Frontiers: Observational Signatures of Strong Gravity

As we said a few lectures ago, general relativity is in a unique position among theories of fundamental interactions, because of the relative weakness of gravity. One can, for example, probe EM or strong/weak interactions using particle accelerators, and by this can test the predictions of these theories in relatively extreme environments. But experimental, local tests of GR predictions are limited to weak gravity. These include things like the gravitational redshift of light, light deflection by the Sun, delays of radio waves, and GR precession of planets. However, GR corrections are typically of order M/r compared to the Newtonian predictions. This is very small in things to which we have access; for example, at their limbs, $M/r \approx 2\times 10^{-6}$ for the Sun and $M/r \approx 10^{-9}$ for the Earth. Even for signals from binary pulsars, it is their separation of $\sim 10^{11}$ cm that matters, so again $M/r \ll 1$.

Clearly, the direct detection of gravitational waves from coalescing black holes has given us a rather direct glimpse into strong gravity! More about that near the end of this lecture, but let's first think about electromagnetic signatures of strong gravity.

As an example, suppose that black holes are pseudo-Newtonian, in the sense that they have horizons but no ISCO. Therefore, gas will spiral in nearly circular orbits right down to the horizon, then get sucked in. This means that they will release 50% of their mass-energy as they spiral. **Ask class:** how would we use this, plus the Eddington luminosity, to estimate how long it would take a black hole to grow in mass? Since L_E is the maximum luminosity of accretion, the maximum accretion rate is $\dot{M}_E = L_E/\epsilon c^2$, which is 3×10^{17} g s$^{-1}(M/M_\odot)$, or 2.2×10^8 yr for an e-folding time. If black holes are originally formed with roughly stellar masses, $\sim 10-100\,M_\odot$, then they need more than 10 e-foldings to reach supermassive status. This would take 2-3 billion years, so we wouldn't expect any AGN at $z > 4-5$, even if the black holes all accrete at Eddington. This would pose problems. In contrast, with an ISCO the accretion efficiency is lower, so the problem is eased somewhat although not eliminated (for example, the existence of a $\sim 10^9\ M_\odot$ black hole at $z = 7.1$ [Mortlock et al. 2011, Nature, 474, 616] still poses difficulties). In addition, one could no longer be sure about the existence of black holes at all, if GR were to be dramatically wrong in the strong-gravity limit.

In this lecture, then, we'll talk about various possible and claimed signatures. You'll get a chance to use your skeptical faculties to think about what might be problematic for these claims. That may sound purely negative, but it gives a better appreciation for the more solid claims when these are encountered.

Types of signatures

The point, then, is to look for qualitatively new aspects of GR compared to Newtonian predictions, and think of how these might be manifest in the data. **Ask class:** what are some qualitatively new aspects of GR? ISCO, frame-dragging, horizon, epicyclic frequencies. **Ask class:** what are some ways they might imagine detecting effects due to these? In general, one has imaging, spectral, and timing information. How can these be used? With Starship Enterprise-like resolution, one could think of imaging the event horizon of a black hole, and seeing a variety of effects on background stars or the accretion disk that could be compared with predictions. **Ask class:** how can we estimate the angular resolution needed? We need to think of the largest angular scale that a black hole's horizon could subtend. First let's think about a stellar-mass black hole. In round numbers let's say the mass is about $10\,M_\odot$, so for a nonrotating (Schwarzschild) hole the horizon is about 30 km across. There are probably around 10^8 stellar-mass black holes in the Galaxy (maybe 1 in 2000 stars becomes a black hole, and we might have 2×10^{11} stars in our Galaxy), so if the Galaxy has a volume of $(10~\mathrm{kpc})^2{\times}1$ kpc, then the average number density of black holes is $10^{-3}\mathrm{pc}^{-3}$, so the nearest BH could be 10 pc away. The angular size of that hole is then about $3 \times 10^6/3 \times 10^{19} = 10^{-13}$ rad, or about 2×10^{-8} arcseconds. The black hole in the center of our Galaxy has a mass of $4 \times 10^6\,M_\odot$ and is $\sim$8 kpc distant, for an angle of 4×10^{-11} rad, or 6×10^{-6} arcseconds. These are really, really tiny, although at millimeter wavelengths current VLBI can get to 10^{-10} rad, and the aim of the Event Horizon Telescope (which actually uses many existing facilities; see http://www.eventhorizontelescope.org/) is to resolve our Galactic center black hole (and the supermassive black hole in M87, which is $\sim$ 1500 times more massive and $\sim$ 2000 times more distant than our SMBH) to see its shadow; we hope that complexities such as plasma effects or jet emission don't mess this up.

Spectra

Our next try is spectra. **Ask class:** what kind of spectral signatures might reveal strong gravity effects? There are two types that have been suggested: line profiles or continuum spectra. We'll start with continuum spectra to emphasize the need for line profiles!

One type of continuum fit that attracted a lot of attention a few years ago was spectral fits to an accretion disk. A few lectures ago we discussed geometrically thin, optically thick disks, and gave a rough derivation of their emission spectrum assuming that each annulus radiates as a blackbody, but with a temperature that depends on the radius and on the mass accretion rate. An idea dating to at least the mid-80s is that this may provide a signature of the ISCO. Suppose, people argued, that one does a careful fit of the spectrum. The model parameters include things like the viewing angle, but more importantly include $R_{\rm in}$, the innermost radius of the nearly circular flow, and the innermost radius of the significant emission. Black hole sources have varying mass accretion rates, but if $R_{\rm in}$ is the ISCO, its value should remain constant. In a few sources this seems to be the case, and some press releases were sent out indicating that the long sought after strong-gravity signature had been seen.

Ask class: what are some of the things that could go wrong here? One problem is that the fits are nonunique, to put it mildly. The real regions are more complicated, probably with hot coronae above the disk that reprocess radiation (and in fact this fitting must be done very carefully, because although the spectra from individual portions of the disk may *look* Planckian, they are actually very inefficient compared with blackbodies, and this makes a difference to the fits). Also, if you fool around with different parameters you see that several of them are practically degenerate, meaning that you can change $R_{\rm in}$ if you change the spin of the black hole or even the emissivity. Observationally, many sources have variable $R_{\rm in}$, down to unphysical values such as 2 km, so researchers have learned that they need to focus on particular spectral states where $R_{\rm in}$ appears to be closer to constant.. Incidentally, this type of fitting is being used by some researchers to infer other properties such as the spin of the black hole. The continuum models are better now than they were a few years ago, so this has some prospects, but I'm still a bit skeptical.

One lesson that I think comes from this is that smooth continuum spectra are often difficult to interpret correctly. From an information-theoretic standpoint, they just don't contain that much information. Power laws, broad bumps, etc., can be produced by many mechanisms, so picking one and doing detailed fits is a dangerous procedure. People are still working on it, though.

For this reason, another active area of research into spectral signatures deals with line profiles. The star of this show is the Fe Kα fluorescence line. That's because (1) fluorescence (reradiation of incident radiation in a particular line) is stronger for higher-Z elements, (2) Fe is the highest-abundance heavy element around, and (3) Fe K shell transitions are at 6.4 keV, which is easily detectable with X-ray instruments and is not absorbed much. The idea, then, is that this emission happens everywhere in an accretion disk that the gas is hot enough (as long as the iron still has at least three electrons left), so this line can act as a tracer for the motion of the gas. If so, that's great, because the particular motion of the gas could tell us a lot about GR. For example, suppose there is an ISCO and that there is negligible emission inside it. Then since most of the energy is emitted close to the black hole, the Kα line will be dominated by that emission. It would therefore be redshifted (by gravity) and broadened (by the circular motion and Doppler shifts). This would lead to a particular integrated line profile that, in detail, could in principle even tell us about the spin of the black hole as well as confirming the existence of the ISCO. The line is weak, though, so to infer its width and shift one has to subtract the continuum very carefully.

This idea has been pursued by a number of researchers. Locally, our expert is Chris Reynolds, and indeed for his work on iron lines and a number of other issues in high-energy astrophysics he was awarded the 2005 Warner Prize by the American Astronomical Society. Our former grad student Laura Brenneman has also done high-quality modeling of the line data. The best data for this idea are those with the highest spectral resolution. There is one AGN, MCG-6-30-15, which seems to be a beautiful exemplar of this idea. Many detailed fits have been done to it. In addition, the superb spectral resolution of Chandra and XMM seemed to be perfect for this kind of analysis.

Ask class: what could go wrong here? From the theoretical side, it might be that the spectra aren't as simple as all that. Scattering or reprocessing of the radiation could play a role, and it might be that, e.g., magnetic interactions could produce emission from well inside the ISCO. Something that wasn't expected is that the "emissivity profile" (the strength of emission of the Fe Kα line as a function of the distance from the black hole) increases much more rapidly with decreasing distance than expected in the standard model. This is typically modeled using a "lamppost" picture, in which there is a source of ionizing radiation above the black hole (e.g., this could be the base of a jet) and the photons the source produces are strongly bent by the gravity of the hole. It gives good fits, but is ad hoc. Another issue might be that if only one instrument sees such a broad line, one would have to examine that instrument carefully to exclude issues of calibration. Now, however, the lines have been seen with many X-ray satellites, and everything is still consistent with broad lines and highly relativistic motion. Also, it happens that for sources that have both line and continuum estimates of spin parameters, although they don't always agree with each other to within their stated error bars, to my eye they seem reasonable consistant (see Table 1 in my review with Jon Miller: http://www.astro.umd.edu/∼miller/reprints/miller15a.pdf).

Evidence for a Horizon?

For completeness, we should mention another claim for evidence of a strong-gravity effect that doesn't easily fit in our imaging/spectra/timing categories. The granddaddy of all GR discoveries would be conclusive evidence for the existence of the event horizon of a black hole, since that is GR at its most extreme. A big difference between BH and NS is that NS have a surface whereas BH don't, so (for example) stuff that falls onto a NS inevitably releases 20–30% of its mass-energy in radiation, whereas stuff that falls onto a BH doesn't have to.

This was the basis for another high-interest claim for the existence of a horizon. A number of researchers have, for the last few decades, worked on the Advection-Dominated Accretion Flow (ADAF) model of accretion. In this model, at low accretion rates matter releases only a small fraction of its mass-energy before entering the black hole. Therefore, the luminosity could be very small at low accretion rates: for some particular models, for example, the accretion efficiency scales as $\dot{M}/\dot{M}_E$ below $0.1\,\dot{M}_E$. Thus for transients, in which $\dot{M}$ can vary over two or three orders of magnitude in a few months, one would expect in this model to see an enormous change in luminosity (maybe 5-6 orders of magnitude) whereas in neutron star sources the luminosity would only scale with the accretion rate. Lo and behold, when one plots ratio of active to quiescent luminosity for suspected BH and suspected NS sources, the ratio is significantly higher for BH than NS. This was widely claimed to be evidence for a horizon in BH.

Ask class: what might go wrong with this? There are several potential problems. One is that there are other things different between the two systems. For example, BH are several times more massive than NS, so whatever causes the transient behavior might also be different, e.g., in BH the actual mass accretion rate might drop more than in NS sources. Another problem is that the mass accretion rate *at the compact object* does not have to be the same as far away (cf. dwarf nova instability). That is, matter could pile up at some more distant radius. In addition the flow itself can easily throw away most of the matter before it reaches the central object (see the "ADIOS" model of Begelman and Blandford). Therefore, this evidence, while interesting and worth keeping in mind, is not conclusive.

Timing

The variability of sources can be a powerful way to study them, particularly the fast variability. That's because if one sees variability at hundreds or thousands of Hertz, the gas producing this must be orbiting very near to the black hole or neutron star, so it might contain information about strongly curved spacetime. If the variability is periodic (like a pulsar), one might be able to see this in a set of countrate data: the countrate goes up and down periodically. If the variability is weak or aperiodic (e.g., ranging over a variety of frequencies), one instead takes a Fourier transform and squares it to produce a power density spectrum.

Ask class: what signatures of strong gravity might they imagine could show up in such a plot? Here, we need to think about some of the characteristic frequencies. These could include orbital frequencies, frame-dragging frequencies, or epicyclic frequencies. A signature of the ISCO could be a cutoff in these frequencies, e.g., because motion of gas inside the ISCO is a rapid inspiral, so it would be difficult to produce strong, relatively coherent oscillations. However, a mere cutoff of a broadband spectrum has problems similar to that of doing continuum energy spectra fits. Too much might be able to explain it. Instead, you'd like the equivalent of spectral lines: sharp features in a power density spectrum that indicate narrow, special regions in the disk.

Such features, called kilohertz QPOs, were detected using the Rossi X-ray Timing Explorer starting in early 1996. From neutron stars, these often come as a pair of sharp (but not completely periodic) features, separated by typically ~ 300 Hz, with the upper peak at $\sim 1000 - 1300$ Hz. Moreover, the peaks can change their frequencies by hundreds of Hertz while the separation frequency doesn't change much (maybe tens of Hertz). From black holes, there can also be a pair of high frequency peak is seen, but they are at lower frequencies (60–300 Hz), and the black hole frequencies do not vary. Many, many other trends and features are now established, and in detail it's rather confusing. This, by the way, is an example of how having a new instrument with dramatic new capabilities can mean that a completely unsuspected phenomena (kHz QPOs) can suddenly become data-rich!

Debate rages about these features, particularly in the neutron star case, and there is no universal consensus (although I have my own opinions, of course...). Here, though, are some highlights. Most people agree that the upper peak frequency has to be the orbital frequency at some special radius in the disk. But that means that there is an upper limit to this frequency; inside the ISCO it would just spiral in. Combined with the fact that the frequency of the oscillation increases as the luminosity goes up, this suggested to us that there should be a rollover in the frequency at $\nu_{\rm ISCO}$. In addition, that frequency would tell you the mass of the star, because since $R_{\rm ISCO} = 6M$, the orbital frequency is $\nu_{\rm ISCO} = \sqrt{GM/R^3_{\rm ISCO}} \sim M^{-1}$.

In fact, starting with analysis by Will Zhang and colleagues, and later by Didier Barret, Jean-Francois Olive, and me, there has been evidence that some of these signatures actually exist and suggest mass of order $2\,M_\odot$ in some cases! That's rather high for a neutron star, and when we noted this it was taken by some to be a weakness of our interpretation, because at that time no neutron star mass was definitively known to be above 1.44 $M_\odot$. However, since that point a neutron star has been seen at 2.01 $M_\odot$, so our masses really are reasonable. There are important implications for the state of matter at extremely high density (particularly, that it is comparatively hard, as allowed equations of state go). Pretty amazing stuff: two fundamental discoveries from one phenomenon. However, "extraordinary claims require extraordinary proof", and it still needs to be determined whether other things might cause the behavior that we attribute to the ISCO.

There have also been claims of evidence for frame-dragging, as reflected in other QPOs in neutron stars and black holes. I am very skeptical about these claims, though one must keep an open mind.

Gravitational Waves

The LIGO detection of gravitational waves on September 14, 2015 was a landmark event in the study of gravity. From the standpoint of strong gravity, it is noteworthy that after the best-fit general relativistic waveform was subtracted from the signal, less that 4% of the signal remained. This tells us that to the degree that we can tell from this signal, there cannot be *large* deviations from general relativity.

There are other implications of these data that aren't so obvious. For example, in general relativity, signals from gravity propagate at the speed of light independent of the frequency of the signals. This would be one consequence of the graviton (the hypothetical particle that carries gravity; it isn't an explicit part of general relativity) having zero rest mass. Suppose, though, that the graviton has finite mass or, more generally, that different frequencies propagate at different speeds. Then the billion year propagation time from GW150914 to us would afford ample opportunity for the faster-moving frequencies to distance themselves from the slower-moving frequencies. This would change the waveform we see with LIGO, because this would change the amplitudes and arrival times at different frequencies. The lack of any observed distortion allows us to set a strong limit on the mass-energy of the graviton: it has to be less than 2×10^{-22} eV. Note, by the way, that there are stronger but more model-dependent limits that can be set on the mass from other arguments (e.g., bounds from galaxy clusters).

But is this the end of the story? Not really. For example, there are gravitational theories that predict *exactly* the same things as general relativity when there is no matter, but that suggest there will be deviations when there is matter. Black holes don't have matter, so such theories can't be ruled out by GW150914 or other double black hole events. Events involving neutron stars will be needed.

There is an industry that has developed over the past few decades that studies possible deviations from general relativity. Until the discovery of gravitational waves, the most rigorous observational tests of such theories involved binary pulsars. Now, however, we have a new toy to play with! In the more distant future, the European Space Agency (with, we hope, some contribution from NASA) will fly the Laser Interferometer Space Antenna (LISA), which will see much stronger double black hole coalescenses (signal to noise ratios of thousands, rather than the ~ 25 that was the strong event GW150914). This will give us new *types* of tests, such as tests of the no-hair theorem: in particular, after the merger of the holes the remnant will "ring down" to a final Kerr configuration, and the way it rings down will provide us with a strict self-consistency check of general relativity. Strong events are needed to get the required signal.

All in all, gravitational waves, plus continued developments in X-ray and radio astronomy, mean that there should be a host of new and precise probes of strong gravity in the upcoming years and decades.

Additional references: For a more thorough discussion of timing phenomena in black holes and neutron stars, see http://www.astro.umd.edu/∼miller/reprints/miller04.pdf. For more discussion of iron lines and other topics in X-ray probes of black holes, see Chris Reynolds' research page http://www.astro.umd.edu/∼chris/Site/Research.html. For my perspectives on the implications of the first announced LIGO discovery of gravitational waves from coalescing black holes, see http://www.astro.umd.edu/∼miller/reprints/miller16d.pdf.