Engineering Einstein: Astrophysical Black Holes

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with

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Accretion onto black holes, a process once thought to be an exotic sideplot in the story of the Universe, is now understood to be an important theme. Although accreting black holes are comparatively rare, they are so efficient at producing light that their total emission, integrated over a Hubble time, is only one order of magnitude smaller than that of all the stars in the Universe [22]. Moreover, the strong correlations between the masses of black holes in galactic nuclei and the mass and binding energy of the bulges of the galaxies housing them (e.g., as summarized in [3]) demonstrate that the growth of these black holes is tightly coupled to the growth of the surrounding stellar bulge; in other words, mass accretion onto black holes is an integral part of the construction of galaxies.

Black holes also serve as a proving ground for one of the central ideas of theoretical physics, general relativity. Along with some neutron stars, the immediate environs of black holes are the *only* place in the Universe where the unique properties of strong field gravity can be seen in action. Near black hole horizons, frame-dragging and gravitational redshifts are order unity effects, and stable circular orbits disappear. Merging black holes are expected to be the most powerful source of detectable gravitational radiation. Despite decades of formal study, it will only be through understanding *observations* of extreme black hole phenomena that we will fully recognize the implications of general relativity for strong-field gravity. Such observations may even present opportunities to test directly the basic theory in ways that will never be possible in the weak-field conditions of the Solar System.

At the same time, there are many other aspects of black hole systems that are fascinatingly exotic. Many of them drive jets of bulk plasma to relativistic speeds, radiating photons whose energy spectrum can peak near ~ 1 GeV (e.g., 3C 279: [57]). Gamma-ray bursts are very likely the product of new black hole creation (as reviewed in [46]). It is possible that the most energetic cosmic rays yet detected ($\sim 10^{21}$ eV) are accelerated by processes associated with them ([1,2,26,15]).

In addition to the intrinsic interest of the subject, there is another reason why the study of black holes has blossomed in the last decade: it has, at last, become an experimental science. We can now measure in detail relativistically-broad Fe Kα emission line profiles in dozens of AGN and Galactic black hole binaries (reviewed in [42]). Radio VLBI techniques offer time-resolved imaging of relativistic jet-launching with spatial resolution as fine as ~ 100 gravitational radii [39], while mm-band VLBI observations of Sgr A* have achieved resolutions of only $\simeq 7$ gravitational radii [16]. Quasi-periodic oscillations with frequencies comparable to the orbital frequency near the innermost stable circular orbit have been observed in the X-ray output of numerous Galactic black hole binaries [49] and perhaps an AGN [28]. The dramatic alterations of spectral shape seen in many Galactic black hole binaries [19] suggest that relativistic gravity can lead to wholesale changes in the physical conditions of gas on its way toward the event horizon.

In the upcoming decade, we expect to see observational techniques of a wholly new character, promising enticing fresh avenues of investigation. After decades of struggle to improve sensitivity, there are now several different proposals for practical X-ray spectropolarimeters [34,40,56,36]. Direct detection of gravitational waves may at last become a reality with Advanced LIGO or LISA.

In parallel to these exciting observational developments, theorists have been rapidly improving their tools for the investigation of black hole-related phenomena. With the identification of MHD turbulence driven by the magneto-rotational instability as the fundamental mechanism of angular momentum transport in accretion [7], it became reasonable to begin large-scale numerical simulation of this process. Codes now exist that treat 3-d MHD turbulence in a global accretion context with full general relativity [14,53,44,24]. Given an emissivity model, radiated photons can be traced from their source to infinity (or into the black hole) while also tracking travel-time and/or polarization-dependent transfer effects, e.g., [33,23]. Numerical relativists, after a struggle at least as long and difficult as the one that faced X-ray polarimeter builders, now have the ability to trace black hole mergers from start to finish and compute in detail the gravitational waves emitted [48,6,12]. The field of black hole astrophysics is in the midst of a transformation from a discipline constrained to phenomenological models to one characterized by detailed and predictive simulations.

What will enable completion of this transformation in the coming decade is the expected widespread availability of unprecedented computational power. Breakthrough simulations will be feasible with the petascale (or larger) computational platforms planned for the next decade by NSF and other agencies [43]. To take full advantage of this substantial investment in hardware infrastructure, we must create an environment that enables broader collaboration within the astrophysical research community. We must link those who develop new algorithms to the writers and maintainers of community codes, and ensure that there is easy communication from them to those who would apply the codes to specific scientific problems and analyze the resulting data.

One way to picture the goal of all these activities is by analogy to our understanding of stellar processes. Main-sequence stellar structure is thoroughly understood: given a mass and a chemical composition, we can predict the luminosity and surface temperature of a star right up to the end of its life, and do a moderately good job of predicting its detailed spectrum along the way. We can also compute its nucleosynthetic output, placing the elements in their respective shells within the star. Spherical symmetry and hydrostatic equilibrium put stellar modeling within the limited capabilities of earlier generations of computers. Success with black hole astrophysics might be defined as a comparable state of knowledge: given the mass and spin of a black hole and some idea of the magnetic field embedded in the accretion fuel at large distance, we should be able to predict (at least in a statistical way) the basic properties of its emitted light and any associated material or Poynting flux outflows. Indeed, without the connection from MHD dynamics to observables, we will have no way of testing how well our simulations resemble reality. Beyond this milestone, we would also like to be able to say something about the photons radiated by matter in the grip of the non-stationary spacetime created by a black hole merger.

It is this hoped-for ability to make detailed quantitative predictions of processes near black holes that we call "Engineering Einstein." No longer will we be limited to treating simplified special cases with symmetries imposed in order to make the equations tractable. Instead, given the boundary conditions and underlying fixed parameters, we should be able to make clear, testable statements about spectral features, time-variability, polarization, and so on.

Achieving that goal will, at a minimum, require answers to questions in four specific research areas:

1) Elucidating the physics of MHD dissipation is key to connecting accretion *dynamics* to accretion *thermodynamics* and therefore radiation.

MHD turbulence drives accretion, but what physical conditions set the stress levels?

For example, in the last several years there have been suggestions based on unstratified shearing-box simulations that competition between resistivity and viscosity on the microscale may influence the saturation strength on the stirring scale [25]. Can these results be extrapolated to physical disks, in which vertical stratification and radial gradients introduce additional characteristic lengthscales? If they can, we need to understand better what determines the Prandtl number, the ratio of these two dissipation rates.

What are the criteria determining whether dissipated energy is thoroughly thermalized? When the density and optical depth of the matter are too low to enforce rapid thermalization, how is the energy distributed—does it go primarily to the electrons or the ions or is it shared? Similarly, for both species, how well coupled are the random motions parallel and perpendicular to the magnetic field? Under what circumstances are the particle distribution functions Maxwell-Boltzmann or power-law or something else entirely?

When the dissipation is due to driven magnetic reconnection, what is the shape of the reconnecting field lines, and how is the energy distributed? Because magnetic geometry, whether of closed loops within the plasma or large-scale boundary conditions, is key to many aspects both of accretion and jet-driving [8], understanding the topological characteristics of reconnection is of particular interest.

The importance of many of these questions extends far beyond black hole problems. Plasma physicists interested in contexts ranging from the Solar corona to controlled fusion would also like to improve their grasp of how turbulence in plasmas is dissipated and magnetic fields reconnect. In fact, the recent confluence of laboratory experiments, space observations, and theory on the plasma kinetics of reconnection offers promise that soon these results may illuminate astrophysical examples (e.g., [20]). Cross-fertilization between astrophysicists, laboratory plasma physicists, and space physicists will undoubtedly prove beneficial to all. Although astrophysical applications may emphasize aspects of these questions that differ from those of greatest importance to space physics or laboratory plasmas, there is much overlap and considerable opportunity for interdisciplinary efforts.

2) Our rudimentary knowledge of how radiation processes and radiation forces interact with MHD turbulence needs to be deepened.

Radiation losses are the primary cooling mechanism for nearly all astrophysical structures, including accretion disks. The balance between them and dissipative heating (see question group 1) determine the fluid's equation of state; pressure forces thus depend strongly on the rate of radiative cooling. In typical accretion conditions, in which the gas is optically thick, how efficient is this?

When the accretion rate is more than a small fraction of Eddington, throughout the inner portion of the accretion disk the primary support of matter against the component of gravity perpendicular to the orbital plane is radiation forces [54]. What internal structure results? If the stress carrying angular momentum through the disk were strictly proportional to the total pressure, disks in this state would be unstable both to thermal and inflow perturbations [55,38]. We now know that this strict proportionality does not apply when MHD turbulence accounts for most of the stress, so that disks are thermally stable [31]; what about the inflow fluctuations? These questions are vital to an understanding of the most luminous accreting black holes because most of the energy is released at small radii, exactly where radiation forces should be the most important.

In some relativistic accretion disks, we see evidence for high-speed mass outflows (e.g., the broad absorption line gas in quasars, traveling outward at speeds up to $\simeq$

$25,000$ km s^{-1}; the most complete recent compilation is in [27]). Phenomenological hints suggest that the primary driving force is radiation, e.g. [4], but how exactly does this happen?

Where the matter density is especially high (most notably in gamma-ray bursts [47] and core-collapse supernovae [9], whether the latter event creates a neutron star or a black hole), neutrinos substitute for photons both in terms of determining the cooling and in terms of creating radiation forces. In both cases, there are strong hints that these effects may be central to driving the explosion, but the specific mechanisms remain poorly understood.

Progress on all these questions has been retarded by technical difficulties in incorporating radiation transfer into numerical simulations of dynamics. In some accreting black holes, the gas should be optically thin, and the known repertory of radiation mechanisms can be easily included in numerical calculations, e.g., [24]. However, in most cases we expect the gas to be optically thick [54]. When that is so, the cooling rate depends on how rapidly photons diffuse out, and the radiation force depends on both the diffusion rate and the direction of the flux. Some progress has been made in the context of vertically-stratified shearing boxes by the use of the flux-limited diffusion approximation assuming thermally-averaged opacities [32]; however, the quality of this approximation degrades severely as the geometry of the photosphere becomes less one-dimensional, e.g., [45]. Algorithms for more efficient computation of 3-d transfer will be essential to removing this roadblock, with special effort required to make relativistic versions. Thus, progress on these issues lies largely in the hands of numerical astrophysicists, aided by the continuing rapid growth in computational power.

3) The inner disk, where most of the light is made, should be optically thick enough to thermalize radiation and the emergent spectrum should be primarily soft X-rays (for black hole masses $\sim$ 1–10$M_\odot$) or UV (for black hole masses $\sim 10^6$–$10^9 M_\odot$). Why then, is a significant fraction of the bolometric luminosity nearly always found in the hard X-ray band, and why do binary black hole systems switch between highly distinct spectral states?

In non-blazar AGN (i.e., those in which a jet aligned with the line of sight does not dominate what we see), a quasi-thermal component peaking in the UV is usually the single largest contributor to the total luminosity, but soft X-rays account for $1 - 10\%$ and the hard X-ray luminosity (when it can be measured) is often smaller than the UV luminosity by only factors of a few [50,51]. What is it about disk dynamics that separates out tens of percent of the liberated energy and delivers it to a region outside the disk, in which the heating rate per unit mass is high enough to raise the temperature from $\sim 10^5$ K to $\sim 10^9$ K? The importance of magnetic turbulence to accretion has led to widespread expectation that somehow magnetic buoyancy conveys energy liberated by accreting matter deep inside the disk to lower density regions on its outskirts, but specific mechanisms have yet to be identified. Progress on question 1) will be helpful in answering these questions.

The spectral phenomenology of Galactic black hole binaries is more complicated than that of AGN (that contrast itself raising a question, as the magnitude of the black hole mass factors out of most considerations of accretion dynamics), but, in a single system, at various times we can see hard X-rays carrying anywhere from a few to nearly 100% of the luminosity [19]. The hard state (in which ~ 100 keV photons dominate the radiative output) is widely believed to signal a "disappearance" of the inner disk, perhaps due to a change in physical state to one in which electrons receive little heating [21,17]—is this the correct interpretation? In the other spectral states, we face the same question raised in connection with AGN: why is there any substantial hard X-ray emission at all?

Deeper understanding of this phenomenon will unlock the door to understanding many problems raised by observations. For example, if we knew the underlying causes of "coronal" conditions, we would be able to predict the distribution of hard X-ray emissivity within a source. That, combined with knowledge of the density profile in the upper layers of the disk body, would permit prediction of the Fe Kα line profile, allowing quantitative testing against observations. This would represent a truly powerful diagnostic of the inner workings of relativistic accretion, tremendously adding to the value of the large amount of observational work expended on measuring these profiles. Similarly, the emissivity distribution would also enable much more specific interpretation both of conventional spectral data and of X-ray polarization data once they become available. All of these properties are spin-dependent; understanding more precisely the physics controlling them would permit determinations of black hole spin of far greater reliability.

4) What are the electromagnetic signals associated with black hole mergers?

Galaxy mergers are central to contemporary understanding of galaxy formation. Because we see a single large black hole in the center of essentially every galaxy with a sizable bulge [37], it follows that black hole mergers are likely to accompany galaxy mergers. If we had greater knowledge of the accretion properties of massive black hole binaries before merger, during the event itself, and in the post-merger system, we might be able to identify distinct photon signatures of this process. With specific characteristics for which to search, many different kinds of conventional astronomical surveys, from COSMOS to PAN-STARRS to LSST or other projects yet to be envisioned, could be culled for indications of such events even before direct gravitational wave observations become possible. When, at some time in the future, LISA or some other instrument provides direct detections, their limited angular resolution will mean that photon measurements will be of great aid in identifying the galaxies in which detected mergers happened and squeezing the errorbars on the parameters, such as luminosity distance, inferred from their waveforms [5].

Attempts to do this are already being made. Some seek supermassive black hole binaries that may eventually merge, e.g., [10,18]. Others look for traces of a past merger, e.g., [11,52,41]. Unfortunately, no one really knows what any of these systems should look like, making candidate confirmation controversial [30]. Nor do we know how to spot a merger in process or immediately before it begins (a sampler of speculative ideas is presented in [29]).

Predicting photon signals of active mergers is an especially complex problem. Gravitational shear produces anisotropic magnetic stresses. These stresses combine with any MHD turbulence already present, raising the question of whether the ultimate dissipation of this turbulence is different in any way when gravitational waves, rather than the magneto-rotational instability, are the "stirring" agent. All the issues of radiation transfer discussed earlier also come into play, but in this new arena in which photon geodesics are time-dependent.

Thus, to determine more reliably what light might be generated requires several steps: First we must determine how much gas resides near a close black hole binary immediately prior to merger, and in what state it is (orbital and thermal). Next, the numerical techniques listed separately above (general relativistic MHD and thermodynamics, numerical relativity) must be combined so that we can follow the behavior of magnetized plasma in a fluctuating spacetime. These are formidable assignments, and will require much hard work on the part of both relativists and numerical astrophysicists. When completed, these methods will also be applicable to related problems, such as core-collapse supernovae and γ-ray bursts.

Because gravitational wave astronomy is so different from any sort of astronomy that has been done before, it is this fourth question that likely offers the greatest scope for deep discoveries. Linking gravitational to photon astronomy will be essential to maximizing the potential of this new discipline for all the same reasons that optical astronomy was vital to the growth of radio astronomy, X-ray astronomy, and all the other new wavebands first explored in the past fifty years. It will be up to photon astronomy both to fill in crucial details, such as precise identification with specific objects and measurement of their redshifts (key to cosmological applications, e.g., [13]), and to provide the broad astrophysical context (e.g., the character of the galaxies in which these events take place). To make this possible, it is essential to deepen our understanding of how matter behaves in the vicinity of black holes. Moreover, studying matter in a dynamical spacetime is a wholly new subject and offers the prospect of uncovering wholly new physical phenomena.

In summary, the next decade should be transformational in terms of our understanding of black hole astrophysics and the basic behaviors of black hole systems. Ongoing and planned satellites will return observations of unprecedented detail which will not be interpretable within the framework of current conventional phenomenological models. New codes and algorithms, coupled with unprecedented computational power, should finally enable the development of truly predictive black hole accretion models grounded in fundamental physics. Only when this connection is made secure will we harvest the maximum benefit from the many observational missions devoted to the study of black holes.

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