Massive Black Holes, AGN Feedback, and Galaxy Formation

Amount Requested: $370 K/yr for three years

Program Areas: relativistic astrophysics and cosmology, massive black holes, radiation transport, gravitational waves, software development, training and education.

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Summary: The study of the assembly history and environmental impact of the massive black holes (MBHs) that are ubiquitous in the nuclei of luminous galaxies provides invaluable insight into the quasar phenomenon, the role played by active nuclei in regulating the thermodynamics of the interstellar, intracluster, and intergalactic medium, and the formation and fate of MBH binaries. We propose to conduct theoretical studies of the processes that drive MBH binaries to coalescence, of the signatures of off-nuclear quasar activity from recoiling holes, of the MBH radiation and mechanical feedback mechanisms that may determine the turn-over scale in the galaxy luminosity function, all in the context of current theories of structure formation. This program brings together the expertise in relativistic astrophysics, cosmology, and numerical computations needed to answer some fundamental questions in the co-evolution of MBHs and their host galaxies. The proposed research will impact current observations with *Chandra*, *XMM*, *Spitzer, GLAST*, and *HST*, and will help refine the planning for *JDEM, LSST, JWST*, *TMT*, and *LISA*. The proposed suite of numerical simulations and the comparison of results against observations provide research opportunities for one post-doctoral fellow and two graduate students.

Motivation: The co-evolution of MBHs and their host galaxies remains one of the main unsolved problems in cosmic structure formation studies. The recent observational breakthroughs achieved in this field by ground and space-based facilities – from the discovery of quasars at redshifts in excess of 6 to the population of highly absorbed Type 2 quasars believed to be responsible for the hard X-ray background, from the tight correlation measured between hole masses and the stellar velocity dispersion of the host stellar bulge to the presence of MBH binaries revealed in the nucleus of NGC 6240 and the radio core of 3C 66B, from the discovery of the bimodality of galaxy colors to the recent detailed studies of the formation and evolution of early-type galaxies – have not yet been accompanied by equally significant progress on the theoretical side. N-body+ hydro simulations are not yet able to predict the formation path of the first MBH seeds at cosmic dawn. If MBHs were common in the past (as implied by the notion that distant galaxies harbor active nuclei for a short period of their life), and if their host galaxies experience multiple mergers during their lifetime, as dictated by cold dark matter (CDM) hierarchical cosmologies, then close MBH binaries will inevitably form in large numbers during cosmic evolution.

The merging history of MBH binaries is almost *terra incognita*. Observationally, the paucity of active MBH pairs may point to binary lifetimes far shorter than the Hubble time, indicating rapid inspiral of the holes down to the domain where gravitational waves lead to their coalescence. In general, gravitational waves also remove net linear momentum from the binary and impart a kick to the center of mass of the system. The outcome of this "gravitational rocket" has been the subject of many recent numerical relativity studies. The relative roles of gas and stellar dynamical processes in driving wide binaries to coalescence, and the effect of black hole mergers and gravitational wave recoil on nuclear stellar cusps and off-nuclear AGN activity, remain poorly understood. Accreting black holes can release large amounts of radiative and kinetic energy to their surroundings; however, the detailed physics of these processes and their importance in regulating star formation in the host galaxies remain open questions. While it may be true that the brightest quasars are associated with galaxy mergers, data from galaxies both nearby and at higher redshifts suggests that AGN continue to shine brightly for many hundreds of Myr after the peak of starburst activity. How the MBHs responsible for this activity are fueled, and how the resulting radiation is transported out of the galaxy nucleus and coupled to the surrounding intragalactic and intracluster material, are crucial questions that need to be clarified before we understand the role of MBHs in cosmic evolution.

Proposed Research: We propose to perform and analyze a suite of state-of-the-art numerical simulations of some key processes in MBH evolution, fueling, binary merging, and AGN feedback. The *COSMOS*++ code will allow us to run both non-relativistic and fully general relativistic simulations of the relevant astrophysical processes, including magnetohydrodynamics. Madau, Primack, and their groups have run many hydrodynamic simulations of galaxy formation and mergers, including gas heating and cooling, star formation, feedback, and the crucial role of dust, but these simulations and those of other groups have not yet been able to resolve the galaxy nuclei and study the detailed physics of MBH binary formation, gas fueling, and radiation and mechanical feedback. The first ultra-high resolution N-body + smoothed particle hydrodynamics (SPH) simulations of two galaxy+MBH mergers having enough dynamic range to follow the holes from a hundred kiloparsecs down to parsec scales and bridging about ten orders of magnitude in density have been recently reported by a group that includes the PI (Mayer et al 2007). The radiation physics in the refined simulation, however, was modeled via an effective equation of state with adiabatic index γ that accounts for the net balance of radiative heating and cooling. We will use larger-scale simulations to provide outer boundary conditions for much higher-resolution computations using *COSMOS*++ in collaboration with Anninos and Salmonson. We will check whether binary hardening by gravitational torques against the gas continues down to subparsec scales to the gravitational wave emission stage. MBH pairs that are able to coalesce in less than a Hubble time will give origin to the loudest gravitational wave events in the Universe and will be detectable by *LISA*.

Incorporating the Monte Carlo code *SUNRISE* into *COSMOS*++ will permit us to treat the transport of radiation from MBH accretion to their surroundings including the effects of dust, and to study the resulting astrophysical phenomena. During the final phases of inspiral, a MBH binary experiences a recoil due to the asymmetric emission of gravitational waves. Non-spinning holes recoil with velocities below 200 km/s that only depend on the binary mass ratio, whereas much larger kicks are predicted for rapidly rotating holes, depending on the orientations of their angular momenta. Galaxy mergers are a leading mechanism for supplying gas to their nuclear black holes, and a recoiling hole can retain the inner parts of its accretion disk, providing fuel for a continuing luminous phase along its trajectory. We will study the possible observational manifestations of gravitational-radiation ejection and address the possibility that off-nuclear AGN may be detected in significant numbers in deep optical and X-ray imaging studies. As we improve our simulations of MBH formation, merging, accretion, and feedback, we will continually compare the results to the steadily improving observations. Such theoretical-observational comparisons are the best way to understand such complex phenomena, in order to allow us to predict with improved confidence the consequences of galaxy and MBH mergers for proposed missions such as *JDEM*, *LSST*, and *LISA*. For example, *LISA* can determine absolute luminosity distances to merging MBHs with ~1% accuracy. But for such *LISA* detections to be useful for constraining Dark Energy, it is essential to determine the redshift of the galactic host of the merger. Our proposed simulations can clarify the likely rate and the other astrophysical signatures of such MBH mergers.

Tools: Originally conceived and written at LLNL, the astrophysics code *COSMOS*++ has a wide variety of physics capabilities implemented. With its modular architecture and object-oriented polymorphism design, it has a proven track record of development, implementation and production of a variety of new physics packages, numerical methods, and unstructured mesh generation. Postdocs to undergraduate summer students have been able to make substantive contributions to the code in short and timely fashion. *COSMOS*++ is actively developed and used by many LLNL scientists and researchers at more than a half-dozen universities to study such diverse problems as magnetized black hole accretion flows, supernova enrichment of the intergalactic medium, jet-induced star formation, magneto-rotational effects in collapsing stars, bar-mode instabilities, and gamma-ray-burst afterglows.

In brief, *COSMOS*++ (Anninos et al. 2005) is a massively parallel, multi-dimensional, fully covariant, modern object-oriented (C++) radiation-magneto-hydrodynamics code written to support structured and unstructured adaptively refined meshes, and for both Newtonian and general relativistic astrophysical applications. It includes numerous hydrodynamics solvers (conservative and non-conservative), radiation multi-group flux-limited diffusion, a network of more than 30 non-equilibrium chemical gas-phase, molecular, and dust-grain activated reactions, ideal and non-ideal magnetic fields, relativistic scalar (inflaton) fields for phase transitions in the early universe, isotropic FLRW cosmologies, radiative and neutrino cooling, dark matter particles, self-gravity, geodesic transport, thermal conduction, and generic tracer fields. A new solver package has been recently implemented into *COSMOS*++ to solve the fully general relativistic Einstein equations for evolving spacetime manifolds. We propose to extend the development of this vacuum capability to include interactions of matter and magnetic fields with spacetime curvature. Fully coupled general relativistic magnetohydrodynamics is a new field that is still maturing, and we are poised to make substantial contributions in this area. These capabilities will allow one to model self-consistently the collapse of a realistic large stellar progenitor with rotation and magnetic fields down to the formation of a black hole, or conversely the dynamical feedback of black holes to their host galactic environments while allowing the black hole to grow simultaneously through active accretion processes.

Another key area we propose for development is frequency dependent radiation transport. *COSMOS*++ currently has flux-limited multi-group diffusion, a framework for implicit Monte Carlo particle and geodesic transport, and interface functions for retrieving absorption and emission coefficients from opacity data servers. However, all of these features require substantial work to make them more robust, scalable, and optimized for production. The particle transport framework should allow for the *SUNRISE* Monte Carlo transport code (written by Primack's postdoc Patrik Jonsson and incorporating the *MAPPINGS* -- Modelling And Prediction in PhotoIonised Nebulae and Gasdynamical Shocks -- code by Mike Dopita et al.) to be incorporated cleanly into *COSMOS*++ as another transport option, providing a means of communicating, storing, and interacting with particle attributes across the two code frameworks. *COSMOS*++ is now a fairly mature, highly portable, and well-tested code that has been released to the general scientific community. It has been ported (with essentially no effort) to more than a dozen computing platforms, including Atlas, Zeus, ASCI Blue, ASCI Frost, Berg, GPS, Thunder, MCR and Yana at LLNL, plus the NCSA Teragrid, the NASA Columbia machine, the California Nanosystems Institute Xeon cluster, the University of Notre Dame beowulf cluster, the College of Charleston Xeon cluster, and the MareNostrum machine in the Barcelona Supercomputer Center (BSC). This versatility allows the code development and production work to be carried out on resources available to both LLNL and UCSC personnel. For example, LLNL's Grand Challenge allocations program provides millions of CPU hours on the Atlas and Thunder clusters. We also have active allocation grants on the NCSA Teragrid, on NASA's supercomputer Columbia, at NERSC at LBNL, and substantial Linux cluster resources at UCSC.

Budget and Personnel: Senior personnel: Anninos: ~$40K/yr (~10% time); Salmonson: ~$80K/yr (~20% time); Madau: ~$45K/yr (2 summer mos); Dekel ~$15K/yr (1 summer mos); Primack: ~$25K/yr (1 summer mos). Plus 1 postdoc (~$75K/yr) and 2 graduate students (2x$40K/yr), and funds for travel (~$10K/yr). 33% of the budget is for LLNL scientists, 22% for faculty salaries at UCSC, and 42% for graduate students and postdocs at UCSC. Note that no indirect costs have been applied to the UCSC portion of the budget. This proposal is part of a larger proposal for a Center for Explosive Phenomena in Astrophysics (CEPA) that is being submitted by PI Stan Woosley. In the event that the CEPA proposal were funded this proposal would be withdrawn.