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THE *HUBBLE SPACE TELESCOPE* QUASAR ABSORPTION LINE KEY PROJECT: THE UNUSUAL ABSORPTION-LINE SYSTEM IN THE SPECTRUM OF PG 2302+029—EJECTED OR INTERVENING?[1]

B. T. JANNUZI,[2] G. F. HARTIG,[3] S. KIRHAKOS,[4] W. L. W. SARGENT,[5] D. A. TURNSHEK,[6] R. J. WEYMANN,[7] J. N. BAHCALL,[4] J. BERGERON,[8] A. BOKSENBERG,[9] B. D. SAVAGE,[10] D. P. SCHNEIDER,[11] AND A. M. WOLFE[12]
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ABSTRACT

We report the discovery of a high-ionization broad absorption line system at a redshift of $z_{abs} = 0.695$ in the spectrum of the $z_{em} = 1.052$ radio-quiet quasar PG 2302+029. Broad absorption with FWHM from 3000 to 5000 km s^{-1} is detected from C IV, N V, and O VI in *Hubble Space Telescope* (*HST*) Faint Object Spectrograph spectra of the quasar. A narrow-line system (FWHM ~ 250 km s^{-1}) at $z_{abs} = 0.7016$ is resolved from the broad blend and includes absorption by Lyα and the C IV, N V, and O VI doublets. No absorption by low-ionization metal species (e.g., Si II and Mg II) is detected in the *HST* or ground-based spectra for either the broad or the narrow system. The centroids of the broad system lines are displaced by ~56,000 km s^{-1} to the blue of the quasar's broad emission lines. The reddest extent of the broad-line absorption is more than 50,000 km s^{-1} from the quasar. The properties of this system are unprecedented, whether it is an intervening or an ejected system.
Subject headings: cosmology: observations — galaxies: clusters: general — intergalactic medium — quasars: absorption lines — quasars: individual (PG 2302+029)

1. INTRODUCTION

Extremely broad high-ionization absorption complexes with velocity extents of 2000–25,000 km s^{-1} occur in approximately 10% of radio-quiet quasi-stellar objects (QSOs) (Weymann et al. 1991). This absorption is almost certainly produced by material ejected from the source producing the observed emission. Such objects are broad absorption line QSOs (BALQSOs; see Weymann et al. 1991 and Turnshek 1995 for reviews). Broad absorption features produced by intervening gaseous material associated with clusters of galaxies were anticipated by Bahcall & Salpeter (1965), but only a small number of such features have been convincingly demonstrated. One dramatic example is the extensive complex of absorption near $z_{abs} = 2$ in the spectra of two quasars (Q1037−2704, $z_{em} = 2.193$, and Q1038−2712, $z_{em} = 2.33$: the "Tololo Pair") separated by 17$'$.9 on the sky (Jakobsen et al. 1986). It is very probable that the extensive absorption observed in these quasars (and in additional quasars subsequently observed in the same field) is produced by gaseous material associated with a supercluster of galaxies (Sargent & Steidel 1987; Jakobsen & Perryman 1992; Dinshaw & Impey 1996). Broad absorption features in quasar spectra can evidently be a tracer both of large-scale structure in the Universe and of material intrinsic to the QSOs.

In this Letter, we report the discovery of a very broad high-ionization absorption complex at a redshift of ~0.695 in the spectrum of PG 2302+029 ($\alpha = 23^h04^m45^s.0$, $\delta = +03°11'46''$, J2000; Schneider et al. 1992). The quasar has an emission-line redshift of $z = 1.052$ (Steidel & Sargent 1991) and is radio quiet (Kellerman et al. 1989).

2. OBSERVATIONS

Hubble Space Telescope (*HST*) Faint Object Spectrograph (FOS; description by Ford & Hartig 1990) spectra obtained using the G190H (covering ~1600–2300 Å) and G270H (2250–3250 Å) gratings provide the new data presented in this Letter. Characteristics of the observations are presented in Table 1 and the spectra are displayed in Figure 1. We obtained the G190H spectrum as part of the *HST* quasar absorption-line survey, an *HST* Key Project, during Cycles 1–4 (Bahcall et al. 1993). The spectrum was processed using IRAF, as described by Schneider et al. (1993). Burbidge and coworkers obtained a G270H spectrum of PG 2302+029 in 1994. In 1992, Impey et al. (1995) made spectropolarimetry observations of PG 2302+029 using the G270H grating, the pre-COSTAR FOS, and a large aperture (4$''$.3), resulting in significantly lower spectral resolution in their spectrum than either the G190H or 1994 G270H spectra. Both of the G270H spectra were extracted from the *HST* archive, making use of the standard STScI processing of the data.

The spectra were searched for absorption lines that were fit with Gaussians using the Key Project software described in Schneider et al. (1993). The 1992 G270H spectrum was only

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[2] National Optical Astronomy Observatories, P.O. Box 26732, Tucson, AZ 85719; jannuzi@noao.edu.
[3] Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218.
[4] Institute for Advanced Study, School of Natural Sciences, Olden Lane, Princeton, NJ 08540.
[5] Robinson Laboratory 105-24, California Institute of Technology, Pasadena, CA 91125.
[6] Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, PA 15260.
[7] The Observatories of the Carnegie Institution of Washington, 813 Santa Barbara Street, Pasadena, CA 91101.
[8] Institut d'Astrophysique, 98 bis Boulevard Arago, F-75014 Paris, France.
[9] Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 OHA, UK.
[10] Department of Astronomy, University of Wisconsin, 475 North Charter Street, Madison, WI 53706.
[11] Department of Astronomy, The Pennsylvania State University, University Park, PA 16802.
[12] Center for Astrophysics and Space Sciences, C011, University of California, San Diego, La Jolla, CA 92093.

TABLE 1

HST/FOS OBSERVATIONS OF PG 2302+029

UT Date	Exposure Time (s)	Detector/Grating	Aperture (arcsec)	FWHM[a] (Å)	S/N[b]	Shift[c] (Å)
1994 Oct 05[d] ...	4422	Red/G190H	0.26	1.33	30	0.85
1994 Aug 02[e] ...	1400	Red/G270H	0.86	1.97	50	1.14
1992 Jul 28[f].....	7920	Blue/G270H	4.30	~4.0	80	...

[a] The size in Å of a spectral resolution element.
[b] Signal-to-noise ratio per resolution element in the continuum.
[c] The wavelength zero-point offsets that were applied to the observed G190H and 1994 G270H spectra in order to place them in a frame with Galactic interstellar medium lines at rest (see Schneider et al. 1993 for discussion).
[d] Spectrum obtained by Key Project, Bahcall PI.
[e] Spectrum obtained by GTO program, Burbidge PI.
[f] Spectropolarimetry data obtained with the pre-COSTAR FOS; published by Impey et al. 1995.

used to check for variability of spectral features (no significant changes were found). Measurements and identifications of all the absorption features will be included in the next Key Project catalog paper. The focus of this Letter is the broad absorption features and their associated narrow components. Measurements of these lines are presented in Table 2. The continuum fit was subjectively adjusted in the regions of the broad features, and the separation of broad and narrow features near 2100 Å was done interactively.

The narrow absorption lines were identified using the algorithmic line identification software described by Bahcall et al. (1996). Among the identifications is a high-ionization $z_{abs} = 0.7016$ system including Lyα, the C IV, N V, and O VI doublets, as well as a possible detection of C III (the line is located in a low signal-to-noise region of the G190H spectrum). Fe III, if present, is blended with other lines. The lines in this system are marginally resolved at the resolution of our observations (~250 km s^{-1}).

In addition to the narrow features, the UV spectrum of PG 2302+029 includes three broad features centered at 2626.52, 2103.24, and 1750.49 Å (blended with 1773.86 Å). Impey et al. (1996) noted the 2626 Å feature but did not offer an identification. The G190H spectrum revealed two broad absorption features that, when combined with the line in the G270H spectra, allowed us to identify these features as broad (or heavily blended) C IV, N V, and O VI at $z \sim 0.695$. In Figure 2, we display the broad and narrow systems near $z = 0.7$ on a velocity scale zeroed on the center of the broad C IV absorption. Unlike the narrower system at $z = 0.7016$, we identify no Lyα absorption associated with the broad system. The broad features have widths (FWHM) ranging from ~3000 km s^{-1} for C IV and N V to ~5000 km s^{-1} for O VI.

We can place limits on the amount of absorption that might be present from broad components of Lyα, C III (977.03 Å), Si III (1206.51 Å), and Si IV (1393.76, 1402.77 Å). However, our limits are very uncertain since the detection of weak, broad absorption is very sensitive to the placement of the continuum. Placement of the continuum is complicated by the broad emission lines from the quasar and the low signal-to-noise ratio in some regions of the spectra. Assuming that additional broad components of the $z \sim 0.695$ system would have widths comparable to those already observed, we place the following 3 σ limits on the equivalent widths of broad absorption: Lyα < 6 Å, C III < 5 Å, Si III < 5 Å, and Si IV < 3 Å. No low-ionization lines associated with either the broad or narrow systems described above (e.g., from Si II, S II, Fe II, C II, O I, Al II, N I, Mg II, or Mg I) are present in the FOS (no unresolved lines with $W > 0.4$ Å) or optical spectra (Petitjean & Bergeron 1990; Steidel & Sargent 1992).

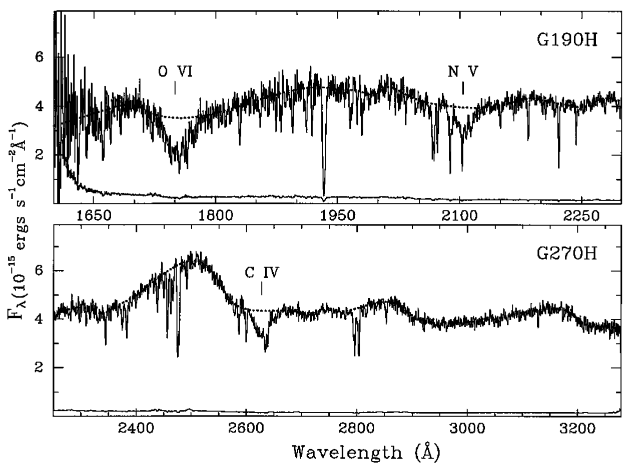

FIG. 1.—Ultraviolet spectra of PG 2302+029 obtained with the FOS of the *HST*. Each panel contains a single spectrum obtained with the indicated grating (G270H, G190H) and the Red digicon detector. G190H and G270H observations were obtained with the 0".26 and 0".86 circular apertures, respectively. Dotted line is the "continuum" fit; see § 2 and Schneider et al. (1993). Lower line in each panel is the 1 σ uncertainty in the flux as a function of wavelength.

3. DISCUSSION

We have considered three possible causes for the broad complex of high-ionization absorption observed at $z_{abs} \sim 0.7$ in the spectrum of PG 2302+029: (1) absorption by material ejected from the QSO with an extremely high ejection velocity (56,000 km s^{-1}) but no low velocity absorbing gas along the line of sight; (2) absorption by material in the galaxies or intergalactic medium of a cluster or supercluster of galaxies; and (3) absorption by gas in a supernovae remnant in a galaxy at a redshift of about 0.7. With the current observations we cannot make a definite choice between these alternatives. The third suggestion might produce a broad velocity profile similar to what we observe. The narrow high-ionization system that is resolved from the broad system might then be a galaxy associated with the host galaxy of the supernovae (the centers of the broad system's lines and of the detected narrow system are more than 1500 km s^{-1} apart) or a chance coincidence. In the remainder of this section, we consider the other two suggested causes of the broad high-ionization system.

PG 2302+029 and its broad absorption system have several similarities to BALQSOs. Wampler (1986) demonstrated that

TABLE 2

PG 2302+029 (z = 1.052) SELECTED REDSHIFT SYSTEMS

λ_{obs} (Å)	$\sigma(\lambda)$ (Å)	W_{obs} (Å)	$\sigma(W)$ (Å)	SL[a]	FWHM (Å)	LINE ID Ion	LINE ID (Å)	$\Delta\lambda$ (Å)	z_{obs}
1750.49.......	0.07	12.56	0.65	144.88	28.02	O VI Bl	1034.79	−3.58	0.695
1773.86.......	0.44	1.13	0.27	17.71	6.05	O VI? Bl	1034.79	19.79	0.695
2103.24.......	0.55	5.67	0.25	147.11	24.23	N V Bl	1240.81	0.00	0.695
2626.52.......	0.83	6.34	0.43	130.00	26.20	C IV Bl	1549.49	0.00	0.695
1661.55.......	0.15	1.75	0.17	17.10	3.29	C III? Bl	977.03	−0.95	0.7016
1755.75.......	0.15	0.54	0.11	6.83	2.08	O VI	1031.95	−0.18	0.7016
1765.20.......	0.14	0.66	0.14	8.26	1.83	O VI	1037.63	−0.39	0.7016
2068.50.......	0.06	1.06	0.09	25.40	1.75	Lyα	1215.67	−0.03	0.7016
2107.92.......	0.16	0.23	0.06	7.01	1.65	N V	1238.82	−0.01	0.7016
2113.85.......	0.22	0.35	0.08	10.59	2.51	N V	1242.80	−0.84	0.7016
2634.53.......	0.12	0.66	0.10	13.60	2.85	C IV	1548.20	0.18	0.7016
2638.72.......	0.12	0.45	0.09	9.30	2.06	C IV	1550.77	0.00	0.7016

[a] SL is the significance level of the line; defined to be the measured equivalent width (W) divided by the 1 σ uncertainty in the measurement of an unresolved line at the same wavelength. See Schneider et al. 1993 for complete discussion.

the spectrum of PG 2302+029, particularly its very strong Fe II emission, is remarkably similar to the well-known BALQSO PG 1700+518. Typical of BALQSO absorption systems, the PG 2302+029 z = 0.695 system is composed of high-ionization species and covers a large spread in velocity (more than 3000 km s^{-1}). BALQSOs usually also have detected Si IV and Lyα absorption, but this is not always the case. When these lines are present they are generally weaker than N V and O VI. There are other unusual features about the PG 2302+029 absorption if it is produced by ejected material. First, the absorption troughs of most BALQSOs begin at or close to the systemic velocity of the broad emission line region (BELR) and extend blueward to higher velocities, generally stopping by 25,000 km s^{-1} (see Fig. 9 in Korista et al. 1993). Korista et al. (1993) demonstrate that the typical BALQSO absorption velocity profiles are asymmetric with the strongest absorption at the lowest ejection velocities, decreasing in strength with increasing blueshift from the BELR. In contrast, the PG 2302+029 broad system is detached from the velocity of the BELR by at least 50,000 km s^{-1}, and each component is well fit by a Gaussian (i.e., a symmetric function).

While the PG 2302+029 broad system is not typical of BALQSOs, it does share characteristics with a system that is produced by material ejected from a QSO. Sargent, Boksenberg, & Steidel (1988) identified a broad feature in the spectrum of Q2343+125 (FWHM ~ 1000 km s^{-1}, but not broad enough for Q2343+125 to be considered a BALQSO), which they interpreted as a detached C IV doublet (z_{abs} = 2.24) ejected at a velocity of 23,000 km s^{-1} from the QSO (z_{em} = 2.515). As is the case for PG 2302+029, there are no broad absorption features close to the emission redshift of Q2343+125. Keck HIRES spectra analyzed by Hamann, Barlow, & Junkkarinen (1996) reveal dramatic variations over a period of months in the strength of the Q2343+125 broad absorption features, confirming that the absorption is produced by ejected material. Like the PG 2302+029 broad system, the Q2343+125 system lacks any associated low-ionization absorption (Lyα would be blended with the high-redshift Lyα forest, but Hamann et al. indicate that any Lyα absorption is still weak). While the observed broad system in PG 2302+029 is significantly different from any system identified in a BALQSO, it is similar to the system observed in Q2343+125 and might be produced by material ejected from a QSO. If both the broad and narrow systems near z = 0.7 are produced by ejected material, they will evolve with time, with the broad component losing its prominence. This raises the possibility that older versions of such systems might appear as "normal" narrow intervening systems.

Could the PG 2302+029 broad absorption system with its velocity span of more than 3000 km s^{-1} be produced by some

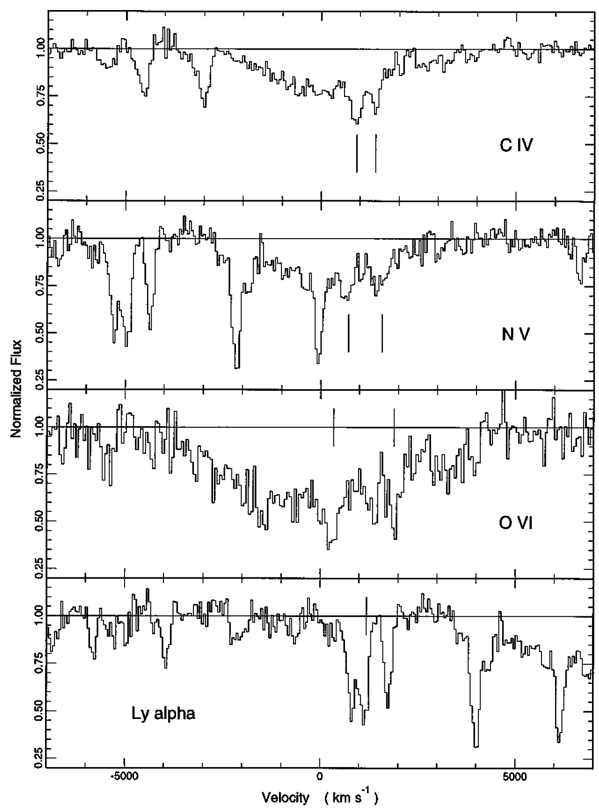

FIG. 2.—Regions of the *HST* FOS spectra containing the broad absorption by C IV, N V, O VI, and the expected position for absorption by Lyα are plotted on a velocity scale with zero velocity corresponding to z = 0.6951. Location of the C IV, N V, O VI, and Lyα absorption lines from the narrower z_{abs} = 0.7016 system are indicated with vertical tick marks on the figure.

kind of large-scale structure? The range of velocities observed for the PG 2302+029 broad absorption system is similar to that over which we reported clustering of Lyα absorbers around extensive metal line systems (Bahcall et al. 1996). The PG 2302+029 broad absorption system is also very similar to a broad system in Q1038−2712, which is most probably produced by gas associated with some large-scale structure, perhaps a supercluster of galaxies. One of the two QSOs composing the "Tololo Pair" (see § 1), Q1038−2712 has a broad absorption system at $z_{abs} = 2.08$ that is matched by similar systems in the spectra of other QSOs in the same field. Jakobsen et al. (1986), Sargent & Steidel (1987), and Dinshaw & Impey (1996) use energy arguments to conclude that it is unlikely for material ejected from one of these quasars to produce the apparently correlated absorption along these multiple lines of sight, and therefore the observed broad and complex absorption is produced by gas associated with a supercluster of galaxies. When the C IV absorption complexes in these QSOs are observed at $\sim$30 km s^{-1} resolution (Dinshaw & Impey 1996), most are resolved into multiple C IV doublets, as expected if the absorption is produced by gas associated with the halos of individual members of a group of galaxies. The exception is the $z_{abs} = 2.08$ system in Q1038−2712, which remains smooth and broad. Dinshaw & Impey (1996) speculate that this line of sight might be passing through a cooling flow associated with the core of a cluster and/or group of galaxies.

Like the systems in the "Tololo Pair," the high-ionization absorption systems in PG 2302+029 span a large velocity extent and reveal some substructure. However, unlike the PG 2302+029 system, the "Tololo Pair" systems all have associated low-ionization absorption lines (e.g., Si II, O I; Sargent & Steidel 1987), which might be expected if the lines of sight pass through the halos and disks of galaxies. The broad absorption systems seen in the spectra of the "Tololo Pair" are imperfect analogues to the PG 2302+029 broad system, and we cannot be certain that the latter is caused by absorption by gas in a cluster or supercluster of galaxies.

The observed levels of ionization of the broad system may place interesting constraints on the ionization mechanism and metallicity of the absorbing material. These would be aids in identifying the nature of the absorbing gas. If collisional ionization dominates, temperatures between 150,000 and 300,000 K would be consistent with our limits on Lyα/O VI and Lyα/N V, but the Lyα/C IV limit might be more difficult to explain unless the metallicity is slightly enhanced with respect to solar, especially if we are dealing with cooling behind a shock front (cf. Schmutzler & Tscharnuter 1993). Photoionization mechanisms are consistent with our observations, but until detections or better limits on other ions (especially C III, Si III, Si IV, and Lyα) are obtained, the constraints are not very useful (see Turnshek et al. 1996 for an example of the use of such measurements to constrain the ionization mechanisms and metallicities of the absorbing gas in BALQSOs).

A variety of subsequent observations might allow us to determine what is producing the broad system in PG 2302+029. Higher resolution spectroscopy of the quasar, multiband imaging and spectroscopy of galaxies in the field, and X-ray observations of the field might each provide evidence of a cluster or supercluster of galaxies at $z \sim 0.695$ and help confirm the interpretation of the absorption features as tracers of large-scale structure. Detection of variability in the strength of the broad system of PG 2302+029 would provide strong evidence that this system is produced by ejected material.

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REFERENCES

Bahcall, J. N., et al. 1993, ApJS, 87, 1
———. 1996, ApJ, 457, 19
Bahcall, J. N., & Salpeter, E. E. 1965, ApJ, 142, 1677
Dinshaw, N., & Impey, C. D. 1996, ApJ, 458, 73
Ford, H. C., & Hartig, G. F. 1990, Faint Object Spectrograph Instrument Handbook (Baltimore: STScI)
Hamann, F., Barlow, T., & Junkkarinen, V. 1996, private communication
Impey, C., Malkan, M. A., Webb, W., & Petry, C. E. 1995, ApJ, 440, 80
Impey, C., Petry, C. E., Malkan, M. A., & Webb, W. 1996, ApJ, 463, 473
Jakobsen, P., & Perryman, M. A. C. 1992, ApJ, 392, 432
Jakobsen, P., Perryman, M. A. C., Ulrich, M. H., Machetto, F., & Di Serego Alighieri, S. 1986, ApJ, 303, L27
Kellermann, K. I., Sramek, R., Schmidt, M., Shaffer, D. B., & Green, R. 1989, AJ, 98, 1195
Korista, K. T., Voit, G. M., Morris, S. L., & Weymann, R. 1993, ApJS, 88, 357
Petitjean, P., & Bergeron, J. 1990, A&A, 231, 309
Sargent, W. L. W., Boksenberg, A., & Steidel, C. C. 1988, ApJS, 68, 539
Sargent, W. L. W., & Steidel, C. C. 1987, ApJ, 322, 142
Schmutzler, T., & Tscharnuter, W. M. 1993, A&A, 273, 318
Schneider, D. P., et al. 1992, PASP, 104, 678
———. 1993, ApJS, 87, 45
Steidel, C. C., & Sargent, W. L. W. 1991, ApJ, 382, 433
Steidel, C. C., & Sargent, W. L. W. 1992, ApJS, 80, 1
Turnshek, D. A. 1995, in ESO Workshop, QSO Absorption Lines, ed. G. Meylan (Berlin: Springer), 223
Turnshek, D. A., Kopko, M., Jr., Monier, E., Noll, D., Espey, B. R., & Weymann, R. J. 1996, ApJ, 463, 110
Wampler, E. J. 1986, A&A, 161, 223
Weymann, R., Morris, S. L., Foltz, C. B., & Hewett, P. C. 1991, ApJ, 373, 23