TESTING GR WITH BLACK HOLES: EVIDENCE FOR THE EVENT HORIZON

Ramesh Narayan
Testing Theories of Gravity: Quantitative vs Qualitative

- Many tests of gravity are quantitative: Metric, No-Hair Theorem, etc.
- But gravity theory makes some amazing qualitative predictions
- Black Hole Event Horizon
  - Does the Event Horizon really exist?
  - Verifying the Event Horizon would be a Qualitative but Deep Test of Gravity
In Search of the Event Horizon

- Accretion flows are very useful, since inflowing gas reaches the center and “senses” the nature of the central object.

- X-ray binaries have an additional advantage — we can compare NS and BH systems — event horizon vs hard surface.
Evidence for the Event Horizon

- Differences in quiescent luminosities of XRBs (Narayan, Garcia & McClintock 1997; Garcia et al. 2001; ...)
- Differences in Type I X-ray bursts between NSXRBs and BHXRBs (N & Heyl 2002; Remillard et al. 2006)
- X-ray colors of XRBs (Done & Gierlinsky 2003)
- Thermal surface emission of NSXRBs and BHXRBs (McClintock, Narayan & Rybicki 2004)
Physics of Accretion

- Gas with angular momentum goes into orbit at a large radius around the BH
- Slowly spirals in by viscosity (magnetic fields) and falls onto central object: $M$, $R$
- **Potential energy** is converted to
  - Orbital KE $\approx \frac{GM}{2R} \approx 50\%$ of PE
  - Thermal energy $\approx 50\%$ of PE
- What happens to the two forms of energy?
Case I: Radiatively Inefficient Accretion

- Many accretion systems are radiatively inefficient (advection-dominated: ADAF)
  - Accretion luminosity: $L_{\text{acc}} \ll L_{\text{thermal}}$
    - i.e., $L_{\text{acc}} \ll 0.1 \text{ Mdot } c^2$
  - What happens to the remaining energy?
    - If BH, energy disappears through EH
    - If NS, released from the surface of the accreting object when gas crashes on it:
      $L_{\text{surface}} \approx G\text{M}\text{Mdot}/R \approx 0.2 \text{ Mdot } c^2 \ll L_{\text{acc}}$
Light Curves of Transient X-ray Binaries
Event Horizon in XRBs


Accretion is known to be advection-dominated (N, McClintock & Yi 1996), so we expect

- **BH:** $L_{BH} = L_{acc} \leq 0.1 \dot{M} c^2$
- **NS:** $L_{NS} = L_{acc} + L_{surface} \approx 0.2 \dot{M} c^2 \leq L_{BH}$

Therefore, if BH candidates in XRBs have EHs, they should be much fainter than NSs

**They sure are!!**
- Transient XRBs in quiescence have ADAFs (N, M & Yi 96)
- Binary period $P_{\text{orb}}$ determines $\dot{M}$ (Lasota & Hameury 1998; Menou et al. 1999)
- At each $P_{\text{orb}}$, we see that $L/L_{\text{Edd}}$ is much lower for BH systems. True also for raw $L$ values. (Garcia et al. 2001; McClintock et al. 2003; ...)

GS 1354-64 (BH) Reynolds & Miller (2011)
- Transient XRBs in quiescence have ADAFs (N, M & Yi 96)
- Binary period $P_{\text{orb}}$ determines $\dot{M}$ (Lasota & Hameury 1998; Menou et al. 1999)
- At each $P_{\text{orb}}$, we see that $L/L_{\text{Edd}}$ is much lower for BH systems. True also for raw $L$ values. (Garcia et al. 2001; McClintock et al. 2003; ...)

GS 1354-64 (BH) Reynolds & Miller (2011)
Two Key Assumptions

- Our evidence for the EH from quiescent XRBs requires BH and NS systems to have radiatively ineff. accretion (ADAF)
- Also, $P_{\text{orb}}$ has to be a good proxy for $\dot{M}$
- Both assumptions are very reasonable
- But the argument would be stronger if we could avoid these assumptions
- We can do this at the Galactic Center
Black Hole Candidate at the Gal. Ctr.: Sagittarius A*  

- Dark mass $\sim 4 \times 10^6 \, M_\odot$ at the Galactic Center  
- Compact radio source Sgr A* is associated with the dark mass (Reid & Brunthaler 2005)  
- Sgr A* is very compact: $< 10 G M/c^2$ (Doeleman)  
- Sgr A* is ultra-dim: $L \sim 10^{36} \, \text{erg/s}$  
- Minimum accretion rate: $\dot{M}_{\text{min}} = 10^{-10} \, M_\odot \, \text{yr}^{-1}$
Luminosity and Spectrum of Sgr A*  

- Sgr A* is a very dim source. It has a luminosity of only $\sim 10^{36}$ erg/s  
- Most of the luminosity comes out in the sub-mm  
- Most likely we have an ADAF (Narayan, Yi & Mahadevan 1995)  
- But we won’t use this fact
Case II: Radiatively Efficient Accretion

- If the accretion system is radiatively efficient (e.g., standard thin disk)
  - Accrn lum: \( L_{\text{acc}} \approx L_{\text{thermal}} \approx 0.1 \, \text{Mdot} \, c^2 \)
- What happens to the remaining energy?
  - If BH, energy disappears through EH
  - If we have an object with a surface:
    \( L_{\text{surface}} \approx L_{\text{KE}} \approx 0.1 \, \text{Mdot} \, c^2 \approx L_{\text{acc}} \)
  - (Recall, for ADAF: \( L_{\text{surface}} \nless L_{\text{acc}} \))
The Radiation we see in Sgr A* is from the Accretion Disk

- Any “surface” in Sgr A* will produce optically thick radiation (opaque to its own radiation)
- Measured mm/sub-mm flux, coupled with small angular size, implies high brightness temperature: $T_B > 10^{10}$ K. Requires gas temperature $\geq 10^{10}$ K.
- Optically thick emission at this temperature would peak in $\gamma$-rays (and outshine the universe!!)
- Therefore, the radiation from Sgr A* must be emitted by gas that is optically thin in IR/X-rays/$\gamma$-rays
- Sub-mm radiation is from the accretion flow
Is there any “Surface” Luminosity from Sgr A* 

- The surface luminosity is expected to be
  \[ L_{\text{surface}} \approx L_{\text{acc}} \] (at least, could be much more)
- Since we know \( L_{\text{acc}} \approx 10^{36} \text{ erg/s} \), we predict:
  \[ L_{\text{surface}} \approx 10^{36} \text{ erg/s} \] (perhaps \( \Box 10^{36} \text{ erg/s} \))
- Moreover, surface should be optically thick (blackbody-like emission) and for likely radii \( R \) of the surface, radiation should be in Infrared

- No Sign of this Radiation
Maximum Mdot from IR Flux Limits

- IR flux limits place stringent constraints on accretion onto a surface
- Limits are well below minimum possible Mdot in Sgr A*
- Therefore, Sgr A* cannot have a surface
  ➔ has Event Horizon

Broderick, Loeb & Narayan (2009)
Summary of the Argument

- The observed sub-mm emission in Sgr A* is definitely from the accretion flow.
- Radiation is way too hot to be from the "surface" of a compact object.
- If Sgr A* has a surface we expect at least $\sim 10^{36}$ erg/s from the surface.
- This should come out in the IR, but measured limits are $\sim 100$ times lower.
- Therefore, Sgr A* cannot have a surface.
Can Strong Gravity Provide a Loophole?

- Under all reasonable conditions, the radius of the surface must be larger than \((9/8)R_s\) (Buchdahl 1959) ➔ grav. redshift < 3

- In some very unusual models (gravastar, dark energy star), it is possible to have a smaller radius: \(R = R_s + \Delta R\), \(\Delta R \leq R_s\)

- Extreme relativistic effects are expected
Effects of Strong Gravity

- Radiation may take forever to get out
- Surface emission may be redshifted away
- Emission may not be blackbody radiation
- Emission may be in particles, not radiation
- Surface may not have reached steady state

It is easily shown that none of these effects can get around the observational evidence
One Key Assumption

- Our argument for an EH in Sgr A* makes only one important assumption
  - It assumes that the source is accreting and sub-mm radiation is produced by accretion

- The only way out of an Event Horizon is to say that Sgr A* is powered by something other than accretion
Summary

- By now, there is a variety of astrophysical evidence – two were presented here -- for the reality of **BH Event Horizons**
- Each argument by itself is pretty strong
- Combined, the evidence is **Very Strong**
- Virtually impossible to get around...
A Question for Physicists!

- Can we say that the search for the Event Horizon is a done deal?
- Can we chalk up a victory for gravity and move on?
- If “NO”, what else must we do?
- We need guidance on when we can claim victory...