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, laboratory 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, $M/r \approx 2 \times 10^{-6}$ 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 $M/r \ll 1$.

Therefore, many of the predictions of GR in strong gravity are untested experimentally. Since these predictions are used to model all black holes and neutron stars, the actual behavior of gravity in these regimes is very important. Here's 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 there is no problem. Other consequences would be that one could no longer be sure about the existence of black holes at all, if GR is 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 guess: stellar-mass black hole. Typically about $10\,M_\odot$, so for Schwarzschild the horizon is about 30 km across. The number in the Galaxy is probably around 10^8, so if the Galaxy has a volume of $(10\text{ kpc})^2 \times 1$ kpc, the average density of black holes is 10^{-3}pc^{-3}, so the nearest BH is probably 10 pc away. The angular size 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 $3.5 \times 10^6\,M_\odot$ and is 8 kpc distant, for an angle of 4×10^{-11} rad, or 8×10^{-6} arcseconds. These are really, really tiny, and probably out of reach for quite a while, although at slightly larger scales VLBI might be able to do something.

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 seemed 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. 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, most sources have variable $R_{\rm in}$, down to unphysical values such as 2 km, so this is not a promising direction. Incidentally, this type of fitting is still used by some researchers to infer other properties such as the spin of the black hole. I am highly dubious about this, because this is an even finer level of detail and cannot (at least at this time) be interpreted uniquely.

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.

For this reason, a more 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, 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. At Maryland (and indeed internationally), our own Chris Reynolds has been one of the most careful and innovative researchers in this field. Work by Chris and others, including our recent Ph.D. graduate Laura Brenneman (now a postdoc at NASA's Goddard Space Flight Center) has led to a lot of excitement. Data from many satellites, including ASCA, Chandra, XMM-Newton, and Suzaku, have been analyzed, and it appears that a number of supermassive black holes are rotating very rapidly.

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. It has also been claimed that a complex "warm absorber" composed of gas farther away from the hole could carve out a feature similar to a Fe Kα line, although that seems rather ad hoc.

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

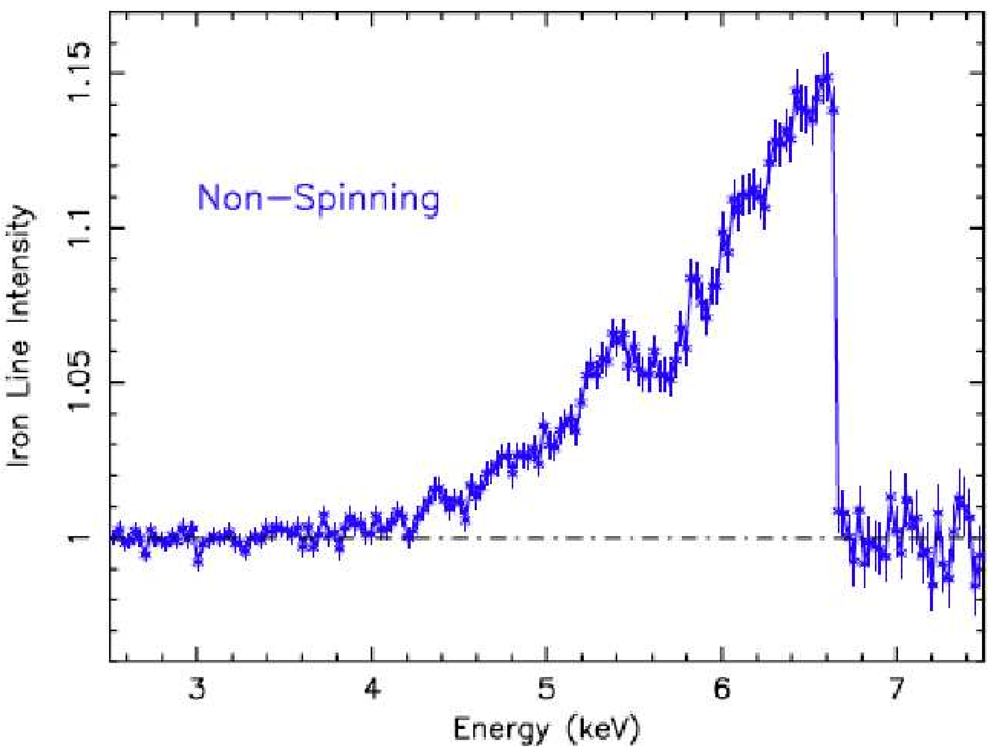

Fig. 1.— Simulation of an iron Kα line from a nonrotating black hole, as would be seen with the Constellation-X observatory. Here the continuum has been divided out. From http://constellationx.nasa.gov/images/science/black_holes/nonspinning_bh_simulation.gif

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 about 20% 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 (esp. Ramesh Narayan) have, for the last decade, worked on the 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. 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, 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 with 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. From black holes, a pair of peaks is sometimes seen, at lower frequencies (60–300 Hz). 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 $\nu_{\rm ISCO} = \sqrt{GM/R^3_{\rm ISCO}} \sim M^{-1}$. Well, two years ago it seems to have been observed in the source 4U 1820–30 by Zhang et al. (GSFC). If so, this is pretty remarkable: not only the first direct evidence of the ISCO, but if you calculate the mass it turns out to be $2\,M_\odot$! That's rather high for a neutron star, and would imply mighty and portentious things about the state of matter at extremely high density (particularly, that it is comparatively stiff, as allowed equations of state go). Pretty amazing stuff: two fundamental discoveries in one data set. However, "extraordinary claims require extraordinary proof", and it still needs to be determined if this apparent rollover is really due to a spectral state change that fools us about the true accretion rate (such things can happen).

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.

Intuition Builder

When gravitational waves are detected directly, any that come from mergers of two black holes will test strong-field general relativistic predictions. This, however, might be almost a decade off. Can you think of any other electromagnetic signatures of very strong gravity?