Gas Accretion onto Galaxies

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Andrew Fox • Romeel Davé
Editors

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Editors
Andrew Fox
Space Telescope Science Institute
Baltimore, MD, USA

Romeel Davé
University of the Western Cape
Cape Town, Western Cape
South Africa

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Foreword

Astrophysics is hard. This branch of physics presents a number of obvious challenges to observers and experimental scientists. The targets are at tremendous distances, signals are weak, experimental setup is difficult or impossible to control (i.e., we must analyze the data that nature provides and cannot carefully design experiments), and results are often limited by cosmic variance and telescope time. Edwin Hubble's famous characterization of observational astrophysics is apt: "...we search among ghostly errors of observations for landmarks that are scarcely more substantial." Similarly, modern astrophysics makes intense demands on theorists. Current problems are rarely tractable with analytical treatments, and computer simulations require exquisite resolution and extreme dynamic range in order to adequately capture crucial small-scale microphysical processes in a cosmological (large-scale) context. Indeed, in the area of galaxy formation and evolution, full numerical modeling of all of the relevant physics is usually impossible; many important but unresolved processes must be handled with sub-grid prescriptions, and different prescriptions for sub-grid physics can lead to profoundly different results. To make progress today, theorists must be inventive and resourceful, but they must also exercise caution about systematic uncertainties in simulation outcomes.

For these reasons, it is perhaps not surprising that just a few years ago, a highly influential paper by Kereš et al. presented a seemingly simple question: how do galaxies get their gas? This is clearly a fundamental question about galaxy evolution, and at first glance this seems like a relatively straightforward issue. After all, the (presumably pristine) intergalactic gas reservoir from which galaxies form is mostly a simple hydrogen plasma, and many of the complications that plague other topics (e.g., dust, molecules, turbulence, magnetic fields, and cosmic rays) might be negligible or at least of secondary importance. However, in reality this simple question has proved to be a recalcitrant problem, for many reasons. On the observational side, accreting intergalactic gases have very low densities, and at the expected densities, emission from the accreting gas is very difficult (often impossible) to detect. Moreover, the infalling material can be shock heated into temperature ranges (e.g., the so-called warm-hot intergalactic medium at 10^5–10^7 K) that require ultraviolet or X-ray observations with cutting-edge telescopes in space, an expensive endeavor. This seemingly simple question creates headaches for theorists as well, e.g., in addition to shock heating, infalling gas can be shredded by processes such as the Kelvin-Helmholtz instability. Conversely, some accreting material could be thermally unstable and could fragment into rather small and low-mass clouds that ultimately drop into a galaxy and fuel star formation. These processes can be difficult to accurately model in computational simulations, especially if the simulation has a large enough size to provide a proper cosmological context. In addition, gas accretion is not an isolated phenomenon; as the material descends into a galaxy, it may encounter outflowing and enriched material driven away by star formation or feedback from supermassive nuclear black holes, and the interactions between the infalling and outflowing matter can significantly change how accretion works (and the theoretical predictions to be tested with observations). Stripping of gas from satellite galaxies may play a role in addition to infalling primordial material, and of course dark matter cannot be ignored. In the end, understanding how galaxies get their gas turns out to be a very difficult question.

However, there are reasons to feel optimistic about the likelihood of progress on understanding galactic gas accretion. Absorption spectroscopy can detect low-density gas and is orders of magnitude more sensitive than emission studies, and access to high-resolution spectroscopy in the rest-frame UV and X-ray bands provides detailed information on all of the likely phases in circumgalactic and intergalactic media from $z = 0$ to $z > 5$, including the elusive warm-hot gas. The deployment of the Cosmic Origins Spectrograph (COS) on the Hubble Space Telescope has been particularly transformative. By providing coverage of UV resonance lines from a wide variety of elements and ionization stages at low and intermediate redshifts, COS has enabled statistically useful studies of absorption lines from circumgalactic/intergalactic plasmas in a variety of contexts, and programs such as the COS-Halos survey have led to rapid progress on low-density and highly ionized gas in galaxy halos. On the theoretical side, Moore's Law continues to hold, and advances in computational power support increasingly sophisticated simulations. Theoretical modeling is improving by leaps and bounds.

For these reasons, this is an ideal time for a set of detailed reviews of recent observational and theoretical work on the topic of how galaxies acquire their gas. The chapters in this book present a set of reviews that span many of the key observations of circumgalactic material ranging from cool and neutral matter to hot and highly ionized plasma over a wide range of redshifts. The book also presents excellent discussions of theoretical motivations and progress on several aspects of accretion and galactic feedback. I expect that this publication will provide a valuable tool for pundits and highly experienced researchers as well as students that are just beginning to come up to speed on galaxy evolution. I am sure that I will often reach for this set of reviews, and I commend the authors and editors for assembling an excellent compendium on a crucial aspect of galaxy evolution.

Amherst, MA, USA
November 2016

Todd Tripp

Preface

From majestic spirals to behemoth ellipticals to disordered dwarfs, the richness and diversity of galaxies has been a subject of study since the time of Hubble. A common feature among all galaxies is that their growth is driven by accretion of material from a vast reservoir of surrounding intergalactic gas, which provides fuel for forming new stars and growing supermassive black holes. Yet this ubiquitously predicted accretion has been notoriously difficult to detect directly. Until recently accretion was only seen around our own Milky Way, but advancing facilities have now enabled astronomers to obtain tantalizing evidence of accretion out to much earlier epochs, back to when galaxies were in their heyday of growth. Meanwhile, supercomputer simulations have highlighted that simple gravitationally driven accretion is only one aspect of a vast and complex story for how galaxies obtain their fuel, a story that includes energetic processes such as supernova-driven winds and black hole accretion. This edited volume presents the current state of accretion studies from both observational and theoretical perspectives, and charts our progress towards answering the fundamental yet elusive question, *"how do galaxies get their gas?"*

Understanding how galaxies form and evolve has been a central focus in astronomy for over a century. These studies have accelerated in the new millennium, driven by two key advances: the establishment of a firm concordance cosmological model that provides the backbone on which galaxies form and grow, and the recognition that galaxies grow not in isolation but within a "cosmic ecosystem" that includes the vast reservoir of gas filling intergalactic space. This latter aspect in which galaxies continually exchange matter with the intergalactic medium via inflows and outflows has been dubbed the "baryon cycle", and is featured as one of the central questions in the 2010 Astronomy Decadal Survey (*New Worlds, New Horizons*). The topic of our book is directly related to the baryon cycle, in particular its least well-constrained aspect, namely gas accretion.

Accretion is a rare area of astrophysics in which the basic theoretical predictions are established, but the observations have been as yet unable to verify the expectations. Accretion has long been seen around the Milky Way in so-called High Velocity Clouds, but the inferred accretion rates are uncertain. Detecting accretion even around nearby galaxies has proved challenging; its multiphase nature requires sensitive observations across the electromagnetic spectrum for full characterization. Theory also strongly predicts that accretion is much more rapid in the early universe, so much effort has gone into developing new ways to detect accretion in distant, unresolved galaxies. A promising approach involves looking for kinematic signatures, but accretion signatures are often confused with internal motions within galaxies. Meanwhile, theorists have realized that accretion left unchecked would lead to galaxies that look nothing like observed galaxies. Hence accretion must somehow be a self-regulating process. Understanding the physical origin of this delicate balance of the baryon cycle that leads to galaxies as we see them has proved to be an immense challenge, requiring the most advanced supercomputer simulations to model properly. Accretion studies therefore touch a wide range of astrophysical processes, and hence a wide cross section of the astronomical community.

An edited volume on this topic is timely for a number of reasons. Observational facilities are finally able to access the wavelength ranges and depths at which accretion processes may be manifest. Because inflowing gas is diffuse and does not glow like stars, the best hope for direct detection generally lies in absorption-line spectroscopy. It turns out that the ultraviolet waveband contains the most interesting lines for this purpose, which has made the Cosmic Origins Spectrograph on Hubble a game changer for baryon cycle observations. Meanwhile, the emergence of multi-object spectroscopy on 10m-class ground-based telescopes such as Keck and VLT has likewise revolutionized our understanding of baryon cycle processes at intermediate redshifts, where the UV lines are redshifted into the more accessible optical band. These baryon cycle studies represent a key line of investigation for upcoming 30m-class facilities and the proposed next-generation UV/optical space telescope (LUVOIR), which may even be sensitive enough to map UV line emission from accreting gas. At the same time, radio investigations at low redshift continue to unravel the properties of the neutral gas around galaxies in high spatial resolution. Hence the time is right to survey these multiple lines of investigation and determine the state of the field in accretion studies of the baryon cycle.

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Baltimore, MD, USA Andrew Fox
Cape Town, South Africa Romeel Davé
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Contents

Contributors

Nicolas F. Bouché IRAP, 9 Av. Colonel Roche, F-31400 Toulouse, France

Sebastiano Cantalupo Institute for Astronomy, ETH-Zürich, Zürich, Switzerland

Hsiao-Wen Chen Department of Astronomy & Astrophysics and Kavli Institute for Cosmological Physics, The University of Chicago, Chicago, IL, USA

Claude-André Faucher-Giguère Department of Physics and Astronomy and Center for Interdisciplinary Exploration and Research in Astrophysics (CIERA), Northwestern University, Evanston, IL, USA

Kristian Finlator New Mexico State University, Las Cruces, NM, USA

Filippo Fraternali Department of Physics and Astronomy, University of Bologna, Bologna, Italy

Kapteyn Astronomical Institute, University of Groningen, The Netherlands

Glenn G. Kacprzak Center for Astrophysics & Supercomputing, Swinburne University of Technology, Hawthorn, VIC, Australia

Nicolas Lehner Center for Astrophysics, Department of Physics, University of Notre Dame, Notre Dame, IN, USA

Felix J. Lockman Green Bank Observatory, Green Bank, WV, USA

Mary E. Putman Department of Astronomy, Columbia University, New York City, NY, USA

Philipp Richter Institut für Physik und Astronomie, University of Potsdam, Potsdam, Germany

Kate H.R. Rubin Department of Astronomy, San Diego State University, San Diego, CA, USA

Jorge Sanchez Almeida Instituto de Astrofísica de Canarias, Canary Islands, Spain

Departamento de Astrofísica, Universidad de La Laguna, Tenerife, Spain

Kyle R. Stewart Department of Mathematical Sciences, California Baptist University, Riverside, CA, USA

Freeke van de Voort Theoretical Astrophysics, Heidelberg Institute for Theoretical Studies, Heidelberg, Germany

Academia Sinica Institute of Astronomy and Astrophysics, Taipei, Taiwan

Heidelberg Institute for Theoretical Studies, Heidelberg, Germany

Astronomy Department, Yale University, New Haven, CT, USA

Acronyms

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ACS	Advanced Camera for Surveys
AGN	Active galactic nuclei
ALMA	Atacama Large Millimeter/Submillimeter Array
AMR	Adaptive mesh refinement
AO	Adaptive optics
ASKAP	Australian Square Kilometer Array Pathfinder
BAL	Broad Absorption Line
BASIC	Bimodal Absorption System Imaging Campaign
BAT	Burst Alert Telescope
BCD	Blue compact dwarf
BOSS	Baryon Oscillation Spectroscopic Survey
CGM	Circumgalactic medium
CL	Confidence limit
CLUES	Constrained Local UniversE Simulations
COS	Cosmic Origins Spectrograph
DIG	Diffuse ionized gas
DLA	Damped Lyman-alpha (system)
DM	Dark Matter
EAGLE	Evolution and Assembly of Galaxies and their Environments
EBHIS	Effelsberg-Bonn HI Survey
ESI	Echelette Spectrograph and Imager (instrument on Keck)
FIRE	Feedback in Realistic Environments (simulations)
FMR	Fundamental metallicity relation
FWHM	Full width at half maximum
GASS	Galactic All-Sky Survey
GBT	Green Bank Telescope
GMM	Gaussian mixture modeling
GMOS	Gemini Multi-Object Spectrograph

HALOGAS	Hydrogen Accretion in LOcal GAlaxieS (survey)
HST	Hubble Space Telescope
HVC	High-velocity cloud
HzRG	High-z radio galaxy
ICM	Intracluster medium
IFU	Integral field unit
IGM	Intergalactic medium
IMF	Initial mass function
ISM	Interstellar medium
IVC	Intermediate-velocity cloud
JVLA	Jansky Very Large Array
JWST	James Webb Space Telescope
KCWI	Keck Cosmic Web Imager
KMOSS	K-Band Multi-Object Spectrograph
KODIAQ	Keck Observatory Database of Ionized Absorbers toward Quasars
LAB	Leiden Argentine Bonn (survey)
LAB	Lyman-alpha blob
LAE	Lyman-alpha emitter
LBG	Lyman-break galaxy
LBT	Large Binocular Telescope
LINER	Low-ionization nuclear emission line regions
LLS	Lyman limit system
LMC	Large Magellanic Cloud
LRG	Luminous red galaxy
LRIS	Low Resolution Imaging Spectrometer
LUVOIR	Large UltraViolet/Optical/InfraRed (mission concept)
LVC	Low-velocity cloud
ΛCDM	Lambda Cold Dark Matter (cosmology/model)
MANGA	Mapping Nearby Galaxies at APO (survey)
MEGAFLOW	MusE GAs FLOw and Wind (survey)
MOSFIRE	Multi-Object Spectrometer For Infra-Red Exploration
MQN	MUSE Quasar Nebulae
MS	Magellanic Stream
MUSE	Multi-Unit Spectroscopic Explorer (instrument on VLT)
MZR	Mass-metallicity relation
QBCD	Quiescent blue compact dwarf
QSO	Quasi-stellar object
PCWI	Palomar Cosmic Web Imager
PDF	Probability distribution function
PLLS	Partial Lyman limit system
PSF	Point spread function
SDSS	Sloan Digital Sky Survey
SFG	Star forming galaxy
SFR	Star formation rate
SIMPLE	SInfoni Mg II Program for Line Emitters

SINFONI	Spectrograph for INtegral Field Observations in the Near Infrared
SKA	Square Kilometer Array
SLLS	Super Lyman limit system
SN	Supernovae
SPH	Smoothed particle hydrodynamics
Sub-DLA	Sub-damped Lyman-alpha (system)
SXRB	Soft X-ray background
TMT	Thirty-Meter Telescope
TPCF	Two-point correlation function
TTT	Tidal torque theory
UV	Ultraviolet
UVB	Ultraviolet Background
VLT	Very Large Telescope
VMP	Very metal poor (gas or absorbers)
WHAM	Wisconsin H-alpha Mapper
WSRT	Westerbork Synthesis Radio Telescope
XMP	Extremely metal poor (galaxy)