Coevolution of Black Holes and Galaxies

Black holes are among the most mysterious objects in the Universe. Weighing up to several billion Suns, massive black holes have long been suspected to be the central powerhouses of energetic phenomena such as quasars. Recent advances in astronomy have not only provided spectacular proof of this long-standing paradigm, but also revealed the unexpected result that, far from being rare, exotic beasts, they inhabit the center of virtually all large galaxies. Candidate black holes have been identified in increasingly large numbers of galaxies, both inactive and active, to the point where statistical studies are now possible. Recent work has highlighted the close connection between the formation, growth, and evolution of supermassive black holes and their host galaxies. This volume contains the invited lectures from an international symposium that was held to explore this exciting theme. With contributions from leading authorities in the field with diverse but interrelated observational and theoretical expertise, this is a valuable review for professional astronomers and graduate students.

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This series of four books celebrates the Centennial of the Carnegie Institution of Washington, and is based on a set of four special symposia held by the Observatories in Pasadena. Each symposium explored an astronomical topic of major historical and current interest at the Observatories, and each resulting book contains a set of comprehensive, authoritative review articles by leading experts in the field.

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COEVOLUTION OF BLACK HOLES AND GALAXIES

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LUIS C. HO

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Preface

In 1902, Andrew Carnegie, a man of uncommon vision and philanthropy, bequeathed a sizable sum to establish a scientific research organization whose purpose was "to encourage, in the broadest and most liberal manner, investigation, research, and discovery, and the application of knowledge to the improvement of mankind." For the past century, the Carnegie Institution of Washington has been a haven for many influential and creative scientists, covering disciplines ranging from geophysics, earth and planetary science, cellular and genetic biology, plant science, global ecology, and last, but not least, astronomy.

Astronomy has been a major part of the Institution almost from its inception, thanks to persistence and courage of another visionary, George Ellery Hale. Convinced that southern California had conditions favorable for astronomical observations, Hale persuaded Carnegie in 1904 to establish an observatory at Mount Wilson, located near Pasadena, California. There, Hale consecutively built the world's next two largest telescopes, the 60-inch in 1908 and the renowned 100-inch Hooker telescope in 1917. Arguably no other telescope since Galileo's has had a more profound impact on astronomy—indeed in shaping our view of humankind's footing in the cosmos—than those on Mount Wilson. Using the 60-inch to map the distribution of globular clusters in the Milky Way, Harlow Shapley concluded that our Galaxy was significantly larger than previously thought, and deduced that the Sun lies not at the center of the Galaxy but in its remote outskirts. But the Universe proved to be far greater still. With the 100-inch Edwin Hubble established the extragalactic nature of "nebulae," and therefore the existence of a multitude of galaxies beyond our own, followed by the discovery that the Universe is expanding. This was the birth of modern cosmology. Among the many other significant, if less sensational, advances attributable to the 100-inch includes Walter Baade's recognition of two distinct stellar populations, a concept central to the subsequent development of stellar and galactic evolution.

The supremacy of the 100-inch was not eclipsed until the completion in 1948 of Hale's last and most ambitious feat—the mighty 200-inch reflector at Mount Palomar. Although the "Big Eye" was not finished before he died, Hale was chiefly responsible for securing the funding for the project, and he was the main driving force behind its long, difficult construction. The accomplishments stemming from the 200-inch are too numerous and varied to be recounted here. It suffices to say that the Palomar 200-inch, which was operated in partnership with Caltech until 1980, has played a major role in ground-based optical astronomy for the latter half of the twentieth century.

In search of more pristine skies and to gain access to the southern hemisphere, Carnegie astronomers in 1969 established the Las Campanas Observatory in Chile's Atacama Desert, where they operate the Swope 1-meter and the du Pont 2.5-meter telescopes. However, in the era of ever-increasing large telescopes, this was not enough. In the mid-1980's, plans were under way for the design and construction of a pair of large optical telescopes at Las Campanas. The outcome—the twin 6.5-meter Magellan telescopes—is a collaboration between Carnegie, University of Arizona, Harvard University, University of Michigan, and Massachusetts Institute of Technology. Both the Baade and Clay telescopes, each equipped with state-of-the-art instrumentation, are now fully functional. Though nominally smaller than the current generation of 8–10 meter-class telescopes, Magellan is every bit as competitive thanks to its superb image quality and wide field-of-view.

Headquartered at 813 Santa Barbara Street, Carnegie Observatories presently supports a small, but distinguished group of about two dozen scientific staff members and postdoctoral fellows, along with a sizable group of engineers and instrument scientists who are responsible for technical developments. The research interests at the Observatories are diverse, ranging from observational cosmology to galaxy formation and evolution, large-scale structure, the intergalactic medium, stellar populations, stellar chemical composition, supernovae, star clusters, black holes, and accretion processes in galactic nuclei. In keeping with the tradition of the Observatories, some of staff devote considerable effort building innovative instruments for the telescopes.

This year marks the 100th anniversary of the founding of Carnegie Observatories. We stand at an important crossroad. To be sure, we glance back at our accomplishments of the past century with significant pride. But we are also confronted with many challenges for the years ahead, for our discipline is constantly driven by larger and more ambitious telescope enterprises, which carry sky-rocketing price tags and daunting technological hurdles. While the future success of a research institution, no matter how distinguished its past, should not be taken for granted, in reflecting on Carnegie's legacy in astronomy we cannot help but draw from it a measure of inspiration and optimism.

To commemorate our Centennial, we thought it would be fitting to host a series of scientific meetings, organized by Carnegie astronomers, on a range of topics that both celebrates Carnegie's past astronomical contributions and recognizes its current, diverse research interests. In the end, we organized four international-level meetings, held in Pasadena, from Fall 2002 to Winter 2003. The Carnegie Observatories Centennial Symposia covered the following topics: (1) *Coevolution of Black Holes and Galaxies* (hosted by Luis Ho; 20–25 October 2002), (2) *Measuring and Modeling the Universe* (hosted by Wendy Freedman; 17–22 November 2002), (3) *Clusters of Galaxies: Probes of Cosmological Structure and Galaxy Evolution* (hosted by John Mulchaey, Alan Dressler, and Gus Oemler; 27–31 January 2003), and (4) *Origin and Evolution of the Elements* (hosted by Andy McWilliam and Michael Rauch; 16–21 February 2003). The meetings were very well attended, and, by most measures, highly successful.

To complement the Symposia, we have planned from the outset to use the invited papers to compile a set of volumes of sufficiently high standards to have lasting value as an authoritative reference, one that potentially can be used for graduate-level course work. To achieve this goal, we have subjected each contribution to a battery of quality controls atypical for conventional conference proceedings; this includes a formal peer-review process, careful editing by the scientific organizers, and final scrutiny and copy-editing by the series editor. The product of this exercise is the first four volumes of the *Carnegie Observatories Astrophysics Series*.

An undertaking of this scope would not have been possible without the help of many people. First and foremost, I would like to thank the organizers of the Symposia and editors of this *Series*, my colleagues Wendy Freedman, John Mulchaey, Alan Dressler, Gus Oemler, Andy McWilliam, and Michael Rauch, for allowing me to twist their arms into this zany venture. Paul Martini helped me through many queries on how to set up HTML pages and troubleshoot Latex class files. There were myriad details associated with the local organization, from seemingly trivial items like how many cookies to order for coffee breaks to major ones like securing a venue, all necessary for the successful execution of the meetings. They were handled patiently and efficiently by Karen Gross during the initial phase, and later by Silvia Hutchison and Becky Lynn. I am most grateful for their assistance. I also appreciate the help of the facilities staff, especially Steve Wilson, Scott Rubel, Earl Harris, and Greg Ortiz, who worked hard to set up the technical logistics and to ensure the smooth operation of the audio-visual equipment. Lastly, I thank P Street for their financial support to help cover the cost overrun incurred for the meetings.

Luis C. Ho
Carnegie Observatories
January 2004

Introduction

Few subjects in astronomy capture the popular imagination like black holes. Black holes and their varied manifestations as active galaxies certainly occupy the attention of a large segment of the current astronomical community. While Carnegie's involvement in this subject may not be widely known, the fact is that it has had a long historical connection to this field. Following the initial work by Edward Fath at Lick Observatory in 1908 and by Vesto Slipher at Lowell Observatory in 1917, Edwin Hubble himself noted in 1926 the unusual nature of the emission-line spectrum in NGC 1068, NGC 4051, and NGC 4151. But it was really the 1943 paper by Carl Seyfert, based on observations obtained at Mount Wilson, which first systematically studied the class of active galaxies that today bear his name, although the significance of this work remained unrecognized for some time to come.

Carnegie's role in the early development of AGN research was most pronounced after World War II, when advances in radio astronomy led to the discovery of extragalactic radio sources. In the ensuing period, much of the community with access to large optical telescopes was keen on obtaining optical identifications of these mysterious sources. At Carnegie, the early effort was led by Rudolf Minkowski and Walter Baade, and subsequently by Allan Sandage and his colleagues. Sandage's extensive work on optical identification and spectroscopy of radio sources led to the discovery of a large population of radio-quiet objects that show an ultraviolet excess.

Once the redshift puzzle of quasars was solved in 1963 by Maarten Schmidt and Jesse Greenstein, it was thereafter quickly realized that the quasar phenomenon most likely draws its power from the gravitational energy of a massive collapsed object—a massive black hole. There is just too much energy coming out of too tiny a volume for anything else to be viable. In the 1970s, Jerome Kristian, working with Peter Young and others at Caltech, was one of the first to search for supermassive objects in the centers of giant elliptical galaxies. Kristian's work on quasar host galaxies was also very much a forerunner to what has become a lively pursuit. In more recent times, a number of Carnegie astronomers have also been involved in various aspects of black hole and AGN research. Some of the notable examples include Ray Weymann's seminal contributions on quasar absorption-line systems and quasar outflows, Alan Dressler's mass determination for the nuclei of M31 and M32, Pat McCarthy's multifaceted work on radio galaxies, and John Mulchaey's investigations on Seyfert galaxies and AGN fueling.

While it has long been suspected that massive black holes and nuclear activity are somehow related to galaxy formation and evolution, it is fair to say that until recently very few people realized the depth of the interconnection. Most of the practitioners in these subfields belong to communities that rarely overlapped. Though AGN research commands a strong following, it has had a somewhat checkered reputation in the broader community as a largely phenomenological endeavor, too often preoccupied with taxonomy. AGNs are useful for exploring some aspects of relativistic and high-energy astrophysics, and they make good background probes for absorption-line work, but beyond that they are really not that relevant to mainstream work on "normal" galaxies. Such is often the prejudice.

There has been a refreshing change of attitude in the last few years, which is largely triggered, I think, by the persuasive evidence that massive black holes are not only common but evidently tightly coupled to the life-cycle of galaxies. The term "normal galaxy" is woefully inadequate. Most respectable-sized galaxies, we now suspect, come naturally endowed with a massive central black hole, whose mass—somehow— has an uncanny familiarity with the large-scale properties of its host galaxy. A symbiotic relationship between black hole growth and galaxy assembly seems inescapable. As black holes grow through accretion, they ignite briefly as AGNs of many flavors, dumping radiation and kinetic energy into their host galaxies, and perhaps beyond. The cumulative deposition of accretion energy lights up the sky in X-rays. Black holes inspiral during galaxy mergers; some may coalesce, generating gravitational radiation. The landscape for observational and theoretical astrophysics has never been so rich.

Given these healthy developments, it seemed opportune to convene a meeting to bring together specialists working on different but interrelated subjects concerning black holes and galaxies. I had tried such an experiment before, in a 1998 meeting in Nagoya, Japan, entitled *The AGN-Galaxy Connection*, which I co-organized with Anne Kinney and Henrique Schmitt. The justification was strong then, and it is even stronger now.

On the occasion of the Centennial of the Carnegie Institution of Washington, Carnegie Observatories hosted a series of four astrophysics symposia in Pasadena, from Fall 2002 to Winter 2003. The first of these symposia, *Coevolution of Black Holes and Galaxies*, was held on 20–25 October 2002. By most accounts, it was a somewhat unusual, but highly effective gathering, which brought together people with very different backgrounds, in an intense but lively atmosphere. A total of 28 invited speakers covered topics ranging from black hole searches to formation and fueling mechanisms of black holes, gas-dynamical processes, dynamical evolution of dense stellar systems, the central and global structures of galaxies, binary black holes, gravitational radiation, AGN statistics, galaxy formation, AGN feedback, reionization, and the X-ray background. At least 100 other participants gave contributed talks or presented posters.

This book contains the review papers based on the presentations of the invited speakers, which forms the first volume of the *Carnegie Observatories Astrophysics Series*. (The contributed papers are published separately in electronic form at the Carnegie web site.) I am happy to say that these papers are of exceptionally high quality. As explained in the Preface, it has been my intention from the outset that the *Series* should aim for a high standard of scholarship, to ensure that the contributions contained therein would have a lasting impact. I am most grateful to all the authors for the enormous effort they have invested in conscientiously preparing the manuscripts, and for agreeing to have them subjected to a peer-review process and to entrust them to my editorial oversight. I can only hope that they agree that their efforts have been worthwhile.

Luis C. Ho
Carnegie Observatories
January 2004

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