Black Holes in Astrophysics

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X-ray Binaries

Image credit: Robert Hynes (2002)
Galactic Nuclei

Image credit: Lincoln Greenhill, Jim Moran
Outline

- Measuring BH mass
- Estimating BH spin
- Testing Relativity
- Evidence for the Event Horizon
How to Find Black Holes?

- Find a compact star:
  \[ R < \text{few } R_S \]
- Make sure it is not a neutron star:
  \[ M > 2---3 M_\odot \]
- You have an excellent black hole candidate
Dynamical Measurements of Mass in Astronomy

The best mass estimates are dynamical: a test particle in a circular orbit satisfies

\[ GM = \frac{4\pi^2 r^3}{P^2} = \frac{v^3 P}{2\pi} \]

If any two of \( v, r, P \) are measured, we can obtain \( M \)
(easily generalized for elliptical orbit)
Works for binary stars and galactic nuclei
**Mass Function of a Binary**

Observations give

\[ P : \text{orbital period of binary} \]

\[ K_s : \text{line-of-sight velocity of secondary} \]

These two quantities give the mass function:

\[
f(M) = \frac{PK_s^3}{2\pi G} = M_x \frac{\sin^3 i}{(1 + M_s / M_x)^2} < M_x
\]

Even without knowing \( \sin i \) and \( M_s \), guaranteed that \( M_x > f(M) \).

If \( f(M) > 3M_\odot \), it must be a Black Hole

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**GRS 1009-45**

Filippenko et al. (1999)
Radial velocities are very well determined for XRBs in quiescence.

Clear evidence for circular orbits.

Obtain accurate measurements of $P$ and $K_s$. 

Radial Velocity vs. Orbital Phase

- GS2023+338
- A0620-00
- GRS 1124-683
- XTE J1118+480
- GRS 1009-45
- GS2000+250
- H1705-250
- Cygnus X-1
## Best Black Hole X-ray Binaries

<table>
<thead>
<tr>
<th>Binary</th>
<th>Likely $M_X (M_\odot)$</th>
<th>$f(M) = M_{X,\text{min}} (M_\odot)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4U1543-47</td>
<td>$5 \pm 2.5$</td>
<td>$0.22 \pm 0.02$</td>
</tr>
<tr>
<td>GRO J 0422+32</td>
<td>$10 \pm 5$</td>
<td>$1.21 \pm 0.06$</td>
</tr>
<tr>
<td>GRO J 1655-40</td>
<td>$7 \pm 1$</td>
<td>$2.73 \pm 0.09$</td>
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<tr>
<td>SAX J 1819.3-2525</td>
<td>$10.2 \pm 1.5$</td>
<td>$2.74 \pm 0.12$</td>
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<tr>
<td>A0620-00</td>
<td>$10 \pm 5$</td>
<td>$2.91 \pm 0.08$</td>
</tr>
<tr>
<td>GRS 1124-683</td>
<td>$7 \pm 3$</td>
<td>$3.01 \pm 0.15$</td>
</tr>
<tr>
<td>GRS 1009-45</td>
<td>$4.2 \pm 0.6$</td>
<td>$3.17 \pm 0.12$</td>
</tr>
<tr>
<td>H1705-250</td>
<td>$4.9 \pm 1.3$</td>
<td>$4.86 \pm 0.13$</td>
</tr>
<tr>
<td>GS 2000+250</td>
<td>$10 \pm 4$</td>
<td>$4.97 \pm 0.10$</td>
</tr>
<tr>
<td>XTE J 1118+480</td>
<td>$7 \pm 1$</td>
<td>$6.0 \pm 0.3$</td>
</tr>
<tr>
<td>GS 2023+338</td>
<td>$12 \pm 2$</td>
<td>$6.08 \pm 0.06$</td>
</tr>
<tr>
<td>XTE J 1550-564</td>
<td>$10.5 \pm 1$</td>
<td>$6.86 \pm 0.71$</td>
</tr>
<tr>
<td>XTE J 1859+226</td>
<td>$10 \pm 3$</td>
<td>$7.4 \pm 1.1$</td>
</tr>
<tr>
<td>GRS 1915+105</td>
<td>$14 \pm 4$</td>
<td>$9.5 \pm 3.0$</td>
</tr>
</tbody>
</table>
A variety of observations suggest a dark mass of about $3 \times 10^6 M_\odot$ at our Galactic Center (Genzel et al., Ghez et al.)

Spectacular new evidence...
The Black Hole in NGC 4258

- Maser emission clearly delineates a Keplerian gas disk (Miyoshi et al. 1995)
- Central dark mass of $3.9 \times 10^7 M_\odot$ (Herrnstein et al. 1999)
Many BHs identified in galactic nuclei from stellar velocity measurements

BH mass obtained from statistical analysis of the velocity distribution of stars

Not as clean as Sgr A* or NGC 4258, but still very robust

About 30 BH masses presently determined:

\[ M_{BH} \sim 10^6 - 10^{9.5} M_\odot \]
Bimodal Mass Distribution

- Two distinct BH populations
  - BHs in XRBs represent tail end of massive stellar remnants
  - SMBHs in galactic nuclei are clearly related to galactic structure: $M \sim \sigma^4$
- Are there BHs with masses in between?

Ferrarese & Merritt (2000)
Tremaine et al. (2002)
Intermediate Mass BHs

- A population of luminous X-ray sources seen in nearby galaxies with $L_X \sim 10^{39-42}$ erg/s (Colbert & Mushotzky 1999; Makishima et al. 2000)
- By Eddington argument, masses up to $\sim 1000 M_\odot$
- What exactly are these objects?
  - Intermediate mass BHs (Strohmeyer & Mushotzky 2003; Miller et al. 2003)?
  - Stellar-mass BHs with beaming (King et al. 2001; Kaaret et al. 2003)?
- Dynamical evidence for IMBHs in M15 and M31 --- controversial
Estimating Black Hole Spin

- Variety of methods have been used to estimate $a^* = a/M$ from observations of accretion flows.
- All ultimately make use of the fact that the accretion disk terminates at the innermost stable circular orbit (ISCO).
- Disk observations are dominated by this radius.
- Radius of the ISCO depends on $a^*$. 

![Graphs showing estimates for $\Gamma_{\text{ms}}/M$ and $\Omega M (1 - E)$ against $a/M$.]
If disk emission consists of (multicolor) blackbody radiation, observed spectrum gives surface area of emitting region and hence radius of disk inner edge $r_{\text{in}}$.

From $r_{\text{in}}/M$, get an estimate of $a^*$ (Zhang et al. 1997)

- $a^* = 0.93$ (GRO J1655-40)
- $a^* \to 1$ (GRS 1915+105)

But spectral modeling requires corrections for non-blackbody effects, which complicates the analysis.
a* From Broad Iron Line

- Relativistically broadened iron line discovered in X-ray spectrum of MCG-6-30-15 (Tanaka et al. 1995)
- Line in MCG-6-30-15 requires emission from $r \sim$ few M (Wilms et al. 2001)
- Similarly for XTE J1650-500 (Miller et al. 2002)
- Argues for large $a^*$
- But modeling is complicated
- Lines are variable - they come and go - and they are seen only in a few systems

Wilms et al. (2001)
Quasi-Periodic Oscillations

- NS and BH XRBs sometimes exhibit QPOs
- Frequencies are high (kHz QPOs), so the oscillations occur deep in the potential well
- Relativistic effects are likely to be important
Similarity of NS & BH QPOs

BH XRBs have QPOs that are qualitatively similar to NS QPOs.

Also, there seems to be a continuity in QPO properties between NS and BH systems.

So the oscillations cannot be a stellar surface phenomenon, or a magnetospheric effect.

Must be happening in the accretion disk --- probably related to orbital freqs.
Given $M$, the maximum orbital frequency is $\Omega(r_{\text{ISCO}})$.

In some XRBs, the highest observed QPO freq. is larger than $\Omega(r_{\text{ISCO}})$ for a Schwarzschild BH.

Argues for a spinning BH: $a^* > 0.15$ in GRO J 1655-40 (Strohmeyer 2001; Remillard et al. 2002).

If QPO is due to particular disk modes, then...
The majority of BHs that we observe are very luminous.

They seem to convert mass (of accreting gas) to energy with great efficiency:

- Accrn onto Schwarzschild BH: $\varepsilon = 0.057$
- Accrn onto Kerr BH with $a^* = 0.998$: $\varepsilon \approx 0.30$
- AGN have $\varepsilon \approx 0.1--1.0$
Efficiency of Quasar Accretion

- Compare integrated quasar luminosity with local BH mass density (Soltan 1982)
- Ratio gives mean efficiency $\varepsilon$ of quasar accretion
- Recent estimates give very high values for efficiency (Merritt & Ferrarese 2001; Elvis et al. 2002; Yu & Tremaine 2002)
- Requires $a^* > 0$, perhaps close to 1
Geroch-Bekenstein Engine

Accretion disk extends down to innermost stable circular orbit, typically $r \sim \text{few}$

There is some residual kinetic energy at this radius

This KE plus remaining rest mass energy of accreting gas are lost into the BH

Efficiency is thus limited

Geroch-Bekenstein engine can in principle have 100% efficiency (as $r \to 0$)

Just needs a strong enough wire (not trivial!)
An Accretion Flow With GB-Like Efficiency

- With magnetic fields, a natural GB engine is possible
- "Magnetically arrested disk" (MAD!) with the topology shown at right has no free-fall region
- Can, in principle, extract most/all of the rest mass energy of accreting gas
- Efficiency $\varepsilon$ can approach unity even for a Schwarzschild BH

The MAD Counter-Example

- The MAD accretion model appears to be a viable counter-example for every method used so far to estimate \( a^* \)!
  - Emission all the way down to horizon
  - No limit to gravitational redshift
  - High frequencies possible
  - High energy efficiency is natural
- And it is not even contrived --- based on a pretty generic field configuration
Energy from BH Rotation

- A rotating BH has free energy available for extraction (Penrose 1969)
- In principle, with magnetic fields, one might be able to extract this energy (Blandford & Znajek 1977; Li 2000; Punsly 2001; …)
- Much discussed in the literature, e.g., could relativistic jets be produced by this mechanism?
- Fe line in MCG-6-30-15 requires a lot of emission close to BH --- may indicate spin energy? (Wilms et al. 2001)

Wilms et al. (2001)
Testing Relativity with QPOs

Three key relativistic frequencies -- orbital, periastron precession, nodal precession -- may correspond to three observed QPO frequencies (Stella, Vietri & Morsink 1999)

Predicts relationships among the frequencies that appear to be roughly consistent with data
However...

- QPOs in some NS systems seem to be related to NS spin
- Probably indicates a magnetic interaction
- There is continuity all the way down to WDs!
- Perhaps QPOs have nothing to do with relativity?

Warner et al. (2003)
Astronomers have shown that BH candidates are
- compact: \( R \ll \text{few } R_s \)
- Massive: \( M \gg 3M_\odot \)

These are certainly strong reasons to think that the objects are BHs

But, how sure are we that they are really BHs?

Can we find some other independent evidence that our BH candidates actually possess Event Horizons?
What Kind of Evidence?

- We need some phenomenon --- or lack of it --- that can only occur if our BH candidates have event horizons.
- Ideally, we should do a comparison of similar systems, one set with NSs and one with BHs, and we should confirm a predicted difference that differentiates between a surface and an event horizon.
- The difference should not be easily explained away (other than by invoking some very implausible conspiracy).
X-ray Binaries and the Event Horizon

- Accretion flows may be useful, since inflowing gas reaches the center and “senses” the central object.
- X-ray binaries have an additional advantage --- there are both NS and BH systems, so comparison possible.
- However, most of the radiation usually comes from larger radii and is not useful.
- We have to identify radiation that comes from the central mass and look for a signature…
Signatures of the Event Horizon

- Differences in Quiescent luminosities of transient X-ray binaries (Narayan, Garcia & McClintock 1997;…)
- Differences in variability power spectra (Sunyaev & Revnivtsev 2000)
- Differences in occurrence of Type I X-ray bursts (Narayan & Heyl 2002)
- Differences in X-ray colors (Done & Gierlinsky 2003)
BH SXTs are at least 100 times fainter than NS SXTs.

Difference originally predicted by Narayan & Yi (1995), checked by Narayan, Garcia & McClintock (1997), and confirmed with increasingly better data by Menou et al. (2001); Garcia et al. (2001); McClintock et al. (2003);…

The observed large difference in luminosity can be understood if BHs have event horizons and NSs do not (ADAFs). Hard to explain otherwise.

McClintock et al. (2003)
Type I X-ray Bursts

- Discovered by Grindlay et al. (1976)
- Sudden brightening, once every several hrs; lasts about 10-100 s
- Physics understood: unstable nuclear burning of accreted gas
- Very common in XRBs
No Type I Bursts in BHs!!

- No BH candidate has ever exhibited a Type I burst.
- Obvious explanation: They have event horizons, so material cannot pile up, and there can be no bursts.
- But, is the lack of a surface the only reason why the sources do not burst?
- Not obvious, since some NSs also do not burst.

Figure 11: Schematic sketch of the surface layers of an accreting neutron star (adapted from Joss 1979a).
**Bursts vs Surface**

- If a burst is seen, then the object must have a surface, and it is not a BH.
- But, if no bursts are seen, there is no guarantee that the object is a BH.
- To prove that it is a BH, we must:
  - develop a detailed theory of nuclear stability,
  - understand why some NSs do not burst,
  - demonstrate that BH candidates would certainly burst if they had surfaces.
Results: \(1.4\,M_{\odot}\) Neutron Star

- Studied a variety of accretion rates (0.001 -- 1 \(L_{\text{Edd}}\)) and NS radii (1.6 -- 4 Schw. radii, i.e., 6.5 -- 16 km), for three choices of the core temperature.

- We find that accreting NSs will produce Type I bursts over a range of accretion rates, but no bursts when close to Eddington.

- Agrees fairly well with observations.

\[ M=1.4M_{\odot}, \, T_{\text{core}}=10^8\,\text{K} \]
Studied a variety of accretion rates (0.001 -- 1 Eddington) and BH radii (9/8 -- 3 Schw. radii, i.e., 33 -- 85 km), with three different choices of $T_{\text{core}}$.

The model predicts that accreting BH candidates should exhibit Type I bursts over a wide range of conditions.

$M=10 M_\odot$, $T_{\text{core}}=10^{7.5}$K
So Why Don’t BH XRBs Burst?

- The obvious reason is that they have event horizons: no surface, no burst

- But, before accepting this explanation, we have to eliminate all other “plausible” explanations for the lack of bursts
Some Obvious Explanations

- Perhaps the fuel is different: He, H missing? But the companion stars are very normal: H/He lines are seen in the star and disk.
- Perhaps core temperature is too high? But, quiescent luminosity constrains $T_{\text{core}}$ to be low.
- Perhaps the burst durations or recurrence times make the bursts hard to see? Not according to our calculations.
- Perhaps accretion rate is wrong? But these are transient systems that sample a wide range of accn. rates.
Other Explanations

- Rotation
- Magnetic fields
- Burning front propagation
- Strange stars
Strange Matter?

- What if our BH is a Q-star or some other strange star all the way to the surface? Will it burst?
- Accreting gas will still very likely form a crust of normal matter, so bursts are unavoidable.
- To avoid bursts, we need a form of matter that converts normal matter on contact to something strange? (No nuclei, no bursts.)
Strange Matter?

- What if BH candidates are made of non-interacting fermions or bosons?
  - Accreted gas would then sink to the center
  - But there would still be a surface, and there should still be bursts
  - What sort of bursts remains to be seen…
Summary

- Many BH candidates have been discovered: $M > 3M_\odot$
- Bimodal mass distribution
  - XRBs: $10^{0.5-1.5}M_\odot$
  - Galactic nuclei: $10^{6-9.5}M_\odot$
  - Are there intermediate mass BHs? ($10^{2-4}M_\odot$)
- Many spin measurements claimed
  - All are very model-dependent (MAD counter-example)
- Attempts to test relativity in strong gravity
  - Broad Fe fluorescence line
  - Quasi-periodic oscillations (QPOs)
- Searches underway for signatures of the Event Horizon
  - Luminosities of quiescent XRBs
  - Absence of Type I X-ray bursts