Predicting Electromagnetic Signatures of Gravitational Wave Sources

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Scientific discovery is driven by observations. To date, the vast majority of all such observations and corresponding scientific conclusions are founded on the detection of photons, the messenger of the electromagnetic interaction. This is changing as we enter the era of multi-messenger astronomy, where observations of high energy neutrinos and cosmic rays will (and have already begun to) teach us about the most energetic explosions in the universe and the phenomenal events which trigger them, gamma-ray bursts, supernovae, and the unknown (*e.g.* Hirata et al., 1987; Bionta et al., 1987; IceCube Collaboration, 2013). Only months before completing this dissertation, on September 14, 2015, the laser interferometer gravitational wave observatory (LIGO) made the the first observation of gravitational waves, the messenger of the gravitational interaction (Abbott et al., 2016). The field of gravitational wave astronomy will allow us to study the most extreme gravitational environments in the universe, the collision of black holes, and the fractions of a second following the Big Bang, otherwise inaccessible with photons. The task of decoding the multi-lingual music of the electromagnetic plus neutrino plus gravitational wave universe and making predictions for what type of multi-messenger signals to expect and hence how to utilize multi- messenger signals in order to maximize scientific returns now falls to the burgeoning field of multi-messenger astronomy.

The work laid out in this dissertation is a contribution to this effort, specifically to maximize our observations of gravitational wave sources by predicting the nature of electromagnetic signatures that should accompany them, or signify their existence beforehand. Such an endeavor not only provides ways to find sources of gravitational waves and learn about their operation, but also drives investigation into the astrophysics that creates gravitational wave sources, and into the workings of physical processes in the extreme environments that generate gravitational radiation.

This dissertation investigates the signatures of electromagnetic radiation that may accompany two specific sources of gravitational radiation: the inspiral and merger of massive black hole binaries (MBHBs) in galactic nuclei, and the coalescence of black hole-neutron star pairs.

Part I considers the interaction of MBHBs, at sub-pc separations, with a circumbinary gas disk. Accretion rates onto MBHBs are calculated from two- dimensional hydrodynamical simulations as a function of the relative masses of the black holes. The results are applied to interpretation of the recent, sub-pc separation MBHB candidate in the nucleus of the periodically variable quasar PG 1302-102. We advance an interpretation of the variability observed in PG 1302-

102 as being caused by Doppler boosted emission sourced by the orbital velocity of the smaller black hole in a MBHB with disparate relative masses.

Part II considers black hole-neutron star binaries in which the black hole is large enough to swallow the neutron star whole before it is disrupted. As the pair nears merger, orbital motion of the black hole through the magnetosphere of the neutron star generates an electromotive force, a black-hole battery, that could power luminosities large enough to make the merging pair observable out to cosmic distances for magnetar-strength neutron star surface fields. Fully analytic, relativistic solutions for vacuum fields of a magnetic dipole near a horizon are given, and a mechanism for harnessing the power of the black-hole battery is put forth in the form of a fireball emitting in hard X-rays to γ-rays.

A more detailed synopsis of each chapter comprising this dissertation follows.

Part I: Massive Black Hole Binaries

Accretion into the central cavity of a circumbinary disk

A near-equal-mass binary black hole can clear a central cavity in a circumbinary accretion disk; however, previous works have revealed accretion streams entering this cavity. Here we use 2D hydrodynamical simulations to study the accretion streams and their periodic behavior. In particular, we perform a suite of simulations, covering different binary mass ratios $q = M_2/M_1$ in the range $0.003 \leq q \leq 1$. In each case, we follow the system for several thousand binary orbits, until it relaxes to a stable accretion pattern. We find the following results: (i) The binary is efficient in maintaining a low-density cavity. However, the timeaveraged mass accretion rate into the cavity, through narrow coherent accretion streams, is suppressed by at most a factor of a few compared to a disk with a single black hole with the same mass; (ii) for $q \gtrsim 0.05$, the accretion rate is strongly modulated by the binary, and depending on the precise value of q, the power spectrum of the accretion rate shows either one, two, or three distinct periods; and (iii) for $q \lesssim 0.05$, the accretion rate becomes steady, with no time-variations. Most binaries produced in galactic mergers are expected to have $q \gtrsim 0.05$. If the luminosity of these binaries tracks their accretion rate, then a periodogram of their light-curve could help in their identification, and to constrain their mass ratio and disk properties.

A transition in circumbinary accretion disks at a binary mass ratio of 1:25

We study circumbinary accretion disks in the framework of the restricted three-body problem (R3Bp) and via numerically solving the height-integrated equations of viscous hydrodynamics. Varying the mass ratio of the binary, we find a pronounced change in the behavior of the disk near mass ratio $q \equiv M_s/M_p \sim 0.04$. For mass ratios above $q = 0.04$, solutions for the hydrodynamic flow transition from steady, to strongly-fluctuating; a narrow annular gap in the surface density around the secondary's orbit changes to a hollow central cavity; and a spatial symmetry is lost, resulting in a lopsided disk. This phase transition is coincident with the mass ratio above which stable orbits do not exist around the L4 and L5 equilibrium points of the R3B problem. Using the DISCO code, we find that for thin disks, for which a gap or cavity can remain open, the mass ratio of the transition is relatively insensitive to disk viscosity and pressure. The $q = 0.04$ transition has relevance for the evolution of massive black hole binary+disk systems at the centers of galactic nuclei, as well as for young stellar binaries and possibly planets around brown dwarfs.

A reduced orbital period for the massive black hole binary candidate in the quasar PG 1302-102?

Graham et al. (2015a) have detected a 5.2 yr periodic optical variability of the quasar PG 1302-102 at redshift $z = 0.3$, which they interpret as the redshifted orbital period $(1+z)t_{\rm bin}$ of a putative massive black hole binary (MBHB). Here, we consider the implications of a $3-8$ times shorter orbital period, suggested by hydrodynamical simulations of circumbinary disks with nearly equal–mass MBHBs ($q \equiv M_2/M_1 \gtrsim 0.3$). With the corresponding $2-4$ times tighter binary separation, PG 1302 would be undergoing gravitational wave dominated inspiral, and serve as a proof that the black holes can be fueled and produce bright emission even in this late stage of the merger. The expected fraction of binaries with the shorter $t_{\rm bin}$, among bright quasars, would be reduced by one to two orders of magnitude, compared to the 5.2 yr period, in better agreement with the rarity of candidates reported by Graham et al. (2015a). Finally, shorter periods would imply higher binary speeds, possibly imprinting periodicity on the light curves from relativistic beaming, as well as measurable relativistic effects on the Fe K α line. The circumbinary disk model predicts additional periodic variability on time-scales of $t_{\rm bin}$ and $\approx 0.5 t_{\rm bin}$, as well as periodic variation of broad line widths and offsets relative to the narrow lines, which are consistent with the observations. Future observations will be able to test these predictions and hence the circumbinary disk hypothesis for PG 1302.

Relativistic boost as the cause of the periodicity in a massive black hole binary candidate

As most large galaxies contain a central black hole, and as galaxies often merge Kormendy & Ho (2013), black hole binaries are expected to be common in galactic nuclei Begelman et al. (1980). Although they cannot be imaged, periodicities in the light curves of quasars have been interpreted as evidence for binaries Komossa (2006); Valtonen et al. (2008); Liu et al. (2015), most recently in PG 1302-102, with a short rest-frame optical period of 4 yr (Graham et al., 2015a). If the orbital period matches this value, then for the range of estimated black hole masses the components would be separated by 0.007-0.017 pc, implying relativistic orbital speeds. There has been much debate over whether black hole orbits could be smaller than 1 pc Milosavljević & Merritt (2003). Here we show that the amplitude and the sinusoid-like shape of the variability of PG 1302-102 can be fit by relativistic Doppler boosting of emission from a compact, steadily accreting, unequal-mass binary. We predict that brightness variations in the ultraviolet light curve track those in the optical, but with a 2-3 times larger amplitude. This prediction is relatively insensitive to the details of the emission process, and is consistent with archival UV data. Follow-up UV and optical observations in the next few years can test this prediction and confirm the existence of a binary black hole in the relativistic regime.

Reverberation of doppler boosted emission from massive black hole binaries: A lighthouse in the dust

We consider the reverberation of AGN emission by dust in the context of massive black hole binaries which emit periodic continuum emission due to both spatially isotropic variations and anisotropic variations caused by orbital relativistic Doppler boosting. We develop the first models for IR emission from AGN harboring such MBHBs, providing an additional test to vet the Doppler boosting model for MBHB candidates, and a tool for constraining properties of the dusty environments around MBHBs. We show that the phase, amplitude, and average brightness of reverberated IR radiation is dependent on the ratio of light travel time across the emitting dust region as well as dust geometric properties, and in the case of Doppler boosted emission, the relative inclination of binary orbital plane and dust torus. We determine also that, in the Doppler boost model, IR variability and UV/optical variability need not be coincident; UV emission could be steady, while the IR is periodically modulated, or vice versa. IR surveys should look for such orphan IR variability.

In the near future these model will help to corroborate evidence for the growing number of (presently $\gtrsim 100$) MBHB candidates (Graham et al., 2015b; Charisi et al., 2016), find new candidates, and also constrain their physical properties and the properties of their surrounding, dusty environments.

Part II: Black Hole-Neutron Star Binaries

Big black hole, little neutron star: magnetic dipole fields in the Rindler spacetime

As a black hole and neutron star approach during inspiral, the field lines of a magnetized neutron star eventually thread the black hole event horizon and a short-lived electromagnetic circuit is established. The black hole acts as a battery that provides power to the circuit, thereby lighting up the pair just before merger. Although originally suggested as an electromagnetic counterpart to gravitational-wave detection, a black hole battery is of more general interest as a novel luminous astrophysical source. To aid in the theoretical understanding, we present analytic solutions for the electromagnetic fields of a magnetic dipole in the presence of an event horizon. In the limit that the neutron star is very close to a Schwarzschild horizon, the Rindler limit, we can solve Maxwell's equations exactly for a magnetic dipole on an arbitrary worldline. We present these solutions here and investigate a proxy for a small segment of the neutron star orbit around a big black hole. We find that the voltage the black hole battery can provide is in the range $\sim 10^{16}$ statvolts with a projected luminosity of 10^{42} ergs/s for an $M = 10M_{\odot}$ black hole, a neutron star with a B-field of $10^{12}G$, and an orbital velocity $\sim 0.5c$ at a distance of $3M$ from the horizon. Larger black holes provide less power for binary separations at a fixed number of gravitational radii. The black hole-neutron star system therefore has a significant power supply to light up various elements in the circuit possibly powering bursts, jets, beamed radiation, or even a hot spot on the neutron star crust.

Bright transients from strongly magnetized neutron star - black hole mergers

Direct detection of black hole-neutron star pairs is anticipated with the advent of aLIGO. Electromagnetic counterparts may be crucial for a confident gravitational-wave detection as well as for extraction of astronomical information. Yet black hole-neutron star star pairs are notoriously dark and so inaccessible to telescopes. Contrary to this expectation, a bright electromagnetic transient, introduced in the previous chapter, can occur in the final moments before merger as long as the neutron star is highly magnetized. The orbital motion of the neutron star magnet creates a Faraday flux and corresponding power available for luminosity. A spectrum of curvature radiation ramps up until the rapid injection of energy ignites a fireball, which would appear as an energetic blackbody peaking in the X-ray to γ - rays for neutron star field strengths ranging from 10^{12}G to 10^{16}G respectively and a $10M_{\odot}$ black hole. The fireball event may last from a few milliseconds to a few seconds depending on the neutron star magnetic field strength, and may be observable with the Fermi Gamma-Ray Burst Monitor with a rate up to a few per year for neutron star field strengths $\gtrsim 10^{14}$G. We also discuss a possible decaying post-merger event which could accompany this signal. As an electromagnetic counterpart to these otherwise dark pairs, the black-hole battery should be of great value to the development of multi- messenger astronomy in the era of aLIGO.

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