STIS Spectroscopy of PKS 0405-123

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We present results for QSO PKS 0405–123 \((z = 0.574, V = 14.9)\), as part of a STIS Investigation Definition Team (IDT) key project to study weak Ly\(\alpha\) forest systems at low \(z\). We detect 59 (47) Ly\(\alpha\) absorbers at 4.0\(\sigma\) significance to an 80\% completeness limit of column density \(\log(N_{\text{HI}}) = 13.3 (13.1)\) for Doppler parameter \(V_{\text{Dop}} = 40 \text{ km s}^{-1}\) over \(0.002 < z < 0.423\) \((0.020 < z < 0.234)\). We find 4 intervening O\(\text{VI}\) systems, useful for studies of hot intergalactic gas. We do not distinguish between metal and Ly\(\alpha\)-only systems in the following analysis.

The redshift density is consistent with previous measurements for \(\log N_{\text{HI}} \geq 14.0\), but exhibits twice as many systems at \(13.1 < \log N_{\text{HI}} < 14.0\) compared to the mean number density of lines at \(z < 0.07\) toward 15 extragalactic objects. The difference possibly arises from cosmic variance. The Doppler parameter distribution has \(\langle V_{\text{Dop}} \rangle = 48 \pm 21 \text{ km s}^{-1}\); line blending possibly inflates the value. We find evidence for Ly\(\alpha\)-Ly\(\alpha\) clustering in our sample on a scale of \(\Delta v \leq 250 \text{ km s}^{-1}\), and there is evidence for a void at \(0.032 < z < 0.081\) with probability \(P = 0.0005\). We find line-of-sight velocity correlations of up to 250 km s\(^{-1}\) between Ly\(\alpha\) absorbers with \(\log(N_{\text{HI}}) \geq 13.1\) and 45 galaxies taken from the literature and unpublished data at \(0 < z < 0.47\); the transverse distances cover up to 1.5 \(h_{70}^{-1}\) Mpc in the local frame. The Ly\(\alpha\)-galaxy clustering is stronger for higher \(\log(N_{\text{HI}})\) systems.

1 Introduction

PKS 0405–123 \((V = 14.9, z = 0.574)\) is one of the brightest QSOs in the sky, and illuminates a much longer span of the Ly\(\alpha\) forest than most of the other QSOs of similar or brighter magnitude. It is therefore a prime target for studies of the low \(z\) Ly\(\alpha\) forest and metal absorbers and mid-latitude \((\ell = 295^\circ, b = -42^\circ)\) studies of Galactic absorption. We use \(\sim 7 \text{ km s}^{-1}\) resolution STIS data to calculate the Ly\(\alpha\) forest redshift density, Doppler parameter, clustering and void statistics, and to cross-correlate the Ly\(\alpha\) forest and field galaxy redshifts.
2 Observations, reductions and absorber sample

PKS 0405–123 was observed with HST+STIS using grating E140M for ten orbits (27208 sec) on 1999 Jan 24 and 1999 Mar 7. We used the 0.2″ × 0.06″ slit for maximal spectral purity. The data were reduced and extracted using STIS IDT team software at Goddard Space Flight Center. We constructed a continuum using a combination of automated AUTOVP by R. Davé and interactive LINE_NORM by D. Lindler, as the regions around emission lines were problematic. Absorption features were selected at the 4.0σ significance level with a Gaussian filter, with half-widths of 10, 15, 20 pixels (~3 km s⁻¹/pixel), and confirmed with a simple equivalent width significance criterion for contiguous absorption pixels.

Williger and R. Carswell (IOA, Cambridge) independently profile-fitted the data with vp-fit (Webb 1987) using Voigt profiles convolved with the STIS line spread function, with largely consistent results. We then analyzed 1440 simulated Lyα lines to determine the 80% completeness limit, parametrized by \( \log N_{\text{HI}} = 12.870 + 0.344 \log(V_{\text{Dop}}/24.7) - 1.012 \log(\text{snr}/7) \) for signal to noise ratio (per pixel) snr. We define two samples, one for HI column density threshold \( \log(N_{\text{HI}}) \geq 13.3 \) \((0 < z < 0.423, 59 \text{ Lyα absorbers})\) and one for \( \log(N_{\text{HI}}) \geq 13.1 \) \((0 < z < 0.234, 47 \text{ absorbers})\). The column density of the partial Lyman limit system at \( z = 0.1671 \) was fixed at the value derived by Prochaska et al. (2003) from FUSE observations.

In addition to H I lines, we find many metal absorption lines. Intervening systems are at \( z = 0.167 \) (C II, Fe II, III; N II, V; O I, VI; Si II, III, IV); \( z = 0.1829 \) (O VI); \( z = 0.3608 \) (Si III, C IV); \( z = 0.3633 \) (O VI); \( z = 0.4951 \) (C III, O VI). We find Galactic absorption from Al II, C I, II, II*, IV; Fe II, N I, Ni II, O I, P II, S II, III; Si II, II, III, IV. All Galactic absorption is at \(-58 < v < 37 \text{ km s}^{-1}\), so there is no evidence for any high-velocity clouds.

3 Lyα forest statistics

We examine the Lyα forest redshift density \( dN/dz \), Doppler parameter distribution, clustering via the two point correlation function and the void distribution for the two subsamples with \( \log N_{\text{HI}} \geq 13.3, 13.1 \).

The Lyα forest redshift density has been studied intensively for over 20 years. We compare our data against recent VLT UVES observations (Kim et al. 2002) and the literature, and find a consistent value for \( 14.0 < \log N_{\text{HI}} < 17.0 \) at \( z \sim 0.2 \) (Fig. 1). However, for \( 13.1 < \log N_{\text{HI}} < 14.0 \) the redshift density varies by a factor of two compared to measurements at \( z < 0.07 \) with GHRS toward 15 extragalactic objects (Penton et al. 2000). Cosmic variance may produce the discrepancy, though the path length in this work of 600 \( h^{-1} \text{ Mpc} \) at 0.020 < \( z < 0.234 \) \((H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}, \Omega = 0.3, \Lambda = 0.7)\) is large for such a variation.

The Doppler parameter distribution for \( \log N_{\text{HI}} \geq 13.3 \) (13.1) has mean, median and standard deviation \( \langle V_{\text{Dop}} \rangle = 48 \) (45), 47 (45) ± 21 (20) \text{ km s}^{-1}. The large mean arises from a tail at large values, which likely results from unresolved blends.

Clustering in the Lyα forest has been studied in a number of cases (Janknecht et al. 2002 and references therein), with weak clustering indicated on velocity scales of \( \Delta v < 500 \text{ km s}^{-1} \). We use the two point correlation function \( \xi(\Delta v) \equiv [n_{\text{obs}}(\Delta v)/n_{\text{exp}}(\Delta v)] - 1 \) where \( n_{\text{obs}} \) and \( n_{\text{exp}} \) denote the observed and expected numbers of systems in a relative velocity interval \( \Delta v \). We created \( 10^4 \) Monte Carlo simulations weighted in \( z \) using \( dN/dz \propto (1+z)^\gamma \), \( \gamma = 0.26 \) (Weymann et al. 1998). For each simulation we drew a number of absorbers from a Poissonian distribution with a mean equal to the number actually observed in our sample. We find a signal for \( \log N_{\text{HI}} \geq 13.2 \) at \( \Delta v < 250 \text{ km s}^{-1} \) of \( \xi(\Delta v) = 1.3 \), with 15 pairs observed and 6.49 ± 2.71 expected (Fig. 2), which has probability \( P = 0.006 \) to be matched or exceeded by the simulations. The signal weakens at higher \( \log N_{\text{HI}} \), likely suffering from small number statistics, and at \( \log N_{\text{HI}} \geq 13.1 \), perhaps as a reflection of weaker clustering among weaker perturbations.
We searched for regions in velocity space devoid of Lyα systems using the same $10^4$ Monte Carlo simulations, and find evidence for a void at $0.0320 < z < 0.0814$ ($\Delta v = 14023$ km s$^{-1}$) for $N_{\text{HI}} \geq 13.3$ with probability $P = 0.0005$ to be matched or exceeded among over $5.7 \times 10^5$ Lyα absorber spacings. For $N_{\text{HI}} \geq 13.2$, we find two voids of similar significance at $0.0320 < z < 0.0590$ and $0.1030 < z < 0.1310$ ($\Delta v = 7744, 7512$ km s$^{-1}$, $P = 0.005$), while for $N_{\text{HI}} \geq 13.1$, the lower redshift void persists ($0.0320 < z < 0.0590$, $P = 0.002$).

4 Lyα-galaxy correlations

Spinrad et al. (1993) and Ellingson & Yee (1994) surveyed for galaxies in a $10 \times 8$ arcmin$^2$ field around PKS 0405–123. Data from the NASA Extragalactic Database (NED) and unpublished data from E. Ellingson provide a list of 45 galaxies at $z < 0.47$ (Fig. 3a) covering $17.75 < r < 22.94$ ($\langle r \rangle = 20.8 \pm 1.1$, $\langle M_r \rangle = -19.9 \pm 1.7$ from the distance modulus for $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega = 0.3$, $\Lambda = 0.7$), with redshifts for a further 34 galaxies out to $z = 0.78$. The spectroscopic completeness is difficult to judge accurately because some of the objects are stars and there were positional selection constraints from the multi-slit spectroscopic setup; for $r < 22.0$ we have spectroscopic redshifts for 36 of 213 objects (17%).
We cross-correlated our galaxy sample with the Lyα forest, including all galaxies within 1.5\,h_{70}^{-1}\,Mpc in the local frame. There is a signal at $\Delta v \leq 250\,\text{km\,s}^{-1}$ (Fig. 3b, $\xi(\Delta v) = 2.0$, 5.3$\sigma$ significance, 35 pairs observed, $11.8 \pm 4.3$ expected) which comes from higher $N_{\text{HI}}$ absorbers. The signal is still detectable for $\log N_{\text{HI}} \geq 14.4$, and persists to $\log N_{\text{HI}} \geq 13.1$, though at 3.0$\sigma$ significance (14 pairs observed, $5.8 \pm 2.7$ expected). There is an apparent cluster around the $z = 0.1671$ partial Lyman limit system, with another around the metal absorbers at $z \approx 0.36$. There is also only one galaxy (at $z = 0.0791$) in any of our listed Lyα forest voids. Bowen et al. (2002) suggested a correlation between the density of Lyα components along a sightline and the volume density of $M_B < -17.5$ galaxies within $\sim 2\,\text{Mpc}$. Although our data are highly incomplete, they appear consistent with this hypothesis. The field around PKS 0405-123 provides an excellent opportunity to explore the galaxy-Lyα absorber relationship in detail.

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