Discovery of multi-phase cold accretion in a massive galaxy at z=0.7

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ABSTRACT
We present detailed photo+collisional ionization models and kinematic models of the multi-phase absorbing gas, detected within the HST/COS, HST/STIS, and Keck/HIRES spectra of the background quasar TON 153, at 104 kpc along the projected minor axis of a star-forming spiral galaxy (z = 0.6610). Complementary g′r′i′Ks photometry and stellar population models indicate that the host galaxy is dominated by a ~ 4 Gyr stellar population with slightly greater than solar metallicity and has an estimated logM∗ = 11 and a logMvir = 13. Photoionization models of the low ionization absorption, (Mg i, Si i, Mg ii and C iii) which trace the bulk of the hydrogen, constrain the multi-component gas to be cold (logT = 3.8 – 5.2) and metal poor (~1.68 < [X/H] < ~1.64). A lagging halo model reproduces the low ionization absorption kinematics, suggesting gas coupled to the disk angular momentum, consistent with cold accretion mode material in simulations. The C iv and O vi absorption is best modeled in a separate collisionally ionized metal-poor (~2.50 < [X/H] < ~1.93) warm phase with logT = 5.3. Although their kinematics are consistent with a wind model, given the 2 – 2.5 dex difference between the galaxy stellar metallicity and the absorption metallicity indicates the gas cannot arise from galactic winds. We discuss and conclude that although the quasar sightline passes along the galaxy minor axis at projected distance of 0.3 virial radii, well inside its virial shock radius, the combination of the relative kinematics, temperatures, and relative metallicities indicated that the multi-phase absorbing gas arises from cold accretion around this massive galaxy. Our results appear to contradict recent interpretations that absorption probing the projected minor axis of a galaxy is sampling winds.

Key words: —galaxies: ISM, haloes —quasars: absorption lines.

1 INTRODUCTION
Over the last decade, simulations have shown that galaxy evolution is highly dependent on gas accretion occurring via two modes: hot and cold accretion. Current cosmological simulations demonstrate that the majority of gas accreted at early epochs onto galaxies occurs via the cold mode, which has temperatures of T ~ 10^4 – 10^5 K and metallicities of Z ~ 0.01Z⊙. Cold-mode gas is preferentially accreted along cosmic filaments/streams and have high densities and low cooling times providing a large supply of gas penetrating through hot halos surrounding galaxies (Kereš et al. 2005; Dekel & Birnboim 2006; Ocvirk et al. 2008; Kereš et al. 2008; Brooks et al. 2009; Dekel et al. 2009; Ceverino et al. 2010; Stewart et al. 2011a,b; van de Voort et al. 2011; van de Voort & Schaye 2011; Faucher-Giguère et al. 2011).

It is expected that cold accretion should comprise no more than 7% of the total H i mass density at z ~ 1 (Kacprzak & Churchill 2011).

It is further expected that cold accretion truncates when the host galaxy mass exceeds ~ 10^12 M⊙, since infalling gas becomes shock heated to the halo virial temperature (~ 10^6) and is predicted to dramatically reduce the cold accretion cross-section to a tiny fraction (e.g., Dekel & Birnboim 2006; Kereš et al. 2005; Ocvirk et al. 2008; Dekel et al. 2009; Kereš et al. 2009; Stewart et al. 2011a; Brooks et al. 2009; van de Voort et al. 2011; van de Voort & Schaye 2011; of the observed halo gas cross-section (Kacprzak et al. 2008; Chen et al. 2010). However, it is expected that these dense filaments can still survive within hot halos and could provide an efficient means of feeding massive galaxies with pristine gas (e.g. Kereš et al. 2005).

The study of absorbing foreground gas detected in background quasar spectra allows us to probe these otherwise unob-
sorbed comic filaments and outflows. Mg\textsc{ii} absorption is ideal
for detecting cold mode and hot mode accretion, wind outflows, etc., since it probes gas with a large range of neutral hydrogen column densities, \(10^{16} \leq N(\text{H}_1) \leq 10^{22} \text{ cm}^{-2}\) (Churchill et al. 2000a; Rigby, Charlton, & Churchill 2002) with gas temperature of around 30,000–40,000 K and average total hydrogen densities of \(\sim 0.1 \text{ atoms cm}^{-3}\) (Churchill, Vogt, & Charlton 2001; Ding, Charlton, & Churchill 2005). It has also been thoroughly demonstrated that Mg\textsc{ii} absorption is produced within gaseous halos surrounding galaxies and is not produced within the intergalactic medium (IGM) (see Churchill, Kacprzak, & Steidel 2005).

Over the last decade, strong Mg\textsc{ii} absorption has also been observed to directly trace 100–1000 km s\(^{-1}\) galactic-scale outflows ( Tremonti et al. 2007; Weiner et al. 2008; Martin & Bouche 2009; Rubin et al. 2010; Coil et al. 2011; Martin et al. 2012) that extend out to at least 50 kpc along the galaxy minor axis (Bordoloi et al. 2011; Bouche et al. 2011; Kacprzak et al. 2012). Galactic winds have been observed over a large range of redshifts and detected using a range of ions (see Steidel et al. 2010, and references therein). Correlations between galaxy colors and star formation rates with Mg\textsc{ii} equivalent widths also indirectly suggest that absorption is produced in outflows (Zibetti et al. 2007; Noterdaeme et al. 2011; Nestor et al. 2011).

However, Mg\textsc{ii} has been observed infalling (Martin et al. 2012) into highly inclined galaxies with velocities of 100–200 km s\(^{-1}\) (Rubin et al. 2011). This is consistent with Kacprzak et al. (2011b) who showed that absorption strength is correlated with the orientation of the galaxy major axis, implying that a significant fraction of weaker Mg\textsc{ii} absorption systems are likely accreting toward the galaxy via cold flows. The bimodal azimuthal angle distribution of quasar sight-lines around Mg\textsc{ii} absorption selected galaxies also suggests that infall occurs along the projected galaxy major axis (Bouche et al. 2011; Kacprzak et al. 2012). These cold-flow streams likely produce a circumgalactic co-rotating gas component that is predominately infalling towards the galaxy and, in absorption, these structures are expected to have \(\sim 100 \text{ km s}^{-1}\) velocity offsets relative to the host galaxy and in the same direction of galaxy rotation (Stewart et al. 2011b). These models are consistent with previous observations of Steidel et al. (2002) and Kacprzak et al. (2010a) that show Mg\textsc{ii} absorption residing fully to one side of the galaxy systemic velocity and usually aligned with expected galaxy rotation direction, with the absorption essentially mimicking the extension of the galaxy rotation curve out into the halo. We expect low ionization states, such as Mg\textsc{ii}, Mg\textsc{i}, Si\textsc{ii}, Cu and Cu\textsc{i} to be ideal for tracing cold mode accretion given metallicity, temperatures and densities expected.

A reliable means of determining the origins of the absorbing gas is to obtain both the host-galaxy and absorption-line metallicity. Absorption-line metallicities for a handful of systems have been determined to range between \([\text{M/H}] < -1.8 \text{ to } -1\) while existing near sub-L\(^{*}\) galaxies that have nearly solar metallicities (Zonak et al. 2004; Chen et al. 2005; Tripp et al. 2005; Cookeve et al. 2008; Kacprzak et al. 2010b; Ribaudo et al. 2011; Thom et al. 2011). It has been postulated that these extremely low metallicity absorption systems are likely accreting onto their host galaxies and possibly trace cold mode accretion, which is still expected for these sub-L\(^{*}\) galaxies. In the rare case where absorption-line metallicities are larger than the host galaxy is suggestive that the absorption is probing winds (Péroux et al. 2011).

Here we target a particular galaxy that has Mg\textsc{ii} absorption consistent with disk-like kinematics, possibly tracing cold accretion. The absorption also contains a separate warm phase as indicated by separate strong C\textsc{iv} absorption that does not coincide with Mg\textsc{ii}. We have obtained supplementary HST/COS data in order to determine the physical properties of the gas. In this paper, we perform kinematic and photo-collisional ionization models of multi-phase absorbing gas obtained from HST/COS, HST/STIS, and Keck/HIRES, which is associated with star-forming spiral galaxy at \(z = 0.6610\). In §2 we describe our targeted galaxy and our data. We discuss our absorption-line analysis in §3. In §4 we describe the host galaxy properties determined from broad-band photometry and stellar population models. In §5 we describe the results of our kinematics and photo-collisional ionization models and the physical properties of the absorbing gas. In §6 we discuss the possible origins of the absorption and our concluding remarks are in §7. Throughout we adopt an H\(_{0} = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}\), \(\Omega_{\text{m}} = 0.3\), \(\Omega_{\Lambda} = 0.7\) cosmology.

2 TARGET FIELD AND OBSERVATIONS

TON 153, also known as Q1317+227, is a bright (V = 16.0 mag) quasar at \(z_{\text{em}} = 1.017\). Inspection of a low resolution quasar spectrum revealed two Mg\textsc{ii} absorption systems at \(z_{\text{abs}} = 0.29\) and \(z_{\text{abs}} = 0.66\) (Steidel & Sargent 1992). Following a spectroscopic survey of galaxies in close angular proximity to the quasar sightline, Steidel et al. (2002) discovered galaxies G1 and G2 shown in Figure 1. The quiescent early-type galaxy G1 has a redshift of \(z_{\text{gal}} = 0.6719\) and the star-forming disk galaxy G2 has a redshift of \(z_{\text{gal}} = 0.6610\) (Churchill et al. 2007) demonstrated that G1 was associated with a Ly\(\alpha\) complex that did not have any observable metals even though it resides at \(D = 58.1 \text{ kpc}\); well within the 100 kpc where metals are expected (e.g., Chen et al. 2001; Kacprzak et al. 2008; Chen et al. 2010; Tumlinson et al. 2011). In a companion paper (Churchill et al. 2012b), we further discuss G1 and its associated absorption lines. The galaxy G2 is at \(D = 103.9 \text{ kpc}\) and is associated with extensive metal-line/LLS absorption at \(z_{\text{abs}} = 0.6601\) (Steidel & Sargent 1992; Bahcall et al. 1993; 1996; Churchill et al. 2004a; Ding, Charlton, & Churchill 2005; Churchill et al. 2007) and is the focus of this paper.

2.1 HST Imaging

In Figure 1 we present a 4700 second HST/WFPC–2 F702W image (PID 5984; PI Steidel) that was reduced using the WFPC-2 Associations Science Products Pipeline (WASPPI). Note that the F702W filter provides a bandpass similar to a rest-frame Johnson B-band filter for galaxies at \(z \sim 0.6\). Galaxy magnitudes and luminosities were obtained from Churchill et al. (2012a) and are based on the AB system. The GIM2D software Simard et al. (2005) was used to obtain quantified galaxy morphological parameters that were published in Kacprzak et al. (2011b) and Churchill et al. (2012a).

2.2 Ground-based Imaging

To further constrain the properties of G2, we analyzed multi-band \(g’r’i’\) and \(Ks\) imaging. The \(g’r’i’\)-bands were obtained using SPIcam CCD imager on the APO 3.5 m telescope. SPIcam has a field of view of \(4.78 \times 4.78\) and a spatial resolution of 0.14”/pixel. Our

\footnote{http://archive.stsci.edu/hst/wfpc2/pipeline.html}
observations were taken with on-chip binning of $2 \times 2$ which provides a plate scale of 0.28′′/pixel. The images were taken as part of a large survey program and were observed over 4 nights between March 2006 and March 2007 providing total exposure times in the $g',r'$ bands of 5190, 4630 and 4350 seconds, respectively, with typical seeing of 1.1 – 1.6′′.

Multiple frames were taken in each filter and each frame was individually reduced using standard IDL and IRAF packages. Pixel-to-pixel variations were removed using a combination of dome and twilight sky flat fields. Due to PSF/seeing variations over the long exposures, cosmic rays were removed from each frame separately. The SPIcam pixels are sufficiently small that interpolation errors do not lead to significant photometric uncertainties. The astrometry was calibrated by matching field stars from each frame to USNO A2.0 catalog stars.

The photometric zeropoints were established using a number of stars from the SDSS catalog. Since the APO images were part of an extensive Mg II galaxy survey of Steidel, Dickinson, & Persson (1994). The images were reduced using the contributed IRAF package DIMSUM. The photometric zeropoints were established using a number of stars from the 2MASS point-source catalog Skrutskie et al. (2006).

In Figure 1 we present a $g',r',Ks$ color composite image centered on TON 153 with galaxies G1 and G2 labeled. See companion paper Churchill et al. (2012b) for further discussions of the properties of G1. Note that all other objects near the quasar sight-line are red compared to the two $z \sim 0.65$ galaxies, indicating that all the other objects are likely at much higher redshifts and that G1 and G2 are likely isolated objects. Churchill et al. (2012b) noted that the ROSAT X-ray luminosity limit for this field is four orders of magnitude lower than what is expected for cluster centers and is consistent with the expected luminosity for early-type galaxy halos at $z = 0.67$. In addition, the absorption metallicities determined by Churchill et al. (2012b) for G1, and those found here, are $1-2$ dex lower than expected for inter-cluster medium. Thus, it is likely that the absorption does not arise in a cluster environment.

The galaxy G3 is located within ~1″ northeast of the quasar (G3) has not been successfully identified spectroscopically since the quasar is bright. Note the quasar sight-line passes near the minor axis of the moderately inclined disk of G2. — (top right) A Keck/LRIS spectrum of G1 containing Can H & K confirms the redshift of G1 to be $z_{\text{gal}} = 0.6719$. — (bottom left) A Keck/LRIS spectrum of G2 containing [O ii] emission confirms the redshift of G2 to be $z_{\text{gal}} = 0.6610$.

February 24 using the Kitt Peak 4-m Mayall telescope and the IRIM NICMOS 3 256 × 256 camera with 0.6′′/pixel. These images were part of a more extensive Mg II galaxy survey of Steidel, Dickinson, & Persson (1994). The images were reduced using the contributed IRAF package DIMSUM. The photometric zeropoints were established using a number of stars from the 2MASS point-source catalog Skrutskie et al. (2006).

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The galaxy G3 is located within ~1″ northeast of the quasar sight-line and has not been successfully identified spectroscopically since the quasar is bright. It is possible that this object is responsible for either the absorption associated with G1, G2, the $z = 0.29$ absorption system, absorption at the quasar redshift, or
Figure 2. — Metal absorption-lines associated with the $z = 0.6610$ galaxy G2 obtained from HST/COS, HST/STIS and Keck/HIRES. In each panel the transition and instrument are labeled. The absorption-line data (black) are relative to the systemic velocity of G2. The regions highlighted by the tick-marks (red) indicate the detected absorption features and the location of the tick-marks are defined to be where the equivalent width per resolution element recovers to a $1\sigma$ detection threshold. The sigma spectrum is shown below the data (green).

other metal-lines identified in this sight-line. If G3 is at $z = 0.67$, than Churchill et al. (2012b) estimates its mass to be a factor of ten less than the mass of G2 and would have a similar metallicity to G2 according to mass-gas metallicity relations (e.g., Savaglio et al. 2005). Thus, if G3 is at the same redshift of G2, it could be considered as a satellite of G2 and would occupy the same gaseous and dark matter halo.

Photometry for calibration and science was extracted using SExtractor (Bertin & Arnouts 1996) using the MAGAUTO measurements. Corrections for Galactic dust extinction were applied to the galaxies using the dust maps of Schlegel et al. (1998). We ob-
2.3 Galaxy Spectroscopy

The galaxies shown in Figure 1 were spectroscopically identified by Steidel et al. (2002) and their spectra were first presented in Churchill et al. (2005). A possible object seen within ~1" from the quasar seen in the image has not been successfully identified spectroscopically since the quasar is bright. The details of the Keck/LIRIS spectroscopic observations can be found in Steidel et al. (2002) and Churchill et al. (2007). The spectra are both vacuum and heliocentric velocity corrected. Galaxy G1, identified by C$\alpha$ H & K absorption yields a $v_{\text{rad}} = 0.6719$, is associated with broad Ly$\alpha$ complex that spans 1400 km s$^{-1}$ and yet contains only very weak metals lines (Churchill et al. 2007; Churchill et al. 2012b). Galaxy G2 was identified by a [O$\text{ii}$] emission line, placing it at $z_{\text{gal}} = 0.6610$. This galaxy is associated with extensive metal-line/LLS absorption at $z_{\text{abs}} = 0.6601$ (Bahcall et al. 1993, 1996; Churchil et al. 2000). Ding, Charlton, & Churchill (2005) and the data reduction details are found in Ding, Charlton, & Churchill (2005) and is the focus of this paper. We discuss G2’s associated metals-lines in the next sections.

2.4 Quasar Spectroscopy

Some of the $z_{\text{abs}} = 0.6601$ absorption properties were measured from a 3600 second Keck/HIRES ($R \sim 45,000$) exposure observed in 1995 January. The details of the observation and data reduction are described in Churchill & Vogt (2001). In addition, a 12,000 second HST/STIS E230M ($R \sim 30,000$) exposure was obtained (PID 8672; PI Churchill) and the data reduction details are found in Ding, Charlton, & Churchill (2005).

Recent HST/COS observations of the quasar ($R \sim 18,000$) were obtained using the FUV G160M grating and the NUV G185M grating (PID 11667; PI Churchill). The FUV observations were centered at 1600 Å and took place on 25 June 2010 with an exposure time of 12,580 seconds. The NUV observations consisted of two exposures that occurred on 26 May 2010 and were optimally co-added. The first 5420 second NUV exposure was centered at 1921 Å and the 4970 second NUV exposure was centered at 1941 Å. The COS spectra were reduced using the standard HST IRAF pipeline. All spectra are both vacuum and heliocentric velocity corrected.

It is important to note that the wavelength solutions across these multiple instruments are consistent at the sub-pixel level. This was verified across all spectrographs by centroiding common ionization absorption lines from the data presented here and the data from Churchill et al. (2012b).

Analysis of the absorption profiles was performed using interactive software (see Churchill et al. 1999, 2000; Churchill & Vogt 2001) for local continuum fitting, objective feature identification, and measuring absorption properties. Velocity widths and equivalent widths of the absorption systems are measured between the pixels where the equivalent width per resolution element recovers to the 1 $\sigma$ detection threshold (Churchill et al. 1999).

3 QUASAR ABSORPTION-LINE ANALYSIS

In Figure 2 we present the absorption-line data and in Table 1 we present the measured equivalent widths and column densities. We discuss below how the column densities and/or limits were computed for each transition. We further discuss how we account for higher redshift hydrogen-line blends that contaminate the OVI $\lambda$1032 and CIV $\lambda$977 transitions (see Figure 3).

The H$\alpha$ column density was adopted from Churchill et al. (2007), obtained by simultaneously fitting the Ly$\alpha$, Ly$\beta$, and Ly$\gamma$ Lyman break obtained from a FOS spectrum, was determined to be $\log[\text{N(H$\alpha$)}] = 18.3 \pm 0.3$. This is consistent with the results of Rao et al. (2006), who fit only the Ly$\alpha$ line, and determined the column density to be 18.57 $\pm$ 0.02. If we were to use the Rao et al value, our derived metallicities would decrease be 0.27 dex.

We also note upon analyzing the CIV $\lambda$1548, 1550 doublet, we have deemed the reddest component seen in the CIV $\lambda$1551 transition, at roughly 80 km s$^{-1}$, to be real and has been included in our analysis. This feature does not appear in the CIV $\lambda$1548 line since this region is contaminated by poor sky subtraction. This component was omitted by the analysis of Ding, Charlton, & Churchill (2005) but included here.

3.1 Accounting for Blends in OVI $\lambda$1032 and CIV $\lambda$977

Churchill et al. (2012b) performed detailed Voigt profile (VP) fits to the Lyman series, using the HST/COS spectra, in order to determine the gas-phase properties of the G1 absorption complex.
The VP fits were performed using our own software MINFIT [Churchill & Vogt 2001; Churchill, Vogt, & Charlton 2001]. The HST/COS instrumental line spread functions for the spectrograph settings, and also for the observed wavelength of each modeled transition, was computed by interpolating the on-line tabulated data [Dixon et al. 2010; Kris 2011]. Churchill et al. (2012b) determined that a portion of the G1 Lyβ complex was blended with the O vi λ1032 associated with G2, while a different portion of the G1 Lyγ complex was blended with Cniλ977 associated with G2 as shown in Figure 3 (the full Lyβ and Lyγ complex is not shown since it spans roughly 1400 km s⁻¹).

The VP fits of the O vi λ1032 blended portion of the Lyβ complex was well constrained by the non-blended Lyα, Lyγ, Lyε, and Lyζ lines. The VP fits of the Cniλ977 blended portion of the Lyγ complex was well constrained by the non-blended Lyα, Lyβ, Lyε, and Lyζ lines. We show the blended and deblended O vi λ1032 and Cni λ977 lines in Figure 3. Given that G1s hydrogen lines are unsaturated and can be well modeled using only the H i series, we are confident that we have a robust correction for the spectral shape of the O vi λ1032 and Cni λ977 lines. Furthermore, these corrections only effect regions redward of the galaxy systemic velocity.

### 3.2 Apparent Optical Depth Method

We employed the apparent optical depth method (AOD) to measure the column densities for each transition using the formalism of Savage & Sembach (1997) and Churchill & Vogt (2001). In the cases that multiple transitions of a given ion were measured, we computed the optimal weighted mean column density in each velocity bin. Since the weighted mean requires the inverse square of the uncertainties, in these cases we treated the non-normal distributions in the uncertainties of the optical depths using the quadratic model of D’Agostini (2000) and Barlow (2003). The quadratic model approximates the probability distribution of the asymmetric uncertainties in each optical depth data point by a parabola fit to the dimidiated Gaussian constructed from the upward and downward measured optical depth uncertainties. Relative to a treatment that neglects the non-normal distribution in the
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Figure 4. — The doublet optimally combined apparent optical depth distribution for Ovi (orange), C Iv (black) and MgII (red). The H i (blue) optical depth distribution was produced by combining the entire Lyman series. The total column densities are integrated over the velocity bins. Note that the H i is still saturated in the center of the profile. Also note the velocity structure difference between the profiles and that the majority of the hydrogen is at velocities consistent with the MgII whereas the majority of the C IV has velocities consistent with a small fraction of the total H i.

In Figure 4 we present the optimal column density distribution for each transition. The MgII, C IV, and OVI AOD distributions were computed using the doublet. For the C IV $\lambda$1548 line, we masked out pixels that were unusable as indicated by the two spikes in the sigma spectrum visible in Figure 2. Note the difference in the optical depth as a function of velocity of each transition, especially between MgII and C IV. We also employed the AOD method to compute the remaining column densities presented in Table 1.

Even though the Lyman series is saturated, we have optimally combined all the series lines to produce the H i column density distribution presented in Figure 4. Note that some central pixels are saturated and we therefore can not obtain a total column density, however, we can compute the H i column density over a range of velocity windows where there is no saturation.

3.3 Curve of Growth Analysis

We use the curve of growth analysis (COG) to determine the column density limits of various transitions of silicon and for MgII, MgI and Cu redward of the galaxy systemic velocity. The equivalent width limits quoted in Table 1 are $3\sigma$ limits for a unresolved single cloud. The single cloud assumption for silicon is motivated by the Si II $\lambda$1527 absorption-line, given that we would likely expect to detect the remaining silicon transition as a single cloud component consistent with the strongest MgII cloud located at roughly $-180 \text{ km s}^{-1}$.

The measured equivalent width limits are small and being on the linear part of the curve of growth implies that the column densities are mostly independent of the Doppler parameter ($b$). In fact, for $b > 5$, the predicted column density are independent of $b$. We find that the Si II column density is best constrained by the Si IV $\lambda$2515 data and the SiIV column density is best constrained by the SiIV $\lambda$1394 data.

There also exists HST/FOS spectra of this quasar that covers additional silicon transitions, among other metal-lines, however, we find that the equivalent widths were inconsistent with the predictions by the COG analysis; this was not the case for the STIS or COS data. We note that the FOS measurements published in Jannuzi et al. (1998); Churchill et al. (2000a) are plagued by unresolved blends from the other H I lines and therefore we do not use the FOS data in our analysis.

It is important to state that although the curve of growth analysis seems to systematically underestimate the column densities of the metal-lines Prochaska (2004), the silicon transitions do not provide sufficient constraints on our analysis and do not affect our results. We provide these column density measurements for completeness.
and is more massive. The model comparison suggests that G2 is dominated by a $\sim$ 4 Gyr stellar population with slightly greater than solar metallicity abundance and formed at redshift $z \sim 2$. We also note that G2 has an $[O\text{iii}]$ rest equivalent width of 3.0 Å, it is consistent with galaxies having $U - B > 1.0$ (Cooper et al. 2006), red galaxies with little-to-no star formation. Thus, the stellar population of G2 should be dominated by an older population as the model suggests. Adopting the K-band mass-to-light ratio associated with this stellar population model, we estimate the total stellar mass of G2 to be $M_\ast \sim 1 \times 10^{11} M_\odot$.

We further estimate the halo virial mass from the stellar mass using GalMass (Stewart 2011). GalMass uses abundance matching models from Moster et al. (2010) along with semi-empirical fits to observed galaxy gas fractions to convert between the stellar and gas mass described in (Stewart et al. 2009). There is roughly a 0.25 dex uncertainty in $M_{\text{vir}}$ at a fixed $M_\ast$ due to the systematics in estimates of $M_\ast$ (Behroozi, Conroy, & Wechsler 2010). The mean galaxy gas and baryonic masses are also estimated from Stewart et al. (2011a) who employed the baryonic Tully-Fisher relation (McGaugh 2005), the stellar, gas, and dynamical mass relation (Erb et al. 2006), and galaxy-gas fraction and stellar mass relation (Stewart et al. 2009). We estimate the halo virial mass, gas mass and baryonic mass to be log $M_{\text{vir}} = 12.9$, log $M_{\text{gas}} = 10.1$ log $M_\ast = 11.1$, respectfully.

5 RESULTS: ABSORPTION

From Figure 2 and Figure 4, it is clear that the absorption properties vary significantly as a function of ionization level. In Figure 6 we overlay selected transitions to further demonstrate this. It is clear that Mg ii and C ii (along with Si ii and Mg i) have similar kinematics and trace the bulk of the hydrogen. While C iv and O vi trace some of the same gas, their kinematics and their relative absorption strengths differ. Furthermore, they both exist where there are diffuse hydrogen column densities and no Mg ii absorption.

In the bottom panels of Figure 6 we show the AOD column densities as a function of the velocity for each transition. Note that the O vi follows similar abundances to C iv across the profile, while Mg ii and C ii differ and decrease toward the positive velocities. It appears quite clear that the kinematics and the abundance patterns show that C iv and O vi trace different phases of gas and this difference become greater redward of the galaxy systemic velocity where the hydrogen column density decreases by 2 dex.

Given the observed kinematic and abundance profile differences, we have broken the absorption regions into two separate components and model them independently. In Table I we list the total column densities for gas blueward, $N(X)^{\text{blue}}$, and redward, $N(X)^{\text{red}}$, of the galaxy systemic velocity. In the following subsections, we present models to explain the observed absorption kinematics and also apply photo-collisional ionization models to determine the origins and the physical properties of the gas.

5.1 Kinematic Models

Steidel et al. (2002) obtained the rotation curve for G2 and is represented in Figure 7. Note that all of the Mg ii, and the majority of the C ii, resides to one side of the galaxy systemic velocity. Churchill & Steidel (2003) noted that the C iv, and here we see the O vi, resides on both sides of the galaxy systemic velocity.

To explore the origins of the Mg ii absorption, Steidel et al. (2002) employed a simple lagging halo model that extended the galaxy rotation velocity out into a co-rotating gaseous disk/halo.
They determined that a lagging halo model can account all of Mg\textsc{ii} absorbing gas kinematics, even though the absorption occurs at $D = 103.9$ kpc. The predicted model velocities are highlighted by the hashed (blue) region below the galaxy rotation curve in Figure 7. Further note that the observed rotation curve does not go deep enough to reach the flat part of the curve. This implies there is additional/higher galaxy kinematics that were not included in the model, thus the vertical solid (blue) line on the left of the absorption profiles would move towards bluer velocities. It is quite clear that the low ionization gas seems coupled to the disk kinematics similar to the models of [Stewart et al. (2011b)]. However, the observed Mg\textsc{ii} absorption extends to larger $D$ than the models of [Stewart et al. (2011b)] since, at $z = 1.4$, their simulated disks extend only to ~40 kpc. Thus, it remains unclear if there is size evolution as a function of redshift or if the simulations (without metals) properly trace the metal-lines or if this is a result of simulating only a few galaxies. Aside from these caveats, the similarities between the observations and the simulations are suggestive that this absorption system exhibits signatures of cold mode accretion.

Note that the rotating disk model does not account for all of the absorption. Perhaps that given that the quasar line-of-sight passes along the minor axis of the galaxy and that G2 is undergoing some star-formation (indicated by the [O\textsc{ii}] emission shown in Figure 1), then it is possible that some of the absorption arises from outflows.

By analyzing $10 \ z \sim 0.1$ Mg\textsc{ii} absorbers selected from [Kacprzak et al. (2011a), Bouche et al. (2011)] found a bi-modal distribution of the azimuthal orientation of the quasar sight-lines: half of the sight-lines aligned with the major axis and half within $\alpha = 30$ degree of the minor axis. The bi-modal azimuthal angle distribution was later confirmed by [Kacprzak et al. (2012)] using a sample of 88 absorption-selected galaxies ($W_r(2796) \geq 0.1 \AA$) and 35 non-absorbing galaxies ($W_r(2796) < 0.1 \AA$). These results indicate that both gaseous disks and strong bipolar outflows could contribute to Mg\textsc{ii} cross-section. Bouche et al. (2011) also applied a simple bi-conical wind model that was able to reproduce the observed Mg\textsc{ii} kinematics for the sight-lines aligned with the minor axis. We apply their model here in an effort to reproduce the observed absorption kinematics. Their galactic wind model consists of $10^3$ "clouds" moving at a constant velocity ($V_{out}$) that is determined from the absorption data. The clouds are contained within a cone that has a 30 degree opening angle.

Figure 7 shows the wind model for G2 using the orientation parameters from [Kacprzak et al. (2011b)]. The top-left panel shows the cone view face-on and the top-right panel shows a side view of the cone, where the galaxy is represented as the filled ellipse and with the QSO line-of-sight marked. The bottom-left panel shows the average cloud line-of-sight velocities as a function of position within the wind. The QSO location is represented as the filled circle.

The wind model for G2 is applied to the Mg\textsc{ii}, C\textsc{iii}, and C\textsc{iv} absorption transitions where the hashed region (blue) shows the rotating thick disk modeled velocities, while the solid shading (red) indicates the wind model velocity predictions. Note that all of the Mg\textsc{ii}, and the majority of the C\textsc{iii}, resides to one side of the galaxy systemic velocity while C\textsc{iv}, and some O\textsc{vi} and C\textsc{iii} also resides redward of the galaxy systemic velocity. Figure 7 shows that an outflow velocity of 150 km s$^{-1}$ produces a good match to the data and comparable to the results found by Bouche et al. (2011). Note the peak of the density distribution coincides with the bulk of the C\textsc{iv} absorption.

By analyzing 10 $z \sim 0.1$ Mg\textsc{ii} absorbers selected from
the data and are comparable to the results found by Bouché et al. (2011).

In the lower-right panel, we see the predicted absorption distribution peaks at roughly 50 km s\(^{-1}\), where the majority of the C\(\text{iv}\) and some O\(\text{v}\) resides. The wind model velocity range is also shown as the solid shaded region over the absorption profiles. The model could also account for the observed C\(\text{iv}\) and O\(\text{v}\) blueward of the galaxy systemic velocity, although the model predicts only predicts of few percent of the gas is expected at these velocities.

If the opening angle or the wind speed is increased, the model velocity range would also increase and could include all of the observed absorption. However, increasing these parameters will not reproduce the observed optical depth distribution of the cold and hot gas. While our current model is tuned to reproduce the absorption reward of the galaxy systemic, a different model would not be able to predict the strong absorption residing at -200 km s\(^{-1}\). A model with increased opening angle and/or wind speed would also predict additional absorption beyond +200 km s\(^{-1}\) where none is observed. Therefore, it is very difficult to reproduce both the velocity and optical depth distributions of the cold and hot gas using only the wind model.

The wind model can not account for the bulk of the Mg\(\text{ii}\), Mg\(\text{i}\), Si\(\text{ii}\) and C\(\text{iii}\). Thus, although the galaxy is forming stars, winds are likely not responsible for the cool gas, but could be responsible for the hot gas. One would naively expect that the infalling gas would be metal poor while the outflowing gas to be metal enriched. We explore the gas-phase metallicities in the next subsections in order to determine the possible origins of the absorption.

5.2 Cold Gas Phase

To determine the physical properties of the cool gas blueward of the galaxy systemic velocity, we use Cloudy (Ferland et al. 1998) to model the ionization conditions. We follow the standard assumption of a photoionized uniform slab of gas that is in ionization equilibrium and is illuminated with a Haardt & Madau (2011) ionizing spectrum, where the UV photons arise from quasars and galaxies. The ionization parameters, \(U\), and the metallicity of the gas are varied to match the observations of \(N(X)\)\(^{\text{blue}}\) in Table 1 (column 6).

In Figure 8 we show the model results computed for \(\log[N(H)] = 18.3 \pm 0.3\) and a metallicity \([X/H] = -1.67\). We find a narrow range of ionization parameters that reproduce the cool gas phase. The thin curves show the models while the thicker curves show the model values permitted by the data. The C\(\text{iii}\) provides the tightest constraints on the ionization parameter of \(-3.25 \leq \log U \leq -3.21\). Less stringent constraints are also found from Si\(\text{ii}\) and Mg\(\text{ii}\) yields \(-3.38 \leq \log U \leq -3.16\).

In Figure 8 the same Cloudy models are shown as a function of \(U\) and metallicity. The constraints placed on \(U\) and the models confine the allowed range of metallicity. The C\(\text{iii}\) measurements limit the metallicity to \(-1.68 \leq [X/H] \leq -1.64\). Recall that the C\(\text{iii}\) column density measurement blueward of the galaxy systemic velocity is the unblended portion of this transition. If we were to include the small contribution of the C\(\text{iii}\) redward of the galaxy systemic velocity our results would still be consistent. The Si\(\text{ii}\) and Mg\(\text{ii}\) yields a less stringent of \(-1.73 \leq [X/H] \leq -1.63\). Thus, this cool gas component has low metallicity and a low ionization parameter.

In summary, the C\(\text{ii}\) column density provides the tightest constraint and yields a \(\log U = -3.23 \pm 0.2\) and \([X/H] = -1.66 \pm 0.02\). The gas is primarily ionized since the ionization fraction \(X(H) = N(H)/N(H) = 0.088 \pm 0.002\) with a hydrogen number den-
of the hydrogen column density. The solid line is the CIV/OVI column density ratio along with its measured error (dotted lines). The long and short dashed lines are the CIII/CIV and CIV/OVI column density ratio, respectively. The CIII/CIV and CIV/OVI dashed curves are lower limits on the allowed temperature range for a given hydrogen density. Note that full self consistency is when the dashed curves fall below the black curve. The gas has a hydrogen density of $n_H > 1.5$ and the CIV/OVI provides a temperature constraint of $\log T = 5.23 - 5.29$. — (bottom) The metallicity as a function of hydrogen density for various hydrogen column densities. We provide conservative limit of $\log n_H < -0.5$.

Figure 9. — (top) The photo-collisional ionization models (Churchill & Klimek 2012) as a function of temperature and hydrogen density. The lines indicate abundance ratios which are independent of the hydrogen column density. The solid line is the CIV/OVI column density ratio along with its measured error (dotted lines). The long and short dashed lines are the CIII/CIV and CIV/OVI column density ratio, respectively. The CIII/CIV and CIV/OVI dashed curves are lower limits on the allowed temperature range for a given hydrogen density. Note that full self consistency is when the dashed curves fall below the black curve. The gas has a hydrogen density of $n_H > 1.5$ and the CIV/OVI provides a temperature constraint of $\log T = 5.23 - 5.29$. — (bottom) The metallicity as a function of hydrogen density for various hydrogen column densities. We provide conservative limit of $\log n_H < -0.5$.

Figure 10. — The photo-collisional ionization models obtained from Churchill & Klimek (2012) as a function of temperature and column density normalized to $N$(CIV). The data points are the AOD measured column densities of absorption redward of G2’s systemic velocity, $N(x)^{mod}$, shown in Table 1 (column 8). We allowed the gas temperature and metallicity to vary for a range of hydrogen densities, $n_H$. The data constrain the gas temperature to be 185,000K and limits $\log n_H > -2.4$. In Figure 11 we provide the constraints on the warm phase metallicity.

5.3 Warm Gas Phase

We employed our own photo-collisional ionization code (Churchill & Klimek 2012) to model the warm gas phase since it is optimally designed for optically thin gas with no ionization structure. In short, the code incorporates photoionization, Auger ionization, direct collisional ionization, excitation-autoionization, photo-recombination, high/low temperature dielectronic recombination, charge transfer ionization by H+, and charge transfer recombination by HII and HeII. All metal transitions and ionization stages for elements up to zinc are modeled. Solar abundance mass fractions are obtained from Draine (2011) and Asplund et al. (2009) and a Haardt & Madau (2011) ionizing spectrum is used for the ultraviolet background. The model inputs are the hydrogen number density ($n_H$), kinetic temperature and the gas metallicity while the model outputs are the electron density, and the ionization and recombination rate coefficients, ionization fractions and the number densities for all ionic species. Our models are consistent with those of Cloudy for $\log(n_H) > -3.75$. For $\log(n_H) < -3.75$, these ions are not part of the cool gas phase and are likely part of a separate “warm/hot” collisional ionized gas phase. In Figure 6 note that the CIV and OVI have different kinematics that the lower ionization species further indicated that the absorption blueward of the galaxy systemic velocity is probing two gas phases. In the next section we model the warm gas.
Figure 11. — (left) The data points are the AOD measured column densities of absorption redward of G2’s systemic velocity, $N(x)^{aod}$, shown in Table 1 (column 8). — (middle) The photoionization models obtained from Churchill & Klimek (2012) for Ciii, Civi and Ovi using a fixed temperature of 185,000 K and $[X/H] = -2.3$. The spread in the models is due to the error in the measured Hi column density of log[N(Hi)]=16.03±0.18 (dotted lines). — (right) The allowed metallicity and $n_H$ for the model on the left. While $n_H$ is not well constrained, we find $-2.50 \leq [X/H] \leq -1.93$ and log$n_H > -3.3$ for the lower metallicity limit and log$n_H > -2.1$ for the upper metallicity limit.

5.3.1 Warm Gas Phase Blueward of Systemic Velocity

In modeling the cold gas phase we noted that we are unable to account for the measured log[N(Ciii)]=14.11 and the log[N(Ovi)]=14.33. Thus, these ions are not part of the cool gas phase and are likely part of a separate warm collisionally ionized gas phase. Here we model the diffuse warm gas found blueward of G2’s systemic velocity. Furthermore, all of the measured Ciii is well modeled as being associated with the cool gas phase, however, there could possibly exist a small fraction of a measurable warm Ciii component hidden. If we assume that the warm component is within the 0.2 dex measurement error of Ciii, then there can be at most log[N(Ciii)]<12.87 in the warm phase.

In Figure 9 we show column density ratios, which is independent of $N$(Hii), as a function of temperature and hydrogen density. The solid line is the Civi/Ovi column density ratio along with its measured error (dotted lines). The long and short dashed lines are the Ciii/Civi and Cii/Ovi column density ratios, respectively. The dashed curves are lower limits on the allowed temperature range for a given hydrogen density since log[N(Cii)]<12.87. Note that full self consistency is when the dashed curves fall below the solid curve. The models indicated that the gas has a hydrogen density of log$n_H > -3.5$ and the Civi/Ovi provides temperature constraints of log$T = 5.23 - 5.29$, where the exact temperature is dependent on $n_H$.

In Figure 9 we also show the gas metallicity as a function of $N$(Hii) and $n_H$. We are unable to measure the Hii column density associated with this warm component. However, Churchill et al. (2007) states that if an additional hydrogen component having log[N(Hii)] > 16.8 was added to the total hydrogen column density, then it would measurably modify the shape of the Lyman limit. Thus, this provides a conservative estimate of the additional $N$(Hii) that could be associated with the warm component since we assume it can not contribute to the Lyman limit. The column density limits provide a metallicity limit of $[X/H] \lesssim -0.5$. Note that the metallicity scales with hydrogen column density by the same amount. It is likely that the metallicity is much lower, though we can not provide any further constraints.

5.3.2 Warm Gas Phase Redward of Systemic Velocity

Here we model the diffuse warm gas found redward of G2’s systemic velocity. We allowed the gas temperature, the gas metallicity and the hydrogen density to vary to match the column density measurements, $N(X)^{aod}$, from Table 1 (column 8). We only detect Ciii, Civi and Ovi redward of the galaxy systemic velocity. The Hii associated with the warm gas phase was computed from the AOD Hii column density redward of the galaxy systemic velocity. As shown in Figure 10 the Hii absorption profile is not saturated redward of the galaxy systemic velocity and contains a log[N(Hii)]=16.03±0.18.

Figure 10 shows the models column densities normalized to that of Civi. The data are well constrained with the warm phase gas having a temperature of $T = 185,000$ K while there seems to be a larger range in the hydrogen density such that log$n_H \geq -2.4$ for a fixed metallicity. In order to accurately determine the range of metallicities and $n_H$, we show the predicted column densities and metallicities as a function of $n_H$ in Figure 11. Again, the measured (left) and modeled (middle) column densities are shown. The model spread, indicated by the dotted lines, is dominated by the error in the measured Hii column density. We find that the models do not well constrain the $n_H$ but provide reasonable constraints on the metallicity. We find $-2.50 \leq [X/H] \leq -1.93$ and log$n_H > -3.3$ for the lower metallicity limit and log$n_H > -2.1$ for the upper metallicity limit.
Clear from the fit residuals that the kinematics are not well modeled with similar velocity structure although they do have some similarities.

**Table 2. Modeled Absorbing Gas Properties**

| Name   | velocity [km s\(^{-1}\)] | log\(N\)\((H_i)\) | log\((T)\) | log\((U)\) | log\((\alpha_u)\) | \([X/H]\) |
|--------|--------------------------|-------------------|-----------|-----------|-----------------|----------|
| cold   | \(-240 < v_{\text{abs}} < -3\) | 18.3±0.3          | 3.82 – 5.23 | \(-3.25 < \log(U) < -3.21\) | \(-1.87 < \log(\alpha_u) < -1.83\) | \(-1.68 < [X/H] < -1.64\) |
| warm blue | \(-240 < v_{\text{abs}} < -3\) | <16.8\(^{a}\) | 5.23 – 5.29 | \(\log(U) > -3.5\) | \(\log(\alpha_u) > -3.5\) | \([X/H] < -0.5\) |
| warm red | \(-3 < v_{\text{abs}} < 220\) | 16.0±0.18         | 5.27      | \(\log(U) > -3.3\) | \(\log(\alpha_u) > -3.3\) | \(-2.50 < [X/H] < -1.93\) |

\(^{a}\) See text in Section 5.3.2 for a discussion of the \(N\)\((H_i)\) upper limit used and how that affects the absorption metallicity.

6 DISCUSSION

The galaxy G2 has a stellar metallicity greater than solar, yet it contains \([X/H] \sim -2\) halo gas detected in absorption at 104 kpc from the galaxy center. The data likely suggests that the absorbing gas is tracing cold accretion. A summary of the absorption gas properties is presented in Table 2. The kinematic difference seen between the high and low ionization states, as shown in Figure 6 and the photo-ionization ionization models suggest that the absorption is multi-phase. This may imply that the warm and cold gas physically arises in different locations or that the absorbing gas is not well mixed.

The quasar sight-line probes absorption within three degrees of the projected minor axis of G2 (Kacprzak et al. 2011b), which is a location recently interpreted to be favorable for probing galactic-scale winds (Bouché et al. 2011; Bordoloi et al. 2011; Kacprzak et al. 2012). G2 is dominated by a relatively old stellar population, yet it has measurable \([\text{O}]\) emission (3.0 Å) and thus is likely undergoing some current star-formation that could possibly produce winds.

In Figure 7 we show a wind model that can account for the bulk of the warm gas kinematics, both redward and blueward of G2’s systemic velocity, yet it does not reproduce the kinematics of the cold gas. This might imply that some of the warm gas could originate from winds, however, the 2 – 2.5 order of magnitude difference between the galaxy stellar metallicity and the absorption metallicity is inconsistent with a wind model (e.g., Oppenheimer et al. 2010). Assuming a constant wind speed of 150 km s\(^{-1}\), as suggested by the models, the absorbing gas would have left the galaxy 670 Myr ago. Given such a short time scale, G2 still expected to have solar metallicity at that epoch according to mass-gas metallicity relations (e.g., Savač et al. 2005) and simulations (e.g., Oppenheimer et al. 2010). The recycling for wind material is less than 1 Gyr (Oppenheimer et al. 2010), thus, if the gas were wind material and was well mixed, it would be expected to have a metallicity similar to that of the parent stellar population. However, the efficiency at which the gas is mixed within the halo environment is still unclear. Sijacki et al. (2011) shows that poor gas mixing in simulations may be an artifact the suppression of dynamical fluid instabilities demonstrated by comparing smooth particle hydrodynamics codes to that of the moving mesh code AREPO. However, some LLSs exhibit metallicity variations across the absorption profile (e.g., Prochter et al. 2010). Thus, if the gas probed by this absorption system is poorly mixed, it is plausible that the gas is entrained in an outflowing wind (see Alizas et al. 2012; Schaye et al. 2007). Although, the current observational evidence suggests that Mg\(_u\) entrained in outflowing material may,

on average, have a maximum projected extension of \(\sim 50\) kpc (Bordoloi et al. 2011). Thus, the combination of the low metallicity, the relative kinematics between the galaxy and the absorbing gas, and the large projected distance between the gas and the galaxy, corroborate an accretion scenario.

In summary, although the kinematic model works well for the warm gas, it is inconsistent with the expected outflow metallicities and this gas would have already been recycled several times and should have near solar metallicity. This leads to the idea that this meal poor gas could be infalling towards the galaxy.

Galaxy G2 has a stellar mass of \(M_\odot = 1 \times 10^{11} M_\odot\), and a viral mass of \(M_{\text{vir}} = 8 \times 10^{12} M_\odot\). Cold mode accretion is less favored for galaxies with \(M_{\text{vir}} \gtrsim 10^{12} M_\odot\) since the cold gas can become shock-heated as it enters the halo and hot mode accretion becomes the dominant mode of accretion (e.g., Dekel & Birnboim 2006; Kereš et al. 2009; Stewart et al. 2011a,b; Faucher-Giguère et al. 2011). For massive galaxies, infalling gas can be shock heated to temperatures above \(10^8\) K, however, accretion via dense filaments can be maintained past the shock regions, although have dramatically decreased covering fractions compared to low mass galaxies, and still accret onto the galaxy (e.g., Kereš et al. 2009; Stewart et al. 2011a,b; Faucher-Giguère et al. 2011; van de Voort & Schaye 2011). The hot gas pressure compresses cold streams and provides an efficient means of bringing cold pristine gas to the host galaxy and should be traced by LLSs (e.g., Fumagalli et al. 2011). A log \(N\)\((H_i)\) = 18.3 corresponds to \(\Delta p / p > 1000\) at \(z < 1\) (e.g., Davé et al. 1999) indicates that these high densities could make its way into the galaxy center.

Although massive galaxy halos are built up from hot accretion, comprising of \(80 \sim 90\%\) of the total accretion, it becomes less important for accretion on to the ISM (50 \sim 70\% hot mode) (van de Voort et al. 2011). However, van de Voort et al. (2011) states that the cold gas accreting onto the ISM in massive galaxies increases with increasing simulation resolution. This could arise since gas clouds could be easily disrupted in SPH simulations, and the cold fraction would increase if higher densities were reached in higher resolution simulations. A lower hot fraction of gas accreted onto the galaxy occurs because the hot gas temperature increases with the viral temperature, or halo mass, resulting in longer cooling times (e.g., Wiersma et al. 2009), and yielding less hot gas cooling to ISM temperatures. However these results could also be dependent on the type of simulations used (Sijacki et al. 2011).

Using the cosmological formulae for virial quantities of Bryan & Norman (1998), we derived the radius, \(R_{\text{vir}} = 380\) kpc, the circular velocity \(v_{\text{circ}} = 280\) km s\(^{-1}\) and the temperature, \(T_{\text{vir}} = 3 \times 10^6\) K. The quasar is probing along the minor axis of the galaxy within the viral radius at \(R/R_{\text{vir}} < 0.3\), well within the shock radius. Furthermore, the halo gas is expected to be heated to the virial temperature. The temperatures deduced from our models for the warm gas phase is \(1.8 \times 10^7\) K for gas blueward of the systemic velocity.
and $1.9 \times 10^5$ K for the gas redward of the galaxy systemic velocity: both are an order of magnitude cooler than that of the virial temperature. However, this gas can possibly cool after it had been shocked, although as mentioned above, the cooling time for hot shock-heated gas is much longer for massive galaxies.

We can estimate a cool gas phase temperature by using the Doppler parameters derived from Mg ii absorption [Kacprzak et al. 2011b]. The Mg ii Doppler parameters range from 2.1 – 10.8 km s$^{-1}$ and if we assume that all the broadening is thermal, we can compute upper limits on the temperature of $6.6 \times 10^3$ – $1.7 \times 10^5$ K. These temperatures are upper limits since some of the line-broadening could be due to turbulence, and the Voigt profiles fits to the data assume a minimum number of "clouds"; if more clouds were inserted, then the velocity width of each line would decrease. Thus, the cold gas has temperatures well expected for cold mode accretion and not post-shock heated cooling gas accreting within a virial radius ratio of 0.3 [van de Voort & Schaye 2011].

The absorption kinematics also hints to an origin of cold-mode accretion. The metal poor cold-phase, and redward warm-phase, has kinematics consistent with extended disk rotation [Kacprzak et al. 2010a; Steidel et al. 2002]. This result has been interpreted using cosmological simulations to be a signature of cold gas accreting via filaments that drive the angular momentum of the galaxy, thereby mimicking its rotation out at larger impact parameters [Kacprzak et al. 2010a; Stewart et al. 2011b]. This is consistent with van de Voort & Schaye (2011) that shows cold accretion gas having a higher radial velocities and scales with increases mass compared to the flat radial velocity distribution of the hot-mode accretion as a function of mass.

As we previously mentioned, the metallicities of the warm ($[X/H] = -2$ to $-2.5$) and cold ($[X/H] = -1.7$) gas are low and appear to be consistent with metallicities expected for cold-mode accretion at $R/R_{vir} \sim 0.3$ [van de Voort & Schaye 2011] and do not mimic the metallicities expected for the ISM, the hot halo, and the host galaxy (Oppenheimer et al. 2010). The temperatures and kinematics of the absorbing gas is also consistent with what is expected for cold-mode accretion. Thus, it is likely that the absorption is probing cold pristine gas infalling towards the center of the disk, further fueling star formation.

7 CONCLUSIONS

In this paper, we present detailed photo+collisional ionization models and kinematics models of the multi-phase absorbing gas, detected within the HST/COS, HST/STIS, and Keck/HIRES spectra of the background quasar TON 153, associated with star-forming spiral galaxy at $z = 0.661$. The sightline probes the projected minor axis of the galaxy at projected distance of 0.3 virial radii, well inside the virial shock radius predicted for a galaxy of this mass, implying that if the gas is infalling that it is post shock heated accretion or a cold filament. We obtained followup HST/COS data to study other metal-lines in order to determine the halo gas properties and their origins. This galaxy was targeted as a candidate cold accretion probe supported by kinematic and orientation results presented by Steidel et al. (2002); Kacprzak et al. (2010a; 2011b).

Our main results can be summarized as follows:

(i) From $g^\prime r^\prime K_s$ photometry and stellar population models, we determined that G2 is dominated by a ~ 4 Gyr stellar population with slightly greater than solar metallicity abundance and formed at redshift $z \sim 2$. We estimate an $M_e = 1 \times 10^{11}$ M$_\odot$ implying an log $M_{vir}$ = 12.9.

(ii) The low ionization states, Mg I, Si I, Mg II, and Cu I, have similar absorption kinematics, abundance ratios across the profile, and trace the bulk of the hydrogen, while CIV and OVI trace some of the same gas, their kinematics, abundance ratios, and their relative absorption strengths differ. We infer that the low and high ionization states trace different gas phases.

(iii) Modeling the cold gas blueward of G2’s systemic velocity, $N(X)^{blue}$, we constrain $log T = 3.82 – 5.23$, $-3.25 <log(U) < -3.21$, $-1.87 < log(n_e) < -1.83$, and $-1.68 < [X/H] < -1.64$. The gas is cold and very metal poor: consistent with cold accretion. We are unable to account for the measured N(C IV) and N(OVI) when modeling the cold phase, thus, these ions are likely part of a separate warm collisionally ionized gas phase.

(iv) A lagging halo model can account for all of low ionization absorption, hinting that this gas is coupled to the disk and simulations interpret this as a detection cold mode accretion.

(v) Modeling the warm gas blueward of G2’s systemic velocity, $N(X)^{blue}$, we find $n_e > 3.5$ and $log T = 5.23 – 5.29$. Armed with only a conservative limit of hydrogen column density that could be associated with the warm component $[N(H)] > 1.68$, we estimate $[X/H] < -0.5$, although it is highly likely that the metallicity is much lower.

(vi) Modeling the warm gas redward of G2’s systemic velocity, $N(X)^{red}$, we find hot and metal poor gas with $T = 185,000$ K, $-2.50 < [X/H] < -1.93$ and $n_e > 3.3$.

(vii) The quasar line-of-sight passes along G2’s minor axis and a wind model can account for the observed CIV and OVI redward and blueward of the galaxy systemic velocity. However, given the $2 – 2.5$ order of magnitude difference between the galaxy stellar metallicity and the absorption metallicity demonstrates the gas can not arise from galactic winds.

It remains plausible that this low metallicity gas arises from unidentified satellites around the host galaxy or from the incomplete mixing between metal enriched and metal poor halo gas. However, the combination of the relative kinematics, temperatures, and relative metallicities allows us to conclude that the multi-phase gas detected in absorption likely arises from cold accretion around this massive galaxy. For high mass galaxies the cold accretion cross-section is expected to be a few percent, so our absorption system and others cited in the literature could be a by-chance low probability intersection of a filament, or the resolution effects in the simulations (see van de Voort & Schaye 2011) are underestimating the coverage fraction of cold flows. This system also contradicts current results that predict that all absorption detected in quasars probing gas along the projected minor axis of galaxies is produced by winds (Bordoloi et al. 2011; Bouche & et al. 2013; Kacprzak et al. 2012). This is clearly not the case here.

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