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Andrew Fox · Romeel Davé
Editors

Gas Accretion onto Galaxies

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Gas Accretion onto Galaxies

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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
Cape Town, South Africa
December 2016

Andrew Fox
Romeel Davé

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Acronyms

Gas Accretion onto Galaxies, Fox and Davé, eds.

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)

An Introduction to Gas Accretion onto Galaxies

Mary E. Putman

1 Introduction

The idea of gas accretion onto galaxies first came ∼50 years ago. In the 1960s and 1970s, observations of high velocity hydrogen clouds were made and it was proposed that they represent infalling Galactic fuel (Muller et al. 1963; Hulsbosch 1968; Dieter 1971; Oort 1970). This infall was soon understood to have consequences on the Milky Way's star formation and distribution of stellar metallicities (Larson 1972a,b; van den Bergh 1962). Since the original detection of Galactic cold hydrogen halo clouds, observations have been made of halo gas in a variety of phases for galaxies throughout the universe. The observations have made it clear that there are abundant baryons surrounding galaxies and that some of these baryons will accrete and fuel future star formation.

There are numerous observations of galaxies and the intergalactic medium (IGM) that infer gas accretion is needed throughout cosmic time. There are galaxies at all redshifts observable with star formation rates that indicate they will run out of fuel within a few Gyrs without replenishment. The metallicities of their stars also suggest galaxy evolution models without accretion will not work. At the level of the census of baryons in the universe, the decrease in the mass density of cold hydrogen with time does not closely track the steady increase in the mass density of stars, and this requires the ionized IGM to cool and accrete onto galaxies. The first section of this introduction provides an overview of this type of indirect observational evidence for gas accretion.

Theoretically, ongoing gas accretion is required to produce realistic galaxies and it largely occurs through the accretion of the intergalactic medium and satellites.

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Feedback from galaxies is also a key component of galaxy formation models and the interplay between accretion and feedback is important to understand. There is some observational support for the IGM, satellite gas, and feedback material all being sources of future star formation fuel. The second section of this chapter discusses these sources of gas accretion and the different modes with which the gas may ultimately reach the star-forming core of a galaxy.

Direct evidence for gas accretion, as in the kinematic signature of gas falling directly onto the stellar component of a galaxy, is relatively rare and the third section of this chapter summarizes the direct observational evidence currently available. Some of the numerous additional observational claims for gas accretion onto individual systems are also discussed. I conclude this chapter with a brief summary and thoughts on directions for the future.

2 The Need for Accretion Through Cosmic Time

The need for ongoing gas accretion is evident in observations of galaxies and the IGM at all redshifts. In this section, the broader indirect pieces of observational evidence for gas accretion are discussed. This includes the star formation rates of populations of galaxies, the state of the baryons in the universe, and the metal enrichment history of galaxies.

Star formation rates that will exhaust a galaxy's gas supply on a relatively rapid timescale are commonly derived from observations. At high redshift ($z > 1$), there are measured gas depletion times of less than a Gyr (e.g., Genzel et al. 2010; Daddi et al. 2010; Tacconi et al. 2013). The high redshift observations are limited to those galaxies with accessible gas and star formation tracers (Shapley 2011), but this result is found for a wide variety of tracers. At lower redshift, where there is a more complete census of the gas content and star formation rate of galaxies, the measured gas depletion times are longer, but still typically less than a few Gyrs (Kennicutt and Evans 2012; Bigiel et al. 2011; Leroy et al. 2013; Schiminovich et al. 2010). The primary exception is the gas-rich dwarf galaxies that can have depletion times closer to a Hubble time (van Zee 2001; Hunt et al. 2015; Huang et al. 2012). There is evidence that galaxies are undergoing a more efficient mode of star formation at higher redshift, leading to the shorter depletion times and the need for a greater rate of accretion at early times (Scoville et al. 2016; Santini et al. 2014). This is also evident in the evolution of the specific star formation rate (SFR/M_*) that gradually decreases towards lower redshifts at a given stellar mass (Madau and Dickinson 2014; Karim et al. 2011). The accretion process may be key to regulating a galaxy's SFR and without it the depletion times at all redshifts suggest a large fraction of galaxies are not far from being red and dead.

Beyond individual galaxies, the cold gas content of the universe as a whole should decrease as more stars are formed. If it does not correspondingly decrease there must be continuous cooling of the ionized gas in the IGM and halos that harbor the majority of the baryons in the universe (Shull et al. 2012; Bregman 2007).

This can be investigated with a comparison of the mass density of atomic hydrogen to the mass density of stars through cosmic time, as shown in Fig. 1. This figure shows that the HI mass density has an overall decrease from $z = 3$ to $z = 0$ (∼11 Gyr ago to today), but this evolution is mild compared to the increase in stellar mass density with time. Where the decrease in H I mass density specifically happens depends on the measurements adopted (Rao et al. 2006; Lah et al. 2007; Prochaska et al. 2005; Zafar et al. 2013), but the values at $z = 3$ derived from damped Lyman-α absorbers (DLAs) are clearly higher than the H I emission measurements at $z = 0$ (Zwaan et al. 2005; Hoppmann et al. 2015). A recent study by Neeleman et al. (2016) at $z \sim 0.6$ (∼6 Gyr ago) is consistent with a gradual decline from $z = 2$ to today. This measurement was achieved with a blind DLA survey, an improvement over the higher point at approximately this redshift/time that is based on Mg II surveys (see Prochaska and Wolfe 2009). In any case, the evolution of the H I does not appear to closely follow the evolution of the stellar mass density or star formation rate density of the universe (Madau and Dickinson 2014; Putman et al. 2009; Hopkins et al. 2008). Naively a direct correlation would be expected if there is no accretion and cooling of new H I gas.

There is clearly more work to be done to understand the evolution of baryons across time. For the mass density of atomic hydrogen, we are currently limited to using absorption line studies at every redshift but $z = 0$, where H I emission measurements are available. This will improve with H I emission surveys that can reach $z = 0.5$ (∼5 Gyr ago) in progress with the JVLA (Fernández et al. 2016), and planned with SKA precursor telescopes (ASKAP; Duffy et al. 2012). The MeerKAT survey LADUMA is designed to detect H I in emission out to at least $z = 1$ (over half the age of the universe), and this will significantly add to our knowledge of the evolution of the H I mass density. CO surveys with ALMA are also an important component to our future understanding of the evolution of the cold gas content of the universe. The CO has a direct correlation with star formation (i.e., a short consumption time; Bigiel et al. 2011; Leroy et al. 2008), and correspondingly the molecular (traced by CO) to stellar mass ratio already shows indications of a clear decline with redshift (Carilli et al. 2013; Bauermeister et al. 2013). The molecular gas depletion rate does still require continuous replenishment via gas inflow (Bauermeister et al. 2010), but it is not as directly apparent as with the H I evolution.

The final piece of indirect observational evidence for accretion discussed in this section is the metallicity distribution of the stars in galaxies. In the local universe, the metallicity distribution of the long-lived stars supports galaxy evolution models with a continuous inflow of relatively low metallicity gas (Chiappini 2009; Fenner and Gibson 2003; Larson 1972b). Closed box galaxy evolution models produce a wider distribution of stellar metallicities than is observed and this has traditionally been referred to as the G-dwarf problem. This evidence for accretion is strongest in the local universe where the metallicity of individual long-lived stars can be measured (Holmberg et al. 2007; Kirby et al. 2013; Grillmair et al. 1996), but it is also consistent with the metallicities derived from the integrated stellar light observations of galaxies (e.g., Henry and Worhey et al. 1999; Bressan et al. 1994; Stott et al. 2014;

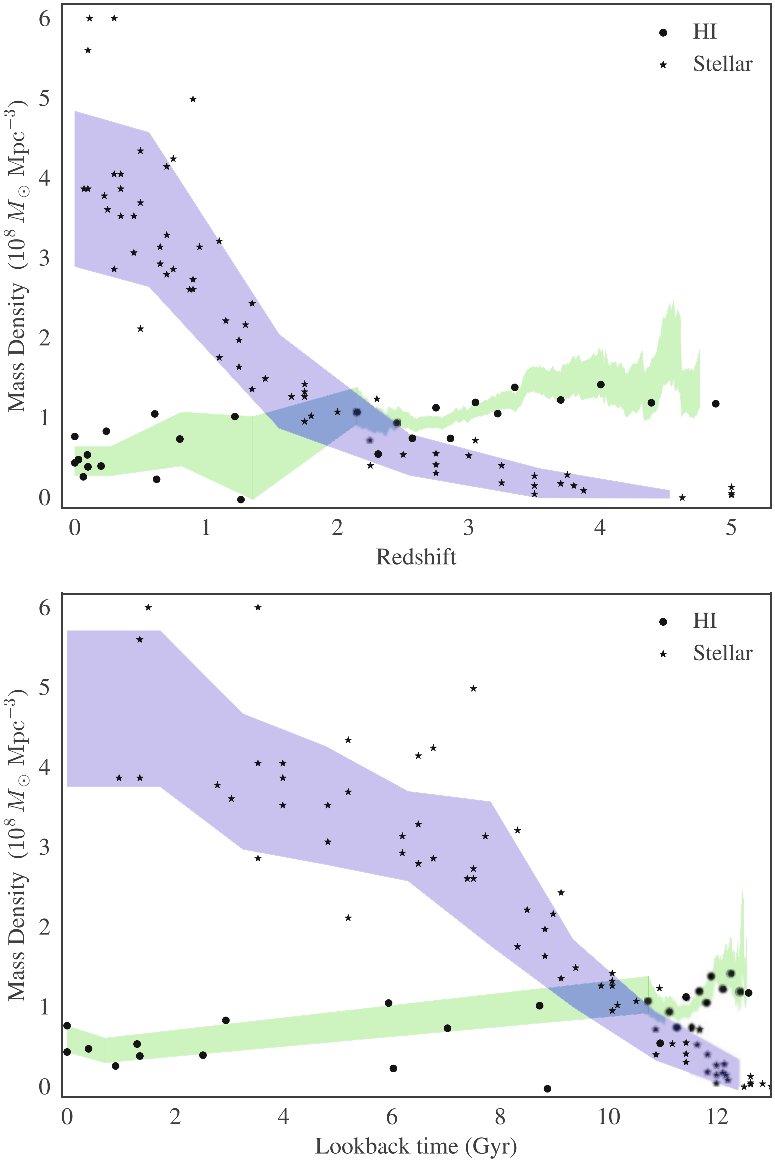

Fig. 1 A comparison of the evolution of the stellar mass density (*stars*/*purple*) and atomic gas (H I) mass density (*points*/*green*) with redshift (*top*) and lookback time (*bottom*). The H I data are from the compilation by Neeleman et al. (2016) and Sánchez-Ramírez et al. (2016), and the stellar mass densities are taken from the Madau and Dickinson (2014) compilation. The H I measurements are largely based on damped Lyman-α absorption measurements except at $z \sim 0$. The *purple* and *green shades* represent the running median and scatter of the data with the shaded H I incorporating the $z > 1.6$ results of Sánchez-Ramírez et al. (2016)

Gallazzi et al. 2005). The metallicity distribution of planetary nebulae has also been used as evidence for gas accretion (e.g., Magrini et al. 2007). These metallicity results are for a variety of galaxy types and the fact that the accreting gas needs to be relatively low metallicity is considered support for the IGM being a major source of accretion.

3 Expected Modes of Accretion

Gas accretion onto the stellar component of a galaxy can proceed in several ways and from multiple sources. Most of the gas in the halos of galaxies is ionized, and since the ionized gas mass in a galaxy's disk is smaller than the mass in cold gas ($<10^4$ K; e.g., Ferrière et al. 2001), the halo gas must rapidly cool as it accretes. The gas may come in as large cool clouds, dribble onto the disk from smaller warm clouds, enter preferentially at the edges of the galaxy, or the gas may accrete with a combination of these methods. The dominant mode of accretion at the star-forming component of a galaxy remains to be determined. The interplay between enriched outflowing gas with gas coming in may be key in this process (Fraternali and Binney 2008; Putman et al. 2012; Marinacci et al. 2010; Voit et al. 2015).

The major sources of the accreting material are thought to be the IGM, satellites, and recycled feedback gas (see Fig. 2). Theoretically, all three of these sources are expected and observationally there is evidence for all three, although much of the evidence is indirect. For instance, the continuous distribution of gas from a galaxy through its halo to the IGM, as found with absorption line experiments (Tumlinson et al. 2013; Prochaska et al. 2011; Penton et al. 2002; Wakker and Savage 2009; Chen et al. 2001), is consistent with the IGM as an important fuel source, though not direct evidence of its accretion. Theoretically, the inflowing filaments of IGM are expected to be the largest source of ongoing accretion for a galaxy (Joung et al. 2012a; Kereš et al. 2005; Brooks et al. 2009). Depending on the mass of the galaxy halo, some percentage of the inflowing IGM is heated to high temperatures in the simulations. Figure 3 shows the state of the accreting case for an L_* galaxy and how the filaments of low metallicity IGM (top panel) are partially heated as they move through the halo and also cool in the central regions as they approach the disk. How the gas is able to ultimately cool to below 10^4 K and feed the star formation in the disk may be related to density enhancements in the filaments and the mixing with satellite and feedback material (Joung et al. 2012b; Fraternali and Binney 2008). The simulations also find that much of the ongoing IGM accretion occurs towards the edges of the galaxy to avoid the dominant feedback from the central regions (Stewart et al. 2011; Fernández et al. 2012).

It is clear that satellite gas is stripped within a galaxy halo as observations have captured this directly (e.g., Fig. 4), and satellites closer to galaxies typically do not have gas and are redder (Grcevich and Putman 2009; Spekkens et al. 2014; Geha et al. 2012). Ram pressure stripping by the CGM of the host galaxy is thought to be the dominant stripping mechanism, but other forces can be important, for instance,

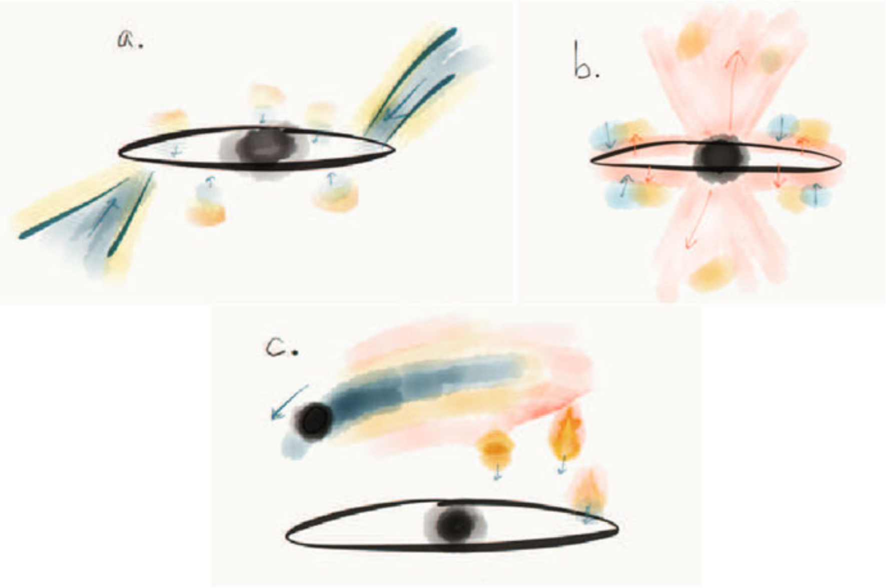

Fig. 2 A representation of the three expected sources of accretion with red indicating hot gas and blue cooler gas. (**a**) (*top-left*) Accretion from the IGM along filaments where the outer parts are heated and the inner parts are able to cool. The hot IGM-originated halo gas cooling near the disk as it mixes with denser gas is also indicated. (**b**) (*top-right*) Feedback material can accrete as part of a fountain flow close to the disk with hot gas from stellar feedback rising and then cooling and falling back down. Gas from a central outflow will mix with existing halo density enhancements and this may also result in cool clumps that eventually accrete. (**c**) (*bottom*) Satellites are stripped of their gas as they move through the diffuse halo medium and this gas will fall to the disk as warm clouds. As the gas slows and mixes with denser feedback material it can potentially re-cool close to the disk

when satellites come in as an interacting pair (Pearson et al. 2016; Marasco et al. 2016). The gas is largely heated when it is ram pressure stripped (Tepper-García et al. 2015; Gatto et al. 2013; Fox et al. 2014), and (again) it is not completely clear how it ultimately cools to feed the galaxy's star formation. It may sink to the disk as density enhancements in the halo and ultimately cool closer to the disk as it slows and encounters a denser surrounding medium (Heitsch and Putman 2009; Joung et al. 2012b; Bland-Hawthorn et al. 2007). The numerous small satellites found in the Local Group and predicted by simulations do not provide a significant amount of gas, but larger satellites, such as the Magellanic Clouds for the Milky Way, can provide gigayears worth of star formation fuel to a galaxy.

There are numerous observed kinematic signatures of feedback mechanisms putting gas into the halos of galaxies (Rubin et al. 2014; Shapley et al. 2003; Weiner et al. 2009; Chen et al. 2010; Heckman et al. 2000). While simulations require many of the metals created by a galaxy are ejected from the system (see panel c of Fig. 3), there is a large mass of metals detected in galaxy halos that remains bound

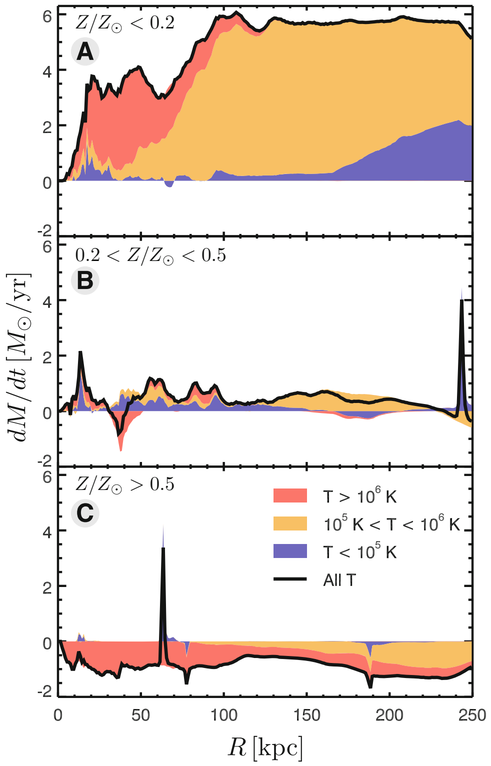

Fig. 3 The mass accretion rate of different temperature and metallicity gas at $z = 0$ in an AMR simulation of a Milky Way mass galaxy (Joung et al. 2012a). Most of the accreting gas is low metallicity material from the IGM as shown in panel (**a**). The highest metallicity gas (panel (**c**)) has a net outflow at all radii. The central panel (**b**) shows the intermediate metallicity gas inflow with the spikes corresponding to satellites. The change in temperature of the accreting gas is largely due to the heating of the inflowing gas as it interacts with existing halo gas and the cooling in the central regions of the filaments

(Tumlinson et al. 2011; Werk et al. 2014). The results therefore indicate there is abundant future star formation fuel that has already cycled through the galaxy. As discussed at the end of Sect. 2, the metallicities of the stars in galaxies indicate feedback should not dominate as the fuel source. Mixing feedback material with IGM and satellite gas is key to balance this out. This is consistent with the results of simulations that can produce the large amount of detected ions in galaxy halos while remaining consistent with the observed mass-metallicity relation for galaxies (Oppenheimer et al. 2016; Muratov et al. 2016).

4 Direct Observational Evidence for Accretion

Direct unambiguous kinematic evidence of gas falling onto a galaxy is relatively rare. The simple approximation of the mass accretion rate is $\dot{M}$ ($M_\odot$/yr) $= Mv/z$, where M is the mass of the accreting material, v is its velocity, and z is the height the material is falling from. Each of these parameters usually has significant uncertainties in the observations depending on the gas phase probed and the geometry of the system. In all cases we are only capable of measuring one

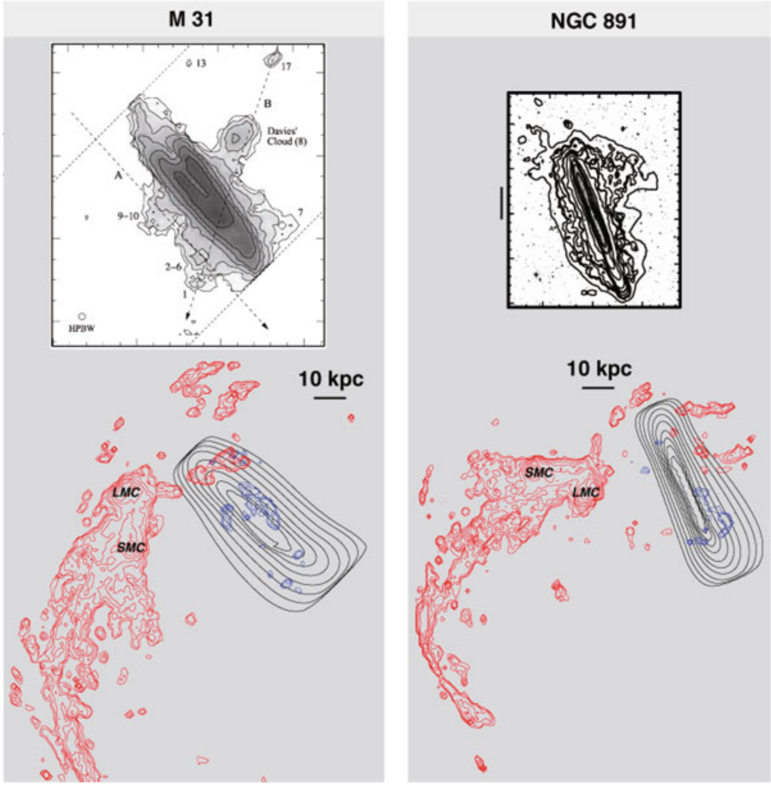

Fig. 4 Evidence for accretion from H I observations for the Milky Way (*bottom*), M31 (*top left*; Westmeier et al. 2007), and NGC 891 (*top right*; Oosterloo et al. 2007). The Milky Way observations are shown from an external point of view with the viewing angle and distance to M31 (*bottom left*) and NGC 891 (*bottom right*). The accreting Milky Way H I halo gas at <10 kpc (*blue contours*) is difficult to discern from the disk gas (*black contours*) with an external view. The *red contours* show the accretion of satellite H I from the Magellanic System (Putman et al. 2003). The origin of the extraplanar H I for M31 and NGC 891 is unknown, but some of the larger H I features are potentially linked to satellite accretion. The extraplanar H I shown is not a substantial amount of mass, but some of it may represent the cooling of the large reservoir of ionized halo gas. This figure is from Putman et al. (2012)

component of the gas velocity, and accretion can be more accurately assessed when the gas is known to be close to the disk and unmeasured tangential velocities cannot easily dominate.

The Milky Way is an example of gas observed at 1–15 kpc above the disk that is clearly infalling. The actual rate of accretion depends on the 3D motions of the gas and the full extent of the accreting layer, but the rates calculated are 0.1–0.4 $M_\odot$/yr for the coldest gas (Putman et al. 2012), and closer to 1 $M_\odot$/yr when the ionized gas is included (Lehner and Howk 2011). Most of the gas thought to be in the halo of the Milky Way has unknown distances. The only halo gas known to be at large radii is that associated with the Magellanic System (Putman et al. 2003; Fox et al. 2014). It is difficult to say when the gas of Magellanic origin will accrete as it is likely to have a large tangential velocity component and will slow and be heated as it falls. An extended, diffuse halo medium is inferred to exist for the Milky Way from the nature of the Magellanic System and stripped satellites (Salem et al. 2015; Emerick et al. 2016; Grcevich and Putman 2009). The motion of this diffuse halo medium is largely unknown, and much of it is thought to be hot and not easily observed. There is at least a consistency between the radial velocities of the ions that probe the warm-hot halo gas and the simulated extended halo medium represented in Fig. 3 (Zheng et al. 2015).

There is limited direct evidence for accretion beyond the Milky Way. Absorption line experiments that use background QSOs do not know the location and motion of the gas relative to the galaxy's stars. Experiments that use objects within the galaxy itself do not have the uncertainty of the gas being on the near or far side and the corresponding ambiguity of the velocity potentially representing inflow or outflow. The vast majority of the observations using the galaxy itself show significant outflows, with only a few examples of detected inflow. Rubin et al. (2012) and Martin et al. (2012) detected Mg II and Fe II absorption for 100+ star-forming galaxies at $z = 0.4$–1.3 and found only 4–6% show cool gas inflow with velocities $<200\,\mathrm{km\,s^{-1}}$. The low detection rate may be related to the covering fraction of the cold gas inflow, the low velocities of the inflow relative to their velocity resolution, and/or significant inflow could be an intermittent process. Rubin et al. (2012) found all but one of the galaxies with inflow have an inclination $>60°$; and this may have helped to differentiate the inflowing material from the ubiquitous outflows. Many other claims of inflow that use the galaxy itself are tenuous given the velocity resolution of the observations and the difficulty in separating the inflow component from the galaxy in the spectrum (Sato et al. 2009; Giavalisco et al. 2011).

One of the strongest examples of the direct detection of gas accretion beyond the Milky Way is for the small spiral galaxy M33 in the Local Group. Zheng et al. (2017) used UV-bright stars in M33's disk as background probes and found the kinematic signature of inflow across the star-forming disk in the Si IV absorption lines (Fig. 5). An accreting layer of gas at the disk-halo interface is the most consistent model with the distribution and velocities of the inflowing gas. A layer close to the disk is consonant with the difficulty in detecting the inflow in other systems. The accretion rate obtained ($\sim 2.9\,M_\odot$/yr) is relatively large for this small galaxy, and may be further evidence for the infall of fuel being intermittent in nature.

With the numerous indirect methods of detecting gas accretion, it is difficult to provide a complete census of the results. This paragraph gives an overview of some of these methods. As mentioned previously, absorption line experiments that use distant background probes and model the likely location of the gas relative to the galaxy are often used to claim accretion (Bouché et al. 2016; Bowen et al. 2016). The actual location of the gas is not known, but cases where the absorbing gas is close in position-velocity space to the galaxy are more likely to be capturing the accretion process. When particularly low metallicity gas is detected in a galaxy halo it is often claimed to be the accretion of the IGM filaments mentioned in

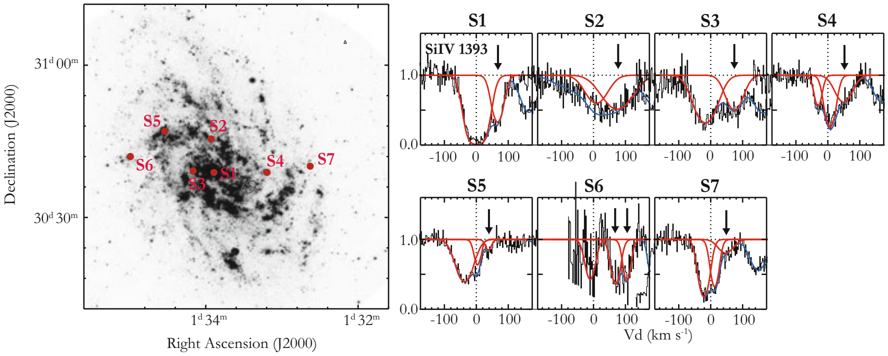

Fig. 5 The direct detection of accretion for the Local Group dwarf spiral galaxy M33 (Zheng et al. 2016). The *left* is a UV image of M33's star formation from *GALEX* with the stars targeted with the Cosmic Origins Spectrograph on *HST* labeled as S1–S7. The *right* shows the Si IV (λ1393) absorption lines detected for each sightline. The $0\,\mathrm{km\,s^{-1}}$ *dotted line* is the observed systemic velocity of the rotating H I disk, the *red* represents the fits to the individual lines and the *blue* is the composite fit. The *arrows* indicate gas that is inflowing with respect to M33's disk

Sect. 3 (e.g., Lehner et al. 2013; Cooper et al. 2015; Crighton et al. 2013). It would be difficult to explain this gas as anything else, but since the exact location and kinematics of the gas is unknown, it may or may not be accreting. It is also difficult to separate an IGM origin from satellite material at low redshift using metallicity alone (Muratov et al. 2016). Filamentary extensions of Lyman-α emission have been taken to be the detection of accretion at high redshift. In cases when multiple datasets are combined, the evidence is particularly strong (e.g., Rauch et al. 2016; Fumagalli et al. 2016; Martin et al. 2016). Finally, at low redshift, extensions of H I emission have been published as evidence for accretion (e.g., Kreckel et al. 2012; Putman et al. 2009; Sancisi et al. 2008, top panels of Fig. 4). The gas detected will certainly eventually accrete onto the nearby galaxy, but the origin of the gas and the direction the gas is currently moving are usually uncertain.

5 Summary

As outlined in this chapter and throughout this book, it is clear that gas accretion onto galaxies is occurring. We now know that the accreting cold hydrogen clouds originally found for the Milky Way are a small component of a process found throughout the universe. There are clear kinematic signatures of infalling gas for multiple galaxies and numerous other observations of individual systems that are consistent with gas accretion (Sect. 4). Beyond the evidence in individual systems, galaxies throughout time have star formation rates and metallicities that require ongoing accretion and the evolution of the H I mass density with time suggests it needs a constant source of replenishment (Sect. 2). The three main sources of