/docs/rst/Sect20/A6.html1)

In a binary system where one of the stars (A in figure 1) is a late stage red giant with a bloated envelope, the other star (B in figure 1) would accrete matter from the giant onto its surface. As the in-falling material adds to the mass of the accreting star, the gravitational force that acts to collapse the star overwhelms the outward pressure of its thermonuclear radiation and the star collapses onto itself. If the accreting star's mass is greater than 3 solar masses (3M☉), the collapse is complete, and all the remaining matter is in the form of a

[1] Lindley, David, 2007, Physical Review Focus, Landmarks: Forgotten Black Hole Birth, http://focus.aps.org/story/v13/st23
[2] A search on "stellar mass black hole detection" on the Smithsonian/NASA Astrophysics Data System yielded 1385 papers.
[3] Kolena, John, 2007, Detecting Extrasolar Planets and Black Holes, http://www.phy.duke.edu/~kolena/invisible.html

superdense clump that warps spacetime so radically that nothing can escape the gravitational well that is created[4].

The resulting black hole is a small, dark object that would be quite difficult to detect. As matter from the donor star continues to fall towards the black hole, it collects in an accretion disk and is accelerated as it spirals inward toward the event horizon (the gravitational point of no return). Tidal forces (unequal forces on each part of an object because of their differing distances from the center of mass) stretch and heat the in-falling matter causing it to emit energy, some in the form of X-rays. High temperature bi-polar jets of very high velocity matter stream outwards from the axis of the accretion disk.

Detecting binary stellar mass black holes (SMBH) should then be a matter of surveying single line spectra of binary systems with spectral line shifts commensurate with companion object masses in excess of 3M⊙ that also coincide with X-ray sources.

Detection of the First Stellar-Mass Black Hole

X-rays are highly attenuated by the earth's atmosphere, so their detection had to wait until detectors were placed in orbit. Bowyer et al (1965) discovered several X-ray sources by mounting crude detectors on Aerobee rockets that briefly visited the upper reaches of the atmosphere before returning to earth. Cygnus X-1 was the brightest of these sources. The 1970 launch of the UHURU satellite with a detector resolution greater than a few square arc minutes[5] pinpointed the location of X-1 closely enough for Bolton (1971) to link its periodic X-ray variability with the similar periodic changes in the spectral lines of the ninth magnitude star HD226868. Using the star's spectral class and luminosity, Bolton determined that the star had a mass of 12 M⊙, with an orbital period of 5.6 days. Using this data, he calculated that the X-ray emitting companion's mass must be greater than 3 M⊙. Any star that massive should have been visually detected. Based on this evidence he postulated that the X-rays were produced by the accretion disk of a black hole orbiting around the star (Bolton 1972).

Recent studies of Cygnus X-1 have shown the black hole mass to be on the order of 8 M⊙ (Shaposhnikov & Titarchuk 2007) and Bolton's assessment of the system is still widely accepted.

The list of binary system SMBH candidates continues to grow as detectors improve[6]. The strongest candidate is V404 Cygni; based on its 6.5-day orbital period, estimates of the black hole's mass are between 8 and 15 M⊙ (Casares et al. 1992).

Decaying Pulse Trains

As the in-falling matter accretes on the disk surrounding a black hole it begins to spiral inward slowly towards the event horizon. Matter very close to the event horizon is in an unstable orbit: periodically, clumps of matter break off of the accretion disk and quickly tumble

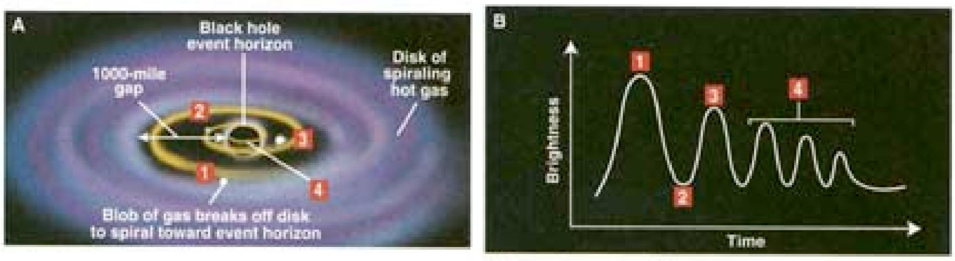

Figure 2: Dying pulse trains. (A) A luminous clump of material detaching from the inner edge of the accretion disk spirals into the event horizon and disappears. (B) Photometric signature of the clump's emission. Dolan (2001)

[4] Author Unknown, 2007, Chandra : Field Guide to X-ray Sources : Stellar Black Holes, http://chandra.harvard.edu/xray_sources/blackholes_stellar.html
[5] Author Unknown, 2003, The Uhuru Satellite, http://heasarc.gsfc.nasa.gov/docs/uhuru/uhuru_about.html
[6] Newman, Philip A., 2006, Black Holes, http://imagine.gsfc.nasa.gov/docs/science/know_l2/black_holes.html

into the black hole. As the matter accelerates rapidly and experiences tidal effects, temperatures rise rapidly and cause the emission of ultraviolet radiation in a pulsed fashion. Dolan (2001) used the Hubble Space Telescope (HST) to capture two distinct pulse trains (figure 2) of ultraviolet (UV) light from Cygnus X-1, and has shown that the pulses represent matter in the last high speed spirals before crossing the event horizon. There's some work to be done before this signature can be used as a detection tool, though, "Looking for the decaying pulse train was like looking for the proverbial needle-in-a haystack," said Dolan[7].

High-Velocity Jets as Predictors of Black Holes

Another way to determine the mass of the dark object in a binary X-ray source is to analyse the nature of the transient jets of material that are ejected at very high velocities along the axis of the accretion disk during mass in-fall from the donor star. GRO J1655-40 is an X-ray binary that has relativistic (near light speed) jets during outbursts. Mass estimates based on spectral analysis put the mass of the compact central object in GRO J1655-40 at more than 3 M⊙, making it a candidate for a SMBH (Zhang et al. 1997). Zhang et al. (1997) showed that GRO J1655-40's jet X-ray spectrum exhibited a signature unique to objects with greater than 3 M⊙, and concluded, "We therefore argue that [the signature] is a very strong indication of a black hole system and should be used for selecting [black hole candidates]."

Gravitational Microlensing: Isolated Black Holes

Could there be SMBHs that are not part of a binary system? Scientists are using one of General Relativity's predictions to find isolated SMBHs.

Since SMBHs curve spacetime strongly in their vicinity, light from a star that is behind a black hole should be bent as it travels past the black hole. The black hole acts like a lens to focus and amplify background starlight, called microlensing. If this line-up coincides with our line of sight, the microlensing event should be observable. In 1992, observers from the MACHO and MPS joint team began using the Mt Stromlo 1.3 meter telescope to do a systematic survey of the galactic bulge to search for microlensing events. This involved assembling time series of the luminosities of millions of stars. If any star's light curve (figure 3) matches the theoretical curve predicted by general relativity, then the star is most likely undergoing microlensing by an object between the star and the observer[8].

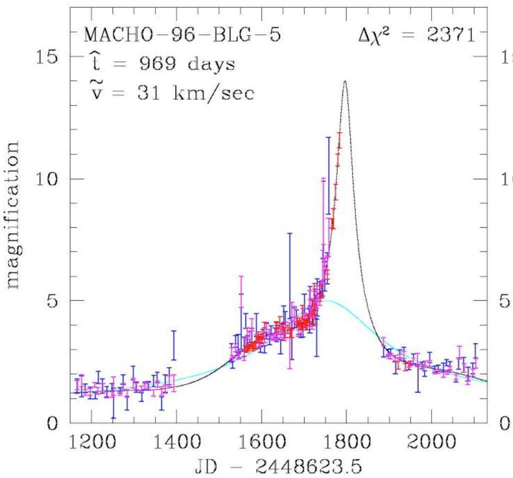

Figure 3: The Light Curve of MACHO-96-BLG-5 (Bennett et al. 2002)

In 2002, using 7 years of data from the MACHO MPS collaboration, Bennet et al. (2002) presented two microlensing events of objects (MACHO-96-BLG-5 and MACHO-98-BLG-6) as SMBH candidates. The microlensing object in each case had a mass around 6M⊙. In 1999, HST's WFPC2 camera imaged Macho-96-BLG-5's background star, allowing for an accurate determination of the mass of the microlensing object[9]. "These results appear to indicate that most stellar-mass black holes do not reside in the X-ray binary systems, where they are most easily observed." (Bennet et al. 2002)

[7] Savage, Don, 2001, HubbleSite: 'Death Spiral' Around a Black Hole Yields Tantalizing Evidence of an Event Horizon, http://hubblesite.org/newscenter/archive/releases/exotic/black-hole/2001/03/text/
[8] Rhie, Sun Hong, Undated, Microlensing Planet Search Project Homepage, http://www.nd.edu/~srhie/MPS/
[9] Savage, Don, 2000, HubbleSite: Lone Black Holes Discovered Adrift in the Galaxy, http://hubblesite.org/newscenter/archive/releases/2000/03/text/

Gamma Ray Bursts

For more than 30 years, astronomers have detected high-energy gamma rays bursts (GRB) that flare up rapidly and die off quickly, but until recently, their source remained unknown. Broad-spectrum detectors must be aimed toward the burst very quickly after the flare-up in order to get a complete light curve. In order to catch these GRBs as quickly as possible NASA launched the Swift satellite in 2004. Swift's instrument for GRB detection is the Burst Alert Telescope that monitors a large field for GRBs. Once Swift detects a GRB, a satellite relayed detection message alerts ground and space-based detectors that can be rapidly slewed to monitor the GRB. On average, one GRB is detected every day[10].

In 1999 Bloom et al. linked characteristics of the afterglow emission of GRB 980326 with a supernova. In 2002 Price et al. extended this work to show that a reasonably nearby (redshift $z = 0.63$) GRB in excess of 2 seconds was concurrent with a supernova. Additionally, Israelian et al. (1999) showed that the spectral signature of GRO J1655-40 (a strong SMBH candidate as noted above) included heavy elements thought to be formed only during supernova events, thus linking the longer duration GRB's to black holes.

Refinements in the GRB alert network allow work to be done on very short duration GRB's (< 2 sec.) and recent studies show these shorter bursts to be the result of neutron star collisions which lead to black holes (Fox 2005).

Conclusion

Modern SMBH detection techniques can be summarized thus:

- Single line spectrum binary systems with X-ray emission from unseen high mass objects was the first detection technique used to determine likely SMBH candidates. Detection using this technique continues today.

- Gravitational microlensing events where background star brightness is magnified by relativistic warping of space by a compact high-mass object provide evidence of non-binary SMBHs.

- Detailed observations of relativistic jets from binary systems may prove to be a powerful detection technique in the search for SMBHs, and further observations of decaying UV pulse trains might yield another telltale signature of SMBHs.

- Gamma Ray Bursts offer strong evidence of SMBHs and further study will help us understand the early stages of their creation.

This is indeed an exciting time to be working on SMBH detection and modelling. When Various divergent lines of evidence lead to the same conclusion it strengthens the argument for the existence of these unusual cosmological structures, and continuing investigation using the latest generation of detectors promises to add to our list of likely SMBH candidates.

[10] Deutsch, George & Hupp, Erica, 2005, Swift News: In A Flash Nasa Helps Solve 35-Year-Old Cosmic Mystery, http://heasarc.gsfc.nasa.gov/docs/swift/news/2005/05-334.html

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