PRESENT OBSERVATIONAL EVIDENCE FOR BLACK HOLES

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ABSTRACT

The paper gives an account of the present tools in the observation of stellar-mass and supermassive black holes. The most important black-hole candidates are summarized.

1. INTRODUCTION

According to general relativity, the end products of stellar evolutionary processes with masses exceeding 2 or 3 solar masses are black holes. The masses that have been measured for the most compact stars are all close to 1.4 solar masses and are believed to represent neutron stars. Many compact objects have been revealed with masses more than 3 and up to 3 times 10^9 solar masses. The black-hole candidates can be divided into stellar-mass (from 3 to $10^2 M_\odot$), massive (from about 10^3 to about $10^5 M_\odot$), and supermassive (from 10^6 to $10^9 M_\odot$) holes. For a recent review on black holes in cosmology and astrophysics, e.g. see Carr (1996).

2. PROPERTIES OF BLACK-HOLE SPACETIMES

The spatial extension of a Schwarzschild black hole is given by its Schwarzschild radius, $r_s = 2GM/c^2$, where M denotes the mass of the black hole. G and c are the Newtonian gravitational constant and the velocity of light, respectively. A Schwarzschild black hole is a non-rotating object. It should be stressed that the Schwarzschild radius r_s is not a measure of the distance of the surface (event horizon) of a black hole to its centre (this measure does not exist), rather it measures the area of the event horizon in the form $4\pi r_s^2$. In units of solar mass, $r_s = 2.9M/M_\odot$ km. For a rotating Kerr black hole, the event horizon is located at $(GM/c^2)(1 + \sqrt{1 - c^2J^2/G^2M^4})$, where J denotes the angular momentum of the hole. The lower limit of the radius of a compact spherically symmetric star is $9r_s/8$ (Buchdahl limit, e.g. see Schutz, 1983). A rigidly rotating, self-gravitating disk of dust can reach the radius of GM/c^2.

Matter orbiting a Schwarzschild black hole faces an innermost stable circular orbit at $3r_s$. This orbit defines the inner rim of an accretion disk around the hole. There the speed of the accreting matter amounts to one half of the speed of light as measured by a local static observer. The frequency ν received at infinity from a particle on this orbit varies periodically between

$$\sqrt{2}\nu_{em}/3 \leq \nu \leq \sqrt{2}\nu_{em}, \tag{1}$$

where ν_{em} is the emission frequency in the particle's rest frame (Shapiro and Teukolsky, 1983). For a maximally rotating Kerr black hole ($J = GM^2/c$), the co-rotating disk in the equatorial plane will have its inner edge at GM/c^2, the counter-rotating at $9GM/c^2$. The strongest binding energy per unit rest-mass energy of an orbiting particle is 5.7% (42.3%) for a Schwarzschild black hole (maximally rotating Kerr black hole). Nuclear fusion reactions only have 0.7% efficiency.

3. PROCESSES IN BLACK-HOLE SPACETIMES

Disk accretion on to a black hole is a powerful radiation mechanism. The accretion rate could build up the Eddington luminosity limit where the pressure of the radiation balances the gravitational attraction. The Eddington limit is given by

$$L_{Edd} = \frac{4\pi GMm_pc}{\sigma_T} = 1.3 \times 10^{38}\frac{M}{M_\odot}\text{erg/s}, \tag{2}$$

where $\sigma_T = 6.7\times10^{-25}\text{cm}^2$ is Thomson cross-section and m_p the proton mass.
The Eddington timescale for increasing the mass of the hole is

$$t_{Edd} = \frac{\sigma_T}{4\pi Gm_pc} \simeq 5 \times 10^8\text{yr}. \tag{3}$$

The radiation temperature T_{ra} should be in the range (Frank *et al.*, 1992)

$$T_b \lesssim T_{rad} \lesssim T_{th}, \tag{4}$$

where T_b and T_{th} denote the black-body and thermal temperature in case of optically thick and thin accretion flows, respectively. They are defined by

$$\sigma T_b^4 = \frac{L_{acc}}{4\pi R^2}, \quad 3k_BT_{th} = \frac{GMm_p}{R}. \tag{5}$$

L_{acc} is the accretion energy flux, R the radius of the inner edge of the accretion disk, and k_B and σ denote the Boltzmann and Stefan-Boltzmann constants, respectively. The frequency spectrum one obtains from the equation $h\nu = k_BT_{rad}$. For a $10M_\odot$ Schwarzschild black

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hole with $L_{acc} = 10^{36}$erg/s one finds $T_{th} = 5.5 \times 10^{12}K$ and $T_b = 10^7K$, and thus for the spectral range

$$1\text{keV} \lesssim h\nu \lesssim 500\text{MeV} \qquad (6)$$

which is in the hard X-ray and γ-ray regimes.

The Blandford-Znajek process could be another powerful mechanism for extracting energy from a black hole, e.g. see Thorne *et al.* (1986). Kerr black holes, rapidly rotating in the magnetospheres of their accretion disks, should be able to power the polar jets through their rotational energy content according to the formula

$$P \sim 10^{45}(\frac{a}{M})^2(\frac{M}{10^9 M_\odot})^2(\frac{B_n}{10^4 Gauss})^2\text{erg/s}, \qquad (7)$$

where $a = cJ/GM$ is smaller or equal (maximally rotating hole) to M and B_n is the normal component of the magnetic field near the black hole's event horizon.

4. MEASURING MASSES OF STELLAR-MASS BLACK HOLES

Black holes can be observed only through their effects on surrounding matter and radiation, including gravitational waves. The decisive parameter of a dark compact object to be a black hole is its mass. The currently most reliable way to measure stellar masses is by exploiting the radial-velocity (line-of-sight-motion) curve of a companion star throughout its orbit. This Doppler curve allows the precise measurement of the mass function f using the relation

$$f(M_{bh}, M_{st}, i) \equiv \frac{(M_{bh}\,\sin i)^3}{(M_{bh} + M_{st})^2} = \frac{P v_{st}}{2\pi G}, \qquad (8)$$

where P denotes the orbital period and v_{st} the range of the orbital velocity of the star ($v_{st} = (2\pi/P)a_{st}\,\sin i$, where a_{st} is the semi-major axis of the star's orbit). Both are directly measurable quantities, see Fig. 1 which relates to circular orbits.

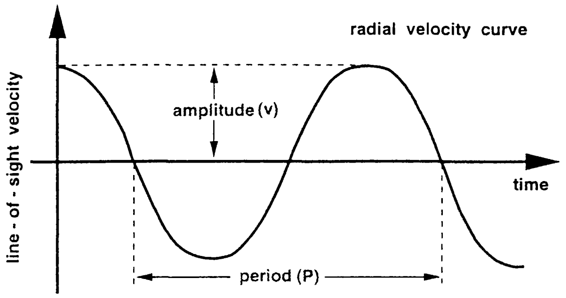

FIG 1.

The inclination angle i is the angle between our line of sight to the binary system and the normal of its orbital plane. If M_{st} is not small compared to M_{bh}, then f is small, and M_{st} and i must be determined accurately in order to derive a reliable value for M_{bh}. If M_{st} is small, then f provides a lower limit for M_{bh} in setting $i = 90°$, and a precise measurement if i is known.

The inclination angle i can be determined by measuring the system's light-curve properties that result from the companion's tidal distortion by the black-hole candidate and, of course, from the eclipses in the system's light curve.

The companion's mass can be estimated by its spectral type. The binary's mass ratio can be determined from the companion's rotation rate (same as orbital period) combined with the spin-induced Doppler broadening of the companion's spectral lines if one assumes that the companion fills its "Roche lobe".

The X-ray emission originates from high-temperature gas flowing on to a compact object from a binary companion. The variability of the X-ray output on small timescales is characterized by $(G\rho)^{-1/2}$, where ρ is the mean density in the volume containing the motion. Millisecond flickering needs densities larger than 10^{12}g/cm^3. The found high-energy X- and γ-ray power-law spectra are indicative for black-hole candidates.

5. MEASURING MASSES OF SUPERMASSIVE BLACK HOLES

Motions of stars or gas in large-scale strong gravitational field are unique indicators of supermassive black-hole candidates. With a black hole in its centre, the rotation curve of a galaxy strikingly differs from a standard galaxy rotation curve, see Fig. 2.

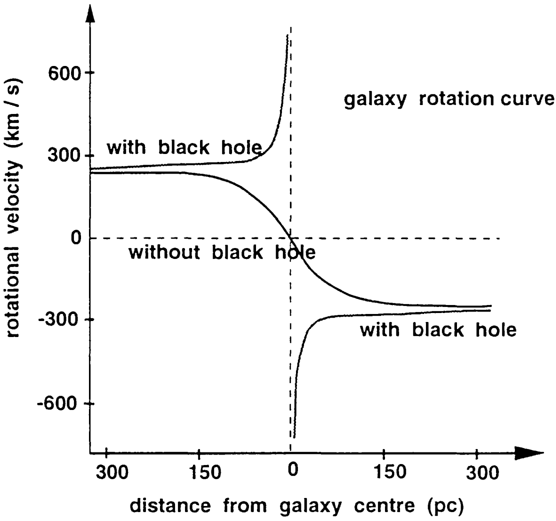

FIG 2.

Typical are the ever-faster orbital motions of stars as they approach the centre (Ford and Tsvetanov, 1996). A rough estimate for the mass M of the hole is $M = v^2R/G$, where v and R denote respectively the velocity and distance from the galaxy's centre of the observed object. Even for the nearest galaxies sub-arcsecond resolution is needed for a reliable measurement of R. For v, values of up to six hundreds of kilometer per second have been found.

The mass-to-light ratio M/L is also an important indicator for a black-hole candidate in a galaxy's core. M/L, in units of the Sun, reaches 3 to 5 for globular clusters and 5 to 10 for a typical galaxy's central few thousand light-years. If a galaxy's central region, tens or hundreds of light-years across, shows a considerably larger value, there is strong evidence for a supermassive black hole.

The X-ray spectra allow to probe the region a few Schwarzschild radii above a supermassive black hole's event horizon where the accretion disk is orbiting at several tenths the speed of light. If X-ray variability studies establish the diameter of the accretion disk's inner edge, restrictions on the black hole's mass and spin rate can be obtained.

6. BLACK–HOLE CANDIDATES IN BINARY X-RAY SOURCES

The X-ray binaries are divided into high-mass X-ray binaries (HMXRBs) and low-mass X-ray binaries (LMXRBs), White and van Paradijs (1996), see Table 1. The latter are mostly soft X-ray transients (SXT) or X-ray novae. In the former systems a star much heavier than the Sun is paired with a neutron star or black hole, in the latter systems the pairing is with a low-mass star. The sources Cygnus X-1 and LMC (Large Magellanic Cloud) X-3 are currently the best HMXRB-black-hole candidates. Cygnus X-1 is known to be the first black hole candidate. It was identified in 1971 with HDE 226868, a 9th-magnitude O-type supergiant.

Name	ID	Mass ($M_\odot$)	Satellite
High–Mass X–Ray Binaries			
Cyg X–1	HDE 226868	10–15	Uhuru
LMC X–3		4–11	Einstein / HEAO–1
LMC X–1		4–10	HEAO–1
Low–Mass X–Ray Binaries			
GS 2023+338	V404 Cyg	8–15	Ginga
GS 2000+25	QZ Vul	5.3–8.2	Ginga
GS/GRS 1124-68	XN Mus 91	4–6	Ginga / Granat
GRO J1655-40	XN Sco 94	4–5.2	CGRO
GRO J0422+32	V518 Per	4.5	CGRO
H 1705-25	XN Oph 77	>4.1	Ariel 5 / HEAO–1
A 0620–00	V616 Mon	3.3–4.2	Ariel 5

TAB 1.

The X-ray transient A0620-00 in Monoceros, also known as V616 Monocerotis, is a typical SXT. It was discovered in 1975 by Ariel 5. More recently, in 1994, the Compton Gamma Ray Observatory (CGRO) discovered J1655-40 in Scorpius; it is also known as Nova Scorpii 1994. The X-ray transient GS 2023+334 (V404 Cygni) harbours with 8 to 15 solar masses the heaviest black hole candidate (Charles and Wagner, 1996).

7. BLACK–HOLE CANDIDATES IN GALACTIC NUCLEI

The study of Seyfert galaxies, quasars, and radio galaxies brought clear evidence for enormous energy production in active galactic nuclei (AGN), Kormendy and Richstone (1995).

Spectral lines of Seyfert galaxies have been found with unusual broad profiles with redshifts of more than 1,000 km/s and luminosities of more than 10^{43}erg/s. Quasars release energy at the rate of typically more than 10^{47}erg/s, that is more than $1M_\odot$ per year. The variability of quasars on timescales ≤ 1 month requires energy production within a region of $\leq 10^{12}$km. The high efficiency of energy release by accretion on to a black hole (typically 10%) suggests that this process could provide the measured radiation power.

In the following several black-hole candidates of Table 2 will be described.

Name	Mass ($10^6 M_\odot$)	Observatory
NGC 4486 (M 87)	3,000	HST
NGC 3115	2,000	CFHT
NGC 4594 (M 104)	500	CFHT
NGC 4261	500	HST
NGC 3377	80	CFHT
NGC 4258 (M 106)	36	VLBA
NGC 224 (M 31)	30	Mount Palomar
NGC 221 (M 32)	3	Mount Palomar
NGC 5194 (M 51)	3	HST
Galactic Centre	2.5	NTT

TAB 2.

Messier 87 (NGC 4486), located at the heart of the Virgo Cluster, is the galaxy which is currently known to harbour the heaviest supermassive black hole, $3 \times 10^9 M_\odot$. The mass is concentrated within a sphere whose radius is less than 10 light-years. The mass-to-light ratio of this region is $M/L \simeq 110 M_\odot/L_\odot$. The observed rotation curve of the accretion disk varies between 600 and 1,800 km/s and clearly shows the pattern of a high mass concentration in the nucleus (Marconi *et al.*, 1997; Macchetto *et al.*, 1997).

Sagitarius A^* at the Galactic Centre is the lightes black hole candidate in the family of supermassive holes. Its mass is $2.5 \times 10^6 M_\odot$ within the central 5×10^{-2} light-years. The measured star velocities approach 1,500 km/s (Eckart and Genzel, 1997).

The radio-bright elliptical galaxy NGC 4261 shows velocities along the disk's major axis of 250 km/s. A mass of $5 \times 10^8 M_\odot$ seems to be concentrated within 50 light-years in diameter. The mass-to-light ratio turned out to be extremely high, $M/L = 2,100 M_\odot/L_\odot$.

The most massive central object in an ordinary, quiescent galaxy is in NGC 3115.

The Seyfert galaxies M106 (NGC 4258) and MCG-6-30-15 (not shown in Table 2) allowed quite remarkable observations.

In a region surrounding the centre of M106 in less than 0.4 light-years in radius a water maser is active which allowed the determination of a $3.6 \times 10^7 M_\odot$ object within this radius (Miyoshi *et al.*, 1995).

The Japan's Advanced Satellite for Cosmology and Astrophysics (ASCA) measured the K_α (6.4 keV) line of iron ions from MCG-6-30-15. The spectrum not only showed the two-horned shape expected from a rotating disk, it also showed a 50% shift to the red. This is a clear indication of a steep gravitational well (Tanaka *et al.*, 1995).

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