THE DIRECT DETECTION OF COOL, METAL-ENRICHED GAS ACCRETION ONTO GALAXIES AT z ∼ 0.5

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ABSTRACT

We report on the discovery of cool gas inflow toward six star-forming galaxies with redshifts z ∼ 0.35–1. Analysis of Mg ii and Fe ii resonance-line absorption in Keck/LRIS spectroscopy of the galaxies reveals positive velocity shifts for cool gas of 80–200 km s−1 with respect to the host galaxy velocity centroids, and equivalent widths for this inflow of ≥0.6 A in five of the six objects. The host galaxies exhibit a wide range of star formation rates (SFRs ∼ 1–40 M⊙ yr−1) and have stellar masses similar to that of the Milky Way (log M∗/M⊙ ∼ 9.6–10.5). Imaging from the Hubble Space Telescope Advanced Camera for Surveys indicates that five of the six galaxies have highly inclined (i > 55°), disk-like morphologies. These data represent the first unambiguous detection of inflow into isolated, star-forming galaxies in the distant universe. We suggest that the inflow is due to the infall of enriched material from dwarf satellites and/or a galactic fountain within the galaxies. Assuming that the material has been enriched to 0.1 Z⊙ and has a physical extent approximately equal to that of the galaxies (implied by the high observed gas covering fractions), we infer mass inflow rates of dM/dt ≥ 0.2–3 M⊙ yr−1 for four of these systems. Finally, from comparison of these absorption lines to the profiles of Mg ii and Fe ii absorption in a larger spectroscopic sample of ∼100 objects, we measure a covering fraction of cool inflow of at least 6%, but cannot rule out the presence of enriched inflow on as many as ∼40 of these galaxies.

Key words: galaxies: evolution – galaxies: halos – galaxies: ISM – quasars: absorption lines

Online-only material: color figures

1. INTRODUCTION

The accretion of gas onto galaxies is regarded as a process fundamental to their formation (e.g., Rees & Ostriker 1977) and is required to reconcile the limited cool gas supply in galactic disks with the cosmic star formation history (Kennicutt 1983; Wong et al. 2004; Prochaska et al. 2005). Likewise, the star formation activity (∼1 M⊙ yr−1; Robitaille & Whitney 2010) in the inner Milky Way will consume the available gas on timescales ∼2 Gyr and can be maintained only if the local gas reservoir is replenished (Blitz 1996). Recent semi-analytic and cosmological hydrodynamic simulations (Benson et al. 2003; Kereš et al. 2005; Dekel & Birnboim 2006) suggest that the requisite baryons are delivered from the intergalactic medium (IGM) or low-mass satellites to high-redshift (z ≥ 2) galaxies via cool (temperature ∼103 K) filaments of dense gas. At z < 1, these filaments are truncated in massive halos, but accretion in the form of dense, cold clouds may persist.

In the Milky Way, the accretion of cool gaseous material in high velocity clouds (HVCs) such as the Magellanic Stream is observed directly in 21 cm emission at distances of 5–20 kpc (Wakker 2001; Lockman et al. 2008; Lehner & Howk 2011). Previously expelled material may be recycled to provide additional fuel for star formation (i.e., in a galactic fountain; Shapiro & Field 1976; Bregman 1980; Marasco et al. 2012) and likely gives rise to intermediate velocity clouds (IVCs) at distances <5 kpc (Wakker 2001; Bregman 2009). In addition, nearby spirals exhibit both extraplanar H i clouds and morphological disturbances which may be attributed to gas infall (Sancisi et al. 2008). However, the emission from these diffuse structures is difficult to map beyond ∼250 Mpc (Martin et al. 2010), and empirical evidence for gas accretion (or re-accretion) onto more distant galaxies is poignantly lacking.

Cool accreting gas which has been enriched to modest metallicities (i.e., Z ∼ 0.1 Z⊙) may give rise to absorption in background light sources in rest-frame ultraviolet transitions such as Mg ii λλ2796, 2803 or C iv λλ1548, 1550. However, studies of cool gas absorption along the sightlines toward star-forming galaxies have instead reported the ubiquity of outflows at z ∼ 1 (Weiner et al. 2009; Rubin et al. 2010; Steidel et al. 2010). In one of the only studies showing evidence for inflows in distant systems, Sato et al. (2009) reported redshifted Na i λλ5890, 5896 self-absorption in spectra of red, early-type objects, some of which exhibit line emission from active galactic nucleus (AGN) activity. Due to the low ionization potential of the Na i ion (5.1 eV), however, HVC analogs rarely exhibit column densities N_{Na i} > 10^{12.5} cm^{-2} (Ritcher et al. 2011). The moderate resolution and signal-to-noise (S/N) spectra of Sato et al. (2009) are therefore likely sensitive to N_{H i} ≥ 10^{20} cm^{-2} clouds, which are typically found near (within <5 kpc of) the Galactic disk (Wakker 2001; Richter et al. 2011). Le Floc’h et al. (2007), Coil et al. (2011), Ribaudo et al. (2011), Rauch et al. (2011), and Giavalisco et al. (2011) have also recently reported evidence for cool accretion primarily from absorption-line analysis, though the latter three detections are tentative (see also C. L. Martin et al. 2012, in preparation).

The lack of evidence for the inflow phenomenon is hardly surprising given that the predicted covering factor of accreting gas is small (e.g., < 10% at z ∼ 1.5; Fumagalli et al. 2011b). Further, studies of cool gas kinematics in galaxy spectra are likely to identify inflows only if they achieve S/N levels adequate for analysis of individual spectra, rather than co-added data. In this Letter, we report on S/N ∼ 6–11 pixel^{-1} Keck/LRIS spectra of a sample of six star-forming galaxies at 0.35 < z < 1 found to exhibit inflows traced by Mg ii and/or Fe ii λλ2586, 2600 absorption. We adopt a ΛCDM cosmology...
### Table 1

**Galaxy Properties and Inflow Measurements**

| Galaxy properties | TKRS3974 | TKRS4045 | TKRS4387 | EGS12027936 | J033249.53 | J033227.84 |
|-------------------|----------|----------|----------|--------------|------------|------------|
| Right ascension   | 12:37:01.65 | 12:36:39.70 | 12:36:54.99 | 14:19:26.49 | 03:32:49.52 | 03:32:27.83 |
| Declination       | +62:18:14.3 | +62:15:26.1 | +62:16:58.2 | +52:46:09.4 | −27:46:29.9 | −27:55:48.8 |
| z                 | 0.43708   | 0.37687   | 0.50334   | 1.03847     | 0.52313    | 0.66424    |
| M_d (mag)         | −20.08    | −19.79    | −20.54    | −21.34      | −20.37     | −20.68     |
| u − B (mag)       | 0.91      | 1.00      | 0.93      | 0.46        | 0.60       | 0.65        |
| R (kpc)           | 3.2       | 5.1       | 4.7       | 3.9         | 2.6        | 5.2         |
| R (arcsec)        | 0.6       | 1.0       | 0.8       | 0.5         | 0.4        | 0.7         |
| i (deg)           | 56.8      | 67.3      | 57.2      | 56.6        | 38.1       | 67.2        |
| SFR (M_⊙ yr⁻¹)    | 1.8⁺⁻⁰.₂ | 1.3⁺⁻⁰.₂ | 1.5⁺⁻⁰.₂ | 4.1⁺⁻⁰.₂   | 4.1⁺⁻⁰.₂   | 11.3⁺⁻⁰.₂  |
| log M_⋆/M_⊙       | 10.26⁺⁻⁰.⁹ | 10.30⁺⁻⁰.⁵ | 10.47⁺⁻⁰.⁶ | 10.14⁺⁻⁰.⁶ | 9.59⁺⁻⁰.⁵  | 9.83⁺⁻⁰.⁵  |

**Notes.** Galaxies are named according to ID numbers listed in With et al. (2004, TKRS), the AEGIS survey (Davis et al. 2007, EGS), and Giavalisco et al. (2004, J0332...). SFRs and M_⋆ are calculated by fitting model spectral energy distributions to the broadband photometry listed in Section 2 using the code MAGPHYS (da Cunha et al. 2008).

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2. **OBSERVATIONS**

Our galaxy sample is drawn from a larger, magnitude-limited (B_AB < 23) Keck/LIRIS survey of cool gas kinematics in 101 galaxies at redshifts 0.3 < z < 1.4 (K. H. R. Rubin et al. 2012, in preparation) located in fields imaged by the *Hubble Space Telescope* Advanced Camera for Surveys (HST/ACS; Giavalisco et al. 2004; Davis et al. 2007). We derive rest-frame magnitudes and colors from these data and complementary ground-based optical^4^ and near-IR photometry (Table 1; Barro et al. 2011; Kajisawa et al. 2011; Wuyts et al. 2008) using the code KCORRECT (Blanton & Roweis 2007).

We obtained spectroscopy of this sample using the Low Resolution Imaging Spectrometer (LIRIS) on Keck 1. We used 0.9 slitlets and collected between four and eight ∼1800 s exposures with FWHM ∼ 0.6–1.4 seeing between 2008 May 30 UT and 2009 April 3 UT. Our configuration of the two cameras with the 600/4000 grism, the 600/7500 grating, and the D560 dichroic provided FWHM ∼ 200–400 km s⁻¹ and wavelength coverage λ ∼ 3200–8000 Å. The data were reduced using the XIDL LowRedux^5^ data reduction pipeline.

An iron-clad detection of inflow toward (or outflow from) a galaxy hinges on a precise and accurate determination of

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^4^ http://www.cfht.hawaii.edu/Science/CFHTLS-DATA/

^5^ http://www.ucolick.org/~xavier/LowRedux/
the systemic velocity. We derived redshifts for the galaxies by calculating the best-fit lag between observed spectra and a linear combination of Sloan Digital Sky Survey (SDSS; York et al. 2000) galaxy eigenspectra. We prefer redshift measurements based on stellar absorption, as they trace better the systemic velocity of the associated ensemble of dark matter and stars. Therefore, where the stellar continuum S/N is adequate, we mask nebular emission lines in the data prior to redshift fitting. The median and standard deviation of the offset between redshifts measured with and without nebular emission masking are 7 km s\(^{-1}\) and 19 km s\(^{-1}\), although this offset exceeds 40 km s\(^{-1}\) in ∼6 objects (e.g., Rodrigues et al. 2012). For EGS12027936, we adopt the redshift measured by the DEEP2 survey (Davis et al. 2003). From a detailed analysis of our full LRIS sample, we find an rms redshift uncertainty of 28 km s\(^{-1}\).

Figure 1 demonstrates the results of the eigenspectra fits for two galaxies in our inflow sample. Note the offset of the nebular emission (∼50–60 km s\(^{-1}\)), which is indicative of a difference in the velocities and/or spatial distributions of stars and the interstellar medium (ISM) of these objects. Figure 2 presents images, Fe\(\text{II}\), and Mg\(\text{II}\) absorption spectra for the remaining “inflow” galaxies.

3. ABSORPTION-LINE ANALYSIS

To assess the signatures of cool gas outflow and inflow, we analyze the line profiles of the Mg\(\text{II}\) and Fe\(\text{II}\) transitions in our spectra (K. H. R. Rubin et al. 2012, in preparation). We
construct two distinct models: (1) a single-component model which assumes a Gaussian profile (parameterized by a centroid, column density $N$, and $b$-value) with a constant covering fraction $C_f$ independent of velocity; and (2) a two-component model with one component fixed at systemic and having $C_f = 1$ (fitting a uniform screen for ISM absorption) and the other described as above with a floating centroid (fitting inflowing or outflowing absorption).

We assume that the likelihood function is given by the $\chi^2$ distribution for the model, and sample the posterior probability density function (PPDF) using the Multiple-Try Metropolis Markov Chain Monte Carlo technique (Liu et al. 2000) as implemented in ROOT/RooFit, an object-oriented framework written in C++ (Brun & Rademakers 1997). Our code calculates the marginalized PPDF for each parameter and the equivalent width (EW) of the model absorption lines.

This analysis has been implemented for our full spectroscopic sample. While the majority of galaxies exhibit significantly blueshifted absorption indicative of outflows, the model fits for six galaxies indicate redshifted absorption with high probability. That is, >95% of the marginalized PPDF for the one-component model lies at >0 km s$^{-1}$ ($P_{\text{in,1}} > 0.95$) for both Mg $\text{II}$ and Fe $\text{II}$ profiles where coverage is available. Table 1 reports $P_{\text{in}}$ and the fitted velocity offsets ($\Delta v$), $C_f$, and EW for the one-component and two-component models, subscripted with “1” and “2,” respectively.

4. ANALYSIS OF THE GALAXIES

Figure 3 shows the rest-frame colors and magnitudes of our six inflow galaxies and the parent spectroscopic sample (K. H. R. Rubin et al. 2012, in preparation). The inflow and parent samples occupy similar areas of the diagram. Three inflow objects lie in the blue cloud and have star formation rates (SFRs) $\sim 10$–$40 M_\odot$ yr$^{-1}$ and stellar masses $M_* / M_\odot \sim 9.6$–$10.1$ (Table 1). The remaining (redder) objects have low SFRs ($1$–$2 M_\odot$ yr$^{-1}$) and lie between the red sequence and the blue cloud. These latter galaxies have disk-like rather than disturbed or early-type morphologies; their green colors likely result from enhanced dust reddening and their relatively modest SFRs, rather than the sudden cessation of star formation. Further, the $HST$/ACS imaging of these objects reveals several compact, star-forming knots in the outskirts of the galactic disks. Taken together, the stellar masses ($\log M_* / M_\odot \sim 10.3$–$10.5$), SFRs, optical colors, and morphologies of these three galaxies indicate that they are close analogs to the Milky Way, while the higher-SFR subset of the inflow sample has slightly lower stellar masses and more diffuse morphologies.

The distribution of inclinations measured from standard SExtractor analysis (Bertin & Arnouts 1996) among the parent spectroscopic sample is compared with that of the inflow sample on the right in Figure 3. All but one of the six inflow galaxies are highly inclined (having $i \gtrsim 60^\circ$). The Kolmogorov–Smirnov test indicates only a 1.1% probability that the inflow and parent populations are drawn from the same distribution. Five out of six inflow objects have inclinations close to (within $2^\circ$) or greater than the 54th-percentile value of inclination in the larger sample. This preferential detection of inflow toward more edge-on galactic disks suggests that inflow is more likely to occur near the plane of these disks.

5. DISCUSSION

We have discovered a sample of late-type, highly inclined, star-forming galaxies whose spectra show redshifted cool gas absorption. We interpret these kinematics as evidence for gaseous infall and discuss these findings in the context of galaxy formation models below, but first critique alternative explanations. If a galaxy’s motions are dominated by rotation, the ISM absorption may appear offset from the systemic velocity for an asymmetric gas distribution. Because this inflow sample is nearly edge-on, we are sensitive to velocity offsets in the direction of rotation. Weiner et al. (2006) analyzed line-emission in two-dimensional spectra of two of these objects, finding line-of-sight terminal rotation velocities of 64 km s$^{-1}$ and 176 km s$^{-1}$ for TKRS4045 and TKRS4387, respectively. In an extreme scenario in which all Mg $\text{II}$-absorbing ISM is located on only the receding side of these galaxies (such that $C_f \sim 0.5$),
it may appear to be offset in velocity by \(\sim 30\text{–}90 \text{ km s}^{-1}\) from the integrated stellar absorption. The majority of our measured inflow velocities are \(\Delta v_2 > 90 \text{ km s}^{-1}\), though TKRS4387 has \(\Delta v_2 \approx 125 \text{ km s}^{-1}\). However, given our velocity resolution and spectral S/N, we would be unlikely to detect such absorption unless it covered well over half (\(\gtrsim 70\%\)) of the galaxy continuum (i.e., the profile is sufficiently deep). A spurious inflow signature could additionally result from error in the galaxy systemic velocities due to, e.g., a spatial offset between our slitlets and the centroid of the stellar emission, such that the spectra are dominated by light from the approaching part of the disks. However, most of the galaxies have diameters \(<1.6\), and a 0\'9 slit width was used in \(\sim 1''\) seeing conditions; in addition, this scenario would yield an artificial inflow velocity of only \(\sim 30\) and 90 \text{ km s}^{-1}\) in the cases of TKRS4045 and TKRS4387. We therefore adopt the interpretation that the absorption arises from metal-enriched gas flowing toward each galaxy from the IGM, as part of an orbiting or accreting satellite (either prior to or during its final encounter), or from recycled wind material circulating in a galactic fountain.

At the most conservative level, the detection of six galaxies with inflows in a sample of 101 (with sufficient S/N) implies a rate of occurrence of such material of \(\approx 6\% \pm 2\%\). This estimate should be considered a firm lower limit, however. These six galaxies are unique not for the presence of strong absorption redward of systemic velocity, but instead for the absence of strong, blueshifted absorption. Figure 4 shows Mg II line profiles for one object in our inflow sample and three other objects drawn from the parent LRIS sample. A by-eye (analysis and our fitting results) suggests that profiles (a) and (b) exhibit outflows, i.e., an excess of absorption blueward of systemic velocity. Profile (c) is symmetric and dominated by absorption at systemic velocity. However, the profiles have similar Mg II \(\lambda 2803\) EWs (\(\gtrsim 1.3\) \AA) redward of systemic velocity, and thus could easily be tracing significant amounts of gas moving toward the host galaxies at \(> 100 \text{ km s}^{-1}\). The difference in the measured kinematics is due to the differences in EWs at systemic velocity and blueward; i.e., profiles (a)–(c) have blueward EWs at least 0.5 \AA\ larger than the profile from the inflow sample (d). We are therefore sensitive to inflows only in the absence of strong outflows and are likely missing instances of cool accretion in our larger parent sample.

For instance, the fraction of the parent sample with Fe II \(\lambda 2600\) or Mg II \(\lambda 2803\) EWs in the velocity range \(30 \text{ km s}^{-1} < v < 300 \text{ km s}^{-1}\) that are at least as large as those measured for our inflow sample (0.61 and 0.74 \AA, respectively) is 26\%–47\%. Furthermore, 23\% of the parent sample has Mg II \(\lambda 2803\) EW > 0.37 \AA\ in the velocity range \(150 \text{ km s}^{-1} < v < 300 \text{ km s}^{-1}\) (i.e., at least as large as the EWs for those inflow galaxies with \(P_{\text{in,2}} > 0.95\)). We therefore suspect the presence of inflow traced by saturated metal-line absorption in up to \(\gtrsim 40\%\) of our parent sample, and conservatively speculate that it is occurring in at least 20\% of the galaxies. Finally, the low frequency of detected inflows in individual spectra implies that the observed inflow signatures would be completely obscured in co-adds of the parent sample, similar to the composite spectra analyzed in Steidel et al. (2010).

Our observations provide almost no constraint on the distance between this inflowing gas and the galaxies or the spatial distribution of the gaseous material. However, the generally large model \(C_{f,2}\) values (\(\gtrsim 0.7\); Table 1) suggest that the material extends at minimum to sizes of order the size of the stellar disks. In cases with high values of \(P_{\text{in,2}}\), we use the derived velocities and column densities to estimate a mass inflow rate. We assume that the absorbing gas has a surface area \(\pi R^2\), where \(R\) is the average of the galaxy semimajor and semiminor axes, and that the gas will accrete onto the galaxies with a timescale \(R/\Delta v_2\). Neglecting ionization corrections, dust depletion, and assuming metallicities \(Z = 0.1 Z_\odot\), we find mass inflow rates \(\dot{M}_{\text{in}} / dt \sim 0.2 \sim 3 M_\odot \text{ yr}^{-1}\) (Table 1). The values are slightly lower than the SFRs of the low-SFR half of the sample, and an order of magnitude lower than the SFRs in the remaining galaxies. The inflow rates are also consistent with mass inflow rates derived for the Milky Way (0.8–1.4 \(M_\odot \text{ yr}^{-1}\); Lehner & Howk 2011).

Given the strength of the metal-line absorption and the low redshift of these systems, the observed inflows are unlikely to arise from the “cold flows” which are invoked to provide pristine hydrogen to star-forming galaxies from the IGM (Fumagalli et al. 2011b). Instead, this gas may have been enriched by star formation in satellite dwarf galaxies or may have already cycled through the host galaxy’s ISM. IVCs and HVCs in our own Galaxy could easily give rise to the inflow signatures observed in our sample, as they have a wide range of velocities (up to \(> 300 \text{ km s}^{-1}\)) and are mostly optically thick in H I.
with metallicities $\geq 0.1$ $Z_\odot$ (Wakker 2001). The cosmological hydrodynamic simulations of Oppenheimer et al. (2010) suggest that the recycling of gas blown out by winds is the dominant mode of accretion in halos with masses above $10^{11.2} M_\odot$ at $z \sim 0$, with recycling times $\ll 1$ Gyr. Further, detailed simulations of individual galaxy halos show that accretion occurs in the plane of the galactic disk, rather than along the minor axis (Stewart et al. 2011; Brook et al. 2011; B. Ménard & N. Murray 2012, in preparation). Winds vent out of the galaxy along the path with the lowest ambient gas pressure, i.e., out the galactic poles, or along the minor axis (e.g., Bordoloi et al. 2011), preventing accretion from occurring in locations other than along the disk plane. While we have not ruled out the presence of infall onto galaxies along their minor axes, results from these simulations are fully consistent with our detection of inflows along the line-of-sight toward several highly inclined, disk-dominated galaxies.

These results highlight the importance of analysis of cool gas kinematics in individual, distant galaxies. Only through examination of absorption-line profiles for a large sample of objects were a handful of examples of cool gas accretion, a process fundamental to galaxy formation, identified. At the same time, these spectra provide only a cursory view of the complexities of gas infall and recycling. Studies of gas kinematics at higher spectral resolution (e.g., Pettini et al. 2001; Dessauges-Zavadsky et al. 2010) and in large galaxy samples are needed to achieve tighter constraints on the frequency of inflows and the concurrent action of outflows and inflows. Equally propitious are studies of cool gas abundances along sightlines to background QSOs that may differentiate between pristine gas accreted from the IGM and material that has been previously recycled (Ribaudo et al. 2011; Fumagalli et al. 2011) and in large galaxy samples are needed to achieve tighter constraints on the frequency of inflows and the concurrent action of outflows and inflows. Equally propitious are studies of cool gas abundances along sightlines to background QSOs that may differentiate between pristine gas accreted from the IGM and material that has been previously recycled (Ribaudo et al. 2011; Fumagalli et al. 2011a). The combination of these experiments in studies of individual halos will in turn enable the simultaneous mapping of gas abundances and kinematics relative to the host galaxies. In concert with hydrodynamic simulations that track the accretion, expulsion, and recycling of gas, these observations will provide unprecedented insight into the processes regulating galaxy growth.

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