ASCA Observation of the Lyman-limit Quasar PKS2145+067

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Abstract

X-ray observation of a famous Lyman-limit quasar PKS2145+067 at \( z_{em} = 0.990 \) was carried with ASCA. The source showed a 2-10 keV flux of \( 1.3 \times 10^{-11} \text{ erg cm}^{-2} \text{ sec}^{-1} \) \( (L_X = 2.5 \times 10^{46} \text{ erg s}^{-1} \) for \( H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1} ) \) described by a power-law spectrum with a photon index \( \Gamma = 1.63 \pm 0.04 \). In the ASCA energy band, no excess absorption was detected implying the absorption column density at \( z_{ab} = 0.791 \) was less than \( 1.6 \times 10^{21} \text{ cm}^{-2} \) if absorbing medium had a metal abundance of 0.5 solar. Comparison with previous Einstein and ROSAT observations shows that PKS2145+067 has increased its luminosity by a factor of 2~3 between 1991 and 1998.

Key words: Galaxies: intergalactic medium — Quasars — X-rays: spectra

1. Introduction

PKS2145+067 \( (4C +06.69, [\alpha_{2000}, \delta_{2000}] = [21h48m05s,06\degree57'39'']) \) is an X-ray luminous AGN at \( z_{em} = 0.990 \) and is known to show a Lyman limit system at \( z_{abs} = 0.791 \) which accompanies many metal lines indicating low and high ionization states (C III, C IV, N III, N V, O VI, Si III, Si IV, and Mg II) (Bahcall et al. 1993, Bergeron et al. 1994). The source is a radio-loud QSO and is classified as a flat-spectrum radio quasars (FSRQ) (see ex. Padovani 1992). The polarization of this quasar is as low as \( 1.0 \pm 0.6 \% \) (Visvanathan & Wills 1998), and a submilliarcsecond imaging by the Very Long Baseline Array (VLBA) at 15GHz does not detect any jet-like structure (Kellermann et al. 1998).

The Lyman limit system exhibits a neutral hydrogen column density as large as \( N(\text{HI}) = 3.2 \times 10^{17} \text{ cm}^{-2} \) \( (1.6 \times 10^{16} \leq N(\text{HI}) \leq 6.3 \times 10^{17} \text{ cm}^{-2} ) \) with a Doppler parameter \( b \) of \( 35 \leq b \leq 63 \text{ km s}^{-1} \) (Bergeron et al. 1994). An
associated galaxy is identified at $55h^{-1}_{100}$ kpc away from the line of sight (Bergeron & Boissé 1991) and is considered to be in star formation activity. The co-existence of the absorption lines from a low-ionized element Mg II and a high-ionized O VI suggest that there are at least two states of clouds with different densities. Based on the detailed observational results, Bergeron et al. (1994) constructed a two-phase photo-ionized cloud model. The inner core zone which exhibits Mg II absorption doublet has an intermediate dimension ($\sim 7$ kpc) with a density of $n_H \sim 6 \times 10^{-3}$ cm$^{-3}$ and a temperature of $T \sim 1.2 \times 10^{4}$ K. The outer O VI phase is homogeneous, with a lower density $n_H \sim 3 \times 10^{-4}$ cm$^{-3}$, with a high temperature of $T \sim 2.5 \times 10^{4}$ K and of a large extent ($\sim 70$ kpc). The total mass of the gas is $10^9 M_\odot$ and the common metal abundance is about half the solar value. The average neutral hydrogen fraction is HI/H = $3 \times 10^{-3}$ at the core and the neutral and ionized hydrogen column density is $N_H = 1.7 \times 10^{20}$ cm$^{-2}$.

Considering the similarity in the size, temperature and high metal abundance, a link between the O VI phase gas and a group of galaxies is suggested (Bergeron et al. 1994). A Gunn-Peterson test using HST FOS detect an absorption trough with $\tau_{GP-HI} = 0.12 \sim 0.14$, which corresponds to an over-density by a factor of 3–7 in the intergalactic medium near $z \sim 0.8$ (Khersonsky et al. 1997).

If there is such a hot and dense intervening cloud in the line of sight, ionized heavy elements could produce absorption features in the X-ray spectrum. We observed PKS2145+067 with ASCA (Tanaka et al. 1994) to search for an evidence of this hot intervening cloud using X-ray absorption features. The observation was performed on 5th December 1998 with a net exposure time of 36 ksec with GIS and 29 ksec with SIS, respectively. The observation mode was nominal PH mode for GIS (Ohashi et al. 1996, Makishima et al. 1996) and 1CCD FAINT mode for SIS.

In this paper, we assume $H_0 = 50$ km sec$^{-1}$ Mpc$^{-1}$ and $q_0 = 0.5$ and the solar number abundances of the elements are followed by Anders & Grevesse (1989).

### 2. Analysis & Results

#### 2.1. Energy Spectrum of PKS2145+067

The source has been clearly detected with all the four detectors of ASCA. To make the energy spectra, we applied the standard data reduction criteria for the data and integrated the photons within a radius of 6 arcmin from the source. Then we subtracted recent blank sky data in the same observation mode to correct for both the cosmic X-ray background and non-X-ray background. For the GIS background, a 80 ksec deep survey observation of the
Lockman hole carried out in November 1998 (PI: Y. Ishisaki) is used. As for the SIS background, we used 1CCD FAINT mode data taken in the L1157 observation in September 1998 (PI: T. Furusho), in which L1157 dark cloud containing a class 0 proto-star has not been detected in X-ray band (Furusho et al. 2000). Since the background data were taken within 3 months before the QSO observation, the long-term variation of the detector background and performances does not cause a problem in the subtraction process. In the L1157 data, selection of the same event discrimination level yields a net exposure time of the background to be 10.9 ksec. However, the data still have better photon statistics than using the annular region of the on-source SIS data because we can maximize the on-source integration area. In both GIS and SIS cases, S/N ratios are larger than 5 in all energy bands, and the total flux uncertainty due to the fluctuation of the background is less than 1%.

The derived spectra after the background subtraction are shown in figure 1. To avoid the uncertainty in the SIS response matrix which tends to cause a systematic excess absorption of a few times $10^{20}$ cm$^{-2}$ (Cappi et al. 1998) due to the drop of the detection efficiency below 1 keV (see web pages of ASCA GOF, [http://heasarc.gsfc.nasa.gov/docs/asca/watchout.html](http://heasarc.gsfc.nasa.gov/docs/asca/watchout.html)), we use only the data between 1.0 keV and 10.0 keV for SIS, while the GIS data are used between 0.6 keV and 10.0 keV. Spectral fitting package XSPEC ver 10.0 is used for the model fitting throughout this paper. We fit the SIS and GIS data simultaneously and minimize the sum of the $\chi^2$ assuming an absorbed power-law model.

As for the absorber model, we first assume the interstellar matter in our Galaxy represented by a XSPEC “wabs” model at $z = 0$, which is the photoelectric absorption with a metal abundance of one solar (Morrison & McCammon 1983). All the data from SIS and GIS are consistent with each other and well described by a power-law with interstellar absorption. The resultant parameters are summarized in table 1. The absorption column density $N_H$ is consistent with the Galactic value of $4.8 \times 10^{20}$ cm$^{-2}$ (Dickey & Lockman 1990). A 90 % upper limit for the equivalent width of an iron-K emission line, assuming a narrow ($\sigma < 500$ eV ) Gaussian line at 6.4 keV in the quasar frame ($z = 0.990$) is 50.4 eV. The total flux between 2 and 10 keV in the observer frame is $1.3 \times 10^{-11}$ erg cm$^{-2}$ sec$^{-1}$ which corresponds to the luminosity $L_{\text{X}:2-10\text{keV}} = 2.5 \times 10^{46}$ erg sec$^{-1}$ assuming $H_0 = 50$ km sec$^{-1}$ Mpc$^{-1}$ and $q_0 = 0.5$. 
### Table 1. The spectral parameters of PKS2145+067

| Model                        | $N_H(z=0)$ (10^{20} cm^{-2}) | $\Gamma$       | $F_X:(2-10\text{keV})$ (erg cm^{-2}sec^{-1}) | $\chi^2$/dof |
|------------------------------|------------------------------|----------------|-----------------------------------------------|--------------|
| wabs×power-law               | 4.1^{+2.7}_{-2.6}            | 1.63±0.04      | 1.3×10^{-11}                                 | 792.7/853    |
| wabs×zwabs(z=0.791)×power-law| 4.8(fixed)                  | <8.5           | 1.64^{+0.03}_{-0.02}                         | 1.3×10^{-11} | 792.6/853 |

#### 2.2. Upper limit for the absorption at $z=0.791$

We added an additional absorption component at $z=0.791$ in the model and fit the spectra again. The assumed model is described by a formula; $\text{wabs} \times \text{zwabs} \times \text{a power-law}$. The “$\text{wabs}$” model again represents the absorption by the interstellar matter in our Galaxy and the column density $N_H$ is fixed to the Galactic value of $N_H = 4.8 \times 10^{20}$ cm$^{-2}$. The “$\text{zwabs}$” model is a redshifted “$\text{wabs}$” model, which stands for the absorption by neutral matter with an abundance of 1 solar. In this fit, we fixed the redshift of “$\text{zwabs}$” to be $z=0.791$ assuming its association to the Lyman limit clouds. The fitting results are also listed in table 1. The 90 % upper limit for the absorption column at $z=0.791$ is $8.5 \times 10^{20}$ cm$^{-2}$. A contour plot of the photon index $\Gamma$ vs. the absorption column density $N_H$ at $z=0.791$ is shown in figure 2.

For the next step, we assumed that the metal abundance in the absorbing matter at $z=0.791$ is less than the solar level. We adopted a variable abundance photoelectric absorber using the XSPEC model of “$\text{zvphabs}$” (Balucinska-Church & McCammon 1992), therefore, the model spectrum is described by the following formula; $\text{wabs}(N_H = 4.8 \times 10^{20}$ cm$^{-2}$ fixed) $\times \text{zvphabs} (z=0.791) \times \text{power-law}$. In this fit, all the elements are assumed to have a common abundance, except for He which has an abundance of 1 solar. In figure 3, we plot upper limits of the absorption column density as a function of the metal abundance. If the metal abundance is 0.5 solar, the 90 %
upper limit of the X-ray absorption column is $1.6 \times 10^{21}$ cm$^{-2}$. This does not contradict with the two-phase model ($N_H = 1.7 \times 10^{20}$ cm$^{-2}$) by Bergeron et al. (1994).

We further searched for absorption features due to discrete elements, for which ASCA data have good sensitivity. We added a redshifted absorption edge of Si. In the photo-ionized cloud model of Bergeron et al. (1994), the most dominant population of Si is Si VII in the hot halo and Si III in the core. These ions produce a Si III edge at 1852 eV (in the rest frame) of Si III and a Si VII edge at 2001 eV which can be tested in the ASCA sensitivity band.

Again, we fitted the energy spectra with a absorbed power-law and an edge structure model given by the following formula: $w_{abs} (N_H = 4.8 \times 10^{20}$ cm$^{-2}$ fixed) $\times$ “edge” (redshifted K-edge) $\times$ power-law. The 90\% upper limits for the optical depth of the edges are $\tau < 0.15$ for 1852 eV (at $z = 0.791$) Si III edge and $\tau < 0.08$ for 2001 eV Si VII edge. These optical depths correspond to column densities of $9.7 \times 10^{17}$ cm$^{-2}$ and $6.3 \times 10^{17}$ cm$^{-2}$ for Si III and Si VII ions (Verner et al. 1994), or assuming 0.5 solar abundances, the upper limits for the total hydrogen column density of $5.4 \times 10^{22}$ cm$^{-2}$ and $3.5 \times 10^{22}$ cm$^{-2}$, respectively.

### 2.3. Comparison with previous X-ray observations

We compared the flux of PKS2145+067 with the previous X-ray results. *Einstein IPC* observed the quasar in May 5th 1980. Wilkes et al. (1994) report the flux between 0.16 and 3.5 keV to be $3.8 \times 10^{-12}$ erg cm$^{-2}$ sec$^{-1}$ assuming a photon index of 1.5. This is about 1/3 of the level, $F_{X:0.16-3.5keV} = 1.1 \times 10^{-11}$ erg cm$^{-2}$ sec$^{-1}$, estimated from the extrapolated spectrum of the ASCA observation (wabs $\times$ power-law) without excess absorption. *ROSAT PSPC* also observed the quasar on 9th May 1991 and the flux between 0.1 and 2.0 keV is $3.3 \times 10^{-12}$ erg cm$^{-2}$ sec$^{-1}$ (Perlman et al. 1998), which is about half of the extrapolated ASCA level ($F_{X:0.1-2keV} = 7.1 \times 10^{-12}$ erg cm$^{-2}$ sec$^{-1}$).

These flux comparison suggests two possibilities; the first is that the X-ray luminosity of PKS2145+067 has become higher in 10 years by a factor of 2~3. The radio flux of the source was monitored at 318 and 430 MHz between 1980 and 1994 and showed little variation only by 7\% rms (Salgado et al. 1999). Sambruna (1997) compile *ROSAT* results and report that typical X-ray flux variation of flat-spectrum radio quasars (FSRQs) on timescales of months/years does not exceed a factor of 2, characterized by a typical amplitude of the order of 10~30\% with no accompanying spectral changes. If the X-ray flux of PKS2145+067 has really varied by a factor of 3, this amplitude is the largest among the reported FSRQ variations.

The second possibility is that the energy spectrum is strongly cut off below the ASCA energy limit of 0.6 keV.
Unfortunately, the spectral information from ROSAT and Einstein observations is not available. We added an excess absorption in the fitting model to suppress the extrapolated flux in the low energy band to be consistent with the previous results. In this case, however, the required excess absorption becomes larger than \(10^{22}\) cm\(^{-2}\) using the zvphabs model at \(z = 0.791\) with a metal abundance of 0.5 solar. This is significantly larger than our upper limit of \(1.6 \times 10^{21}\) cm\(^{-2}\). So it seems unlikely that the flux difference between ASCA and the previous soft X-ray observations is only caused by a strong absorption associated with the Lyman limit clouds. It is, therefore, more plausible that the intrinsic luminosity of PKS2145+067 has increased by a factor of 2~3 in these 10 years.

3. Discussion & Conclusion

ASCA observation of PKS2145+067 shows that the 0.6–10 keV spectrum is well described by a power-law model (\(\Gamma = 1.6\)) absorbed by the Galactic interstellar absorption. An upper limit for the \(z = 0.791\) absorbing cloud is \(N_H < 1.6 \times 10^{21}\) cm\(^{-2}\) (90 \% U.L.).

These results are consistent with the two-phase ionized cloud model by Bergeron et al. (1996). However, to obtain a simple view of the absorbing cloud, we calculated simple one-phase photoionization models using CLOUDY ver 94.00 (Ferland 1993, van Hoof et al. 2000). We studied the requirement for the UV radiation field which satisfies the upper limit of the total hydrogen column density. We assume the absorber cloud to be a plane-parallel slab of constant density, illuminated on both sides by an ionizing radiation field. The density of the cloud is varied between \(1.0 \times 10^{-3}\) and \(1.0 \times 10^{-5}\) cm\(^{-3}\) and the calculation is stopped when the neutral hydrogen column density reaches \(N_H = 3.2 \times 10^{17}\) cm\(^{-2}\). The metal abundance is assumed to be 0.5 solar. Considering the uncertainty of the UV radiation field at \(z = 0.791\), the intensity of the UV flux at 912\(\AA\) is assumed to be \(0.3, 1, 3 \times 10^{-22}\) erg cm\(^{-2}\)sec\(^{-1}\)sr\(^{-1}\)Hz\(^{-1}\) (Okoshi & Ikeuchi 1996), and the energy index \(\alpha\) is assumed to be \(-0.5\) and \(-1.0\). In these cases, the ionizing parameter \(U = n_\gamma / n_H\) takes the values between \(-2.72 < \log(U) < -0.28\). There are 4 cases of strong radiation field, for the 912 \(\AA\) intensity of 1 and \(3 \times 10^{-22}\) erg cm\(^{-2}\)sec\(^{-1}\)sr\(^{-1}\)Hz\(^{-1}\) and the index \(\alpha\) of \(-0.5\) and \(-1.0\). In these cases, the neutral hydrogen fraction becomes too low and the inferred total hydrogen column density \(N_H\) exceeds \(1.7 \times 10^{20}\) cm\(^{-2}\) for the fixed neutral hydrogen of \(N_H = 3.2 \times 10^{17}\) cm\(^{-2}\). In weaker radiation field cases, the cloud size becomes smaller than 1 Mpc only when the hydrogen density is larger than \(4 \times 10^{-4}\) cm\(^{-3}\), or \(\log(U) < -1.9\). The electron temperature is \(1.4 \times 10^4 < T_e < 2.2 \times 10^4\) K and the dominant species of Oxygen are O III and O IV. As the hydrogen density is larger than \(4 \times 10^{-4}\) cm\(^{-3}\), which is close to the typical values at the
center of clusters and groups of galaxies, it is possible that the cloud undergoes a gravitational collapse. If collisional ionization is going on in the absorbing cloud, the fraction of highly ionized ions would become large and they could be detected as X-ray absorption structures.

Comparison with the previous *Einstein IPC* and *ROSAT PSPC* observations indicates that the X-ray luminosity of PKS2145+067 has increased by a factor of 2–3 between 1991 and 1998 and that this discrepancy is not due to an excess absorption. Sambruna (1997) studied time variability of 10 FSRQs in timescales of months–years and found that the maximum flux change is a factor of 2 drop in 0836+710 during ~8 months. The large flux change in PKS2145+067 shows that the X-ray luminosity of FSRQs can vary by more than a factor of 2 in a long timescale of the order of 10 years.

The present *ASCA* observation have shown that an improved sensitivity for the X-ray absorbing matter would enable us to study optically observed Lyman limit or metal line systems and that a wide-band spectroscopy with good energy resolution will bring us a unique science. We hope that new X-ray instruments with superior energy resolution on board *XMM-Newton* and *Chandra* will be able to detect the ionizing hot intervening cloud directly by absorption lines and edges and reveal the physical conditions such as density, temperature, metal abundances of the inter-galactic medium.

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**References**

Anders E., Grevesse N. 1989, Geochem. Cosmochim. Acta, 53, 197

Bahcall J.N., Bergeron J., Boksenberg A., Hartig G.F., Jannuzi B.T., Kirhakos S., Sargent W.L.W., Savage B.D. et al. 1993, ApJS 87, 1

Bahucinska-Church M., McCammon D. 1992, Ap.J 400, 699

Bergeron J., Petijean P., Sargent W. L., Bahcall J.N., Boksenberg A., Hartig G.F., Jannuzi B.T., Kirhakos S. et al. 1994, Ap.J. 436, 33

Bergeron J., Boissé P. 1991, A&A 243, 344

Cappi M., Matuoka M., Otani C., Leighly K.M. 1998, PASJ 50, 213
Dickey J.M., Lockman F.J. 1990, Ann. Rev. Ast. Astr. 28, 215
Ferland G.J. 1993, International Rept., Univ. Kentucky, Dept. Phys. and Astron.
Furusho T., Yamasaki N.Y., Ohashi T., Saito, Y. Voges, W. 2000, will appear in PASJ, 52
Kellermann K.I., Vermulen R.C., Zensus J.A., Cohen M.H. 1998, AJ 115, 1295
Khersonsky V.K., Turnshek D.A., Strub S.M. 1997, ApJ 491, 29
Makishima K., Tashiro M., Ebisawa K., Ezawa H., Fukazawa Y., Gunji S., Hirayama M., Idesawa E. et al. 1996, PASJ 48, 171
Morrison R., McCammon D. 1983, ApJ. 270, 119
Ohashi T., Ebisawa K., Fukazawa Y., Hiyoshi K., Horii M., Ikebe Y., Ikeda H., Inoue H., et al. 1996, PASJ 48, 157
Okoshi K., Ikeuchi S. 1996, PASJ 48, 441
Padovani P. 1992, MNRAS 257, 404
Perlman E.S., Paolo P., Giommi P., Sambruna R., Jones L., Tzioumis A., Reynolds J. 1998, AJ 115, 1253
Salgado J.F., Altschuler D.R., Ghosh T., Dennison B.K., Mitchel K.J., Payne H.E. 1999, ApJS 120, 77
Sambruna R.M. 1997, ApJ 487, 536
Tanaka Y., Inoue H., Holt S.S. 1994, PASJ 46, L37
van Hoof P.A.M., Martin P.G., Ferland G.J. 2000, astro-ph/0001196
Verner D.A., Ferland G.J., Korista K.T. 1996, ApJ 465, 487
Visvanathan N., Wills B.J. 1998, AJ 116, 2119
Wilkes B.J., Tanabaum, H., Worrall D.M., Avni Y., Oey M.S., Flanagan J. 1994, ApJS 92, 53
Fig. 1. The pulse height spectra of PKS2145+067 taken by SIS0, SIS1, GIS2, and GIS3, corrected for the background. The best-fit power-law model with interstellar absorption is shown. The bottom panel shows the residuals of the fit.
Fig. 2. The Contour plot of the photon index $\Gamma$ vs. the absorption column density $N_H$ at $z=0.791$. The absorbing gas is assumed to have a metal abundance of 1 solar. Lines show 67%, 90%, and 99% confidence levels.
Fig. 3. The upper limit of the absorption column density at $z=0.791$ for different metal abundances. Dashed, solid and dotted lines show 99%, 90% and 67% confidence levels, respectively.