# **Gas Accretion in Star-Forming Galaxies**

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Abstract Cold-mode gas accretion onto galaxies is a direct prediction of  $\Lambda$ CDM simulations and provides galaxies with fuel that allows them to continue to form stars over the lifetime of the Universe. Given its dramatic influence on a galaxy's gas reservoir, gas accretion has to be largely responsible for how galaxies form and evolve. Therefore, given the importance of gas accretion, it is necessary to observe and quantify how these gas flows affect galaxy evolution. However, observational data have yet to conclusively show that gas accretion ubiquitously occurs at any epoch. Directly detecting gas accretion is a challenging endeavor and we now have obtained a significant amount of observational evidence to support it. This chapter reviews the current observational evidence of gas accretion onto star-forming galaxies.

# **1** Introduction

Cosmological simulations unequivocally predict that cold accretion is the primary growth mechanism of galaxies. The accretion of cold gas occurs via cosmic filaments that transports metal-poor gas onto galaxies, providing their fuel to form stars. Observationally, it is quite clear that galaxy gas-consumption timescales are short compared to the age of the Universe, therefore galaxies must acquire gas from the surroundings to continue to form stars. However, observational data have yet to conclusively show that gas accretion flows are ubiquitously occurring inand-around galaxies at any epoch. Since the first discoveries of circumgalactic gas around star-forming galaxies (Boksenberg & Sargent , 1978; Kunth & Bergeron, 1984; Bergeron, 1986), we have wondered where does this gas come from and if/how it drives galaxy growth and evolution.

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This Chapter reviews the current observational evidence and signatures of cold accretion onto star-forming galaxies. In the following sections, we review the data that suggest accretion is occurring and cover the main topics of circumgalactic gas spatial distribution, kinematics and metallicity. In a few cases, there exists the combination of all of the above which provides the most tantalizing evidence of cold accretion to date. This Chapter primarily focuses on observations using background quasars or galaxies as probes of the circumgalactic medium around intervening foreground galaxies.

## 2 The Spatial Distribution of the Circumgalactic Medium

In order for galaxies to continuously form stars throughout the age of the Universe, they must acquire a sufficient amount of gas from their surroundings. In fact, roughly 50% of a galaxy's gas mass is in the circumgalactic medium (Zheng et al., 2015; Wolfe et al., 2005). Using background quasars as probes of gas surrounding foreground galaxies, we have discovered that galaxies have an abundance of multiphased circumgalactic gas.

#### 2.1 Circumgalactic Gas Radial Distribution

The quantity and extend of the circumgalactic medium has been traced using a range of absorption features such as  $Ly \alpha$  (Tripp et al., 1998; Chen et al., 2001b; Wakker & Savage, 2009; Chen & Mulchaey, 2009; Steidel et al., 2010; Stocke et al., 2013; Richter et al., 2016), Mg II (Steidel et al., 1994; Steidel, 1995; Guillemin & Bergeron, 1997; Zibetti et al., 2007; Kacprzak et al., 2008; Chen et al., 2010; Nielsen et al., 2013a), CIV (Chen et al., 2001a; Adelberger et al., 2005; Steidel et al., 2010; Bordoloi et al., 2014a; Liang & Chen, 2014; Burchett et al., 2015; Richter et al., 2016), and OVI (Savage et al., 2003; Sembach et al., 2004; Stocke et al., 2006; Danforth & Shull, 2008; Tripp et al., 2008; Wakker & Savage, 2009; Prochaska et al., 2011; Tumlinson et al., 2011; Johnson et al., 2013; Stocke et al., 2013; Johnson et al., 2015; Kacprzak et al., 2015). These studies all have shown that regardless of redshift (at least between z = 0 - 3), galaxies typically have hydrogen gas detected out to  $\sim 500$  kpc with "metal-enriched" gas within 100-200 kpc. Furthermore, the data show an anticorrelation with equivalent width and impact parameter, with the covering fraction being unity close to the galaxy and declining with increasing distance. This is demonstrated in Figure 1, which shows the  $\sim$ 200 kpc extent of MgII absorbing gas around typical galaxies from the MAGIICAT catalog (Nielsen et al., 2013b) along with well fit anti-correlation between equivalent width and impact parameter  $(\log W_r(2796) = 0.015 \times D + 0.27)$ . Note also that the gas covering fraction, for an equivalent width limit of 0.3 Å, is roughly unity near the galaxy and decreases to about 20% beyond 100 kpc.



**Fig. 1** *Top*: the rest-frame MgII equivalent width as a function of impact parameter for the MAGI-ICAT catalog for "isolated" galaxies (Nielsen et al., 2013a,b). The closed symbols are detections while open symbols are  $3\sigma$  are upper limits. The fit, and  $1\sigma$  confidence levels are shown  $(\log W_r(2796) = [0.015 \pm 0.002] \times D + [0.27 \pm 0.11])$ . Note the large extent of gas surrounding galaxies, which begs the question of what is the origin of this gas and is it some combination of gas outflows and accretion. *Bottom*: the radial decline of the gas covering fraction as a function of impact parameter for an equivalent detection limit of 0.3 Å. Image courtesy of Nikole Nielsen.

Interestingly, Richter (2012) demonstrated, using the distribution of high-velocity clouds around the Milky Way and M31, that high-velocity clouds could give rise to the majority of the absorption systems seen around other galaxies. The accretion rate of high-velocity gas at z = 0 is almost equivalent to the star formation density of the local Universe and thus, at least at low redshifts, high-velocity clouds could provide a significant fraction of the gas mass accreted onto galaxies (see chapter by Philipp Richter for further discussion of gas accretion onto the Milky Way).

Simulations predict that gas accretion should occur via a "hot" or "cold" mode, which is dependent on a galaxy being above or below a critical halo mass ranging between  $\log(M_h) = 11 - 12$  (Birnboim & Dekel, 2003; Kereš et al., 2005; Dekel & Birnboim, 2006; Ocvirk et al., 2008; Brooks et al., 2009; Dekel et al., 2009; Kereš et al., 2009; Stewart et al., 2011; van de Voort et al., 2011). A repercussion of these models is that the covering fraction of cool accreting gas should drop significantly to almost zero for massive galaxies (Stewart et al., 2011). However, observational evidence shows that the covering fraction of cold gas is constant over a larger range of halo masses  $10.7 \le \log(M_h) \le 13.9$  within a given impact parameter (or impact parameter normalized by the virial radius) and that gaseous galaxy halos are self-similar (Churchill et al., 2013a,b). This is suggestive that either outflows and/or other substructures contribute to absorption in high-mass halos such that low- and high-mass gas halos are observationally indistinguishable or the data indicate that predictions of a mass dependent shutdown of cold-mode accretion may require revision. This area needs to be examined further in order to address the discrepancy between observations and simulations.

Although the average radial gas profiles around star-forming galaxies are well quantified, it does not provide much insight into the nature of the circumgalactic gas. Thus, it is critical to determine the geometric distribution of gas relative to its host galaxy to help improved our understanding of its origins.

# 2.2 Circumgalactic Gas Spatial Distribution

In the mid-90s, the exploration of circumgalactic medium geometry started with Steidel (1995) who acquired a large sample of 51 galaxy-quasar pairs. The data were suggestive that, independent of galaxy spectroscopic/morphological type, Mg II gas resided within a spherical halo with unity gas covering fraction. The data fit well to a Holmberg-like luminosity scaling between a characteristic halo radius and galaxy K-band luminosity. However, even Steidel noted that spherical halos were likely a tremendous over-simplification of the true situation, however, the data did not disprove it. Using simple geometric models, Charlton & Churchill (1996) determined that both spherical halos and extended monolithic thick-disk models could be made consistent with the current data. They suggested that the kinematic structure of the absorption profiles could be used to further constrain the gas geometry, which we further discuss in Section 3.

Cosmological simulations commonly show that gas accretion should occur along filaments that are co-planar to the galaxy disk, whereas gas outflows are expected to be expelled along the galaxy projected minor axis (e.g., Shen et al., 2012; Stewart et al., 2013). Reminiscent of Charlton & Churchill (1996), Kacprzak et al. (2011b) reported that the MgII equivalent width measured from high resolution quasar spectra was dependent on galaxy inclination, suggesting that the circum-galactic medium has a co-planer geometry that is coupled to the galaxy inclination. It was noted however that the absorbing gas could arise from tidal streams, satel-

lites, filaments, etc., which could also have somewhat co-planer distributions. By stacking over 5000 background galaxies to probe over 4000 foreground galaxies, Bordoloi et al. (2011) found a strong azimuthal dependence of the MgII absorption within 50 kpc of inclined disk-dominated galaxies (also see Lan et al., 2014). They found elevated equivalent width along the galaxy minor axis and lower equivalent width along the galaxy minor axis and lower equivalent width along the major axis. Their data are indicative of bipolar outflows with possible flows along the major axis. Later, Bordoloi et al. (2014b) presented models of the circumgalactic medium azimuthal angle distribution by using joint constraints from: the integrated MgII absorption from stacked background galaxies as seen from background quasar spectra (Kacprzak et al., 2011b). They determined that either composite models consisting of a bipolar outflow component plus a spherical or disk component, or a single highly softened bipolar distribution, could well represent data within 40 kpc.

Bouché et al. (2012), using 10 galaxies, first showed that the azimuthal angle distribution of absorbing gas traced by MgII appeared to be bimodal with half of the MgII sight-lines showing a co-planar geometry. Kacprzak et al. (2012a) further confirmed the bimodality in the azimuthal angle distribution of gas around galaxies, where cool dense circumgalactic gas prefers to exist along the projected galaxy major and minor axes where the gas covering fraction are enhanced by 20%–30% as shown in Figure 2. Also shown in Figure 2 is that blue star-forming galaxies drive the bimodality while red passive galaxies may contain gas along their projected major axis. The lower equivalent width detected along the projected major axis is suggestive that accretion would likely contain metal poor gas with moderate velocity width profiles.

The aforementioned results provide a geometric picture that is consistent with galaxy evolution scenarios where star-forming galaxies accrete co-planer gas within a narrow streams with opening angles of about 40 degrees, providing fuel for new stars that produce metal-enriched galactic scale outflows with wide opening angles of 100 degrees, while red galaxies exist passively due to reduced gas reservoirs. These conclusions are based on MgII observations, however both infalling gas and outflowing are expected to contain multi-phased gas.

Mathes et al. (2014) first attempted to address the azimuthal angle dependence for highly ionized gas traced by OVI and found it to have a spatially uniform distribution out to 300 kpc. Using a larger sample of OVI absorption selected galaxies, Kacprzak et al. (2015) reported a bimodality in the azimuthal angle distribution of gas around galaxies within 200 kpc. Similar to MgII, they found that OVI is commonly detected within opening angles of 20–40 degrees of the galaxy projected major axis and within opening angles of at least 60 degrees along the projected minor axis. Again similar to MgII, weaker equivalent width systems tend to reside on along the project major axis. This would be expected for either lower column density, lower kinematic dispersion or low metallicity (or a combination thereof) gas accreting towards the galaxy major axis. Different from the MgII results, non-detections of OVI exist almost exclusively between 20–60 degrees, suggesting that OVI is not mixed throughout the circumgalactic medium and remains confined within the accretion filaments and the gas outflows.

Further supporting this bimodality accretion/outflow picture is the recent work using HI 21-cm absorption to probe the circumgalactic medium within impact parameters of < 35 kpc around z < 0.4 galaxies. (Dutta et al., 2016) found that the majority of their absorbers (nine) exists along the projected major axis and a few (three) exists along the projected minor axis. The data are supportive of high column density co-planer HI thick-disk around these galaxies. In addition, the three minor axis absorption systems all reside within 15 kpc, therefore they conclude that these low impact parameter minor axis systems could originate from warps in these thick and extended HI disks.

Although gas geometry is highly suggestive of (and consistent with) our exception of gas accretion onto star-forming galaxies, it alone is not sufficient enough to determine if gas is actually fact accreting onto galaxies. Gas and relative gas-galaxy



Fig. 2 Binned azimuthal angle mean probability distribution function (PDF) for MgII absorbing galaxies (solid line). The binned PDFs are normalized such that the total area is equal to unity, yielding an observed frequency in each azimuthal bin. Absorption is detected with increased frequency toward the major ( $\Phi = 0$  degrees) and minor ( $\Phi = 90$  degrees) axes. Also shown is the galaxy color dependence of the distribution split by a  $B - R \le 1.1$  representing late-type galaxies (dashed blue line) and B - R > 1.1 representing early-type galaxies (dotted red line). The data are consistent with star-forming galaxies accreting gas and producing large-scale outflows while quiescent galaxies have much less gas activity.

kinematics can provide additional data that can be used to address whether we are detecting gas accretion or not.

### **3** Circumgalactic Gas Kinematics

Absorption systems produced by the circumgalactic medium hold key kinematic signatures into unlocking the the behavior of gas around galaxies. High resolution spectroscopy of the background quasars is critical to resolving the velocity substructures within these complex absorption systems. These data can be used to differentiate between scenarios of gas accretion, disk-rotation and outflows.

## 3.1 Internal or Intrinsic Gas Kinematics

For the most part, metal-line absorption systems are not composed of a uniform velocity distribution of "clouds", but tend to exist in groupings closer together in velocity with occasional higher velocity clouds offset from the groupings. For a handful high-resolution MgII absorption profiles, Lanzetta & Bowen (1992) inferred that their velocity structure was dominated by coherent motions as oppose to random. They further showed that the absorption profiles are consistent with a rotating ensembles of clouds similar to a co-rotating disk. With a larger sample of high-resolution absorption profiles, Charlton & Churchill (1998) applied statistical tests for a variety of kinematic models and concluded that pure disk rotation and pure accretion models are likely ruled out. However, models with contributions from both a rotating disk and infall/halo can reproduce velocities that are nearly consistent with the observed kinematics.

Similar work focusing on the low-ion transitions (such as SiII) associated with damped Ly  $\alpha$  systems, Prochaska & Wolfe (1997) examined if a range of models such as rotating cold disks, slowly rotating hot disks, massive isothermal halos, and a hydrodynamic spherical accretion models could explain the observed absorption kinematics. They determined that thick rapidly rotating disks are the only model consistent with the data at high confidence levels. Their tests suggest that disk rotation speeds of around 225 km s<sup>-1</sup> are preferred, which is typical for Milky Way-like galaxy rotation speeds. Furthermore, the gas is likely to be cold since ratio of the gas velocity dispersion over the disk rotation speed must be less than 0.1. These data are suggestive of thick, cold and possibly accreting disks surrounding galaxies.

All these studies are based on absorption-line data alone and therefore it is important to quantify how the absorption kinematics changes with galaxy properties.

Using primarily Lyman limits systems, Borthakur et al. (2015) found Ly $\alpha$  absorption from the circumgalactic medium has similar velocity spreads to that of their host galaxy's interstellar medium as observed via HI emission. The combination of the correlation between the galaxy gas fraction and the impact-parameter-corrected

Ly  $\alpha$  equivalent width is consistent with idea that the HI disk is fed by circumgalactic gas accretion (Borthakur et al., 2015). Furthermore, they find a correlation between impact-parameter-corrected Ly  $\alpha$  equivalent width and the galaxy specific star formation rate suggesting a link between gas accretion driving star formation (Borthakur et al., 2016).



Fig. 3 Shown are pixel-velocity two-point correlation functions (TPCFs) examining how the spread in the pixel velocities of absorption profiles differ for different galaxy properties. The TPCFs presented give the probability of having pixel velocities at a given velocity offset from the absorption redshift defined by the optical depth weighed mean. The shaded regions are the  $1\sigma$  bootstrap uncertainties. For all azimuthal angles, the TPCFs are shown for blue and red face-on galaxies (left) and edge-on galaxies (right). Note the dramatic differences between the absorber velocity dispersions for blue and red galaxies for face-on orientations (left). The larger velocity spread is suggestive of of high velocity outflows being ejected from the galaxy, while red galaxies are less active. On the other-hand, there is no difference between blue and red for edge-on orientations (right). The velocity spread is comparable to the rotation speed of galaxies, which is consistent with gas accretion and/or gaseous disk co-rotation around the galaxies.

Nielsen et al. (2015) has quantified the Mg II absorber velocity profiles using pixel-velocity two-point correlation functions and determined how absorption kinematics vary as a function of the galaxy orientation and other physical properties as shown in Figure 3. While they find that absorption profiles with the largest velocity dispersion are associated with blue, face-on galaxies probed along the projected minor axis, which is suggestive out outflows, they find something different for edge-on galaxies. For edge-on galaxies probed along the major axis, they find large Mg II absorber velocity dispersions and large column density clouds at low velocity regardless of galaxy color, which is used as a tracer of star formation rate. It is suggested that the large absorber velocity dispersions seen for edge-on galaxies (Figure 3 -right) may be caused by gas rotation/accretion where the line-of-sight velocity is maximized for edge-on galaxy inclination. Furthermore, the large cloud column densities may indicate that co-rotating or accreting gas is fairly coherent

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along the line-of-sight. The only way to test this scenario is to compare the absorption velocities relative to the rotation velocity of the host galaxies.

In addition, some evolution in the circumgalactic medium has also been observed. Blue galaxies do not show an evolution in the velocity dispersions and cloud column densities with redshift (between  $0.3 \le z \le 1$ ), while red galaxies have a circumgalactic medium that becomes more kinematically quiescent with time (Nielsen et al., 2016). This is suggestive that the gas cycle in blue star-forming galaxies is active, be it via accretion or outflows, while red galaxies exhibit little-tono gas activity. This is consistent with the little-to-no OVI found around  $z \sim 0.25$ quiescent galaxies from the COS–Halos survey (Tumlinson et al., 2011).

## 3.2 Relative Gas-Galaxy Kinematics

It is interesting that the internal velocity structure of absorption systems are reflective of their host galaxy type, orientation and redshift, however the question then arises of how/if the circumgalactic medium is kinematically connected to their host galaxies. The most direct measure of gas accretion is observing it down-the-barrel by using the host galaxy as the background source. This method is ideal since there are no degeneracies in the line-of-sight direction/velocity. Although this method does have its difficulties too since metal-enriched outflows and the interstellar medium will tend to dominate the observed absorption over the metal-poor accreting gas. These down-the-barrel gas accretion events have has been observed in a few cases with absorption velocity shifts relative to the galaxy of  $80 - 200 \text{ km s}^{-1}$  (Martin et al., 2012; Rubin et al., 2012). These down-the-barrel gas accretion observations are discussed in detail in the chapter by Kate Rubin. It is still unknown if these observations are signatures of cold accretion or recycled material falling back onto galaxies, yet they are the most direct measure of accreting gas to date.

Using quasar sight-lines, we find that the distribution of velocity separations between MgII absorption and their host galaxies tends to be Gaussian with a mean offset of 16 km s<sup>-1</sup> and dispersion of about 140 km s<sup>-1</sup> (Chen et al., 2010). Although there are much higher velocity extremes, typically expected for outflows, it is interesting that the velocity range is more typical of galaxy rotation speeds having masses close-to or less-than that of the Milky Way.

When galaxy masses are known, one can compare the relative galaxy and absorption velocities to those of the escape velocities of their halos. Figure 4 shows escape velocities, computed for spherically symmetric Navarro–Frenk–White dark matter halo profile (Navarro et al., 1996), as a function of halo mass. It can be seen that very few absorption velocity centroids exceed the estimated galaxy halo escape velocities. This is surprisingly true for a full range of galaxy masses from dwarf galaxies probed by C1V absorption (Bordoloi et al., 2014a) to more massive galaxies probed by OVI (Tumlinson et al., 2011). Consistently, it has been found that the vast majority of absorption systems that reside within one galaxy virial radius are bound to the dark matter halos of their hosts (Stocke et al., 2013; Mathes et al.,



**Fig. 4** Combined CIV (Bordoloi et al., 2014a) and OVI (Tumlinson et al., 2011) absorption velocity centroids with respect to the systemic redshift of their host galaxies as a function of the inferred dark matter halo mass for star-forming (blue squares) and passive (red diamond) galaxies. The range bars indicate the maximum projected kinematic extent of each absorption system. The histogram represents the distribution of individual component velocities. The dashed lines show the mass-dependent escape velocities at R = 50, 100, and 150 kpc, respectively. Note that all absorption-line systems appear to be bound to their halos and have velocities (and velocity ranges) comparable to galaxy circular velocities. This means that both outflowing and accreting gas could give rise to the observed kinematics. Image courtesy of Jason Tumlinson, Rongmon Bordoloi and the COS–Halos team.

2014; Tumlinson et al., 2011; Bordoloi et al., 2014a; Ho et al., 2016). It is worth noting that some of the velocity ranges covered by the absorption profiles are comparable to the escape velocities but are typically for the far wings of the profiles where the gas column densities are the lowest. Therefore two possible scenarios, or a combination thereof, can be drawn: 1) gas that is traced by absorption can be driven into the halo by star formation driven outflows and eventually fall back onto the galaxy (known as recycled winds) and/or 2) the gas is new material accreting from the intergalactic medium. With these data alone, we likely cannot distinguish between these scenarios.

To test how the circumgalactic gas is kinematically coupled to their galaxy hosts, Steidel et al. (2002) presented the first rotation curves of five intermediate-redshift MgII selected absorbing galaxies. Interestingly, they found that for four of the five cases, the absorption velocities lie entirely to one side of the galaxy systemic redshift and consistent with the side expected for rotation. Using simple thick disk-halo models, they concluded that the bulk of Mg II gas velocities could be explained by an extension of disk rotation with some velocity lag (Steidel et al., 2002). This was further confirmed by Kacprzak et al. (2010a) who also showed that infalling gas or lagging rotation is required to explain the gas kinematics. Using cosmological hydrodynamical galaxy simulations to replicate their data allowed them to concluding that coherently rotating accreting gas is likely responsible for the observed kinematic offset.

There have now been over 50 galaxies/absorbers pairs that have been compared this way and the vast majority exhibit disk-like and/or accretion kinematics (Steidel et al., 2002; Chen et al., 2005; Kacprzak et al., 2010a, 2011a; Bouché et al., 2013; Burchett et al., 2013; Keeney et al., 2013; Jorgenson & Wolfe, 2014; Diamond-Stanic et al., 2016; Bouché et al., 2016; Ho et al., 2016) and some show outflowing wind signatures (Ellison et al., 2003; Kacprzak et al., 2010a; Bouché et al., 2012; Schroetter et al., 2015; Muzahid et al., 2016; Schroetter et al., 2016) while some exhibiting group dynamics (Lehner et al., 2009; Kacprzak et al., 2010b; Bielby et al., 2016; Péroux et al., 2016). Even for systems with multiple quasar sight-lines (Bowen et al., 2016) or for multiply-lensed quasars near known foreground galaxies (Chen et al., 2014) provide the same kinematic evidence that a co-rotating disk with either some lagging rotation or accretion is required to reproduce the observed absorption kinematics. One caveat is that above works have a range of galaxy inclinations and quasar sight-line azimuthal angles, which could complicate the conclusions drawn. It is likely best to select galaxies where the quasar is located along the projected major axis where accreted gas is expected to be located.

Ho et al. (2016) designed an experiment where they selected Mg II absorbers associated with highly inclined (i > 43 degrees) star-forming galaxies with quasars sight-lines passing within 30 degrees of the projected major axis. Presented in Figure 5 are the rotation curves and the velocity spread of the absorption shown as a function of distance within the galaxy viral radius. It is clear that there strong correlation between the Mg II absorption velocities and the galaxy rotation velocities. The majority of the Mg II equivalent widths are detected at velocities less than the actual rotation speed of the dark matter halo (blue squares), while the Keplerian falloff from the measured rotation curve provides lower limits on the rotation speed of the circumgalactic medium (dashed, black line). The cyan curves illustrate constant  $Rv_{rot}(R)$  and show that the infalling gas would have specific angular momentum at least as large as that in the galactic disk, for which some of the gas has comparable specific angular momentum. The Mg II absorption-line velocity widths cannot be generated with circular disk-like orbit and a simple disk model with a radial inflowing accretion reproduced the data quite well (Ho et al., 2016).

We have shown that lagging or infalling gas appears to be a common kinematic signature of the circumgalactic gas near star-forming galaxies from  $0.1 \le z \le 2.5$  and is consistently seen for a range of galaxy inclination and position angles. These observations are consistent with current simulations that show that large co-rotating gaseous structures in the halo of the galaxy that are fueled, aligned, and kinemati-

cally connected to filamentary gas infall along the cosmic web. (Stewart et al., 2011; Danovich et al., 2012; Stewart et al., 2016; Danovich et al., 2015; Stewart et al., 2013). The predictions and results from simulations are discussed further in the chapters by Kyle Stewart and Claude-André Fauchèr-Giguere. Stewart et al. (2013) demonstrated that there is a qualitative agreement among the majority of cosmological simulations and that the buildup of high angular momentum halo gas and the formation of cold flow disks are likely a robust prediction of  $\Lambda$ CDM. These simulations naturally predict that accreted gas can be observationally distinguishable from outflowing gas from its kinematic signature of large one-sided velocity offsets. Thus, it is plausible we have already observed gas accretion through these kinematic velocity offsets mentioned above.

It is also important to note that the vast majority of systems discussed above have column densities typical of Lyman Limit Systems (N(HI)>  $10^{17.2}$  cm<sup>-2</sup>), which



**Fig. 5** Galaxy rotation curves of 10 galaxies, normalized by the rotation speed as a fraction of the halo virial radius, are compared to the kinematics of their circumgalactic gas. The Mg II absorption velocities are deprojected such that the velocity shown represents the tangential motion in the disk plane that would give to the observed sight-line velocities. The measured and intrinsic velocity range of each Mg II absorption system after deprojection is indicated by the green and orange bars with the Mg II absorption velocity along the quasar sight-line (green circles). Note that the absorption systems align with the expected side for extended disk rotation. Also shown are dark matter halo rotation speed models (blue squares) and the Keplerian fall off from the galaxy rotation curves, which sets a lower limits on the rotation speed in the circumgalactic medium (dashed, black line). The cyan curves illustrate constant  $Rv_{rot}(R)$  and indicates that the infalling gas would have specific angular momentum at least as large as that in the galactic disk.

are exclusively associated with galaxies. At the lowest column densities of N(HI) <  $10^{14}$  cm<sup>-2</sup>, Ly  $\alpha$  absorption was found to not mimic the rotation of, and/or accretion onto, galaxies derived from HI observations (Côté et al., 2005). Maybe this is not unexpected since this low column density gas is not likely to be associated with galaxies and likely associated with the Ly  $\alpha$  forest (gas associated with galaxies have N(HI)>  $10^{14.5}$  cm<sup>-2</sup> – Rudie et al., 2012).

#### 4 Circumgalactic and Galaxy Gas-Phase Metallicities

It is possible that metallicity can be used to determine the origins of absorbing gas observed around galaxies since outflows are expected to be metal-enriched while accreted gas should have lower metallicity (e.g., Shen et al., 2012). Gas accretion is expected to be metal poor but not purely pristine given that the first generations of Population III stars have likely enriched the gas to  $10^{-4}$  Z<sub>☉</sub> by a redshift of 15 - 20(e.g., Yoshida et al., 2004). In fact, there is a metallicity floor whereby it is rare to find absorption systems with metallicities much lower than  $10^{-3} Z_{\odot}$  even out to  $z \sim$ 5 (Prochaska et al., 2003; Penprase et al., 2010; Cooke et al., 2011; Battisti et al., 2012; Rafelski et al., 2012; Jorgenson et al., 2013; Cooke et al., 2015; Cooper et al., 2015; Fumagalli et al., 2016a; Lehner et al., 2016; Quiret et al., 2016). Although a few systems do have metallicities  $<10^{-3} Z_{\odot}$  (Fumagalli et al., 2011b; Cooke et al., 2011, 2015; Lehner et al., 2016) and possibly have Population III abundance patterns (Crighton et al., 2016). Cosmological simulations predict gas accretion metallicities should be between  $10^{-3} - 10^{-0.5}$  Z<sub>o</sub>, which is dependent on redshift and halo mass (Fumagalli et al., 2011a; Oppenheimer et al., 2012; van de Voort & Schaye, 2012; Shen et al., 2013; Kacprzak et al., 2016), however this metallicity range does have some overlap with the metallicities of recycled outflowing gas.

There has been an abundance of studies that have identified galaxies with circumgalactic gas metallicity measurements in an effort to determine the source of the absorption. The general census shows that absorption systems near galaxies are either metal-poor with metallicities between -2 < [X/H] < -1 (Tripp et al., 2005; Cooksey et al., 2008; Kacprzak et al., 2010b; Ribaudo et al., 2011; Thom et al., 2011; Churchill et al., 2012; Bouché et al., 2013; Crighton et al., 2013; Stocke et al., 2013; Kacprzak et al., 2014; Crighton et al., 2015; Muzahid et al., 2015; Bouché et al., 2016; Fumagalli et al., 2016b; Rahmani et al., 2016) or metal-enriched with metallicities of [X/H] > -0.7 (Chen et al., 2005; Lehner et al., 2009; Péroux et al., 2011; Bregman et al., 2013; Krogager et al., 2013; Meiring et al., 2013; Stocke et al., 2013; Crighton et al., 2015; Muzahid et al., 2015, 2016; Péroux et al., 2016; Rahmani et al., 2016). Determining the fraction of metal-rich and metal-poor systems is complicated since all the aforementioned studies have a range of observational biases due to the way the targets were selected – some selected from the presence of metallines. A clear complication of tracing the circumgalactic gas using metal-lines as tracers may bias you towards metal enriched systems. Ideally, the best way to avoid such a biases is to select absorption systems by hydrogen only.

Selecting only by hydrogen (but not necessarily with known galaxy hosts), has shown that the metallicity distribution of all Lyman limit systems below z < 1 appear to have a bi-modal distribution (Lehner et al., 2013; Wotta et al., 2016). The shape of Lyman limit systems (17.2 <log N(HI) < 17.7 in their study) metallicity bimodality distribution could be explained by outflows producing the high metallicity peak ([X/H]~ -0.3) while accreting/recycled gas could produce the low metallicity peak ([X/H] ~ -1.9) (Wotta et al., 2016). Interestingly, between 2 < z < 3.5, the metallicity distribution of Lyman limit systems uni-modal peaking at [X/H]= -2, in contrast to the bimodal distribution seen at z < 1 (Fumagalli et al., 2011b; Lehner et al., 2016). Therefore it is likely that there exists a vast reservoir of metal-poor cool gas that can accrete onto galaxies at high redshift and outflows build up the circumgalactic medium at a later time. These results are discussed in detail in the chapter by Nicolas Lehner.

The overall knowledge of the metallicity distribution of the circumgalactic medium provides critical clues to the physics of gas cycles of galaxies. The bi-modal metallicity distribution is suggestive that we are observing both outflows and accretion, but our assumptions rely strongly on predictions from simulations, which still have some issues with modeling the circumgalactic medium since it is extremely feedback dependent. One way to determine if we are observing outflows and gas accretion is to combine our expectation of the gas geometry of accretion being along the minor axis and metal poor, while outflows are metal-enrich and ejected along the minor axis.

Preliminary work by Péroux et al. (2016), using nine galaxies, indicate that there is a very weak anti-correlation with metallicity and azimuthal angle. Figure 6 show the relative metallicity of the absorbing gas with respect to the host galaxy metallicity as a function of azimuthal angle, which are two independent indicators of gas flow origins. Note that in the figure a positive difference in metallicity indicates a circumgalactic medium metallicity lower than that of the host galaxy's HII regions (expected for metal-poor accreting gas) while a negative value indicates a higher circumgalactic medium metallicity than the host galaxy (expected for metal-enriched outflows). For the few objects shown in Figure 6, there is not clear correlation as expected under simple geometric and metallicity assumptions. Note that, different from expectations, there does not appear to be any high metallicity gas at high azimuthal angles. At low low azimuthal angles, there are a range of metallicity differences including negative values, which is unexpected for accreting gas. Given the few number of systems and only a weak anti-correlation, more systems are required to understand if there is a relation between the spatial location of the circumgalactic medium and metallicity. This is an active area of research and may be the most promising avenue to peruse in the future.

# **5** Putting it all Together

The previous sections describe the individual geometric, kinematic and metallicity indicators as evidence for cold-mode accretion. On their own, they are quite suggestive that we have detected signatures of gas accretion, however, combining all of these accretion indicators together can provide quite compelling evidence.

There are a few of such examples that exist where some point to their circumgalactic medium originating from metal enriched outflows along the galaxy minor axis (Kacprzak et al., 2014; Muzahid et al., 2015) or the circumgalactic medium is kinematically consistent with gas arising from tidal/streams or interacting galaxy



**Fig. 6** Metallicity difference between the host galaxy and absorber as a function of azimuthal angle. In this plot, accreted gas is expected to reside in the upper-left corner (for low/co-planer azimuthal angle and high metallicity difference), while outflowing gas should reside in the lower-right corner (high/minor axis azimuthal angle and metallicity similar to the host galaxy) as indicated by the red arrows. Note outflowing gas appears to be metal-poor, while accreting gas exhibits a range in metallicity. Additional observations are necessary to better relate metallicity and geometry in gas flows as only a minor anti-correlation is currently measured. Image from Péroux et al. (2016).

groups (Kacprzak et al., 2011b; Muzahid et al., 2016; Péroux et al., 2016) or even enriched gas that is being recycled along the galaxy major axis (Bouché et al., 2016).

Bouché et al. (2013) presented a nice example of a moderately inclined z = 2.3 star-forming galaxy where the quasar sight-line is within 20 degrees of the galaxy's projected major axis. They derived the galaxy rotation field using IFU observations and found that the kinematics of circumgalactic medium at 26 kpc away could be reproduced by a combination of an extended rotating disk and radial gas accretion. The metallicity of the circumgalactic medium is -0.72, which is typically for gas accretion metallicities from cosmological simulations at these redshifts (van de Voort & Schaye, 2012; Kacprzak et al., 2016). The mass inflow rate was estimated to be between  $30 - 60 \text{ M}_{\odot} \text{ yr}^{-1}$ , which is similar to the galaxy star-formation rate of  $33 \text{ M}_{\odot} \text{ yr}^{-1}$  and suggestive that there is a balance between gas accretion and star-formation activity. This particular system is described in detail in the chapter by Nicolas Bouché.

In a slightly different case, a star-forming galaxy at z = 0.66 was examined where the quasar sightline is within 3 degrees of the minor axis at a distance of 104 kpc (Kacprzak et al., 2012b). Contrary to expectations, they identify a cool gas phase with metallicity  $\sim -1.7$  that has kinematics consistent with a accretion or lagging halo model. Furthermore, they also identify a warm collisionally ionized phase that also has low metallicity ( $\sim -2.2$ ). The warm gas phase is kinematically consistent with both radial outflows or radial accretion. Given the metallicities and kinematics, they conclude that the gas is accreting onto the galaxy, however this is contrary to the previously discussed interpretations that absorption found along a the projected minor axis is typically associated outflows. This could be a case where there is a miss-alignment with the accreting filaments and the disk or is an example of the three filaments typically predicted by simulations (e.g., Dekel et al., 2009; Danovich et al., 2012), thus making it unlikely that all accreting gas is co-planer.

Detailed studies like these are one of the best ways of constraining the origins of the circumgalactic medium and to help us understand how gas accretion works. Larger samples are required to build up a statistical sample of systems to negate cosmic variance. Large IFU instruments like the Multi Unit Spectroscopic Explorer (MUSE) will provide ample full field imaging/spectra datasets and help us build up these larger samples with less observational time. Gas accretion studies using IFUs are further discussed in the chapter by Nicolas Bouché.

# 6 Direct Imaging of Gas Accretion

All of the aforementioned efforts are possibly direct observations of gas accretion, yet the scientific community is not satisfied since it is difficult to prove conclusively that we have detected cold gas accretion onto galaxies. The only way to conclusively do so is by direct spectral imaging of cosmic flows onto galaxies. Obviously this is quite difficult due to the faintness and low gas column densities of these cold-flow filaments. However, we may be on the verge of being able to detect these cold



**Fig. 7** a) Mean velocity obtained with an intensity-weighted velocity moment within a narrow 7 Å band image shown in panel b). The data were obtained using Palomar cosmic web imager. The disk and filamentary candidates are indicated. – b) A pseudo slit is placed over the narrow-band image covering the disk and filaments 1 and 3 indicated by the curved white lines with tick marks indicating the distance in arcseconds along the slit. – c) The narrow-band image produced using the sheared velocity window slit indicating the distance along the slit as in panel b) – d) The mean velocity (green) and velocity dispersion (red) from the above panels. Note observed rotation with high velocity dispersions seen along the filament. This is also seen for the remaining filaments (not shown here). This is potentially one of the first direct images of cold gas accretion. Image courtesy of Chris Martin and modified from Martin et al. (2016).

gas-flows using the new generation of ultra sensitive instruments such as the Keck Comic Web Imager.

It is also possible that we have already observed comic accretion onto two separate quasar hosts (Martin et al., 2015, 2016) with one example shown in Figure 7. The figure shows a narrow-band image obtained with the Palomar Comic Web Imager. The extended nebula and filaments are likely illuminated by the nearby quasar. The streams, as indicted in the figure, extend out to  $\sim 160 - 230$  kpc. It was determined that this nebula/disk and filaments are well fit to a rotating disk model with are dark matter halo mass of  $\sim 10^{12.5}$  M<sub> $\odot$ </sub> with a circular velocity of  $\sim 350$  km s<sup>-1</sup> at the viral radius of 125 kpc (Martin et al., 2016). They further found that by adding gas accretion with velocities of 80 – 100 km s<sup>-1</sup> improved their kinematic model fit. Furthermore, they estimate the baryonic spin parameter is 3 times higher than that of the dark matter halo and has an orbital period of 1.9 Gyr. The high-angular momentum and the well fitted inflowing stable disk is consistent with the predictions of cold accretion from cosmological simulations (Stewart et al., 2011; Danovich et al., 2012; Stewart et al., 2016; Danovich et al., 2015; Stewart et al., 2013).

It is possible that we have direct evidence of cold accretion already, but it has yet to be observed and quantified for typical star-forming galaxies (which is much harder). These types of ultra-sensitive instruments will potentially allow us to directly image cosmic accretion in the near future.

# 7 Summary

Although we only have candidate detections of gas accretion, the community has provided a body of evidence indicating that cosmic accretion exists and is occurring over a large range of redshifts. Individual studies on their own are only suggestive that this accretion is occurring, but taking all the aforementioned aspects together does paint a nice picture of low metallicity gas accreting along co-planar co-rotating disk/filaments. The picture seems nice and simple but understanding how previously ejected gas is also recycled back onto the galaxy is also important since it can possibly mimic gas accretion signatures (Oppenheimer et al., 2012; Ford et al., 2014).

Simulations predict the cross-section of cold flows to be as low as 5% (Faucher-Giguère & Kereš, 2011; Fumagalli et al., 2011b; Kimm et al., 2011; Goerdt et al., 2012) and that the metal-poor cold flow streams signatures should be overwhelmed by the metal-rich outflows signatures detected in absorption spectra. However, signatures of inter-galactic cold gas accretion seem to be quite frequent. Thus, either the simulations are under-producing gas accretion cross-sections due to various reasons such as dust, resolution effects, self-shielding and/or magnetic fields, or the observations are selecting more than just outflowing and accreting gas. Trying to address how recycled winds fit into the picture, and understanding how we can differentiate them from gas accretion, will possibly aide in resolving this issue. It is great to see however, how the simulations and observations have been working together in our community to try and understand the gas cycles of galaxies.

Gas Accretion in Star-Forming Galaxies

Aside from observing accretion directly, the way forward now is to combine geometry, kinematics and metallicity at a range of epochs to try to understand how gas accretion occurs. Hopefully in the near future, we will be able to directly image gas accretion, putting to rest one of the most debated issues in the circumgalactic field.

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