Observations of Supermassive Black Hole Candidates

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OVERVIEW

Introduction:
  – quick reminder of black holes and AGN

SMBH in AGN:
  – gas & dust kinematics
  – water masers
  – reverberation mapping
  – X–ray emission lines

SMBH in normal galaxies:

SMBH in the Milky Way:
  – gas kinematics
  – stellar dynamics

The Future:
  – gravitational waves
  – X–ray spectroscopy
Brief History of Black Holes

1700s  * Michell (& Laplace) realised the theoretical possibility for gravity to be so strong that nothing could escape.
      * such "dark stars" would have to be very massive and unimaginably dense

1916  * Schwarzschild predicts "space time singularities" from the new Einstein Field equations
      * Einstein considers singularities to be "mathematical curiosities" with no physical counterparts

1960s  * Wheeler coins the term "black hole" — scientist theorize that a singularity lies at the centre of a black hole
      * Chandrasekhar, Landau, Oppenheimer predict that black holes are the end result of stellar evolution of massive stars
      * not until the discovery of quasars (AGN) did the existence of BH begin to gain acceptance
Active Galactic Nuclei (AGN)

Seyfert (1943), there exists a distinct class of galaxies with:

- high central surface brightness \( (L_c \sim L_g) \)
- high excitation nuclear emission lines

Woltjer (1959), first indications of something truly exotic in the cores of the Seyfert galaxies

- nuclei are unresolved in the radio; therefore nucleus is \(< 100 \text{ pc}\)
- if the nuclear material is gravitationally bound then simple virial arguments suggest masses of \(10^9 \text{ solar masses}\)

What could be so massive, occupy such a small volume of space, and produce such tremendous energy???

... dense star clusters? supermassive stars? giant pulsars? supermassive black holes???
Quick Summary: What is an AGN?

Characteristics:

> bright compact nucleus
> non–thermal continuum emission
> broad emission lines
> continuum and/or emission line variability
> X–ray emission
> radio, X–ray, or optical jets
Basic Arguments

- the mass of the central source can be estimated by assuming isotropy and stability

- assuming the outward radiation pressure must be counter-balanced by the inward force of gravity

\[ L_{\text{edd}} < 1.26 \times 10^{38} \left( M / M_{\odot} \right) \ \text{[erg/s]} \]

Therefore,

\[ M_{\text{edd}} > 8 \times 10^5 \ L_{44} \ \text{[M}_{\odot}] \]

\[ M_{\text{edd}} \sim 10^6 - 10^9 \ M_{\odot} \]

so, let's look for supermassive black holes!
**Gas & Dust Kinematics**

- Gas kinematics are straightforward to interpret if the gas participates in Keplerian rotation in a disk-like configuration (~5+ reported cases)

![Disk in Galaxy NGC 7052](image)

- dust disk ~3700 ly wide
- 300 million solar mass BH

**WARNINGS!**

1. Gas can be easily perturbed by non-gravitational forces (e.g. shocks, winds, magnetic fields...).
2. There is no reason that gas should be in dynamic equilibrium (as found to be the case in NGC 4594). A Keplerian velocity field must be verified first.
Gas & Dust Kinematics

- gas kinematics are straightforward to interpret if the gas participates in Keplerian rotation in a disk-like configuration.
Gas & Dust Kinematics: M87

disk:
- $D \sim 150$ pc
- rotation axis aligned with optical & radio jet
  $\Rightarrow$ in agreement with BH accretion scenario
- in Keplerian rotation

central object:
- $M \sim 3 \times 10^9$ solar masses
- source is dark
  $M/L > 100$
- source is compact
  radial extent $< 5$ pc
  $\Rightarrow \quad 10^7 \, M_{\odot} \, \text{pc}^{-3}$
Gas & Dust Kinematics: M84

Disk diameter of ~ 80 pc

Dark object mass of $M \sim 2 \times 10^9$ solar masses
Water Masers

- compact clumps of molecular material in the outer disk or dusty torus of AGN, that amplifies a background continuum source through a maser process in edge on systems
- the velocity of the clumps can be derived from 22 GHz, high resolution, VLBI spectroscopy (~4 candidates)

Best example, NGC4258

- maser spectrum arises from a thin Keplerian disk rapidly rotating a $10^7$ solar mass dark object
- inner disk radius 0.13 pc; outer radius 0.26 pc
- Keplerian rotation curve fit with 1% accuracy
- extent of central mass limited to < 0.012 pc

$$5 \times 10^{12} \ M_\odot \ pc^{-3}$$
Reverberation (Echo) Mapping

- main goal is to determine the geometry & kinematics of the BLR; however, a consequence is fairly accurate BH mass estimates
Reverberation (Echo) Mapping: Applied

~ 20 examples, yielding central object masses of $10^6$ -- $10^8$ solar masses

Drawbacks:
- method is robust, but requires very high quality data
- mass estimation is enclosed within the BLR; thus it does not confirm the BH nature of the central object
Fe Kα Emission

The FeKα line in the X-ray spectra of many AGN does not give a direct measure of the central mass. HOWEVER, it may arguably be the most compelling evidence for the existence of a SMBH in AGN.

MCG–6–30–15
NGC 3516
Fe Kα Emission: Line formation

Best-fitting line profiles to real data suggest an inner disk radius of < 6 Schwarzschild radii, and velocities of 0.3 c !!!

==> Consistent with GR effects, and SMBH accretion theory!
Fe Kα Emission

Caveat:

In most (all) cases, the data quality is still not good enough to constrain all the model parameters. Perhaps, the situation will be better with the next generation of X−ray telescopes (XEUS, Con−X)

Other explanations for the line profile:

"...possible, but implausible" (Fabian 1995)

e.g.

> Comptonisation in cold gas

> Doppler shift from outflows
Where have all the quasars gone?

In most cases, the evidence of a SMBH at the centers of AGN is purely circumstantial.

Problem:

Optical surveys showed that the number density of AGN peaked when the universe was about 2.5–5 billion years old (z ~ 2–3) and has been declining steadily since.

AGN were 10000 x more frequent then than now!

Where have all the quasars gone?
Is the local universe filled with "dead" quasars?
Where are these dead quasars?

Look in the centers of "normal" (inactive) galaxies...
SMBH in normal galaxies?

Look in the centers of "normal" (inactive) galaxies...

HOW?

Examine the "black hole sphere of influence"

The gravitational potential of a SMBH will dominate the motions of near−by stars and gas

By studying the velocity distribution of stars in the centers of bulge galaxies (disk galaxies with bulges and elliptical galaxies) an interesting correlation appears.

SMBH mass is proportional to the luminosity (and mass) of the bulge!
SMBH in normal galaxies?

A second correlation is also revealed...

The mass of the SMBH is proportional to the velocity dispersion of the stars in the galaxy — not just in the BH sphere of influence!!!
SMBH in normal galaxies?

Despite the large scatter in BH mass–bulge mass relation the correlation is robust.

The BH mass–velocity relation has lower scatter, and the extreme objects in the mass–bulge relation are no longer extreme ==> this second correlation is more fundamental.

Both correlations are empirical — no theoretical foundation.

However, both imply a close connection between SMBH and galaxy formation.

Number density of SMBH in local universe now agrees with the quasar number densities.
Early radio images provide the first clues of nuclear activity in our Milky Way.

Filaments, rings, & lobes indicate violent activity in the recent past.

A strong, unresolved (< 20 AU) radio source marked the center of the Galaxy ==> Sgr A*.

Gas dynamics in the inner pc indicate a mass of ~ 10 solar masses for Sgr A*.
The Galactic Center: Stellar Dynamics

IR K band:
The Galactic Center: SMBH

No Alternatives?

Best fit model is of a Keplerian orbit about a SMBH!

Alternatives:

> Neutrino ball model
  
  – far too much mass required to be plausible

> Dense cluster of dark objects
  
  – extremely high mass density required
  
  – short lifespan (only ~ 100,000 years)
The Future: Gravitational Waves

Disturbances in the curvature of spacetime caused by the motion of matter

Most predictable sources: Galactic binary systems
Most powerful sources: mergers of SMBHs in distant galaxies

History:

> prediction of Einsteins GR theory

> 1950s, Bondi showed that gravitational waves carried energy; and hence, systems that emit the waves should lose energy

> 1970s, researchers show that a binary pulsar system (PSR1913+16) was spiralling in toward each other (losing energy) at the exact rate predicted by energy lose due to gravitational waves.
The Future: Gravitational Waves: LISA

Laser Interferometer Space Antenna (LISA)

3 space crafts flying in equilateral triangular formation; each craft separated by 5 million km

Will be in solar orbit trailing the Earth by 50 million km

Essentially a Michelson interferometer

As a gravitation wave comes through the separation between the space crafts will change

LISA will be sensitive in the low frequency domain where SMBH mergers are expected to emit the waves. Ground-base detectors (e.g. LIGO) are not sensitive in this range due to terrestrial noise

Technical Challenges:

The shifts expected for SMBH mergers will be on the order of $10^{-12}$ m across!!! Therefore, all sources of noise must be treated (e.g. solar wind, radiation pressure).
The Future: X-ray Spectroscopy: MAXIM

Is a direct image of a SMBH proof enough?

Even in the most massive, and relatively near-by AGN, M87, this would require a resolution of micro-arcsec

"...comparable to seeing the details of a dinner plate on the surface of the sun."

MAXIM: Micro-Arcsecond X-ray Imaging Mission

32 collector spacecrafts in a 200m diameter; a converger spacecraft located 10 km away; and a detector spacecraft 5000 km away!
Conclusions

– SMBH in AGN seems to be a necessity since there is no strong alternative:
  – supermassive stars and pulsars are unstable and would collapse on short time scales
  – compact starburst does not offer an explanation for the X−ray variability, nor for jets

– there is strong evidence for SMBH in normal galaxies however the arguments requires an evolution from AGN to normal galaxies; which has not been proven theoretically.

– best evidence for a SMBH lies in our own Galaxy

– the future will be challenging
Web Sites

Milky Way SMBH:

http://www.mpe.mpg.de/www_ir/GC/gc.html

SMBH in normal galaxies:

http://chandra.as.utexas.edu/~kormendy/bhsearch.html

MAXIM:

http://MAXIM.gsfc.nasa.gov/

LISA:

http://sci.esa.int/home/lisa/

AGN: Echo Mapping:

http://mintaka.sdsu.edu/faculty/wfw/WWWHEMP/hemp.html