Physical properties of galactic winds using background quasars

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ABSTRACT

Background quasars are potentially sensitive probes of galactic outflows provided that one can determine the origin of the absorbing material since both gaseous disks and strong bipolar outflows can contribute to the absorption cross-section. Using a dozen quasars passing near spectroscopically identified galaxies at $z \sim 0.1$, we find that the azimuthal orientation of the quasar sight-lines with strong Mg II absorption ($W_{\lambda 2796}$ > 0.3 Å) is bi-modal: about half of the Mg II sight-lines are aligned with the major axis and the other half are within $\alpha = 30^\circ$ of the minor axis, suggesting that bipolar outflows can contribute to the Mg II cross-section. This bi-modality is also present in the instantaneous star-formation rates (SFRs) of the hosts. For the sight-lines aligned along the minor axis, a simple bi-conical wind model is indeed able to reproduce the observed Mg II kinematics and the Mg II dependence with impact parameter $b$, ($W_{\lambda 2796} \propto b^{-1}$). Using our wind model, we can directly extract key wind properties such as the de-projected outflow speed $V_{out}$ of the cool material traced by Mg II and the outflow rates $M_{out}$. The outflow speeds $V_{out}$ are found to be 150-300 km s$^{-1}$, i.e. of the order of the circular velocity, and smaller than the escape velocity by a factor of $\sim 2$. The outflow rates $M_{out}$ are typically two to three times the instantaneous SFRs. Our results demonstrate how background quasars can be used to measure wind properties with high precision.

Key words: galaxies: evolution, galaxies: formation, galaxies: haloes, galaxies: intergalactic medium, galaxies: kinematics and dynamics, quasars: absorption lines

1 INTRODUCTION

In spite of our understanding of the growth of dark-matter structures from the initial density fluctuations (e.g. [White & Rees 1978; Mo & White 2002]), the halo mass function over-predicts the observed number density of galaxies both at the low- and high-mass ends of the mass function (e.g. Croton et al. 2006; van den Bosch et al. 2007; Conroy & Wechsler 2009; Behroozi et al. 2010; Moster et al. 2010; Guo et al. 2010; Firmani & Avila-Reese 2010 and references therein). This major discrepancy requires a (or several) mechanism to somehow suppress galaxy formation.

Super-novae (SN) driven winds are often invoked because they could suppress star formation in low-mass galaxies ($L < L^*$), (e.g. Dekel & Silk 1986; Oppenheimer & Davé 2006; Oppenheimer et al. 2010) and transport large amounts of energy and gas out of young galaxies and enrich the inter-galactic medium (IGM). This scenario is supported by the fact that galactic winds are ubiquitous in all types of star-forming galaxies: in local starburst galaxies (e.g. Lehnert & Heckman 1996; Heckman et al. 2000; Strickland & Stevens 2000; Strickland et al. 2004; Martin 1998; Martin et al. 2002; Schwartz et al. 2006), in extreme starbursts, such as the Ultra Luminous Infra-Red galaxies (ULIRGs) (e.g. [Martin 2005; Kupke et al. 2005; Martin 2006; Martin & Bouche 2009], and in normal star-forming galaxies both at intermediate (Sato et al. 2009; Weiner et al. 2009; Rubin et al. 2010a,b) and high-redshifts (Pettini et al. 2002c; Shapley et al. 2003; Genzel et al. 2011).

Numerical simulations must often invoke strong galactic outflows in order to reproduce the luminosity function and the enrichment of the IGM (e.g. Oppenheimer & Davé 2006; Oppenheimer et al. 2010; Schaye et al. 2010; Wiersma et al. 2011). These simula-
tions must, however, postulate scaling relations for the wind speeds and outflow rates, etc., in order to reproduce observational constraints. For instance, Davé and collaborators assume that the outflow rate, $M_{\text{out}}$, is proportional to the SFR ($M_{\text{out}} = \eta SFR$), where the loading factor $\eta$ is a function of halo mass. For momentum- (or energy-) driven winds, $\eta$ is proportional to $V_c^{-1}$ (or $V_c^{-2}$), respectively.

Unfortunately, most wind properties (e.g. the opening angle, the outflow rates, the loading factors) are poorly constrained. The best estimates of $M_{\text{out}}$ made by several groups over the past decades (e.g. Heckman et al. 1990, 2000; Pettini et al. 2002b; Martin et al. 2002; Martin 2005) using galaxy absorption line spectroscopy are usually uncertain by orders of magnitude. One reason for these large uncertainties is that one must estimate the total gas column in the wind from the ion column density which requires assumptions for the gas metallicity and the ionization factor. Another reason is that traditional spectroscopy (e.g. Lehnert & Heckman 1996; Heckman et al. 2000; Martin 1998; Kupke et al. 2005; Martin 2006; Schwartz et al. 2006; Weiner et al. 2009; Rubin et al. 2010a,b) probes the wind looking ‘down-the-barrel’, i.e. it provides no information on the physical location of the material, as the blue-shifted material could be located at 0.1, 1 or 10 kpc from the host. In addition, the wind geometry is unknown and as a result the wind-shifted material could be located at 0.1, 1 or 10 kpc from the host.

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The radial extent of the wind can be addressed directly with background galaxies, as demonstrated by Steidel et al. (2010) at $z \sim 2$, and by Bordoloi et al. (2011) at $z \sim 1$. However, apart from exceptional cases (e.g. Rubin et al. 2010a), one must stack the spectra of dozens or hundreds of background galaxies in order to gain sufficient signal-to-noise. This stacking inevitably leads to averages in the geometries involved (Steidel et al. 2010). But when sufficiently large samples are available, the azimuthal dependence can be revealed, as demonstrated by Bordoloi et al. (2011) who showed that the rest-frame Mg II equivalent width of background galaxies is strongest along the minor axis.

One can also use background quasars to probe the radial extent of the wind. Background quasars have several advantages to the other techniques. For instance, they allow us to probe gaseous material of any distant star-forming galaxy irrespective of its luminosity (in Stocke et al. 2004; Bowen et al. 2005; Tripp et al. 2005; Zych et al. 2007). Compared to background galaxies, background quasars are better probes because they require no stacking, i.e. the geometry of the absorbing flow is preserved and no loss of information occurs in azimuthal averages. Compared to galaxy absorption line spectroscopy, they allow us to probe the material at a known distance from the original source.

The low ionization Mg II doublet ($\lambda\lambda 2796, 2803$) seen in background quasars (QSOs) is ideal for probing galactic winds as it can be observed from $z \sim 0.1$ to $z \sim 2.2$ in the optical and has been associated mostly with star-forming galaxies since the work of Bergeron (1988), Bergeron & Boissé (1991), Steidel & Sargent (1994), Steidel et al. (1994). Unfortunately, the physical origin of strong absorbers is still debated. Indeed, Mg II absorbers could probe the cool ($T \sim 10^4$ K) material entrained in galactic winds (e.g. Nulsen et al. 1998; Schaye 2001; Martin 2006; Chleouche & Bowen 2010), the outskirts of gaseous disks (e.g. Prochaska & Wolfe 1997; Steidel et al. 2002; Kacprzak et al. 2010), the halos of galaxies (e.g. Bahcall & Spitzer 1969; Mo & Miralda-Escude 1996; Lanzetta & Bowen 1992; Sternberg et al. 2002; Maller & Bullock 2004), infalling material (e.g. Tinker & Chen 2008; Kacprzak et al. 2010; Stewart et al. 2011) or a combination of these mechanisms (e.g. Charlton & Churchell 1998). While mounting evidence points to galactic winds for strong Mg II systems (Bond et al. 2001; Bouèche et al. 2006; Ménard et al. 2011; Nestor et al. 2011), a direct link between low-ionization metal lines and galactic winds has yet to be established.

The debate on the origin of strong Mg II absorbers arises because it is difficult to build large samples of individual quasar-galaxy pairs. Indeed, at low redshifts ($z < 0.1$), the frequency of such pairs is low (e.g. Bowen et al. 1995; Stocke et al. 2004; Bowen et al. 2005), and at high-redshifts it is time consuming to identify the galaxies associated with QSO absorption lines. Even though significant samples of quasar-galaxy pairs are available (e.g. Churchill et al. 1996; Chen et al. 2001; Noterdaeme et al. 2010; Chen et al. 2010b; Rao et al. 2011; Lovegrove & Simcoe 2011), there are only $19 \sim 0.5$-1 galaxy-quasar pairs where the host galaxy kinematics have been compared to the absorption kinematics (Steidel et al. 2011; Ellison et al. 2003; Chen et al. 2005; Kacprzak et al. 2010), excluding the 14 pairs of Bouèche et al. (2007) whose analysis is in progress.

In this paper, we use the unique sample of about a dozen $z \sim 0$ galaxy-Mg II pairs from Barton & Cooke (2009) and Kacprzak et al. (2011a) in order to investigate the relative orientations of the quasar lines-of-sight with respect to the host galaxy orientation. Section 2 summarizes the properties of the sample. We show in Section 3 that the sample is made of two classes of Mg II absorbers. In Section 4 we discuss the physical properties of galactic outflows for the sub-sample of pairs related to outflows. Finally, we discuss the implications of our results in Section 5.

Throughout, we use a ‘737’ cosmology, with $h = 0.7$, $\Omega_M = 0.3$, and $\Omega_L = 0.7$.

2 SAMPLE

A recent increase in blue sensitivity of the Keck Low Resolution Imaging Spectrograph (LRIS) opened a new redshift window and allows the detection of the Mg II doublet down to $z \sim 0.1$ as demonstrated by Barton & Cooke (2009). In combination with the spectroscopic completeness of the Sloan Digital Sky Survey (SDSS York et al. 2000) and Schneider et al. (2010) at that same redshift, one has the possibility to study large unbiased samples of nearby Mg II galaxy pairs. Barton & Cooke (2009) constructed such a sample designed to probe for the presence (or absence) of Mg II absorption in a well-understood, volume-limited spectroscopic survey of galaxies at $z \sim 0.11$ with luminosity $L_\ast \sim 0.5 \times L_\ast$. Out of the 20 sight-lines passing within $75 h^{-1}$ kpc of $z \sim 0.1$ luminous galaxies, six exhibit strong ($W_\lambda 2796 > 0.3$ A) Mg II absorption at the same redshift as the galaxy. Kacprzak et al. (2011a) extended this sample to 13 such galaxy-Mg II pairs using the same observational strategy.

This is the largest sample of quasar-galaxy pairs at $z \sim 0$, which has the advantage that follow-up observations are either available in the SDSS database or easy to obtain using 4-m or 8-m class telescopes. This strategy led Kacprzak et al. (2011a) to measure the rotation curves of the hosts using the Apache Point Observatory (APO) and present a detailed comparison between the galactic kinematics and the absorption kinematics. Hence, the galaxies in this sample have reliable systemic redshifts, a key aspect for our study.

The galaxy SFRs are computed using the Hα luminosities
measured from SDSS spectra using the formalism of Kewley & Dopita (2002) assuming a Salpeter (1955) initial mass function (IMF) and no intrinsic reddening. Due to the small angular size of the SDSS fiber apertures, the SFRs were scaled by the ratio of the $r$-band galaxy total counts to those contained within the SDSS fiber.

The sample of 13 galaxy-quasar pairs of Kacprzak et al. (2011a) is made of 11 quasars and 13 galaxies, two of which are associated with the same quasar line-of-sight. In this study, we kept only the galaxy with the smallest impact parameter, and were left with 11 unique galaxy-quasar pairs. Table 1 lists the observed properties of the sample, taken from Kacprzak et al. (2011a).

Figure 1. Schematic diagram of an inclined disk, showing the relative azimuth angle $\alpha$ measured with respect to the galaxy major-axis.

Figure 2. The bimodal distribution of azimuth angle $|\alpha|$ for our sample made of 10 galaxy-quasar pairs where $\alpha$ could be determined. About half the sample has $|\alpha|$ less than 20 deg., and the other half has $|\alpha|$ $\geq$ 60 deg. The distribution suggests that extended gaseous disks and galactic winds contribute significantly to the Mg II cross-section if the quasars are preferentially aligned with the minor axis ($\alpha$ $\sim$ 90 deg.), since this is the only mechanism that can produce cool material systematically along the minor axis. Alternatively, one could conclude that the extended parts of gaseous disks, or infalling material (according to Stewart et al. 2011) would dominate the Mg II cross-section if the quasars are preferentially aligned with the galaxy orbital plane (e.g. Charlton & Churchill 1996). Furthermore, if there is no preferred $\alpha$, then this would point towards the halo model where the gas clouds traced by Mg II are uniformly distributed (e.g. Lanzetta & Bowen 1992; Steidel et al. 1994; Mg & Miralda-Escudé 1996; Tinker & Chen 2008).

Looking at the relative distribution of QSO lines-of-sight has previously not been possible because of the low number of unbiased pairs whose kinematic axis is known. Indeed, to our knowledge, at $z$ $\sim$ 0 there exists only one such sample, the sample of 11 galaxy-quasar pairs of Kacprzak et al. (2011a), originally from the volume-limited survey of Barton & Cooke (2009).

We remeasured the azimuth angles because we noticed some inconsistencies in the $\alpha$’s reported by Kacprzak et al. (2011a). To do so, we measured the inclinations ($i$), position angles (PA) of the major axis and azimuth angles ($\alpha$) of the quasar using two methods: a visual inspection of the images and a parametric Sérsc (1963) fit to the SDSS postage stamp images. The inclination (via its axis ratio $b/a$), the Sérsc index, $n$, and the galaxy PA were fitted with custom routines, where the Sérsc profile is convolved with the image Point Spread Function (PSF). We note that our inclination measurements obtained from visual inspection (’Manual’), from our Sérsc fits (’Fit’) and from a full bulge-disk decomposition by Kacprzak et al. (2011a) agree well with each other. Table 2 lists the inclination and azimuth angle measurements.

We found that the inclinations can be reliably determined, as our fitted values are within 10% to those derived by Kacprzak et al. (2011a). On the other hand, we found that our azimuth angles differ significantly, and we attribute the difference to a mistake in the image orientation. We note that for one galaxy (J161940G1), its PA is poorly determined as it is observed almost perfectly face-on ($b/a$ $\sim$ 1.0), i.e. its major-axis PA and its azimuth angle is undefined. Hence, we are left with a sample of 10 galaxy-quasar pairs with reliable azimuth angles.

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3 RESULTS

3.1 Two classes of absorbers

As mentioned in the introduction, the physical mechanism (e.g. galactic winds, infalling gas, extended disks) that can produce Mg II absorption has been debated for decades. As discussed in Kacprzak et al. (2011b), if there are preferred kinematics and spatial distributions of Mg II absorbing gas relative to the host galaxies, then the absorption strengths would follow a predictable behavior as a function of galaxy orientation and/or relative orientation to the QSO sight-line, for instance.

Here, we investigate the distribution of the azimuth angle $\alpha$ of the quasar line-of-sight with respect to the galaxy major axis, as illustrated in Figure 1. By examining the azimuth angle distribution, one could conclude that galactic winds dominate the Mg II cross-section if the quasars are preferentially aligned with the minor axis ($\alpha$ $\sim$ 90 deg.), since this is the only mechanism that can produce cool material systematically along the minor axis. Alternatively, one could conclude that the extended parts of gaseous disks, or infalling material (according to Stewart et al. 2011) would dominate the Mg II cross-section if the quasars are preferentially aligned with the galaxy orbital plane (e.g. Charlton & Churchill 1996). Furthermore, if there is no preferred $\alpha$, then this would point towards the halo model where the gas clouds traced by Mg II are uniformly distributed (e.g. Lanzetta & Bowen 1992; Steidel et al. 1994; Mg & Miralda-Escudé 1996; Tinker & Chen 2008).

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Figure 2 shows the distribution of $|\alpha|$. The distribution is
strongly bi-modal, with a subset made of four galaxies with small $|\alpha|$’s and another made of six with $|\alpha| \sim 90$. In other words, the distribution shows that all the quasar-galaxy pairs are either nearly aligned with the major or with the minor axis. The lack of quasar-galaxy pairs with $\alpha$ between 20 and 60 deg is not consistent with small number statistics. Indeed, the probability of having no quasar-galaxy with $|\alpha|$ between $\sim 20$ and $\sim 60$ deg is 0.2% using 10$^6$ simulated samples (with $N_{\text{pairs}} = 10$) drawn from a uniform distribution $U(0, 90)$. Thus, the central gap in the distribution shown in Fig. 3 is significant at the $\gtrsim 3.0 - \sigma$ level.

In short, we found a strong azimuthal dependence in the presence of Mg$\text{\textsc{ii}}$, in good agreement with the results of Bordoloi et al. (2011) obtained at $z \sim 1$ in the Cosmological evolution Survey (COSMOS). In stacked spectra of background galaxies, Bordoloi et al. (2011) also found a strong azimuthal dependence of the total equivalent width of Mg$\text{\textsc{ii}}$. This exercise will show that the classification based on Mg$\text{\textsc{ii}}$ is strongly supported by our kinematic model. Table 2 lists the classifications.

Having identified two classes of absorbers, we searched for differences in the galaxy properties between the two sub-classes. In Figure 3, we show the galaxy postage stamp images and the quasar location relative to the galaxy major and minor axes. The red and blue squares show the relative QSO positions for the subsample with $|\alpha| > 60$ and $|\alpha| < 20$, respectively. We find no significant differences in the galaxy colors between the two subsamples. The most significant difference between the two is found in their SFR distribution. Figure 4 shows that galaxies with high $|\alpha|$ (classified as ‘windy’) have higher SFRs, while pairs with low $|\alpha|$’s (‘disky’) have lower SFRs. Note the kinematic modeling presented in section 3.2.1 will show that two galaxies are misclassified based solely on the azimuth angle $\alpha$ criterion.

3.2 The Mg$\text{\textsc{ii}}$ kinematics of the Wind sub-sample: Wind modeling

In light of the results presented in section 3.1, we postulate that the Mg$\text{\textsc{ii}}$ absorption is produced by material entrained in galactic winds for the sub-sample made of galaxy-quasar pairs aligned along the galaxy minor axis (with $|\alpha| \sim 90$). To test this hypothesis, we construct a simple bi-conical wind model aimed at reproducing the observed Mg$\text{\textsc{ii}}$ kinematics. Our simple galactic wind model is made of 10$^6$ ‘clouds’ distributed in a cone within an opening-angle $\theta_{\text{max}}$ (and corresponding solid angle $\Omega_w = \pi \theta_{\text{max}}^2 / 4$). The discrete clouds populate the cone from a minimum radius $R_{\text{min}} = 5$ kpc to a maximum radius $R_{\text{max}} \simeq 100$ kpc, covering the range of impact parameters. We assume that the clouds are entrained in the bi-conical wind and are moving at a constant velocity ($V_{\text{out}}$), which is the only model parameter fitted against the data.

All the parameters related to the geometry of the wind can be determined from the data. The wind opening angle is $\theta_{\text{max}} \sim 30$ deg according to the distribution of azimuth angles (Fig. 2) since no QSO-galaxy pairs are found beyond $\pm 30$ deg from the minor axis. The corresponding solid angle is thus of order unity with $\Omega_w \simeq 0.86$. Similarly, the relative geometric orientation of the wind with respect to the quasar line-of-sight is also given by the data. For all galaxy-quasar pairs, the galaxy inclination ($i$) and the relative orientation ($\alpha$) of the sight-line are set by the data. The only degree of freedom left is to choose whether the cone intercepted by the quasar sight-line is pointing either towards or away the observer. We adopt the convention that $x$, $y$ are the coordinates in the plane of the sky, with $x$ along the galaxy major axis and consequently, the $z$-axis along the quasar line-of-sight.

3.2.1 Notes on individual cases

Figure 3(a) shows an example of the wind model for the galaxy J081420G1 (towards the quasar SDSSJ081420.19+383408.3) whose inclination is $i \sim 35^\circ$, and azimuth angle is $|\alpha| \sim 80^\circ$. The top left panel shows the cone view face-on and the top right panel shows a side view of the cone. The solid-blue oval represents the inclined disk and the black circles represent the conical outflow. The bottom left shows the average $z$-velocities of the clouds as a function of position. The QSO location is represented as the filled ellipse.

3 After some experimentation, we found that a hollow cone with $\theta_{\text{min}} \sim 10^\circ$ performed somewhat better in reproducing the shape of the Mg$\text{\textsc{ii}}$ absorption profile. Note the kinematic results (absorption centroid and width) are completely insensitive to $\theta_{\text{min}}$. 

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Figure 4. SFR as a function of $|\alpha|$ shows that galaxies associated with bi-conical galactic winds (high $\alpha$) have higher SFRs than those with low $\alpha$'s. SFR are computed from the nebular emission lines in the SDSS spectra and scaled to take into account the SDSS fiber size. The kinematic modeling in section 3.2.1 show that two galaxies (J092300G1 and J114518G1) are misclassified based solely on the azimuth angle $\alpha$ criterion.
Figure 3. Position of the quasar line-of-sight distribution relative to the galaxy major axis (x-axis) and minor-axis (y-axis) for the galaxy-quasar pairs with high (a, circle symbols) and low (b, square symbols) azimuth angles $\alpha$. The size of the symbols is proportional to the rest-frame $W_{\lambda 2796}^r$. The postage stamp images show the color SDSS image of the associated galaxy. Blue point source objects with squares indicate the QSO location when visible within the field-of-view.
circle. The bottom right panel shows the line-of-sight velocity distribution of the clouds at the location of the quasar. The distribution is convolved with an instrumental resolution of ~ 150 km s\(^{-1}\), corresponding to the LRIS data of Kacprzak et al. (2011a). The LRIS spectra is shown in Figure 5(b). The pink (grey shaded) and blue (grey hatched) areas show the range of velocities accounted by our wind model and by the halo-disk model of Kacprzak et al. (2011a), respectively.

In this particular case, we choose the model where the cone is pointing away from the observer since the observed Mg\(\text{II}\) absorption is redshifted with respect to the galaxy systemic velocity (0 km s\(^{-1}\)). The wind speed \(V_{\text{out}}\) is tuned to match the observed velocity range. For this particular case, we find that \(V_{\text{out}}\sim 200\pm 25\) km s\(^{-1}\) produces a good match to the data.

Figure 7 shows the wind model for J091119G1 towards the quasar SDSSJ091119.16+031152.9. This sight-line has one with the highest impact parameter \((b = 71\) kpc). While the equivalent width is relatively small (\(W_{\lambda 2796} \sim 0.8\) Å), the absorption is spread over a very wide range of velocities (from -300 to 300 km s\(^{-1}\)). In addition, the galaxy is seen almost perfectly edge-on \((i \sim 80\)°). As a result, our constant \(V_{\text{out}}\) model requires a large wind speed of ~ 500 km s\(^{-1}\). We also note that the Mg\(\text{II}\) profile shows little or no absorption around \(V_{\text{sys}}\), which indicates either the absorbing material traces the edges of the cone or that this sight-line caught the wind as it stalls, in which case our assumption of pure radial wind velocities break down.

Figure 8 shows the wind model for J102819G1 towards the quasar SDSSJ102847.00+391800.4. The main difference with the previous example is that this galaxy is less inclined with \(i \sim 55\)°. As a result, the wind produces absorption only redward of the galaxy systemic velocity. Because of the large impact parameter \((b = 89\) h\(^{-1}\) kpc) of the quasar, we extended our wind model to \(R_{\text{max}} = 140\) h\(^{-1}\) kpc and the inferred radial wind speed is \(V_{\text{out}} \approx 300\) km s\(^{-1}\). Note that the observed velocity profile is rather well reproduced.

Figure 9 shows the wind model for J111850G1 towards SDSSJ111850.47+451601.4. This galaxy has SFR= 3.75 M\(_{\odot}\) yr\(^{-1}\), is less inclined with \(i \sim 30\)°, and the quasar impact parameter is \(b \sim 25\) kpc. As a result, this sight-line likely intercepts the wind and the disk at the same time, resulting in significant absorption at \(V_{\text{sys}}\). As a result, our model, which does not include a disk component, cannot reproduce the entire Mg\(\text{II}\) profile and the wind speed is less constrained. In fact, the disk model of Kacprzak et al. (2011a) can reproduce the kinematics not accounted by our wind model (blue hatched).

Figure 10 shows the wind model for J225036G1 towards SDSSJ225036.72+000759.4. This galaxy has a moderate SFR of 1.36 M\(_{\odot}\) yr\(^{-1}\), is highly inclined with \(i \sim 70\)° and the quasar impact parameter is \(b \sim 50\) h\(^{-1}\) kpc. The radial wind speed \(V_{\text{out}}\) is inferred to be ~ 200 km s\(^{-1}\). Given this geometric configuration with the inclination approaching 90°, the sight-line probes a wide range of velocities, a feature that is very consistent with the observed Mg\(\text{II}\) kinematics. Note also that the profile suggests that the cone is hollow, i.e. the Mg\(\text{II}\) absorption arise on the edges on the cone, which is the reason why we used \(R_{\text{min}} = 15\)° in this case.

We next discuss two pairs (J092300G1, J114518G1) whose classification based on \(\alpha\) was misleading once the global aspects of the geometry are taken into account. In particular, the sight-line towards SDSSJ092300.67+073108.2 has the lowest impact parameter \((b = 12\) kpc). Figure 10 reveals that the low impact parameter combined with the high galaxy inclination implies that the sight-line can intercept the other parts of the galaxy in spite of having a high azimuth angle \(|\alpha| = 82\)°. Hence, this galaxy-quasar pair is classified as `ambiguous'. Furthermore, the galaxy has a low SFR of 0.02 M\(_{\odot}\) yr\(^{-1}\), red colors and an early type morphology (Sérsic index of \(n \sim 5\)).

The other ambiguous case is J114518G1 towards SDSSJ114518.47+451601.4. This sight-line has a low \(\alpha\) of \(\sim 15\)°. However, the wind modeling (Figure 11) reveals that the sight-line can very well intercept the wind given the low galaxy inclination \((i \sim 30\)°) if the cone extends a bit beyond our canonical 30 deg to 40 deg. The wind model can account for the Mg\(\text{II}\) kinematics with an outflow speed of \(V_{\text{out}} \approx 125\) km s\(^{-1}\). In addition, the galaxy SFR is high with SFR= 2.59 M\(_{\odot}\) yr\(^{-1}\), blue colors and an exponential profile, which are additional reasons to consider this pair as a `wind' pair.

### 3.2 Summary of the Wind Modeling

In summary, we performed simple kinematic models for the quasar-galaxy pairs whose azimuth angles \(|\alpha|\) are close to 90°. Figures 5, 9 show that a simple geometric model can account surprisingly well for the observed Mg\(\text{II}\) kinematics of four out of five quasar-galaxy pairs classified as `windy' and for two other pairs initially classified as `disky' based on their \(\alpha\) measurement (see table 2). Conversely, the wind model is unable to account for the kinematics of the sight-lines with \(\alpha \sim 0\)° since they do not intercept the conical flow.

In addition, the disk-halo model of Kacprzak et al. (2011a), shown as the hatched areas in Figures 5, 9 has serious difficulties in reproducing the Mg\(\text{II}\) kinematics for the `wind' sub-sample since the projected disk velocities are approximately 0 km s\(^{-1}\) along the minor axis. However, in the case of J111850G1, our wind model cannot reproduce the entire Mg\(\text{II}\) profile but the disk model of Kacprzak et al. (2011a) can account for the extra component.

Quantitatively, our analysis reveals wind speeds \(V_{\text{out}}\) that are typically 100–300 km s\(^{-1}\) (listed in table 2), i.e. are on the order of the maximum circular speed \(V_{\text{circ}}\) determined from the rotation curves by Kacprzak et al. (2011a). Based on these results, we will investigate the wind properties in more detail in the next section 3.4.

### 3.3 Radial Dependence

Using the sub-sample of \(z \sim 0.1\) QSO-galaxy pairs that we associate with galactic outflows, we investigate the radial dependence of the Mg\(\text{II}\) absorption. Figure 12 shows the observed \(W_{\lambda 2796}\) (cyan circles) as a function of impact parameter \(b\). Because the \(W_{\lambda 2796}\) can be skewed due to the various inclination effects, we corrected the \(W_{\lambda 2796}\) (red circle) to a common inclination of \(i = 90\)°. The corrections are calculated by comparing the total number of clouds intercepted at the observed \(i\) to that number for \(i = 90\)°. The most significant correction is for J081420G1 (see Fig. 5) because that sight-line intercepts a small fraction of the cone compared to the edge-on situation.

For comparison, we show in Figure 12 the radial dependence of the cool halo gas from the \(z \sim 0.5\) sample of QSO-galaxy pairs collected and analyzed in Kacprzak et al. (2007, 2011a) (squares). Since, the \(\alpha\) distribution is also bi-modal for this sample (Churchill et al. 2012, Bordoloi et al., 2012), we only show those with \(|\alpha| > 45\)° and whose uncertainty in \(\alpha\) is less than 30° (3\(\sigma\)) in order to remove ambiguous cases. Figure 12 shows that the \(z = 0\) and \(z = 0.5\) data sets share a common \(W_{\lambda 2796} - b\) relation which goes approximately as \(b^{-1}\). A formal linear fit to the data gives \(b = -1.1 \pm 0.5\).
Our radial dependence is significantly different that the one determined by Bordoloi et al. (2011) around of $z \sim 1$ inclined disks using background galaxies. However, we refrain from any direct comparison since the background galaxy technique used by Bordoloi et al. (2011) does not give a measure of the collective absorption of Mg II 'clouds', but gives a measure of the radial dependence of the covering fraction $C_f(r)$ because the background sources are naturally extended.

Given that there is an empirical relation between $W_{\lambda 2796}$ and the total column density $N_{\mathrm{H}1}$ (Ménard & Chelouche 2009), we show on the right $y$-axis of Figure 12 the corresponding column density $N$. The expected radial dependence of the column density $N(b)$ for an optically thin medium, whose density $\rho(r)$ is geometrically diluted \( \rho(r) = \rho_0 (r_0/r)^3 \), is

\[
N(b) \propto \int \frac{dr}{b^2 + x^2} \propto \frac{1}{b} \tag{1}
\]

where the integral is performed perpendicularly to the cone (Eq. 35). Eq. 1 shows that $N(b)$ is expected to go as $\propto b^{-1}$. The solid line in Figure 12 shows that this is a very good description of the data. The scatter around the solid is only 0.20 dex. The match between the data and the expected radial dependence may seem surprising given that Eq. 1 assumes an optically thin medium whereas the $W_{\lambda 2796}$ absorption may be optically thick. This can be understood if one realizes that the $W_{\lambda 2796}$ is also proportional to the number of sub-components or clouds (e.g. Bergeron & Boissé 1991; Churchill et al. 2003; Chelouche et al. 2008).

In summary, Figure 12 shows that, for QSO-galaxy pairs associated with galactic outflows, there is a tight correlation between $W_{\lambda 2796}$ and impact parameter $b$, following the expected $b^{-1}$ dependence. The scatter around $b^{-1}$ is very small, only 0.20 dex for this sub-sample. While this anti-correlation has been known for two decades (e.g. Lanzetta & Bowen 1990; Steidel 1995; Bouché et al. 2006; Chen & Tinker 2008), the scatter has been previously shown to be 0.5 dex (Chen et al. 2010a; Churchill et al. 2012).

Bordoloi et al. (2011b) argues that this scatter is a function of the host inclination, and Chen et al. (2010a) argues that this scatter is correlated with stellar mass and perhaps also with SFR (Chen et al. 2010b). In Appendix A, we discuss the $W_{\lambda 2796}$-$b$ relation for the 'disk' sub-sample and show that the large scatter is caused by the mixing of several physical mechanisms in Mg II samples, namely extended gaseous disks and galactic winds (see also Churchill et al. 2012; Bordoloi et al. 2012). It remains to be
Figure 6. a): Kinematic model of conical wind for J091119G1 as in Fig. 5. b): the observed Mg II kinematics with respect to the systemic velocity as in Fig. 5.

Figure 7. a): Kinematic model of conical wind for J102847G1 as in Fig. 5. b): the observed Mg II kinematics with respect to the systemic velocity as in Fig. 5.
Figure 8. a) Kinematic model of conical wind for J111850G1 as in Fig. 5. b): the observed Mg II kinematics with respect to the systemic velocity as in Fig. 5. Given the low inclination, this sight-line is likely contaminated by absorption from the disk. Indeed, the blue hatched area shows the disk-halo model of Kacprzak et al. (2011a).

Figure 9. a): Kinematic model of conical wind for J225036G1G1 as in Fig. 5. b): the observed Mg II kinematics with respect to the systemic velocity as in Fig. 5.
Figure 10. a) Kinematic model of conical wind for J092300G1 as in Fig. 5 b) the observed Mg II kinematics with respect to the systemic velocity as in Fig. 5.

Figure 11. Kinematic model (a) of conical wind for J114518G1 compared the observed Mg II kinematics (b) with respect to the systemic velocity as in Fig. 5.
demonstrated whether the stellar mass or SFR dependence applies to the ‘disk’ or ‘wind’ sub-sample.

4 EXTRACTING WIND PROPERTIES

Having established that the Mg II kinematics in QSO-galaxy pairs with $|\alpha| \sim 90^\circ$ are consistent with intercepting entrained material in galactic winds, in this section, we focus on the terminal velocity (§4.1) and the mass outflow rate (§4.2) of these galactic winds.

4.1 Terminal velocity

The cool gas in galactic winds traced by Mg II may be driven either by the kinetic energy of supernova ejecta from the entrainment in the hot wind (e.g. Chevalier & Clegg 1985; Heckman et al. 1990; Strickland & Stevens 2000), by momentum injection from the radiation pressure (Murray et al. 2005, 2011) or by cosmic ray pressure (Everett et al. 2008 and references therein). Because these predict different scalings for the wind velocity $V_{\text{out}}$ with galaxy mass and SFR, it is important to investigate whether $V_{\text{out}}$ varies with other galaxy properties.

In our sample of galaxies which have SFRs of a few $M_{\odot}$ yr$^{-1}$, we find that the outflow speeds $V_{\text{out}}$ are typically 100–300 km s$^{-1}$ (listed in Table 2) using the modeling presented in section 3.2. These relatively low speeds are of the order of the circular velocity $V_{\text{max}}$. We note that $V_{\text{out}}$ appears to increase with impact parameter. We caution that a larger sample is required in order to put strong constraints on $V_{\text{out}}(b)$, a function that is directly related to the acceleration mechanism in the wind (e.g. Murray et al. 2005, 2011).

Figure 12. $W_{\text{Ly}\alpha}$ as a function of impact parameter $b$ for QSO-galaxy pairs classified as ‘wind’, i.e. with $|\alpha| > 60$. The cyan circles represent the observed $W_{\text{Ly}\alpha}$, and the red circles show the $W_{\text{Ly}\alpha}$ corrected for inclination effects (see text), for the edge-on case where $i = 90^\circ$. The squares show the $z \sim 0.5$ QSO-galaxy pairs of Kacprzak et al. (2011a) for a similar sub-sample with the azimuth angle $\alpha > 45$. The expected radial dependence ($\propto b^{-1}$) for sight-lines intercepting a cone at $90^\circ$ is shown by the solid line and is a good description of these two data sets. The right y-axis shows the corresponding $N_{\text{H}1}$ using the $W_{\text{Ly}\alpha} - N_{\text{H}1}$ relation from Menard & Chelouche (2009) (MC09). The radial dependence of $N_{\text{H}1}$ is supported by the Mg II doublet ratio shown in the top panel.

Figure 13. Radial dependence of the outflow speed $V_{\text{out}}$ with respect to the escape velocity $V_{\text{esc}}(b)$. This shows that the cool material proved by Mg II is traveling at speeds $\lesssim V_{\text{esc}}$.

We find no correlation between $V_{\text{out}}$ and SFR. This could either be due (i) to our small range in SFRs or (ii) to our H$\alpha$-derived SFRs which may not be related to the SFRs that occurred when the material was launched given that the travel time to the observed impact parameter can be significant. Typically, the travel time is of the order of 0.5 Gyr (see Table 2).

Our measurements of outflow speeds allow us to address the following question: Are these velocities sufficient to expel the gas from the galaxy into the IGM or will the gas eventually fall back onto the galactic disk? The escape velocity $V_{\text{esc}}$ for an isothermal sphere is

$$V_{\text{esc}} = V_{\text{max}} \sqrt{2[1 + \ln(R_{\text{vir}}/r)]}$$

(2)

where $V_{\text{max}}$ is the maximum circular velocity (a proxy for $V_{\text{vir}}$) and $R_{\text{vir}}$ is the virial radius. Since our galaxies are L$^\ast$ galaxies with halo mass around $10^{12} M_{\odot}$, their virial radius is approximately $R_{\text{vir}} \equiv V_{\text{max}}/10H(z) \sim 250$ kpc, where $H(z)$ is the Hubble constant at redshift $z$. Using Eq (2) the escape velocity $V_{\text{esc}}$ is 2.5, 2.3, 1.8 times $V_{\text{out}}$ at $b = 10$, 50, 100 kpc, respectively. We find that most of our galaxies have wind speeds that are about half the escape velocity.

Figure 13 shows the outflow speeds relative to the escape velocity as a function of impact parameter $b$ for our sample of 6 sight-lines. We use the individual rotation velocities ($V_{\text{max}}$) from Kacprzak et al. (2011a) and appropriate virial radii in Eq (2). This ratio $V_{\text{out}}/V_{\text{esc}}$ is $\lesssim 1$ showing that the cool material probed by Mg II is traveling at speeds close to the escape velocity. Interestingly, the ratio $V_{\text{out}}/V_{\text{esc}}$ is about unity for only two sight-lines, which are the two with the largest impact parameter (J102847G1, J091119G1).

4.2 Outflow rates

Given that our $\alpha$ distribution combined with the results of Bordoloi et al. (2011) and Chen et al. (2010c) clearly demonstrate the presence of bi-conical outflows within $\theta_{\text{max}} \sim 30^\circ$ of the minor axis of star-forming galaxies, we can estimate the cold gas mass outflow rate corresponding to such a configuration. The outflow rate $\dot{M}_{\text{out}}$ for a mass-conserved flow moving at a speed $V_{\text{out}}$, with a total solid angle $\Omega_w$, is $\dot{M}_{\text{out}}(r) \equiv \rho(r) \Omega_w r^2 V_{\text{out}}$. In the case of a
radial sight-line looking ‘down-the-barrel’, the outflow rate reduces to $M_{\text{out}} = \frac{\Omega_0}{4\pi} \int_{r_0}^{\infty} \rho(r) dr = \rho(r_0) r_0$. Similarly, in the case of transverse sight-lines at impact parameter $b$ the outflow rate is:

$$M_{\text{out}}(b) \simeq \frac{\pi}{2} \theta_{\text{max}} N_{\text{HI}}(b) b V_{\text{out}}$$

as derived in Appendix B (Eq. B.8). Inserting the numerical values for $\theta_{\text{max}} \simeq 30^\circ$, we have

$$M_{\text{out}}(b) = 0.41 M_{\odot} \text{yr}^{-1} \frac{\Omega_0}{1.5} \frac{30^\circ}{\theta_{\text{max}}} \frac{N_{\text{HI}}(b)}{10^{19} \text{cm}^{-2}} \frac{V_{\text{out}}}{200 \text{ km s}^{-1}} \frac{b}{25 \text{ kpc}}$$

where $\mu$ is the mean atomic weight.

The only unknown parameter in Eq. 4 is the total gas column $N_{\text{HI}}$, since the impact parameter $b$ and the wind speeds $V_{\text{out}}$ are directly or indirectly constrained by the observations. Fortunately, we can estimate the mean H I column using the empirical Mg II–H I relation from Ménard & Chelouche (2009) (see also Rao et al. 2006, Bouché 2008, Rao et al. 2011) used already in Figure 12. Here, we make the implicit assumption that the relation holds for sight-lines associated with galactic winds. This assumption is supported by Bouché (2008) who reported that there are two populations of absorbers, one following the H I–$W_{\lambda 2796}$ relation (corresponding to outflows) with a high metallicity (half solar to solar), and another with roughly constant H I and a low metallicity (1/30) corresponding to typical DLAs/sub-DLAs. A direct determination of the gas column H I would require observations with the Cosmic Origin Spectrograph (COS).

The typical outflow rates derived from Eq. 4 are $\sim 1–5 \times 10^4 M_{\odot} \text{yr}^{-1}$ for all of these galaxies. The most precise outflow rates derived for star-forming galaxies for the cold ($T \sim 10^4$ K) gas $\alpha$ Indeed, the uncertainties in $M_{\text{out}}$ are entirely dominated by the $N_{\text{HI}}$ uncertainties. Assuming 0.25 dex uncertainty for $N_{\text{HI}}$, the relative accuracy for the outflow rate is $\sigma(M) / M \simeq 0.5$. Compared to traditional spectroscopy, where both $N_{\text{HI}}, \Omega_w$ are only known to orders of magnitude (e.g. Heckman et al. 2000, Pettini et al. 2002), our technique to estimate mass outflow rates is a leap forward.

Given that the travel time of the low-ionization gas to the observed impact parameters is significant, a few 100 Myr (see Table 2), we refrain from comparing our outflow rate to the instantaneous SFR. In future work, we intend to compare them to the past SFR determined from stellar population analysis. Overall, the cold gas mass outflow rate $M_{\text{out}}$ seems to be 2 times larger than the current SFR.

5 CONCLUSIONS

In summary, we find that the azimuthal orientation of quasars with Mg II absorbers ($W_{\lambda 2796} > 0.3 \text{Å}$) relative to the host galaxy major axis is not consistent with being uniform at the 3.1–$\sigma$ significance level. The azimuth angle distribution is bi-modal with about half the quasars aligned with the major axis and the other half within $\alpha = 30^\circ$ of the minor axis (Fig. 2). This bi-modal distribution confirms the presence of the azimuthal dependence of low-ionization gas around inclined disks as reported by Bordoloï et al. (2011) at $z \sim 1$ and by Chen et al. (2010c) at $z \sim 0$ and is inconsistent with the halo model of Chen & Tinker (2008), Tinker & Chen (2008) and Chen et al. (2010a).

We associate the sight-lines aligned with the minor axis to sight-lines intercepting bi-conical outflows (‘wind’ sub-sample) and those aligned with the major axis with sight-lines intercepting the outskirts of galaxies (‘disk’ sub-sample). The dichotomy in azimuth angle is also present in the instantaneous SFR (Fig. 4).

Using the ‘wind’ sub-sample, the data show that the outflows traced by low-ionization lines such as Mg II have several properties:

- The bi-modal distribution of the $\alpha$ angle (Fig. 2) shows that the outflows are rather well-collimated, covering a total solid angle $\Omega_w \simeq 2$ accounting for both sides of the cone.
- The wind speeds $V_{\text{out}}$ inferred from the Mg II absorption kinematics and a bi-conical wind model (Fig. 3) are of the order of the rotation speed.
- The wind speeds tend to be smaller than (or equal to) the escape velocity, indicating that the low-ionization gas is not escaping the halo.
- The radial dependence of the Mg II equivalent width follows approximately the expected $b^{-1}$ dependence for pure geometry dilution with a scatter of 0.24 dex (Fig. 12).
- The mass outflow rates are about $2 \times$ the current SFR, ranging from 1 to 6 $M_{\odot} \text{yr}^{-1}$ using the wind speed and the empirical relation between $W_{\lambda 2796}$ and $N_{\text{HI}}$ (e.g. Ménard & Chelouche 2009). Compared to the orders of magnitude uncertainties in the best estimates from galaxy spectroscopy (e.g. Heckman et al. 2000, Pettini et al. 2002a), our mass outflow rates are accurate to within $\sim 50\%$, where most of the uncertainty lies in the $N_{\text{HI}}$ factor.

In Appendix A, we show that our bi-conical outflows are consistent with the inclination dependence reported by Kacprzak et al. (2011b) if the azimuth angle is taken into account. In particular, the scatter in the $W_{\lambda 2796} - b$ relation is reduced (as in Kacprzak et al. 2011b) when a correction of the type $X \propto 1 / \cos^2 \alpha$ is applied to the ‘disk’ sub-sample. On the other hand, this correction increases the scatter for the ‘wind’ sub-sample, as one might have expected since this inclination correction is not appropriate in this case. Interestingly, $W_{\lambda 2796} - b$ relation appears to be much steeper ($\propto b^{-3}$) for the ‘disk’ sub-sample than for the ‘wind’ sub-sample ($\propto b^{-1}$) (see also Churchill et al. 2012).

Our results open a new and promising way to study the physical properties of galactic outflows at high-redshifts using quasar absorption lines. In the near future with larger samples, we will be able to investigate further the properties of galactic outflows. In particular, a larger sample will allow us to test whether the loading factor $\eta \equiv M_{\text{out}}/\text{SFR}$ is a function of circular velocity $V_{\text{circ}}$, as being assumed in numerical simulations by Oppenheimer et al. (2010) and others.

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APPENDIX A: THE KINEMATICS OF THE DISK SUB-SAMPLE

In the main body of this paper, we find that a significant fraction of the Mg II absorbers with $W_{\lambda 2796}^b$ from 0.5 to 3A are found along the minor axis, i.e. are not co-planar with the galaxy host. On the other hand, Kacprzak et al. (2011b) argued that Mg II absorbers are co-planar based on their finding that the disk inclination influences the scatter of the $W_{\lambda 2796}^b$ relation for a sample of $z \approx 0.5$ QSO-galaxy pairs. Thus, their results appear to be incompatible with our conical winds since they both apply to the same $W_{\lambda 2796}$ range of $0.5-3A$.

Here, we attempt to reconcile these two results. In particular, we return to the 'disk' sub-sample with $|\alpha| < 45^\circ$ since an inclination effect should be present predominantly for this sub-sample. For extended gaseous disks, we expect that $W_{\lambda 2796}^b$ is related to the path length $X$ intercepted by the QSO sight-line. Because there are only three pairs in the Barton & Cooke (2009) and Kacprzak et al. (2011a) sample that meet the $\alpha$ criteria, we include pairs from the $z \approx 0.5$ Kacprzak et al. (2011b) sample using the same criteria ($|\alpha| < 45^\circ$), excluding pairs where the uncertainty in the azimuth angle is greater than 30° (3$\sigma$).

Figure A1(a) shows the $W_{\lambda 2796}^b$ as a function of impact parameter $b$ for the $z = 0.1$ ($z = 0.5$) QSO-galaxy pairs shown as the cyan circles (squares) respectively. The solid line shows a fiducial $b^{-3}$ radial dependence. The top panel shows that the residual scatter from this relation are $\sim 0.63$ dex.

For this 'disk' sub-sample, we expect that the absorption equivalent width of inclined disks, as stated in Kacprzak et al. (2011b). This exercise shows that, in some cases, the absorption is co-planar and coupled to the galaxy inclination (Kacprzak et al. 2011b). As stated in Kacprzak et al. (2011b), the absorbing material could also be tracing the accretion of baryons since according to Stewart et al. (2011) such infalling material is predominantly coupled to the galaxy angular momentum and might dominate the Mg II cross-section.

Conversely, for the 'wind' sub-sample presented in section 5, the same path-length correction should not apply and as a consequence it should increase the scatter in the $W_{\lambda 2796}^b$ relation. Figure A2 shows the $W_{\lambda 2796}^b$ relation for the 'wind' sub-sample uncorrected (left) and corrected for the disk path length (right). This figure shows that the scatter increases from 0.24 dex to 0.4 dex and demonstrates that the $X$ path-length is not applicable to this subset of Mg II absorbers. Hence, our bi-polar outflows and the conical winds since they both apply to the same $W_{\lambda 2796}$ range of $0.5-3A$. 
Table 1. Summary for galaxy-QSO pairs.

| QSO             | $z_{\text{abs}}$ | Galaxy  | $z_{\text{em}}$ | W$_\alpha$ (Å) | $M_r$ | $V_{\text{max}}$ sin i | SFR$_{H\alpha}$ (M$_\odot$ yr$^{-1}$) | $b$ (9) | Ref. (10) |
|-----------------|-----------------|---------|-----------------|----------------|------|-----------------------|---------------------------------|--------|----------|
| J081420G1       | 0.1346          | J005244G1 | 0.1342          | 1.46/1.23      | -21.40 | 144                  | 0.05                            | 32.4   | K11      |
| J091119G1       | 0.0983          | J081420G1 | 0.0980          | 0.57/0.28      | -20.13 | 131                  | 1.27                            | 51.1   | K11      |
| J091119G1       | 0.0963          | J091119G1 | 0.0961          | 0.82/0.34      | -20.98 | 231                  | 0.26                            | 71.2   | K11      |
| J091230G1       | 0.1042          | J092300G1 | 0.1038          | 2.25/1.40      | -21.58 | 108                  | 0.02                            | 11.9   | K11      |
| J110284G1       | 0.1141          | J110284G1 | 0.1134          | 0.30/0.13      | -20.22 | 162                  | 3.75                            | 89.8   | K11      |
| J111158G1       | 0.1315          | J111850G1 | 0.1315          | 1.93/1.82      | -20.40 | 116                  | 1.96                            | 25.1   | K11      |
| J111451G1       | 0.1340          | J1114G1  | 0.1339          | 1.06/1.07      | -21.21 | 162                  | 2.59                            | 39.4   | K11      |
| J1114G1         | 0.1043          | J1114G1  | 0.1045           | 1.59/1.25     | -21.58 | 67                   | 0.15                            | 29.1   | K11      |
| J1114G1         | 0.1130          | J114033G1 | 0.11271        | 1.18/0.93      | -20.22 | 112                  | ···                              | 24.9   | K11      |
| J111640G1       | 0.1250          | J111640G1 | 0.12438        | 0.32/0.28      | -21.04 | 74                   | 0.06                            | 45.7   | K11      |
| J122503G1       | 0.1483          | J225036G1 | 0.1486          | 1.08/1.11      | -21.47 | 240                  | 1.36                            | 53.9   | K11      |

(1) Quasar name; (2) Mg ii absorption redshift; (3) Galaxy name; (4) Galaxy spectroscopic redshift; (5) Equivalent widths for Mg ii7296 and 2803Å; (6) Absolute magnitude; (7) Observed rotation curve velocity (km s$^{-1}$); (8) SFR in M$_\odot$ yr$^{-1}$; (9) Impact parameter in kpc; (10) Reference: K11 is for Kaspar et al. (2011).

APPENDIX B: MASS OUTFLOW RATES

Given that we are using quasar absorption lines to determine mass outflow rates $M_{\text{out}}$ for the first time, we show all the steps in deriving the $M_{\text{out}}$ equation used in this paper (Eq. B1). In most general terms, the outflow rate $M_{\text{out}}$ for a fluid moving at a velocity $V$ through an area $\Omega$ is

$$M_{\text{out}}(r) = \int \int dA \rho(r) \mathbf{V} \cdot \mathbf{n},$$

where $\mathbf{n}$ is the normal to the surface. For a cone of opening angle $\theta_{\text{max}}$, the outflow speed is normal to $A$ in spherical coordinate, and this reduces to $M_{\text{out}} = \rho_0 r^2 V_{\text{out}} \Omega$, where $\Omega = 2\pi(1 - \cos \theta_{\text{max}})$. Because the gas column density of a radial sight-line is $N \equiv \int_0^r 4\pi r \rho(r) = \rho_0 r_0$ for a fluid obeying the continuity equation ($\rho(r) r^2 = $const), the outflow rate reduces to the trivial equation $M_{\text{out}} = N r_0 V_{\text{out}} \Omega$. 

In the case of a conical geometry, with a transverse sight-line at impact parameter $b$, the outflow rate reduces to a similar form $M_{\text{out}} \propto N(b) b V_{\text{out}}$.

For a transverse sight-line intercepting the symmetric $z$-axis at $b = b_z$ of a cone, the integral in Eq. [B1] is performed on the cross-section of the cone at $b_z$. Using $t$ as the radius on the cross-section A, the velocity $V_z$ normal to $A$ is $V_z = \mathbf{V} \cdot \mathbf{n} = V_{\text{out}} b_z \sqrt{b_z^2 + t^2}$. Hence, the outflow rate $M_{\text{out}}(b_z)$ is

$$M_{\text{out}}(b_z) = \rho_0 r_0^2 \int_0^{r_{\text{max}}} 2\pi r dt \int_0^{r_{\text{max}}} \frac{1}{b_z^2 + t^2} \frac{V_{\text{out}}}{\sqrt{b_z^2 + t^2}} = \rho_0 r_0^2 2\pi b_z V_{\text{out}} \int_0^{r_{\text{max}}} dt \frac{t}{(b_z^2 + t^2)^{3/2}},$$

where $r_{\text{max}}$ is the maximum radius at which the cone intersects the sight-line. This integral is performed as shown in Fig. B1 and Eq. [B1].

Table 2. PA and $|\alpha|$ measurements.

| Galaxy | $\alpha$ | $\beta$ | PA | $|\alpha|$ | Class | $g - r$ | $V_{\text{out}}$ (km s$^{-1}$) | $M_{\text{out}}$ (M$_\odot$ yr$^{-1}$) | $t_w$ (Myr) | Ref. |
|--------|---------|--------|----|----------|-------|--------|-----------------------------|-----------------------------|---------|-----|
| J081420G1 | 40±2   | 35±2   | 30/18±2 | 79/67±2 | Wind  | 1.27   | 0.57                         | 175±25                      | 2.2±1.1 | 290 |
| J091119G1 | 82±2   | 75±2   | -53±1 | 65/63±1 | Wind  | 0.26   | 1.62                         | 500±100                     | 6.8±3.4 | 140 |
| J092300G1 | 56±2   | 41±1   | 20±2±2 | 82/84±2 | Ambig. | 0.02   | 1.2                         | 200(7)                      | 1.4±0.7 | n.a. |
| J110284G1 | 54±2   | 49±2   | 89/90±5 | 76/83±5 | Wind  | 3.75   | 0.57                         | 300±25                      | 1.0±0.5 | 250 |
| J111850G1 | 30±2   | 34±1   | 86/85±5 | 86/59±5 | Wind  | 1.96   | 0.8                          | 175±80                      | 6.0±3.0 | 140 |
| J225036G1 | 70±2   | 69±3   | 56/65±3 | 77/69±1 | Wind  | 1.36   | 1.1                          | 225±50                      | 2.2±1.1 | 250 |

(1) Galaxy name; (2) Galaxy inclination $i$ (degrees) from Kaspar et al. (2011) assuming a bulge+disk decomposition; (3) Galaxy inclination $\alpha$ (degrees) from a one component S´ersic fit; (4) Galaxy position angle (PA) (degrees) measured manually or from our 2D fits; (5) Azimuth angle $|\alpha|$ of the quasar with respect to the galaxy major axis; (6) Classification of the quasar-galaxy pair. ‘Wind’ refers to sight-lines whose Mg ii kinematics can be explained with our model. ‘Disk’ refers to sight-lines whose Mg ii kinematics are likely related to some other physical process taking place in connection with the major axis. (7) Instantaneous SFR in M$_\odot$ yr$^{-1}$ derived from Hα taken from Kaspar et al. (2011) assuming a Salpeter IMF and no reddening; (8) $g - r$ color; (9) Radial outflow speed in km s$^{-1}$ inferred from the Mg ii kinematics; (10) Mass outflow rates in M$_\odot$ yr$^{-1}$ derived from Eq. (11) Travel time in Myr from the galaxy to the observed impact parameter ($b/V_{\text{out}}$).
where \( t \) is bound to a maximum \( r_m = b_1 \tan \theta_{\text{max}} \) by the cone edge. After integration, we find

\[
M_{\text{out}}(b_1) = \rho_0 b_1^2 V_{\text{out}} 2 \pi [1 - \cos \theta_{\text{max}}] \tag{B4}
\]

The column density \( N(b) \) for a transverse sight-line intercepting the symmetric \( z \)-axis at \( b = b_1 \) is

\[
N(b) = \rho_0 \frac{r_y^2}{b} \int_{-x_1}^{x_1} \frac{1}{\sqrt{b^2 + b^2}} \, dx = \rho_0 \frac{r_y^2}{b} 2 \arctan \frac{x_1}{b} = \rho_0 \frac{r_y^2}{b} 2 \theta_{\text{max}} \tag{B5}
\]

since the opening angle \( \theta_{\text{max}} \) defines the integration range \( x_1 = b \tan \theta_{\text{max}} \).

In the most general case, for a transverse sight-line that is offset from the \( z \)-axis by \( b_y \), where \( x_1 = \sqrt{\tan^2 \theta_{\text{max}} b_y^2 - b_1^2} \) and \( b = \sqrt{b_y^2 + b_1^2} \), we have the column density \( N(b) \)

\[
N(b) = \rho_0 \frac{r_y^2}{b} 2 \arctan \frac{\sqrt{\tan^2 \theta_{\text{max}} b_y^2 - b_1^2}}{b_y^2 + b_1^2} \tag{B6}
\]

which reduces to Eq. (B5) when \( b_y = 0 \).

Combining Eq. (B4) with Eq. (B5) we have that the outflow rate

\[
W_{r}(b) = \rho_0 \frac{r_y^2}{b} 2 \theta_{\text{max}} \tag{B7}
\]
determined from transverse sight-lines is:

\[
\dot{M}_{\text{out}}(b) = \frac{N(b) b}{2\theta_{\text{max}}} V_{\text{out}} 2\pi [1 - \cos \theta_{\text{max}}] \quad (B7)
\]

\[
\simeq N(b) b V_{\text{out}} \frac{\pi}{2} \theta_{\text{max}} \quad (B8)
\]

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