Emergence of a Quasar Outflow

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ABSTRACT
We report the first discovery of the emergence of a high-velocity broad-line outflow in a luminous quasar, J105400.40+034801.2 at redshift z ~ 2.1. The outflow is evident in ultraviolet CIV and SiIV absorption lines with velocity shifts $v \sim 26,300$ km s$^{-1}$ and deblended widths FWHM $\sim 4000$ km s$^{-1}$. These features are marginally strong and broad enough to be considered broad absorption lines (BALs), but their large velocities exclude them from the standard BAL definition. The outflow lines appeared between two observations in the years 2002.18 and 2006.96. A third observation in 2008.48 showed the lines becoming $\sim 40\%$ weaker and $10\%$ to $15\%$ narrower. There is no evidence for acceleration or for any outflow gas at velocities $\lesssim 23,000$ km s$^{-1}$. The lines appear to be optically thick, with the absorber covering just $20\%$ of the quasar continuum source. This indicates a characteristic absorber size of $\sim 4 \times 10^{15}$ cm, but with a BAL-like total column density $\log N_H (\text{cm}^{-2}) \gtrsim 21.2$ and average space density $n_H \gtrsim 2 \times 10^5$ cm$^{-3}$. We attribute the emergence of the outflow lines to a substantial flow structure moving across our line of sight, possibly near the ragged edge of the main BAL flow or possibly related to the onset of a BAL evolutionary phase.

Key words: galaxies: active — quasars: general — quasars: absorption lines — quasars: individual: J105400.40+034801.2

1 INTRODUCTION
Accretion disk outflows are an important part of the quasar phenomenon. They are known to be present in at least 50% of optically-selected quasars (Hamann & Sabra 2004, Nestor et al. 2005, Ganguly & Brotherton 2005, Rodríguez Hidalgo et al. 2008). They might play a critical role in the accretion physics and in the observational properties of quasars, and they might expel enough metal-rich gas and kinetic energy to have a major impact on star formation and galaxy evolution in their surroundings (Kauffmann & Hachnelt 2000, Richards et al. 2004, Di Matteo et al. 2005, Everett 2005, Proga 2005). The outflows appear most conspicuously in quasar spectra as broad absorption lines (BALs), which typically have velocity widths of $5000$–$20,000$ km s$^{-1}$. However, there is also a variety of weaker and narrower outflow lines that are just as common as BALs. These include the so-called “mini”-BALs, which appear at velocities from near 0 to $\sim 0.2c$ with profile widths from the BAL range down to a few hundred km s$^{-1}$. Understanding the relationships between the various outflow lines is fundamental to our understanding of the outflows themselves. For example, in one scenario, the different line types represent different manifestations of a single outflow phenomenon viewed at different angles (Elvis 2000, Ganguly et al. 2001). Alternatively, they might represent an evolutionary sequence, where weak mini-BALs appear near the beginning or end of a more powerful BAL outflow phase (Hamann & Sabra 2004).

Variability studies can help test these ideas by providing constraints on the outflow dynamics, stability, location and basic physical properties. Recent studies have shown, for example, that mini-BALs tend to be more variable than the broader and stronger BALs (Gibson et al. 2003, Rodríguez Hidalgo et al. 2008, Capellupo et al. 2008). Approximately half of mini-BALs show significant variations on time scales from a few years to few months in the quasar rest-frame. In rare cases, weak mini-BALs become much stronger and broader like BALs, or they disappear altogether. Following the emergence of a quasar outflow...
would be particularly valuable, but we know almost nothing about such occurrences because variability programs start with quasars that are already known to have outflow lines. The only known case of an emerging BAL outflow was in a narrow line Seyfert 1 galaxy at redshift \( \sim 0.03 \) \cite{Leighly2005, Leighly2008}. The dramatic appearance of BALs in this object is surprising because it is much less luminous (by a factor of \( \gtrsim 100 \)) than typical BAL quasars.

In this paper, we report the first discovery of an emerging high-velocity BAL-like outflow in a luminous quasar, J105400.40+034801.2 at redshift \( \sim 2.1 \). We observed this quasar as part of a program to study metal-strong damped Ly\(\alpha\) (DLA) absorption systems \cite{Herbert-Fort2006, Kaplan2008}. Those data showed the new appearance of broad outflow lines compared to spectra obtained several years earlier by the Sloan Digital Sky Survey (SDSS).

In the sections below we discuss the observations (\S2), the measured properties of the outflow lines (\S3), and some theoretical implications of our results (\S4).

# 2 OBSERVATIONS

The Sloan Digital Sky Survey (SDSS) obtained the first high-quality spectrum of J105400.40+034801.2 on 5 March 2002 (2002.18). We retrieved the fully reduced spectrum from the SDSS archives, Data Release 6. This spectrum covers wavelengths from 3805 Å to 9210 Å at resolution \( R \equiv \lambda/\Delta\lambda \approx 2000 \) (150 km s\(^{-1}\)). The absolute fluxes measured through a \( \sim 3'' \) aperture fiber are expected to be accurate to within a few percent \cite{Adelman-McCarthy2003}. The emission line redshift and the blue and red magnitudes reported by the SDSS are \( z_{\text{em}} = 2.095 \), \( g = 18.11 \) and \( r = 17.98 \), respectively. We also note that this quasar is radio-quiet based on the absence of the FIRST radio survey \cite{Becker1995}.

We observed J105400.40+034801.2 on 16 December 2006 (2006.96) using the Multi-Mirrored Telescope (MMT) Spectrograph in the blue channel with the 800 groove/mm grating. Combined with a 1.5'' wide slit, this setup provided wavelength coverage from 3090 Å to 5095 Å at resolution \( R \approx 1370 \) (220 km s\(^{-1}\)). The exposure time was 720 s. After noticing the broad outflow lines in the MMT data, we obtained another spectrum on 30 May 2008 (2008.48) using the Low Resolution Imaging Spectrograph (LRIS) at the Keck Observatory. In this case, a 600 groove/mm grating blazed at 6000 Å and a 1'' entrance slit provided wavelength coverage from 3105 Å to 5600 Å at resolution \( R \approx 1000 \) (300 km s\(^{-1}\)). The total exposure time was 400 s. The observations at the MMT and Keck were both performed with the slit at the parallactic angle. The spectra were extracted and processed by standard techniques using the Low Redux Pipeline\(^1\) software package. The relative fluxes were calibrated using spectrophotometric standards observed on the same night. The absolute fluxes have uncertainties up to 50%.

# 3 RESULTS

Figure 1 shows the three spectra obtained in 2002.18 (SDSS), 2006.96 (MMT) and 2008.41 (Keck). The wavelengths in the quasar rest frame are based on \( z_{\text{em}} = 2.095 \) reported by the SDSS. The vertical flux scale in the figure applies to the SDSS spectrum. The other spectra are scaled vertically to match the SDSS fluxes at continuum wavelengths. The SDSS and MMT spectra are shown after smoothing for easier display. This smoothing has no effect on the appearance of broad features like the outflow lines and the broad emission lines (BELs).

Broad high-velocity outflow lines are clearly present in Si\(\text{iv}\) \( \lambda\lambda 1394,1403 \) and C\(\text{iv}\) \( \lambda\lambda 1548,1551 \) in the 2006.96 and 2008.48 spectra. They appeared in \( \lesssim 1.54\text{ yr (rest frame)} \) between the 2002.18 and 2006.96 observations, and then they weakened again 0.47 years later in the 2008.48 measurement. Meanwhile, the BEL profiles and equivalent widths (including Ly\(\alpha\) and C\text{iii}\) \( \lambda \lambda 1909 \) not shown in Fig. 1) varied by \( \lesssim 5\% \). The discovery spectrum of J105400.40+034801.2 obtained in 1988.15 \cite{Clowes1994} is much noisier and has a lower resolution \( (R \sim 400) \) than the data shown in Figure 1. Outflow lines like the ones measured in 2006.96 would probably not be detectable in those data. However, the 1988.15 spectrum does rule out the presence of broad absorption features with \( \sim 2 \) or more times the strength of the lines in 2006.96. No other outflow lines in the broad outflow system are detected in any of the data. The 2006.96 and 2008.48 spectra both have a depression at the position of N\(\text{v}\) \( \lambda\lambda 1239,1243 \) that is consistent with the broad absorption in C\(\text{iv}\) and Si\(\text{iv}\). However, we cannot confirm the reality of this feature because the spectra at those wavelengths are severely contaminated by Ly\(\alpha\) forest lines.

To measure the outflow lines quantitatively, we define a "pseudo"-continuum across the true quasar continuum and the tops of the BELs. This pseudo-continuum matches the 2008.48 spectrum except at the wavelengths of the broad absorption, where it follows the 2002.18 data. The result is shown in the top panel of Figure 2. Notice that the pseudo-continuum ignores the bump in the 2002.18 SDSS spectrum around 3900 Å (1260 Å at rest). We attribute this bump to an anomaly in the SDSS flux calibration. Our experience with many similar SDSS spectra indicates that anomalies like this do sometimes occur near the blue edge of the SDSS wavelength coverage. In any case, this feature is not related to the Si\(\text{iv}\) outflow line because it has no analog near the C\(\text{iv}\) feature.

The bottom panel in Figure 2 shows the 2006.96 and 2008.48 spectra normalized by the pseudo-continuum. We fit the broad Si\(\text{iv}\) and C\(\text{iv}\) absorption lines in these normalized spectra using gaussian optical depth profiles. The Si\(\text{iv}\) and C\(\text{iv}\) transitions are doublets with velocity separations of \( \sim 500 \text{ km s}^{-1} \) and \( \sim 1930 \text{ km s}^{-1} \), respectively. Our fits include one gaussian per doublet member, with the redshifts and doppler velocities tied together. We assume that the doublet members have equal strengths based on the evidence for line saturation described in \S4.1. In our fitting procedure, this means forcing the optical depths within the doublets to be equal even though their actual ratios based on oscillator strengths should be 2:1. The fits assume implicitly that the absorbing gas fully covers the quasar emission.

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\(^1\) \url{http://www.ucolick.org/~xavier/LowRedux/index.html}
Figure 1. Spectra of J105400.40+034801.2 at rest-frame wavelengths (bottom scale) and observed (top) are represented by the black, blue and red curves for the three observations indicated. The broad Si\textsc{iv} and C\textsc{iv} outflow lines are marked by horizontal bars above the data. The locations of BELs are marked across the top. The steep rise at short wavelengths is due to strong N\textsc{v} and Ly\textsc{α} emission. All of the strong narrow absorption lines (not labeled) belong to an unrelated DLA system at $z_{\text{abs}} = 2.0683$. The vertical flux scale applies to the SDSS spectrum. The other spectra are scaled vertically to match. The formal 1$\sigma$ errors are shown by dotted curves near the bottom.

**Table 1. Outflow Line Measurements**

| Line | REW (Å) | $z_{\text{abs}}$ | $v$ (km s$^{-1}$) | FHWM (km s$^{-1}$) | log $N$ (cm$^{-2}$) |
|------|---------|------------------|------------------|-------------------|------------------|
| Si \textsc{iv} | 6.21 | 1.833 | 26,430 | 4830 | $\geq 14.84$ |
| C \textsc{iv} | 4.83 | 1.835 | 26,270 | 3660 | $\geq 15.08$ |
| Si \textsc{iv} | 4.07 | 1.838 | 25,900 | 4330 | $\geq 14.66$ |
| C \textsc{iv} | 2.54 | 1.830 | 26,810 | 3160 | $\geq 14.80$ |

regions. We will discuss the effects of partial covering and line saturation in §4.1 below.

Figure 2 shows the final fits to the broad outflow lines. Table 1 lists some of the derived results, including the rest equivalent width (REW) of the entire blended doublet, and the absorption redshift ($z_{\text{abs}}$), the velocity shift ($v$ measured from $z_{\text{em}} = 2.095$), the full width at half minimum (FWHM) of the individual doublet lines, and the logarithmic ionic column density (log $N$) derived from the weaker doublet members. Note that the column densities are lower limits because of probable saturation effects (§4.1).

The broad outflow lines in 2006.96 had velocity shifts $v \sim 26,300$ km s$^{-1}$ and deblended FWHMs near $\sim 4000$ km s$^{-1}$. The actual measured width of the C\textsc{iv} blend was FWHM $\sim 4320$ km s$^{-1}$. These features are strong and broad enough to be considered BALs. However, their large velocity shifts lead to a balnicity index of zero, which excludes them from the standard BAL definition [Weymann et al. 1991]. Their appearance in 2006.96 corresponds to strengthening by at least a factor of $\sim 5$ compared to the 2002.18 observation. Then they became roughly $\sim 40\%$ weaker and $10\%$ to $15\%$ narrower by 2008.48.

The uncertainties in our measured results are difficult to assess. The C\textsc{iv} data should be more reliable than Si\textsc{iv} because the spectra at the C\textsc{iv} wavelengths are less noisy and there is less blending with underlying BELs. There is no obvious explanation for the different FWHMs and velocity shifts reported for C\textsc{iv} and Si\textsc{iv} lines in Table 1 in terms of our fits to the lines or the pseudo-continuum. These differences might be real, or they might be indications of the true measurement uncertainties, mostly in the Si\textsc{iv} line.

4 DISCUSSION

4.1 Covering Fractions and Optical Depths

If the outflow gas does not fully cover the background emission regions, then our line fits in §3 will underestimate the true optical depths and column densities. Partial covering appears to be common in BALs and it is well documented in many narrow-line outflow systems where resolved doublets provide direct measures of the covering fractions and true optical depths [Hamann et al. 1997; Hamann 1998].
of log $N_H$ (cm$^{-2}$) $\gtrsim$ 19.9 if the Si/H abundance is roughly solar. In the more likely event that the Si IV line is saturated with line-center optical depth $\tau_0 \gtrsim 3$ (§4.1), the total column density in the absorber would be log $N_H$ (cm$^{-2}$) $\gtrsim$ 21.2.

Partial covering of the quasar continuum source (§4.1) implies that the absorbing region is small. The radius of the accretion disk continuum source at 1550 Å is expected to be roughly $R_{1550} \sim 10^{16}$ cm in luminous quasars like J105400.40+034801.2. In simple geometries, the 20% covering fraction indicates a characteristic absorber radius of $\sim$4 $\times$ 10$^{15}$ cm. (We do not consider the possibility of continuum flux scattered from some larger region because the $\sim$20% covering fraction would require that $\gtrsim$80% of the observed continuum is scattered light.) Comparing this size to the minimum column density above indicates further that the average volume density is $n_H \gtrsim 2 \times 10^{-3}$ cm$^{-3}$.

The outflow dynamical times are interesting for comparison to the observed variabilities. BAL-like outflows are believed to be launched from a rotating accretion disk, and the C IV absorption lines might form at radii just beyond the C IV BEL region (Murray & Chiang 1997; Proga, Stone, & Kallman 2000; Everett 2005). A characteristic flow time in this situation would be $t_f \sim R_{CIV}/v \sim 7$ yr, where $v \sim 26,300$ km s$^{-1}$ is the flow speed and $R_{CIV}$ is the C IV BEL region radius. The transit time for absorbing clouds crossing the 1550 Å continuum source depends on the transverse velocities in the flow (i.e., perpendicular to our lines of sight). If the transverse velocities in the Si IV and C IV absorbing gas are similar to the disk rotation speed just beyond $R_{CIV}$, roughly $v_{tr} \sim 3000$ km s$^{-1}$, then the transit time would be $t_{tr} \sim R_{1550}/v_{tr} \sim 1$ yr. Thus it appears that the transit time is more compatible with the observations than the overall flow time.

### 4.3 What Caused the Outflow Line Variations?

Did a new BAL-like outflow emerge from a situation where there was previously no outflow at all? We cannot answer that question except to note that there were no indications of structural changes in the accretion disk that might signal the onset of an outflow. In particular, the BELs and near-UV spectral slope did not change significantly during the absorption line variability period, and we can rule out large (factor of $\gtrsim 2$) changes in the near-UV flux. There are also no clear signs of acceleration. If a new outflow did emerge in J105400.40+034801.2, it probably appeared in our line of sight as Si IV$^{+3}$ and C IV$^{+3}$ after the acceleration to $v \sim 26,300$ km s$^{-1}$ had already occurred.

The emergence of outflow lines might have been caused by changes in the ionization or by the movement of gas across our lines of sight. Changes in the ionization are an unlikely explanation for several reasons. First, the C IV and Si IV BELs did not vary. Their ionization is controlled

### 4.2 Physical Properties and Time Scales

We can place some interesting constraints on the outflow physical properties by making a few reasonable assumptions. For example, in the photoionization calculations just mentioned, our lower limit on the Si IV$^{+3}$ column density in 2006.96 (Table 1) corresponds to a total hydrogen column density of log $N_H$ (cm$^{-2}$) $\gtrsim$ 19.9 if the Si/H abundance is roughly solar. In the more likely event that the Si IV line is saturated with line-center optical depth $\tau_0 \gtrsim 3$ (§4.1), the total column density in the absorber would be log $N_H$ (cm$^{-2}$) $\gtrsim$ 21.2.

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**Figure 2.** Top panel: Spectra of J105400.40+034801.2 in the same format as Figure 1, but with the SDSS data now drawn as a green curve and with fits to the pseudo-continuum and the outflow absorption lines shown by the smooth black curves. Bottom panel: Normalized spectra from 2006.96 (blue) and 2008.48 (red) together with the normalized line fits (black).

**Table 1.** Properties of J105400.40+034801.2

| Ion   | Column Density (cm$^{-2}$) | Equivalent Velocity (km s$^{-1}$) |
|-------|-----------------------------|-----------------------------------|
| Si IV | $\gtrsim 2 \times 10^{-3}$   | $\gtrsim 3000$                     |
| C IV  | $\gtrsim 2 \times 10^{-3}$   | $\gtrsim 3000$                     |

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2 We estimate the bolometric luminosity of J105400.40+034801.2 to be $L \sim 10^{47}$ ergs s$^{-1}$ based on the observed SDSS flux at 1450 Å (rest), a cosmology with $H_0 = 71$ km s$^{-1}$ Mpc, $\Omega_M = 0.27$, $\Omega_{\Lambda} = 0.73$ and a standard bolometric correction factor $L \approx 3.44L_\lambda(1450\text{Å}).$ This implies characteristic radii for the continuum source at 1550 Å of $R_{1550} \sim 10^{16}$ cm and for the C IV BEL region of $R_{CIV} \sim 6 \times 10^{17}$ cm (Peterson et al. 1993; Bentz et al. 2007; Gaskell 2008; Hamann & Simon 2008).
by the same far-UV flux that controls the CIV and SiIV absorption lines. Changes in quasar continuum fluxes are known to cause changes in the BELs after a time lag related to the light travel time between the continuum source and the BEL region. The lag time for the CIV BEL in J105400.40+034801.2 should be about half a year in the rest frame. Therefore, substantial changes in the far-UV flux should have been evident in the CIV BEL. Second, weak SiIV and CIV absorption lines affected by changes in the ionization should exhibit measurable changes in the SiIV/CIV line ratio (see the photoionization calculations mentioned in §4.1). This did not occur in J105400.40+034801.2 because the lines are optically thick. Their strengths depend on the covering fraction much more than the degree of ionization.

We conclude that the outflow line variations were caused by changes in the covering fraction related to the movement of gas across our line of sight (see also Gibson et al. 2008). Our crude estimate of the crossing time, \( \sim 1 \text{ yr} \) (§4.2), is broadly consistent with this conclusion. Instabilities might also play a role by producing transient flow structures capable of CIV and SiIV absorption. However, instabilities might be expected evolve on roughly a flow time, \( \sim 7 \text{ yr} \) (§4.2), which is perhaps too slow to explain the observations. Better assessments of the origins of the variability will require detailed hydrodynamic simulations.

5 SUMMARY AND CONCLUSIONS

We have described the first known case of an emerging broad-line outflow in a luminous high-redshift quasar, J105400.40+034801.2. The outflow is evident in SiIV and CIV absorption lines having FWHM \( \sim 4000 \text{ km s}^{-1} \) and velocity shifts \( v \sim 26, 300 \text{ km s}^{-1} \). These features are not technically BALs because their large velocity shifts lead to a balnicity index of zero. Nonetheless, they represent a powerful outflow with log \( N_H/\text{cm}^{-2} \gtrsim 21.2 \) and \( n_H \gtrsim 2 \times 10^5 \text{ cm}^{-3} \). The outflow lines appeared between two observations 1.54 yr apart in the quasar rest frame. A third observation 0.47 yr later shows the lines becoming weaker again by \( \sim 40\% \). We attribute this behavior to a substantial flow structure crossing our line of sight to the continuum source.

Overall, the outflow lines discussed here are similar to high-velocity mini-BALs observed in other quasars (Rodríguez Hidalgo et al. 2008). These features are characteristically narrower, weaker and more variable than the classic strong BALs. One possible explanation for these outflow lines is that they form along the ragged edge of the main BAL outflow, where the flow structures could be naturally smaller and more volatile. If BAL outflows are typically clumpy or filamentary (Hall et al. 2007), then perhaps the mini-BALs represent individual clumps or filaments along the edges of these flows. Another possibility is that mini-BALs and other similar outflow lines represent the sputtering beginning or end stages of a BAL evolutionary phase. Continued monitoring of quasars like J105400.40+034801.2, e.g., with multi-wavelength measurements to get better constraints on the ionization and column densities, will help to test these theoretical ideas.

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