IdeaFest: Interdisciplinary Journal of Creative Works and Research from Humboldt State University

Volume 3 *ideaFest: Interdisciplinary Journal of Creative Works and Research from Humboldt State University* Article 1

2019

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Acknowledgements
We would like to acknowledge our advisor, Dr. Paola Rodriguez Hidalgo, as well as Abdul Moiz Khatri and Pat Hall.

Preparing a Database of Extremely High Velocity Outflows in Quasars

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ABSTRACT—Quasars are among the most distant and luminous objects in the universe. They form when matter spirals into the supermassive black hole at the center of a galaxy, creating a highly energetic disk of gas called an accretion disk. Our research focuses on outflows, which occur when a body of gas is ejected from the accretion disk at high speed. By examining how light from the quasar is absorbed by matter in an outflow, we can deduce the outflow's velocity relative to the quasar. A special subset of these events, termed extremely high velocity outflows (EHVOs), demonstrate outflows with speeds greater than 30,000 km/s, or 10% the speed of light. The goal of our research is to identify new instances of EHVOs, as there are currently only three confirmed cases in the published literature. Our examination of quasar spectra has yielded 40 new EHVO cases, increasing the number of confirmed cases by a factor of ~13. We are in the process of finishing an EHVO database, which includes quasar spectra and outflow parameters, and we will release it in late 2019 for the community to study the properties of these outflows, quasars, and their host galaxies in greater depth.

KEYWORDS—*astronomy, physics, astrophysics, quasars, active galactic nuclei*

INTRODUCTION—When quasars were first observed in the mid-20th century, their nature was a mystery. Superficially, they resemble stars, as both types of objects appear to us as point sources of light of similar brightness. As a result, they were given the name "quasi-stellar object," later abbreviated to "quasar." However, closer examination of the spectra reveals major discrepancies. First, the background radiation signature of a quasar, known as the continuum, appears to be distinct from that of a star; stellar spectra exhibit absorption lines superimposed on a blackbody spectrum. Second, quasar spectra contain broad emission lines, which are not present in stars. Finally, they display much higher cosmological redshifts than any intragalactic objects, placing most at a distance on the order of billions to tens of billions of light years from Earth. The current record holder for the most distant quasar, designated ttvft J1342 + 0928, is nearly 30 billion light years away.[1]

At first, researchers struggled to reconcile these observations. Given their great distance, these objects would need to have luminosities greater than that of most galaxies, but compacted into a far smaller space. Even nuclear fusion, the driving mechanism in the core of stars, was unable to account for this high energy density. Finally, in 1964 Zel'dovich proposed that clouds of gas falling under the force of gravity toward a supermassive black hole could liberate enough energy to explain the quasar phenomenon.[2] Although we now understand much more about their structure and behavior, quasars and their associated phenomena are still a very active area of research.

Our research focuses on a common phenomenon called an outflow, which occurs when a body of gas is ejected from a quasar's accretion disk at high speed. If an outflow intercepts the line of sight between us and the quasar, it absorbs some light from the continuum, leaving a distinctive signature in the spectrum. Not all spectra show evidence of outflows, but since our observation of

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Kowash, G., Quintero, C., Haas, S., Rodríguez Hidalgo, P. 2019. Preparing a database of extremely high velocity outflows in quasars. *ideaFest Journal: Interdisciplinary Journal of Creative Works & Research from Humboldt State University* 3: 6–9.

outflows depends on their intersection with our line of sight, it is reasonable to suspect that most if not all quasars exhibit outflows, while we perceive only those that have appropriate spatial positioning. Their potential ubiquity supports the idea that outflows play an important role in galactic evolution and star formation, in particular by expelling metal-rich gas with high kinetic energy into the interstellar medium.[3]

Our study focuses on a subset of outflows known as extremely high velocity outflows (EHVOs), which possess velocities greater than 0.1c (where c is the speed of light, approximately 3.00×10^8 m/s) with respect to the quasar rest frame. These outflows have received much less study than their lower-velocity counterparts, and there are currently only three confirmed cases of EHVO in the published literature.[4,5,6] Using quasar spectra from the Sloan Digital Sky Survey Data Release 9 (SDSS DR9), we identified 40 instances of EHVO, expanding the available data set by a factor of ~13.

METHODS—Our identification of EHVOs from quasar spectra revolves around the use of the carbon-IV ion (CIV; carbon three times ionized) as a marker. The signature of CIV appears in the spectrum in two ways: as an emission peak from ions in the broad emission line region, and as an absorption trough from ions in the outflow. If the quasar and the outflow were stationary with respect to each other, then the emission and absorption lines would appear at the same wavelength. In reality, outflow absorption tends to appear at a shorter wavelength than emission, as illustrated in **FIG 1**.

This wavelength offset indicates that the outflow is moving away from the quasar in our direction. Carbon atoms absorb photons at about 1,550 Å, but in the rest frame of the outflow, light emitted from the quasar is redshifted to a longer wavelength. As a result, photons absorbed by outflowing carbon must have a wavelength shorter than 1,550 Å in the quasar's rest frame. By comparing the observed wavelengths of the emission and absorption lines, we can calculate the blueshift of the outflow, and by extension its velocity with respect to the quasar. If this velocity is found to be greater than 30,000 km/s, it is evidence of an EHVO.

One complicating factor is that intervening material between Earth and the quasar may produce absorption features in the same wavelength range as our target CIV absorption. To distinguish between these effects, absorption features are categorized into two groups based on

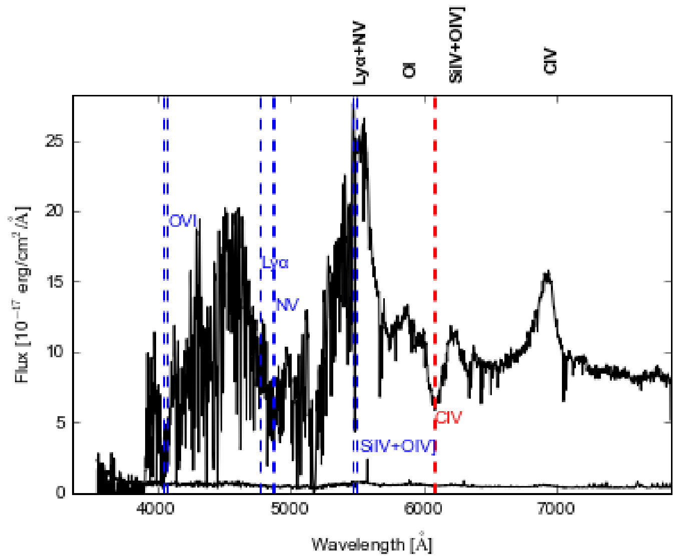

FIGURE 1. Example of a quasar spectrum with distinct CIV emission and absorption features caused by an EHVO. The absorption feature, marked by the red dashed line, appears at an observed wavelength nearly 1,000 Å shorter than the corresponding emission line at 7,000 Å, indicating that the absorbing matter is outflowing at a high velocity. At the top of the spectrum we indicate the location of the quasar emission lines. Other potential ions outflowing at the same speeds as the EHVO CIV are marked as dashed blue vertical lines.

width: broad absorption lines (BALs) and narrow absorption lines (NALs). A number of factors can contribute to the broadening of absorption line profiles, for example Doppler broadening.[7] Individual atoms in an EHVO can have a wide range of velocities, and by extension different blueshifts with respect to the quasar. Atoms with speeds in the faster end of this range will produce absorption lines at a shorter wavelength, and vice versa. As a result, absorption occurs over a range of wavelengths. In contrast, a cloud of intervening matter has a more localized distribution of velocities, so it will produce much narrower absorption lines.

It is worth noting that, although distinguishing between BALs and NALs can help identify the source of an absorption line, it is not an entirely decisive metric; there is evidence that some NALs are physically associated with the quasar, and may even represent outflows themselves.[8,9] Some models suggests that these outflowing NALs may simply result from viewing a standard outflow at a shallower angle, but more research is needed to clarify their true nature.[10]

For our analysis, we used a set of 87,822 quasar spectra obtained from the SDSS DR9.[11] Thresholds were placed both on the signal-to-noise ratio and the cosmological redshift; the signal-to-noise threshold helped ensure that signs of EHVO would not be produced by random signal noise, while the redshift threshold ensured that our region of interest fell within the SDSS spectrograph's range of wavelength. Further details on these cutoffs can be found in our previous publications.[12,13] After applying these two filters, our data set was reduced to 6,760 spectra.

Next, the spectra were normalized before analyzing for emission and absorption features. These features appear in the spectra as regions where the flux rises above or falls below the continuum of the quasar, respectively. However, as shown in FIG 2A, the continuum has a non-zero slope in the UV-optical region, making it difficult to recognize and quantify emission and absorption. Adjusting the data to give the continuum a constant value of one creates a common baseline against which flux values can be compared, as illustrated by the horizontal line in FIG 2B.

This region of the continuum is well approximated by a power law,[14] and by selecting anchor points in the spectrum where there is known to be little contaminating emission or absorption, a curve fit can be calculated for use in normalization in a systematic way. Finally, we removed spectra that were either missing data in the wavelength region of interest or had too complex of a continuum, so we ended up with a parent sample of 6,740 normalized quasar spectra.

Once the spectra were normalized, potential EHVO absorption features were flagged (and if the identification as CIV was correct, quantified) using a modified form of the Balnicity Index (BI), given by the following integral:

$$BI = \int_{30000}^{60000} \left[1 - \frac{f(v)}{0.9}\right] C \, dv$$

where *f(v)* is the normalized flux as a function of velocity, and C is a parameter whose value is either zero or one.[14] If the quantity in brackets remains positive over an interval longer than a specified threshold, the value of C becomes one; otherwise it is given a value of zero. A larger threshold interval means that only broader absorption features are summed under the integral. We required this threshold to be 2,000 km/s to remove potential blends of narrow lines more easily (as discussed below). Thus, by selecting an appropriate threshold and finding all spectra with BI > 0, quasars displaying BALs can be filtered from the data set. In the original definition of the BI introduced in Weymann et al. (1991),[15] the integral bounds extend from 3,000 km/s to 25,000 km/s; however, this interval excludes EHVOs, which have velocities greater than 30,000 km/s, so it was necessary to adjust the bounds.

Only a subset of these BALs will be due to CIV absorption. Broad absorption lines occurring at wavelengths shorter than 1,400 Å may also be caused by SiIV (triply ionized silicon), CII (singly ionized carbon), or OI (unionized oxygen). However, if this is the case, CIV absorption should also be visible, outflowing at similar speeds (or in other words, at the corresponding redshift), since

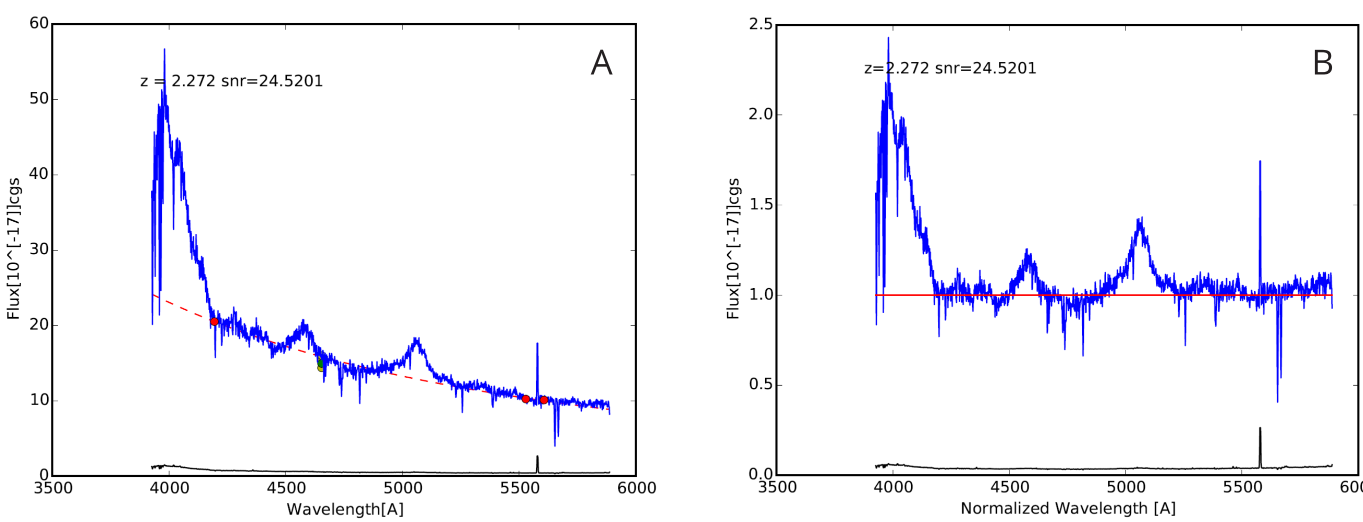

FIGURE 2. (A) Quasar spectrum prior to normalization. The dashed diagonal line shows the continuum of the quasar, and red circles denote anchor points. (B) Spectrum following normalization. Regions above and below the horizontal line indicate emission and absorption, respectively.

CIV is the predominant absorbing ion observed in quasar spectra. Also, in SDSS spectra BAL-like features can be due to the blending of multiple narrow absorption lines, which could correspond to intervening matter as discussed above. These features can be distinguished visually from true BALs by the slope of the trough boundary. If an absorption feature is the result of many superimposed narrow absorption lines, the boundary will tend to have a steep slope, while a true BAL tapers off more gradually. In addition, the presence of spikes at the bottom of the trough suggests it is probably composed of narrow absorption lines. Therefore, visual inspection is used to confirm cases of EHVO out of the potential flagged cases. Additional confirmation that a BAL is due to CIV absorption comes from the presence of NV (nitrogen four times ionized) and OVI (oxygen five times ionized) absorption at the same redshift.[17]

RESULTS—Following the procedure outlined above yielded 40 confirmed cases of EHVOs, such as the one displayed in **FIG 1**, from the parent sample of 6,740 spectra. Our results, including spectral plots and absorption measurements (such as BI, velocity of the outflow, and depth of the absorption trough) for all 40 EHVO cases, will be released in 2019 through a publicly accessible online database, allowing other groups to begin a more in-depth analysis of their properties.

CONCLUSIONS—Extremely high velocity outflows are a highly understudied phenomenon associated with quasars, and they may play an important role in star formation and galactic evolution. Our search of the SDSS DR9 data set yielded 40 confirmed EHVO cases, expanding the current set of 3 published cases by a factor of ~13. Our upcoming work includes publishing our results in an online database in 2019, along with an accompanying journal article that includes a more comprehensive analysis of the properties of our sample, allowing the astronomy community to begin studying the properties of these phenomena in unprecedented depth.

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