IAU Symposium
267

10–14 August, 2009,
Rio de Janeiro, Brazil

Co-Evolution of Central Black Holes and Galaxies

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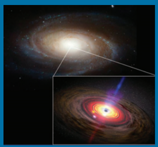

Proceedings of the International Astronomical Union

CAMBRIDGE

IAU Symposium
267

10–14 August, 2009,
Rio de Janeiro, Brazil

ISSN 1743-9213

International Astronomical Union

CAMBRIDGE
UNIVERSITY PRESS

Proceedings of the International Astronomical Union

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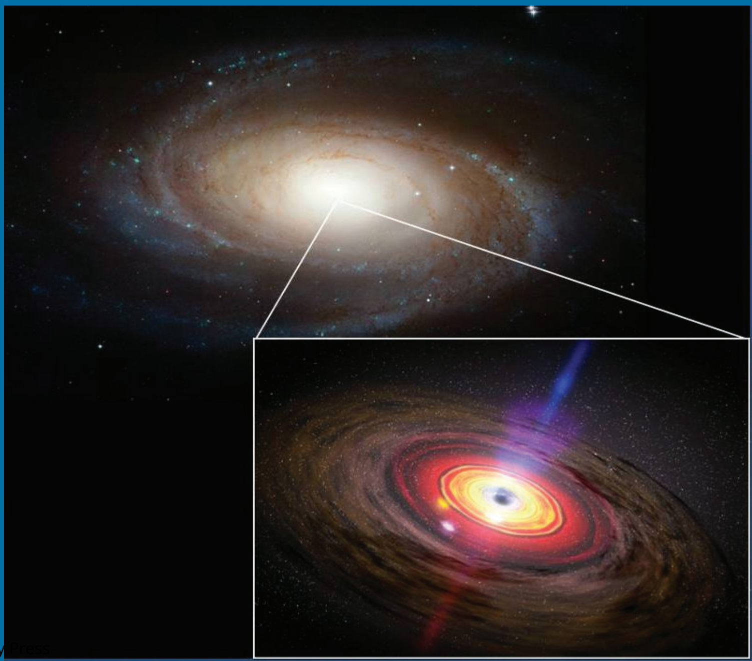
Edited by

Bradley M. Peterson
Rachel S. Somerville
Thaisa Storchi-Bergmann



CO-EVOLUTION OF CENTRAL BLACK HOLES AND GALAXIES

IAU SYMPOSIUM No. 267

COVER ILLUSTRATION:

Despite their remarkably different spatial scales, galaxies and their central supermassive black holes apparently evolve together through a variety of feeding and feedback processes, as discussed at this Symposium.

The upper illustration shows a *Hubble Space Telescope* Advanced Camera for Surveys image of the spiral galaxy M 81, courtesy of NASA, ESA, and the Hubble Heritage Team (STScI/AURA). The lower illustration zooms in on an artist's rendition of the accretion-disk structure around the nuclear supermassive black hole (courtesy of NASA/Dana Berry, SkyWorks Digital).

https://doi.org/10.1017/S1743921310005442 Published online by Cambridge University Press

INTERNATIONAL ASTRONOMICAL UNION

UNION ASTRONOMIQUE INTERNATIONALE

International Astronomical Union

IAU

CO-EVOLUTION OF CENTRAL BLACK HOLES AND GALAXIES

PROCEEDINGS OF THE 267th SYMPOSIUM OF THE INTERNATIONAL ASTRONOMICAL UNION HELD IN RIO DE JANEIRO, BRAZIL AUGUST 10–14, 2009

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CAMBRIDGE
UNIVERSITY PRESS

CAMBRIDGE UNIVERSITY PRESS
The Edinburgh Building, Cambridge CB2 8RU, United Kingdom
32 Avenue of the Americas, New York, NY 10013-2473, USA
477 Williamstown Road, Port Melbourne, VIC 3207, Australia
Ruiz de Alarcón 13, 28014 Madrid, Spain
Dock house, The Waterfront, Cape Town 8001, South Africa

First published 2010

Printed in the United Kingdom at the University Press, Cambridge

Typeset in System $\LaTeX\,2_\varepsilon$

A catalogue record for this book is available from the British Library

Library of Congress Cataloguing in Publication data

This book has been printed on FSC-certified paper and cover board. FSC is an independent, non-governmental, not-for-profit organization established to promote the responsible management of the world's forests. Please see www.fsc.org for information.

ISBN 9780521765022 hardback
ISSN 1743–9213

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Preface

There is now near unanimity that quasars, or more generally, active galactic nuclei or AGNs, are a manifestation of accretion of gas onto supermassive black holes at the centers of galaxies. "Supermassive" black holes are those of more than a million solar masses. Since their discovery nearly fifty years ago, quasars have been considered as possible probes of the evolution of structure in the universe. Quasars themselves seem to be byproducts of the formation of galaxies or, in a more modern perspective, dark matter halos. Beyond their usefulness in understanding the elements of large-scale structure, quasars are also utilized as background sources to probe the intergalactic medium.

A current theme in extragalactic astronomy is that not only are quasars tracers of the evolution of galaxies, they are agents of that evolution – the hypothesis is that it is energetic "feedback" from the active nucleus that determines the physical state of the interstellar medium of the host galaxy and thus the star formation rate. The emerging picture is one where the central black holes grow by accretion, but the accretion process itself eventually produces energetic feedback in the form of intense radiation, mass outflows, and jets, that heats up and can even remove entirely the interstellar medium from the host galaxy, effectively shutting down star formation. This intense feedback leaves behind a galaxy that is "red and dead" with a massive central black hole. IAU Symposium 267 on the "Co-Evolution of Central Black Holes and Galaxies" is a broad attempt to assess and articulate the observational and theoretical state of what is a rapidly developing and exceedingly complex field.

Observational evidence for the possible linkage between the central black holes and host galaxy properties starts with simple and surprisingly tight correlations between the black hole mass and large-scale properties of the host, specifically the luminosity (or, equivalently mass) of the bulge component (the so-called $M_{\rm BH}$–$L_{\rm bulge}$ and $M_{\rm BH}$–$M_{\rm bulge}$ relationships, respectively) and the bulge velocity dispersion (the $M_{\rm BH}$–σ relationship). The emergence of these relationships became possible only when the masses of the central black holes were available for a few dozen galaxies spanning a broad range of mass and luminosity. With a few notable exceptions, such as the Milky Way, M 87, and the megamaser source NGC 4258, these black hole mass measurements required high angular resolution data from *Hubble Space Telescope* and extensive computer modeling of stellar and gas dynamics in the galactic nuclei. There's a certain irony in that supermassive black holes have been invoked as the fundamental drivers for active nuclei, but the first strong evidence for their existence and the first measurements of their masses were in predominantly quiescent (non-active) nuclei. It has subsequently become clear that nearly all galaxies, at least those with prominent bulge components, harbor supermassive black holes at their centers: the difference between quiescent and active nuclei is not whether or not a supermassive black hole is present, but rather by the accretion rate – black holes accreting at around 1% or more of the Eddington rate are AGNs.

In the case of AGNs, the masses of the central black holes are more generally determined through the technique of reverberation mapping, where the size of the broad emission-line region is determined from the time delay between continuum and broad-line flux variations. With the velocity dispersion of the line-emitting gas from the same responding emission line, determination of the mass is straightforward, although subject to a number of uncertainties. Reverberation studies show that AGN black hole masses seem to correlate with the same host galaxy properties as quiescent galaxies. Indeed, while reverberation mapping as it is currently practiced is a direct method of measuring black hole masses (i.e., measuring the motions and positions of gas accelerated by the mass of the black hole), it is still a secondary method in the sense that the normalization of the mass scale refers back to the $M_{\rm BH}$–σ relationship derived from quiescent galaxies.

The number of supermassive black holes whose masses have been determined by direct methods – stellar dynamics, gas dynamics, reverberation mapping, and less commonly megamaser (NGC 4258) or stellar (Milky Way) motions – is growing, but still totals fewer than one hundred. Fortunately there are indirect methods, such as the $M_{\rm BH}$–$L_{\rm bulge}$ and $M_{\rm BH}$–$M_{\rm bulge}$ relationships, of inferring black hole masses from observables that are correlated with black hole mass. Another indirect method for quasars comes from reverberation-mapping experiments that reveal a tight correlation between broad-line region size and the quasar luminosity – by combining the size of the line-emitting region inferred from the luminosity with the emission-line width it is possible to determine the mass of a quasar black hole from a single spectrum again, subject to a variety of uncertainties.

Armed with powerful indirect methods of black hole measurement, we can determine the masses of large numbers of quasars, including those at high redshift and hence look-back times. In principle, we can determine the mass function of supermassive black holes and therefore galaxies through cosmic history, using quasars as tracers. We can ask when and under what conditions did the first supermassive black holes appear and how did they evolve over time? Of course to do this accurately we need deep surveys to probe the quasar population. This requires that we understand the multiwavelength properties of quasars so that we can minimize both the number of undiscovered quasars that we fail to account for and the number of false-positive detections we erroneously include. We have to find ways to test the indirect methods of mass measurement, for the obvious reason of getting the masses right and also for the sake of understanding how these key correlations develop and evolve with time. Why the masses of the central black holes, which amount to only $\sim 0.1\%$ of the total bulge mass, should be so tightly correlated with the large-scale properties of the bulge remains extraordinary and without any explanation that has achieved broad consensus. This, of course, brings us back to the beginning of this discussion: perhaps the ability of an AGN to shut down star formation is achieved once the black hole reaches a luminosity that depends on the mass of the host system.

This is where things get complicated. To determine how black holes grow, we need to be able to determine the radiative efficiency of quasars as well as estimate their lifetimes. We need to assess the feedback role of various AGN components such as the massive outflows detected in UV and X-ray absorption spectra and the more collimated and sometimes relativistic jets detected in the X-ray through radio. We need to understand the relationship between nuclear star formation and nuclear activity and the relative importance of feedback into the interstellar medium from both the stars and the AGN. These are then major components of massive simulations that include the results of hydrodynamical calculations in a modern ΛCDM cosmology. Some important components of these simulations are still under exploration: for example, while mergers and tidal interactions seem to be sufficient for driving gas from the outer regions of galaxies to the inner kiloparsec or so, how to get enough gas into the central parsec to fuel an AGN is still an open issue.

IAU Symposium 267 is intended to define the state-of-the-art in all of these endeavors, from the physics on the sub-parsec scales of accreting black holes to that on the super-Megaparsec scales of large-scale structure.

Bradley M. Peterson, Rachel Somerville, and Thaisa Storchi-Bergmann, co-editors

Dedication

One of the main processes linking the evolution of galaxies to the supermassive black holes at their centers is the feedback resulting from mass accretion. This feedback has been observed as radio jets and "ionization cones" many times associated with mass winds which probably originate in the accretion disk surrounding the black hole. One of the pioneers in the observations of radio jets from AGN as well as in the imaging of ionization cones and measurements of the narrow-line region kinematics was Andrew Stephen Wilson. Unfortunately, Andrew passed away prematurely on 24 May 2008, and, in recognition to his important contribution to the study of the AGN Physics, we dedicate this volume to him.

Back in 1990, when I was deciding where to go for a post-doctoral work, being interested in the optical line emission in Seyfert galaxies, I became fascinated by the work Andrew was doing with his collaborators in the feedback processes from AGN. Besides imaging the emission-line regions and studying their kinematics, he was looking for the relation between the radio and extended optical emission. Together with his many collaborators – some of whom are contributing to this volume – he wrote important papers which are still standard references in the field today. Being also one of his collaborators, I learned a lot from Andrew's "style:" high scientific standards, careful observations, data reduction, and analysis and precise writing. It was usually much harder to meet Andrew's standards than those of the referees!

Andrew worked at the University of Maryland over most of his career, and after being a pioneer in the use of radio telescopes for the study of active galactic nuclei, he became adjunct astronomer at the Space Telescope Science Institute in 1994, using the *Hubble Space Telescope* in many of his studies. Since 1985, he became a NASA Interdisciplinary Scientist and member of the Science Working Group for the *Chandra X-ray Observatory*, and an enthusiastic X-ray astronomer, inspecting the jets he knew from radio observations in X-rays.

Andrew had a unique – and very English – kind of humor, very understated and prone to soto voce comments that could be outrageously funny. And being his friend did not immunize you from his keen wit.

Andrew was an outstanding scientist and a dear friend. We will all miss him.

Thaisa Storchi-Bergmann, on behalf of the editors

https://doi.org/10.1017/S1743921310005442 Published online by Cambridge University Press

Andrew Stephen Wilson (1947–2008)

https://doi.org/10.1017/S1743921310005442 Published online by Cambridge University Press

Acknowledgements

On behalf of the Scientific Organizing Committee, the editors would like to thank the IAU, and particularly Karel van der Hucht and Ian Corbett, for support of this Symposium. We are also grateful for the support of our original proposal from Division VIII (Galaxies and the Universe – Sadanori Okamura, President), as well as Commission 28 (Galaxies – Françoise Combes, President), Commission 44 (Space and High-Energy Astrophysics – Günther Hasinger, President), and Commission 47 (Cosmology – Rachel Webster, President) and for support of the Symposium website by Space Telescope Science Institute. We also thank Vivien Reuter for help with logistics, Luiz Paulo Ribeiro Vaz for technical assistance, Marianne Vestergaard for improving some of the LaTeX macros, and Kelly Denney, Catherine Grier, and Linda Watson for help with proofreading the manuscript.

As this volume goes to press, we were saddened to learn of the death of Geoffrey R. Burbidge. Geoff was supposed to speak at the Symposium, but ill health prevented him from attending. Geoff was a giant in 20th century astrophysics and his work had a very broad impact, notably in the context of this Symposium, on early research on quasars. We regret his passing.

The Editors

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Acknowledgements

The symposium is sponsored and supported by the IAU Division VIII (Galaxies and the Universe) and by the IAU Commissions No. 28 (Galaxies), No. 44 (Space and High Energy Astrophysics), and No. 47 (Cosmology).

The Local Organizing Committee operated under the auspices of the
Observatório Nacional of Brazil.

Funding by the
International Astronomical Union,
Observatório Nacional of Brazil,
and Space Telescope Science Institute
is gratefully acknowledged.

https://doi.org/10.1017/S1743921310005442 Published online by Cambridge University Press