Advances in Quasar Absorption Line Velocity Drift Research (Postprint)

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Outflow represents a crucial form of quasar feedback that holds significant importance for understanding the co-evolution of quasars and their host galaxies. This study compiles relevant literature on velocity drifts in outflow absorption lines, organizes the case data therein, and conducts a comparative analysis of the identification methods, challenges, and underlying mechanisms of absorption line velocity drifts, while exploring future research directions in this field. Although observational cases of absorption line velocity drifts remain limited and their physical mechanisms are not yet well understood, breakthroughs in related research are anticipated with the increasing volume of quasar survey data and advancements in data processing techniques. Investigations into absorption line velocity drifts will not only enhance our understanding of quasar outflow phenomena but also offer novel perspectives for galaxy evolution studies.

Full Text

Preamble

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Research Progress on Velocity Shifts of Quasar Absorption Lines

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Abstract

Outflows represent a crucial form of quasar feedback and are essential for understanding the co-evolution of quasars and their host galaxies. This study compiles relevant literature on velocity shifts in outflow absorption lines, organizes the case data, and comparatively analyzes the identification methods, challenges, and generation mechanisms of absorption line velocity shifts, while discussing future research directions in this field. Although current observational cases of absorption line velocity shifts remain limited and their physical mechanisms are not yet clear, the growth of quasar survey data and advances in data processing techniques promise breakthroughs. Research on absorption line velocity shifts will not only deepen our understanding of quasar outflow phenomena but also provide new perspectives for galaxy evolution studies.

Keywords: quasar; outflow; absorption line; velocity shift

1. Introduction

Astrophysicists widely acknowledge that active galactic nucleus (AGN) feedback mechanisms play a pivotal role in the co-evolution of black holes and galaxies [1-4]. AGNs generate broadband electromagnetic radiation through accretion onto supermassive black holes at their centers, exhibiting observational characteristics such as high luminosity, small spatial scales (compact nuclear regions), multi-wavelength variability (timescales ranging from hours to years), and emission lines of varying widths (10^3-10^4 $\mathrm{km \cdot s^{-1}}$) [1]. These unique properties provide astronomers with a window into investigating galaxy evolution and the extreme physical events occurring during this process [5].

Through long-term observations and research, astronomers have classified AGNs into several categories, including quasars, Seyfert galaxies, radio galaxies, optically violent variable quasars (OVV quasars), and BL Lacertae objects (BL Lacs). Among these, quasars—one of the four major astronomical discoveries of the 1960s—have rapidly become a research focus due to their extreme brightness and activity.

It is generally believed that outflows generated from the bright accretion disks at quasar centers can interact with the surrounding interstellar medium [6-14], potentially propagating to galactic scales and forming large-scale outflow phenomena. Consequently, outflows play a vital role in galaxy evolution by transporting heavy elements away from host galaxies, limiting the growth of central supermassive black holes [15], and providing energy and momentum to the interstellar and intergalactic media [16]. Despite the recognized importance of outflows, key aspects such as their formation mechanisms, physical states, locations, acceleration mechanisms, and three-dimensional structures require further intensive investigation.

Broad absorption lines frequently detected in quasars provide compelling evidence for outflows [17]. Most ultraviolet broad absorption lines exhibit blueshifts, suggesting they are produced by outflows moving away from the central source. In addition to broad absorption lines, some quasars also show narrow absorption lines in the ultraviolet band. The classification criteria typically define broad absorption lines as those with full width at half maximum (FWHM) exceeding 2,000 $\mathrm{km \cdot s^{-1}}$, narrow absorption lines as those with FWHM less than 500 $\mathrm{km \cdot s^{-1}}$, and intermediate-width absorption lines falling between these values. Many studies do not distinguish between broad and intermediate-width absorption lines, focusing only on the difference between narrow and broad absorption lines, primarily because the former are often difficult to attribute definitively to outflows driven by AGN or star formation processes versus absorption from circumgalactic medium (CGM), intergalactic medium (IGM), or foreground gas.

Previous research analyzing broad and intermediate-width absorption lines in quasars has revealed that the enormous kinetic energy carried by outflows exerts significant feedback effects on host galaxies. For example, He et al. [18] confirmed the substantial impact of outflow kinetic energy on galaxy evolution based on a sample of 915 variable broad absorption line quasars from the Sloan Digital Sky Survey (SDSS) [19], a conclusion further substantiated by Hamann et al. [20] using SDSS-III BOSS data. In contrast, studies of narrow absorption line outflows remain relatively limited. Although sporadic reports have explored individual sources, systematic large-sample studies assessing their feedback effects are lacking. Furthermore, the formation mechanisms of these three absorption line types (broad, narrow, and intermediate-width) remain undetermined, with general consensus attributing them to differences in the observer' s sightline angle relative to the outflow axis [21] or different evolutionary stages of the outflow [22].

Analyzing variations in the intensity, profile, and velocity of outflow absorption lines may serve as a method to investigate the physical properties of quasar outflows, providing constraints on aspects such as outflow structure, location, and dynamics [23-25]. Studies have demonstrated that broad, intermediate-width, and narrow absorption lines frequently exhibit intensity and profile changes on timescales of months to years [25-48]. These variations may stem from absorption gas motion perpendicular to the line of sight [26-32], transitions in the ionization state of the absorbing gas [25,33-38], or a combination of both [49-51]. For the former scenario, using the variability timescale as an upper limit on the recombination time allows calculation of a lower limit on the gas density; for the latter, the variability timescale of broad absorption lines can constrain the distance between the absorber and central black hole [52,53].

While changes in absorption line intensity and profile have been confirmed as common phenomena, cases of velocity shifts remain rare [50,54-60]. Absorption line velocity shift refers to the overall offset of the absorption line' s central wavelength across continuous observations while the line profile remains essentially unchanged (as shown in Figure 1 [Figure 1: see original paper]). Velocity shifts can occur toward either the red or blue end of the spectrum. The formation mechanisms of outflow absorption line velocity shifts remain controversial. Although theories propose that velocity shifts may result from real acceleration/deceleration of outflows along the line of sight or from outflows crossing the sightline during circular motion around the central massive black hole, these hypotheses lack sufficient observational verification [50,55,61-63].

When velocity shifts reflect genuine acceleration or deceleration of outflows, they can reveal kinematic characteristics and dynamical mechanisms [59] and test hypotheses regarding outflows as galaxy feedback agents. For instance, galaxy feedback models explain outflow deceleration by suggesting that when outflows reach sufficient distances from the central source, they may interact with host galaxy material, potentially causing deceleration [64]. Such interactions would also alter the ionization and thermal state of the outflow, leading to profile changes. The absence of observed deceleration may indicate that outflows remain very close to the central black hole and have not yet interacted significantly with host galaxy material. Most broad absorption lines exhibit average velocity fluctuations within a 3% range, leading Grier et al. [59] to conclude that broad absorption line clouds may not have traveled to distances where significant interactions with the environment occur. Testing this hypothesis requires more observational data on broad absorption line deceleration. Recent studies have also suggested that genuine broad absorption line acceleration or deceleration events may provide unique insights into the origins of quasar reddening and weak radio emission [65,66].

The physical mechanisms underlying absorption line velocity shifts remain debated. While some scholars attribute these shifts to real velocity changes of outflow material along the line of sight or to circular motion around the central massive black hole, these explanations lack conclusive observational evidence and show discrepancies between theoretical predictions and observations [50,55,61-63]. For example, studies have found that broad absorption line acceleration exhibits inconsistent behavior across different timescales, which traditional accretion disk wind models and geometric projection effects struggle to explain [59]. Additionally, some research has discovered that broad absorption line velocity shifts are accompanied by coordinated enhancements in equivalent width, continuum weakening, and emission line strengthening, suggesting that central source radiation may drive this process [54,56]. Therefore, the complex mechanisms of outflow absorption line velocity shifts require further intensive investigation.

This paper collects literature on absorption line velocity shifts and reviews research findings from four perspectives: identification methods (Section 2), identification challenges (Section 3), case studies (Section 4), and generation mechanisms (Section 5). Section 6 proposes future research directions, followed by a summary. All “times” mentioned in this paper refer to the quasar rest frame.

2. Identification Methods for Broad Absorption Line Velocity Shifts

Currently, three primary methods exist for identifying broad absorption line velocity shifts from spectral data: integer pixel offset method, cross-correlation function combined with chi-square test method, and visual inspection method.

2.1 Integer Pixel Offset Method

Gibson et al. [67] established a velocity shift upper limit of 1 Å for each source, then divided by the sampling time interval to derive an acceleration upper limit. This method has two main limitations: (1) it uses only a small portion of the absorption trough for calculation, failing to capture the complete variation of the broad absorption trough; (2) it assumes a one-pixel velocity offset upper limit to derive acceleration limits, making it unable to detect shifts smaller than one pixel.

2.2 Cross-Correlation Function Combined with Chi-Square Test Method

Cross-correlation functions are commonly used to measure time delays in light curves [68] or radial velocities of exoplanets [69]. Grier et al. [59] combined cross-correlation functions with chi-square tests to screen broad absorption line acceleration/deceleration candidates from large samples. Their screening criteria were: (1) a p-value less than 0.1 between spectra without velocity shifts and subsequent spectra, indicating significant differences in the absorption line between observations; (2) the chi-square value and p-value between the first spectrum showing velocity shift and its subsequent spectrum must meet certain conditions to ensure statistical significance of the velocity difference.

The advantages of this combined method include: (1) high sensitivity to velocity shifts, detecting drifts smaller than one pixel; (2) treating the entire (or at least a portion of) broad absorption trough as a whole to identify whether variations stem from velocity changes or other factors; (3) quantifying errors to derive reliable velocity shift upper limits.

It is important to note that when screening criteria are strict, this method excludes targets exhibiting both velocity shifts and profile or intensity changes. For instance, Grier et al. [59] used this method to exclude absorption lines with profile or intensity variations, retaining only pure acceleration/deceleration candidates.

2.3 Visual Inspection Method

Visual inspection, the most direct and original method, allows researchers to identify velocity shifts based on experience. This approach avoids misjudgments caused by parameter setting issues, such as the problem of the cross-correlation and chi-square test method excluding absorption lines with simultaneous velocity shifts and profile/intensity changes. Lu and Lin [54,56] and Yao et al. [57] both employed visual inspection to identify velocity-shifted broad absorption lines in quasar spectra. However, for large spectral datasets, visual inspection becomes time-consuming and demands high professional expertise and experience. Nevertheless, visual inspection remains an indispensable method for confirming broad absorption line velocity shifts.

3. Challenges in Identifying Broad Absorption Line Velocity Shifts

Identifying broad absorption line velocity shifts in spectra can be affected by multiple factors, including sampling frequency and intervals, spectral resolution and signal-to-noise ratio, the intrinsic complexity of broad absorption lines, and the need to assess whether the spectral zero point has drifted between observations (which can be verified using characteristic absorption or emission lines such as [O III]).

3.1 Sampling Frequency and Intervals

Broad absorption lines may appear to show velocity shifts between two observations due to profile or intensity changes. However, if the shape remains constant across multiple observations, this confirms that the same absorption line has undergone velocity shift rather than other types of variation. Therefore, having three or more observations at different epochs enhances the reliability of detected velocity shift phenomena. Second, sampling intervals must be sufficiently long. Grier et al. [59] demonstrated that most C IV broad absorption lines maintain average velocity variations within 3% over 2.5–5.5 years. Consequently, if sampling intervals are too short, velocity shift amplitudes may be too small to detect.

Wheatley et al. [60] clearly demonstrated the impact of sampling frequency and intervals on velocity shift measurements using an example. Grier et al. [70] studied 32 observations of quasar SDSS J141007.72+541203.6 over one year, finding significant equivalent width variations in a C IV broad absorption line. Subsequently, Hemler et al. [71] analyzed three additional years of data for this quasar, revealing slight intensity weakening without significant equivalent width changes. Wheatley et al. [60] added 70 spectra from the following four years and discovered both equivalent width, intensity, and profile changes, as well as velocity shifts in the broad absorption line. This illustrates that with small samples, insufficient sampling frequency or short intervals may cause velocity shift candidates to be missed.

3.2 Limitations of Spectral Resolution and Signal-to-Noise Ratio

High-resolution spectra are undeniably important for analyzing quasar absorption line velocity shifts. As shown in Table 1 , acceleration values measured by Vilkoviskij and Irwin [72] and Rupke et al. [73] are one to two orders of magnitude smaller than those from other studies, likely because their spectra had higher resolution and signal-to-noise ratios, enabling detection of more subtle velocity shifts. High-resolution spectra are crucial for accurately measuring velocity shift values and studying absorption line variability and line-locking characteristics. Only with high-resolution spectra can one accurately decompose components of an (unsaturated) broad absorption trough without model dependence, which is essential for verifying whether line-locking components truly exist in broad absorption lines.

3.3 Intrinsic Complexity of Broad Absorption Lines

The third challenge in identifying broad absorption line velocity shifts arises from their intrinsic complexity. This complexity first manifests in potential self-blending effects, where mixing of blue and red subcomponents may mask velocity shifts. In recent research, Wheatley et al. [60] demonstrated how to distinguish or decompose subcomponents of broad absorption lines and measure their individual velocity shifts, comparing these with the velocity shift of the entire broad absorption line before decomposition.

Beyond self-blending effects, common variations in absorption line intensity, equivalent width, or profile can also interfere with velocity shift identification. Filiz et al. [25] found that 50%-60% of C IV and Si IV broad absorption lines undergo intensity or profile changes within several years. Hemler et al. [71] discovered significant equivalent width variations in C IV broad absorption lines in more than half of 27 quasars from the Sloan Digital Sky Survey Reverberation Mapping (SDSS-RM) project [74,75], even over very short timescales (less than 10 days in the rest frame). When velocity shifts occur simultaneously with intensity, equivalent width, or profile changes, accurately measuring velocity shift amplitudes becomes challenging even with long-term, high-quality, high-cadence spectral data [76-78].

Furthermore, accelerated outflows may not necessarily show velocity shifts in their spectral absorption lines. For example, when our sightline passes through the main body of an outflow ejected perpendicular to the accretion disk [79], the portion of the outflow along our line of sight may be continuous and maintain constant velocity. In such cases, despite the outflow itself accelerating, the absorption lines in the spectrum may not exhibit obvious velocity shifts [6,80,81].

4. Case Studies of Absorption Line Velocity Shifts

4.1 Early Sporadic Reports

Research on outflow absorption line velocity shifts began in the early 20th century, with initial studies focusing on individual sources. For instance, Vilkoviskij and Irwin [72], Rupke et al. [73], and Hall et al. [63] reported outflow broad absorption lines with accelerations of 0.03-0.1 $\mathrm{cm} \cdot \mathrm{s}^{-2}$ over 1-5 years. In 2003, Gabel et al. [62] discovered the first case of decelerating narrow absorption lines, identifying deceleration in C IV, Si IV, and N V narrow absorption lines from the Seyfert galaxy NGC 3783 over 9-13 months. Subsequently, Gibson et al. [67] and Capellupo et al. [24] attempted to detect broad absorption line velocity shifts in small samples without success. In 2019, Misawa et al. [82] conducted a 2.8-5.5 year tracking study of intrinsic narrow absorption lines in six quasars, also finding no significant velocity shift phenomena. Nevertheless, these studies provided methodologies and recommendations for understanding outflow absorption line velocity shifts.

4.2 First Large-Sample Search

In 2016, based on 140 broad absorption line quasars selected from the Sloan Digital Sky Survey, Grier et al. [59] reported the first successful large-sample search for broad absorption line velocity shifts. Despite the substantially larger sample size compared to previous studies, only three broad absorption lines with velocity shifts were identified—two accelerating and one decelerating—suggesting the rarity of such phenomena.

Grier et al. [59] attempted to explain the origin of the two accelerating broad absorption lines using the classical disk-wind model. Using disk-wind model formulas from Murray et al. [6] and Murray and Chiang [83], they calculated the outflow acceleration rate but found discrepancies with measured values, particularly the model' s inability to explain the large acceleration magnitude. Additionally, based on 76 selected C IV broad absorption lines, Grier et al. [59] concluded that most broad absorption lines exhibit average velocity variations not exceeding 3% over 2.5–5.5 years.

4.3 Deceleration in X-ray Bright Quasars

In 2014, Joshi et al. [50] detected C IV broad absorption line deceleration in two X-ray bright quasars. Over 3.11 and 2.34 years, these two C IV broad absorption lines showed average accelerations of -0.7 $\mathrm{cm \cdot s^{-2}}$ and -2.0 $\mathrm{cm \cdot s^{-2}}$, respectively. The authors evaluated several mainstream velocity shift mechanisms to explain the observations and, considering the X-ray bright nature of these quasars, concluded that the movement of numerous small self-shadowing clouds along curved trajectories provided the most reasonable explanation.

4.4 Coordinated Multi-Ion Velocity Shifts

In 2019, Joshi et al. [55] discovered deceleration in both C IV and Si IV broad absorption lines with identical redshifts in another X-ray bright quasars. Combining their 2014 and 2019 studies, Joshi et al. identified common characteristics in these three sources: (1) decelerating components typically have high ejection velocities exceeding 10,000 $\mathrm{km \cdot s^{-1}}$; (2) other non-shifting absorption lines exist in lower-velocity regions of the spectra; (3) no significant changes occur in the optical continuum. They also noted that accelerated broad absorption lines have not been observed in X-ray bright quasars, and verifying this finding in large samples would enhance our understanding of the physical origins of broad absorption lines in X-ray bright (or weak) quasars.

4.5 Highest Acceleration Broad Absorption Outflow at the Time

Xu et al. [58] studied spectra of quasar SDSS J1042+1646 from 2011 and 2017, discovering velocity shifts in a broad absorption line. The line's velocity centroid changed from -19,500 $\mathrm{km \cdot s^{-1}}$ to -21,050 $\mathrm{km \cdot s^{-1}}$ over 3.2 years, representing a shift of approximately -1,550 $\mathrm{km \cdot s^{-1}}$ and corresponding to an acceleration of 1.52 cm $\cdot$ s^{-2}—the largest reported acceleration for an absorption line outflow at that time. The velocity shift appeared not only in the separated double peaks of Ne VIII λ\$ \$770.41, 780.32 but also in the O V \$ \$629.73 and Mg X λ\$ \$609.79, 624.94 absorption doublets. After excluding photoionization changes and absorber movement into/out of the sightline as potential causes, Xu et al. attributed the velocity shift to outflow acceleration.

4.6 First Narrow Absorption Line System with Coordinated Variability

In 2020, based on two spectral observations of quasar SDSS J143530.49+142338.4, Yao et al. [57] reported the first case of a narrow absorption line system (including C IV λ\$ \$1548, 1551 and N V λ\$ \$1239, 1243) simultaneously showing increased equivalent width and velocity shift. Given the significant continuum weakening, they speculated that changes in outflow ionization state might contribute to the increased equivalent width. While Yao et al. conducted preliminary analysis of the velocity shift mechanism, limited to only two SDSS observations, they could not provide a definitive explanation.

4.7 First Low-Ionization Broad Absorption Line Velocity Shifts

In 2020, Lu and Lin [56] discovered that Mg II and Al III broad absorption lines in quasar SDSS J134444.33+315007.6 underwent velocity shifts of approximately -1,101 km $\cdot$ s^{-1} and -1,170 km $\cdot$ s^{-1}, respectively, over 3.21 years—representing the first reported velocity shifts in low-ionization broad absorption lines. They also identified other significant spectral changes, including notable continuum weakening, synchronous enhancement of multiple emission lines (Mg II, C III, and Al III), and synchronous strengthening of three Al III absorption troughs. These features all indicated substantial influence from background radiation energy, leading to the inference that the broad absorption line velocity shifts likely originated from acceleration of the outflow along the sightline caused by central source radiation pressure.

4.8 Highest Acceleration Broad Absorption Line to Date

In 2021, Aromal et al. [84] reported two distinct C IV broad absorption lines in a quasar, where the bluer line accelerated while simultaneously showing equivalent width variations, while the redder line exhibited complex profile changes. Two absorption components within the redder broad absorption line also showed acceleration and equivalent width changes, with their acceleration and equivalent width variations correlating with those of the bluer line. The bluer broad absorption line' s acceleration between the second and third observations was (8.84\$±3.62)$cm \cdot s$^{-2}\$—the highest acceleration discovered in broad absorption line quasars to date.

4.9 Non-Constant Acceleration Cases

For sources with more than two spectral observations, comparing velocity shift values between each pair of observations reveals that acceleration magnitude is not constant. For example, in Joshi et al.' s 2019 study [55], the deceleration rate of the C IV broad absorption line in quasar J092345+512710 between the second and fourth observations was approximately 1.4 times that between the first and second observations. Similarly, Grier et al. [59] found from three observations of quasar J012415.53-003318.4 that the broad absorption line's average acceleration was 0.9 $\mathrm{cm \cdot s^{-2}}$ between the first two observations but decreased to 0.37 $\mathrm{cm \cdot s^{-2}}$ between the latter two observations.

In 2024, Yi et al. [85] reported four low-ionization broad absorption line acceleration/deceleration candidates, finding that three showed rapid initial acceleration that subsequently leveled off. However, the remaining candidate' s broad absorption line profile remained essentially unchanged, showing a linear relationship between sampling interval and velocity shift across three consecutive spectral observations—representing the first case of constant acceleration in a broad absorption line outflow. Recently, Wheatley et al. [60] also discovered non-constant outflow absorption line acceleration in quasar SDSS J141007.72+541203.6 from 130 observations spanning eight years.

5. Generation Mechanisms of Absorption Line Velocity Shifts

Currently, the main physical mechanisms believed to cause broad absorption line velocity shifts include [61-63]: (1) real acceleration or deceleration of the outflow; (2) changes in line-of-sight velocity as the outflow undergoes circular motion around the central massive black hole; (3) velocity shifts caused by changes in physical properties such as ionization state and column density of outflow material. However, these mechanisms lack strong observational support, and theoretical predictions differ significantly from actual observations.

5.1 Real Outflow Acceleration/Deceleration

Acceleration/deceleration of absorbing clouds along radial trajectories under the central object' s gravity may explain absorption line velocity shifts. To evaluate whether this mechanism can reasonably explain observed shifts, researchers estimate the distance between absorbing clouds and the central source and compare their actual velocities with theoretical escape velocities. For example, Joshi' s team [50,55] studied three velocity shift cases and found that theoretically estimated outflow escape velocities were far lower than observed velocity shift rates, thus ruling out gravity-dominated acceleration/deceleration. It should be noted that accurately estimating the distance between absorbing clouds and quasars requires high signal-to-noise ratio, high-resolution spectra covering multiple ions.

Researchers also employ other methods to determine whether velocity shifts originate from real outflow acceleration/deceleration. For instance, Lu and Lin [54,56] analyzing C IV broad absorption line acceleration in quasar J1208+0355 and Mg II and Al III broad absorption line acceleration in quasar J1344+3150, found that these broad absorption lines simultaneously exhibited coordinated equivalent width enhancement, significant continuum weakening, and emission line strengthening during velocity shifts. These features indicated that outflows in these sources might be influenced by central source radiation, suggesting that their broad absorption line velocity shifts likely originated from radiation-driven outflow acceleration processes.

When analyzing spectral data of quasar J1042+1646 from 2011 and 2017, Xu et al. [58] also discovered a broad absorption line velocity shift. They excluded photoionization changes and absorber movement into/out of the sightline as explanations, concluding that the observed velocity shift should be attributed to outflow acceleration.

5.2 Curvilinear Motion Crossing the Sightline

During curvilinear motion of outflow material, deflection of its trajectory may cause changes in the absorption line’ s velocity along the line of sight. In this scenario, the measured velocity shift value actually represents only the change in the line-of-sight velocity component of the outflow material (see Figure 3 [Figure 3: see original paper] in reference [62]).

For example, Joshi et al. [50] detected velocity shifts in C IV broad absorption lines in two X-ray bright quasars (J0855+3757 and J0911+0550) and concluded that such shifts could be reasonably explained by curvilinear outflow motion. Their conclusion was based on estimates showing that these outflows’trajectories were sufficiently curved to produce the measured velocity shift values (217–620 $\mathrm{km} \cdot \mathrm{s}^{-1} \cdot \mathrm{yr}^{-1}$).

5.3 Changes in Outflow Physical Properties

Variations in the ionization state of the quasar central source can trigger changes in outflow material’ s ionization state and column density, manifesting spectrally as absorption line intensity changes and possible accompanying velocity shifts. Wheatley et al. [60] clearly demonstrated how changes in two subcomponent parameters (center/width/amplitude) of a broad absorption line affect measurements of the entire line’ s centroid (see Figures 12 [Figure 12: see original paper] and 16 [Figure 16: see original paper] in that work).

Photoionization models [44] can serve as auxiliary tools to determine whether absorption line intensity variations originate from central source ionization state changes. For example, Joshi et al. [50] attempted to use photoionization models to analyze the cause of C IV broad absorption line intensity variations in quasar J0911+0550. In the photoionization model, the absence of Si IV or N V absorption lines in five observational spectra suggested that this C IV absorption line would strengthen when the central source’ s ionization level decreased. However, Joshi et al. [50] observed that both the continuum and C IV absorption line weakened, leading them to exclude photoionization changes as the cause of the C IV absorption line intensity variation, indirectly ruling out photoionization changes as the cause of its velocity shift.

Similarly, Xu et al. [58] studying quasar SDSS J1042+1646 found a broad absorption line velocity shift of approximately -1,550 $\mathrm{km \cdot s^{-1}}$ over 3.2 years. They hypothesized that this change might not result from outflow acceleration but from photoionization changes. In this mechanism, absorption line variations are explained by changes in quasar ionization levels. To account for the appearance and disappearance of these stationary outflows would require significant changes in quasar ionization state between the two observations (detailed ionization state analysis in Section 5.1 of reference [58]). However, four other absorption lines in the quasar’ s two spectra remained unchanged during this period, including some unsaturated doublets, leading Xu et al. to exclude photoionization changes as the explanation.

5.4 Geometric Projection Effects from Accretion Disk Rotation

Accretion disk rotation produces geometric projection effects. If broad absorption line material is ejected from a rotating accretion disk, the projected position and velocity of the absorbing material in the observer’s line of sight will change as the disk rotates. This change can cause observed broad absorption line velocity shifts [86]. Grier et al. [59] attempted to explain the acceleration/deceleration of broad absorption lines observed in three quasars using geometric projection effects. By analyzing the rotation period of accretion disk material to calculate the timescales over which broad absorption line acceleration or deceleration could be observed, they found that the accretion disk did not rotate significantly relative to the observer’ s sightline during the observation period, making geometric projection effects from accretion disk rotation an unlikely cause of these velocity shifts.

6. Research Outlook

The aforementioned research progress reveals two major limitations in current studies of outflow absorption line velocity shifts: (1) scarce observational cases, with only 20 reported instances; (2) unclear physical mechanisms behind velocity shifts, with mainstream hypotheses lacking strong observational support. Based on these deficiencies, this paper proposes the following future research directions.

6.1 Expanding Repeated Observation Samples

As shown in Table 1 , only 20 velocity shift cases have been discovered to date. Such limited observational cases constrain further investigation of velocity shifts. Fortunately, we are in an era of rapid development in sky survey projects. For example, the Sloan Digital Sky Survey (SDSS) has released spectral data for over 750,000 quasars by its 16th data release. China’ s Large Sky Area Multi-Object Fiber Spectroscopic Telescope (LAMOST) survey has also observed more than 70,000 quasars. Quasars with repeated observations in large surveys like SDSS and LAMOST can form large samples for searching broad absorption line velocity shifts.

Grier et al. [59] conducted the only successful large-sample search for absorption line velocity shifts to date, but they limited their study to quasars observed at least three times, which significantly constrained the search scope and yielded only three cases from 140 quasars. While Grier et al.’ s goal was to screen outflow acceleration candidates rather than simply identify velocity shift cases —making strict screening criteria reasonable—expanding the search to quasars with only two observations could discover more cases. We recommend first searching for velocity shift candidates in quasars with only two observations, then conducting multiple high-resolution observations of these candidates. This approach would likely have higher success rates than directly searching samples with at least three observations, helping build a statistically significant sample of broad absorption line velocity shifts.

6.2 Comprehensive Study with Line-Locking Observational Features

Line-locking is a concept based on the Doppler effect of absorption line gas clouds, where two outflow absorbers move parallel along the line of sight with a velocity difference matching the spacing of specific ion doublets [87-89]. Studying this phenomenon is crucial for understanding the physical mechanisms of radiation-driven outflows in quasars and is considered a unique signature of radiation-driven outflows [88,89]. However, how radiation-driven mechanisms produce line-locking remains unresolved. Researchers have developed models to explain line-locking: (1) Scargle’ s “S73 model” [88]; (2) Braun and Milgrom’ s “BM89 model” [89]. Neither model has received strong observational support [90,91]. The S73 model is a steady-state model requiring nearly equal inward and outward forces in the line-locking system [88], implying no velocity shifts would occur. The BM89 model is a non-steady-state model not requiring equal forces but only that acceleration differences between “locked” subcomponents remain nearly constant, suggesting that line-locked absorption lines might exhibit velocity shift phenomena [89]. Searching for velocity shifts while identifying line-locking features could test the S73 and BM89 models and reveal the physical mechanisms of radiation-driven outflows.

6.3 Integration with Absorption Line Variability Studies

Analyzing equivalent width variability of quasar absorption lines plays a non-negligible role in studying outflow spatial distribution, velocity structure, and ionization structure [19,33,92]. Equivalent width variability is a common observational feature of quasar absorption lines [38,71,91,93-99], with two main mechanisms: (1) absorber motion across the sightline [26]; (2) absorber ionization state changes [34]. Both mechanisms provide valuable clues for understanding outflow origins [26,34,39] and are important for investigating outflow physical conditions. For instance, under the first mechanism, broad absorption line variability timescales can constrain the distance between absorbers and the central black hole [52,53]; under the second mechanism, variability timescales can serve as upper limits on recombination timescales, allowing calculation of absorber density lower limits.

Studies based on SDSS quasar spectral samples [38,93,95,96] have revealed a significant anti-correlation between absorption line equivalent width variations and quasar UV continuum changes, indicating that most equivalent width variations originate from absorber ionization state responses to central source variability.

Additionally, He et al. [19] used a sample of nearly 1,000 quasar spectra from SDSS to investigate outflow scales and kinetic luminosity distributions, revealing the tremendous potential of using absorption line equivalent width variability to determine outflow scales. Therefore, integrating absorption line velocity shift studies with variability characteristics will provide new perspectives and tools for deeply understanding outflow origins, acceleration processes, and impacts on galaxy evolution.

7. Summary

This paper reviews research progress on quasar absorption line velocity shifts from four aspects: detection methods, search challenges, case studies, and generation mechanisms. Related research is beneficial for revealing outflow structure, location, dynamical properties, and the complex physical environments within quasars.

Current understanding of broad absorption line velocity shifts remains limited. First, the severe scarcity of observational cases constrains investigation of this phenomenon, with only 20 cases reported to date. Second, although several physical mechanisms have been proposed to explain velocity shifts, all lack sufficient observational support.

Based on these deficiencies, this paper proposes future research directions for quasar absorption line velocity shifts. With the accumulation of quasar survey data and technological advancements, we anticipate that research on absorption line velocity shifts will expand and deepen, providing not only more data support for quasar outflow dynamical models but also new clues for revealing complex physical processes within quasars. Ultimately, progress in this field will help us achieve a more comprehensive and profound understanding of the nature of quasar evolution.

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