General Relativity as Seen in X-rays: What Can LISA Tell Us That We Don't Already Know?

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Abstract. If it performs as well as planned, LISA could provide tremendous information on physics and astronomy in the strong field regime of general relativity near black holes. X-ray astronomy has already provided us with tantalizing glimpses of phenomena occurring in the accretion flow onto compact objects in binary systems and active galactic nuclei. Iron K-alpha photons emitted by the accreting plasma provide direct evidence for relativistic motions and gravitational redshifts. In addition, there is evidence for the existence of the event horizon, as well as claims of general relativistic effects being responsible for certain classes of time variability. I review these exciting results, and compare and contrast them with the complimentary information which will be obtained by LISA.

INTRODUCTION

LISA has the potential of revolutionizing experimental gravitational physics and astrophysics. To place this potential in context, it is perhaps useful to briefly review what we are learning about general relativity in astronomical sources from current observational techniques. The exciting results come almost exclusively from the field of X-ray astronomy: many of the black hole and neutron star sources known in the sky emit copious X-ray radiation through the process of accretion of plasma. Three recent examples stand out as being particularly noteworthy: evidence for the existence of black hole event horizons, evidence of relativistic frame-dragging, and the mapping of the circular orbit structure of the Kerr metric. As exciting as these results are, none of them are yet on a solid foundation. This is partly because the interpretation of X-ray data relies on an understanding of complex magnetohydrodynamical and radiative transfer processes in accretion flows onto compact objects, and this understanding is at present incomplete, to say the least. This brings up one of the contrasting features between X-ray astronomy and gravitational wave astronomy: there should be many compact object systems where gravitational wave emission will be much simpler to interpret.

SOFT X-RAY TRANSIENTS: PROOF OF BLACK HOLE EVENT HORIZONS?

Soft X-ray transients arise in binary systems containing a black hole or neutron star which accretes material from a relatively ordinary companion star. In quiescence, i.e. most of the time, the system has a low X-ray luminosity L_{min}. Every few decades or so, however, the system undergoes a several month long outburst in which the X-ray luminosity becomes very large, L_{max}. The difference between these two states is clearly due to different rates of accretion of mass onto the central compact object. Whether that compact object is a black hole or a neutron star is partly inferred from the mass, when it can be measured. In some systems the mass of the compact object is consistent with that of a neutron star, whereas in others the inferred mass is found to be greater than 3 $M_{\odot}$, implying a black hole. In addition, neutron stars are inferred if the system also undergoes so-called type I X-ray bursts, which are thought to be due to thermonuclear flashes on the neutron star surface.

The accretion flow in the outburst state is generally thought to take the form of a standard optically thick accretion disk [1]. The X-rays arise from thermal emission from the disk and, in the case of neutron stars, from material landing on the surface of the star. In both black holes and neutron stars the efficiency of conversion of rest mass energy to luminosity is probably comparable, of order 10 percent. The state of the flow in the low accretion rate quiescent state is not so clear, but an increasingly popular suggestion is that it is an "advection dominated accretion flow", or ADAF [2,3]. In such flows the gravitational energy released by accretion is stored in the ions of the plasma, with very little transferred to the electrons. Much of the heat is therefore advected inward toward the central object instead of being radiated away. ADAFs onto a black hole can therefore have much lower radiative efficiencies than standard accretion disks, as much of the heat flows down through the event horizon. If the flow is onto a neutron star, however, the efficiency of the system remains high because material will still radiate as it strikes the stellar surface.

Narayan, Garcia, & McClintock (1997) [4] have recently noted two additional striking differences between black hole and neutron star soft X-ray transients. The first is that black hole systems have larger outburst luminosities than neutron star systems. This is easily explained as being due to the fact that the black holes in these systems have larger mass than neutron stars, permitting them to have higher Eddington luminosities. The second is that out of nine systems considered, the ratio of quiescent to outburst luminosity L_{min}/L_{max} is much larger for neutron stars than black holes. It could be that the quiescent accretion rate in black hole systems is always smaller than that of neutron star systems, but a more likely explanation perhaps is that the radiative efficiency of the black hole systems is much lower due to the existence of their event horizons, the defining feature of black holes.

However, these results are based on only a small number of sources. In addition, the X-rays are observed in finite and different bandpasses, and accretion models must be used to justify the assumption that the observed luminosity dominates the bolometric luminosity. The theoretical consistency of ADAF models is also uncertain, as there seem to be ways of thermally coupling ions and electrons on the infall time scale or of channeling the accretion power directly into the electrons through magnetohydrodynamic turbulence [5–7]. Finally, ADAFs or other types of quiescent accretion flows may be accompanied by outflows, which would also reduce the radiative efficiency without necessarily requiring an event horizon.

QPO IN LOW MASS X-RAY BINARIES: LENSE-THIRRING PRECESSION?

X-ray binary systems are known to sometimes exhibit quasi-periodic oscillations (QPO) in their X-ray luminosity on a wide range of time scales. QPO on very short, millisecond time scales has recently been detected in a number of sources by the *Rossi X-Ray Timing Explorer*, which is interesting because this is comparable to the dynamical time scale of the accreting compact object. Pairs of kilohertz QPO have been detected in the quiescent emission from neutron star low mass X-ray binaries. The frequencies of these QPO, ν_b and ν_k, can vary with time, but the difference $\nu_s = \nu_k - \nu_b$ between them is remarkably stable. This difference frequency is itself exhibited by QPO during type I X-ray bursts from these systems (e.g [8]). It is very likely that ν_s is the spin frequency of the neutron star, with the QPO arising perhaps from inhomogeneous burning on the surface during the thermonuclear flash. The higher frequency member of the pair of QPO seen in quiescence, ν_k, could be the frequency of the innermost circular orbit of the accretion disk, with oscillations arising because of inhomogeneous blobs of X-ray emitting material orbiting at that radius. The lower frequency member, ν_b, is then a beat frequency between ν_k and ν_s, seen perhaps because of modulation of the accretion rate onto the central star due to the interaction between the stellar magnetic field and the inner region of the disk.

If this interpretation of the observations is correct, then one can use the measured spin frequency of the neutron star and orbital frequency of the inner disk to calculate the Lense-Thirring precession frequency ν_{LT} of a test particle in orbit at the same radius but inclined to the equator of the neutron star. The only unknowns are the mass and moment of inertia of the neutron star, but these are reasonably well-determined from models. The precession frequency ν_{LT} turns out to be ~ 10 Hz, and amazingly, QPO are also observed at comparable frequencies in these same sources. Stella & Vietri (1998) [9] have therefore suggested that these QPO are due to Lense-Thirring precession of an accretion disk which is inclined to the equatorial plane of the star. Corrections must be made to ν_{LT} due to the classical retrograde precession produced by the neutron star quadrupole moment, but this frequency turns out to be smaller than ν_{LT}. Lense-Thirring precession has also been proposed as an explanation for QPO observed in black hole systems [10].

A problem with this interpretation of the observations is that viscosity in the accretion disk should align the plane of the inner disk with the equatorial plane of the compact object, even if the disk is inclined further out [11]. However, gravitomagnetic bending modes of the right frequency do in fact exist in the innermost regions of a viscous disk [12]. These modes are damped, and the question is whether or not they could be excited to sufficiently high amplitude to explain the observations.

Another problem with the Lense-Thirring interpretation is that there are other ways of producing QPO of comparable frequency, some of which are also due to general relativistic effects. For example, general relativity can cause the epicyclic frequency to have a maximum at some radius outside the inner edge of the disk, thereby trapping hydrodynamical gravity wave modes (e.g. [13]). Whatever is the correct explanation, it is likely that general relativity is playing some significant role.

MAPPING OF CIRCULAR ORBITS IN KERR METRIC USING THE FE Kα LINE

Accretion flows onto supermassive black holes in active galactic nuclei also produce copious X-rays. In Seyferts, the X-rays are generally thought to arise from Compton scattering by hot electrons of soft photons emitted by an accretion disk. Some of these X-rays shine back on the disk, where they ionize K shell electrons from iron atoms, causing the iron to fluoresce in Kα line photons as L shell electrons drop to the K shell. This line is observed to be a powerful line in Seyferts. The *Advanced Satellite for Cosmology and Astrophysics* (*ASCA*) has sufficient spectral resolution to measure the line profile, and it has turned out to be very broad [14–16]. Although the interpretation is not universally accepted, it appears likely that this is due to a combination of gravitational redshifts and Doppler broadening at relativistic speeds in the accretion flow very near the black hole. The profile can be well fit by simple power-law radial emissivities of the line in disks around Schwarzschild or Kerr black holes. In fact, one might hope to use the profile to measure the spin of the black hole, due to the fact that the innermost stable circular orbit (ISCO) can exist much closer to the horizon for large spins, producing much broader line profiles. Unfortunately, the spatial form of the line emissivity is not known, and if it declines weakly with radius then the line profiles for Kerr holes become similar to those of Schwarzschild holes. In addition, there may be sufficient iron line emission from the accretion flow inside the ISCO to permit Schwarzschild holes to also produce extremely broadened profiles [17].

ASCA's limited effective area requires long integration times to measure the iron line profile, much longer than the light crossing time of the inner parts of the accretion disk. X-rays are known to vary on short time scales in Seyferts, suggesting that some sort of transient flaring is producing regions of hot electrons above the disk. A large effective area X-ray satellite which is capable of detecting enough photons to measure the line profile on short time scales could measure the line profile changing with time as X-rays from a given flare reach different locations in the disk. Such reverberation mapping will just become feasible with the proposed mission *Constellation-X*, although upcoming missions such as the *X-ray Multi-Mirror Observatory* will provide some interesting data as well.

Reynolds et al. (1998) [18] have explored this idea and shown that such data would contain tremendous diagnostic information. The time between the start of the flare and the first detection of iron line photons depends on the distance between the flare and the disk and the disk inclination angle. The breadth of the instantaneous line profile depends on the disk inclination angle, being quite narrow for face-on disks and very broad for edge-on disks. As time goes on, the iron line becomes increasingly narrow as the X-rays reach the outer parts of the disk. A time-delayed redshifted response in the profile is caused by the Shapiro delay acting on photons passing near the hole. Transient high energy peaks can be produced by highly ionized (hydrogen and helium-like) iron where the Kα photons are at higher energy than for neutral iron.

In principle, such reverberation mapping can map the orbit structure of a Kerr spacetime, at least for circular equatorial orbits, thereby allowing a test of general relativity. However, the iron lines will also depend on the disk inclination angle, the illumination geometry of the flare, and the possible presence of simultaneous, multiple flaring regions. The instantaneous line profiles also depend on the ionization state of the gas in the disk, not only because the line energy depends on the ion species, but also because the line becomes resonant once electrons start being stripped from the L shell. Detailed photoionization and radiative transfer calculations may therefore be necessary to model the data. Finally, the results also depend on the geometry of the fluorescing, cool gas, which in the inner regions of accretion flows in Seyferts may not be smoothly distributed as in simple disk models (e.g. [19]).

CONCLUSIONS

As exciting as they are, each of the three cases I have discussed relies on understanding the complex physical processes occurring in accretion flows - flows where even the geometry is uncertain because direct imaging is impossible at the present time. Instead of QPO and line emission from orbiting gas which exists at all radii, LISA can detect gravity wave emission from the much simpler and cleaner system of a single star in orbit around a supermassive black hole, providing a much simpler test of general relativity. Accretion flows probe mainly equatorial circular orbits, although warping of the disk and photon geodesics probe other orbits off the equatorial plane. A single star need not be in a circular orbit, although in actual fact it may very well be if it is in orbit around an accreting black hole because of drag forces from the disk. However, unlike in X-ray astronomy, the accretion flow need not be there for LISA to be able to detect something. LISA views sources which are "lit up" in gravity waves, and could well see gravity wave emission from black holes which produce very little in the way of electromagnetic radiation. In addition to providing possibly cleaner tests of general relativity, it will also give us a fairer census (or at least biased in a different way from electromagnetic astronomy) of the presence of black holes in the universe.

Astronomical observations have revealed enormously energetic, transient phenomena involving dynamic spacetime curvature (supernovae and possibly gamma-ray bursts), but the electromagnetic data has little to say about dynamic general relativity. This is likely to always be the case because such sources are optically thick, so that photons lose memory of the processes going on at the heart of these sources. This is not a problem for gravitational waves.

The most important conclusion that one should draw from modern X-ray astronomy is that X-ray phenomena in the universe are incredibly rich and diverse, far more so than was predicted prior to the launch of X-ray satellites. The development of X-ray astronomy and astronomy in the other nonvisible bands of the electromagnetic spectrum is perhaps the most compelling argument for opening up a new observing window on the universe through gravitational waves.

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