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ASCA Observation of the Lyman-Limit Quasar PKS 2145+067

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Abstract

An X-ray observation of a famous Lyman-limit quasar PKS 2145+067 at $z_{\mathrm{em}} = 0.990$ was carried out with ASCA. The source showed a 2–10 keV flux of 1.3×10^{-11} erg cm^{-2} s^{-1} ($L_{\mathrm{X}} = 2.5 \times 10^{46}$ erg s^{-1} for $H_0 = 50$ km s^{-1} Mpc^{-1}) described by a power-law spectrum with a photon index of the $\Gamma = 1.63 \pm 0.04$. In the ASCA energy band, no excess absorption was detected, implying that absorption column density at $z_{\mathrm{ab}} = 0.791$ was less than 1.6×10^{21} cm^{-2} if the absorbing medium had a metal abundance of 0.5 solar. A comparison with previous Einstein Observatory and ROSAT observations shows that PKS 2145+067 has increased in luminosity by a factor of 2–3 between 1991 and 1998.

Key words: galaxies: intergalactic medium — quasars: individual (PKS 2145+067) — X-rays: galaxies

1. Introduction

The quasar PKS 2145+067 (4C+06.69, $[\alpha_{2000}, \delta_{2000}] = [21^{\mathrm{h}}48^{\mathrm{m}}05^{\mathrm{s}}, 06°57'39'']$) is an X-ray luminous AGN at $z_{\mathrm{em}} = 0.990$, and is known to show a Lyman limit system at $z_{\mathrm{abs}} = 0.791$, 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, e.g., Padovani 1992). The polarization of this quasar is as low as 1.0±0.6% (Visvanathan, Wills 1998), and submilliarcsecond imaging by the Very Long Baseline Array (VLBA) at 15 GHz does not detect any jet-like structure (Kellermann et al. 1998).

The Lyman limit system exhibits a neutral hydrogen column density as large as $N(\mathrm{H\,I}) = 3.2 \times 10^{17}$ cm^{-2} [$1.6 \times 10^{16} \le N(\mathrm{H\,I}) \le 6.3 \times 10^{17}$ cm^{-2}] with a Doppler parameter, b, of $35 \le b \le 63$ km s^{-1} (Bergeron et al. 1994). An associated galaxy is identified at $55 h_0^{-1}$ kpc away from the line of sight (Bergeron, Boissé 1991), and is considered to be in star-formation activity. The coexistence 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 a Mg II absorption doublet has an intermediate dimension ($\sim$ 7 kpc) with a density of $n_{\mathrm{H}} \sim 6 \times 10^{-3}$ 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 of $n_{\mathrm{H}} \sim 3 \times 10^{-4}$ 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 H I/H $= 3 \times 10^{-3}$ at the core and the neutral and ionized hydrogen column density is $N_{\mathrm{H}} = 1.7 \times 10^{20}$ 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 has detected an absorption trough with $\tau_{\mathrm{GP-HI}} = 0.12$–$0.14$, 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 PKS 2145+067 with ASCA (Tanaka et al. 1994) to search for evidence of this hot intervening cloud using X-ray absorption features. The observation was performed on 1998 December 5 with a net exposure time of 36 ks with GIS and 29 ks with SIS, respectively. The observation mode was the nominal PH mode for GIS (Ohashi et al. 1996; Makishima et al. 1996) and the 1CCD FAINT mode for SIS. In this paper, we assume $H_0 = 50$ km s^{-1} Mpc^{-1} and $q_0 = 0.5$, and the solar number abundances of the elements are followed by Anders and Grevesse (1989).

2. Analysis and Results

2.1. Energy Spectrum of PKS 2145+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

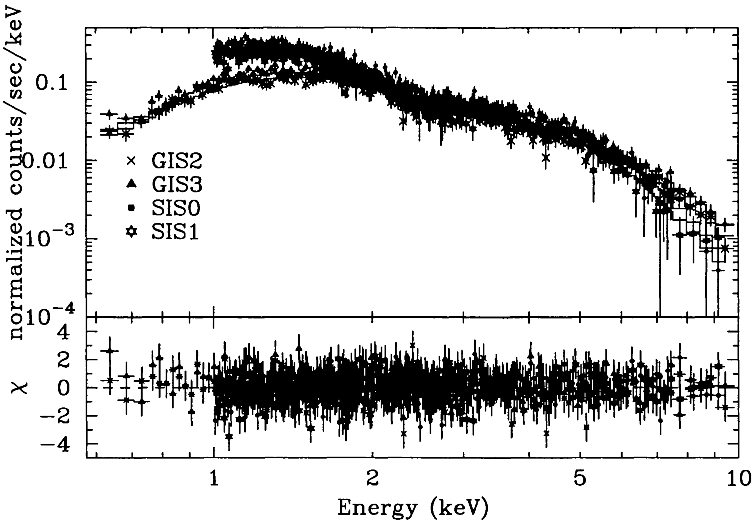

Fig. 1. Pulse height spectra of PKS 2145+067 taken by SIS 0, SIS 1, GIS 2, and GIS 3, corrected for the background. The best-fit power-law model with interstellar absorption is shown. The bottom panel shows the residuals of the fit.

and integrated the photons within a radius of 6′ from the source. We then 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 ks deep survey observation of the Lockman hole carried out in 1998 November (PI: Y. Ishisaki) was used. As for the SIS background, we used 1CCD FAINT mode data taken in the Lynds 1157 observation in 1998 September (PI: T. Furusho), in which the Lynds 1157 dark cloud containing a class 0 proto-star has not been detected in the 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 the performances do not cause any problem in the subtraction process. In the Lynds 1157 data, applying the same event discrimination level yields a net exposure time of the background to be 10.9 ks. 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, the 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 a drop in the detection efficiency below 1 keV (see web pages of ASCA GOF, http://heasarc.gsfc.nasa.goc/docs/asca/watchout.html), we used only the data between 1.0 keV and 10.0 keV for SIS, while the GIS data were used between 0.6 keV and 10.0 keV. The spectral fitting package XSPEC (ver 10.0) was used for model fitting throughout this work. We fit the SIS and GIS data simultaneously and minimized the sum of χ^2, assuming an absorbed power-law model.

As for the absorber model, we first assumed 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 of 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, $N_{\rm H}$, is consistent with the galactic value of 4.8×10^{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 1.3×10^{-11} erg cm^{-2} s^{-1}, which corresponds to the luminosity $L_{\rm X:2-10keV} = 2.5 \times 10^{46}$ erg s^{-1} assuming $H_0 = 50$ km s^{-1} Mpc^{-1} and $q_0 = 0.5$.

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 the formula wabs × zwabs × a power-law. The "wabs" model again represents the absorption by interstellar matter in our Galaxy, and the column density $N_{\rm H}$ is fixed to the galactic value of $N_{\rm H} = 4.8\times10^{20}$ cm^{-2}. The "zwabs" model is a redshifted "wabs" model, which stands for the absorption by neu-

Table 1. Spectral parameters of PKS 2145+067.

	$N_{\rm H}$ ($z=0$) (10^{20} cm^{-2})	$N_{\rm H}$ ($z=0.791$) (10^{20} cm^{-2})	Γ	$F_{\rm X:(2-10keV)}$ (erg cm^{-2} s^{-1})	χ^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

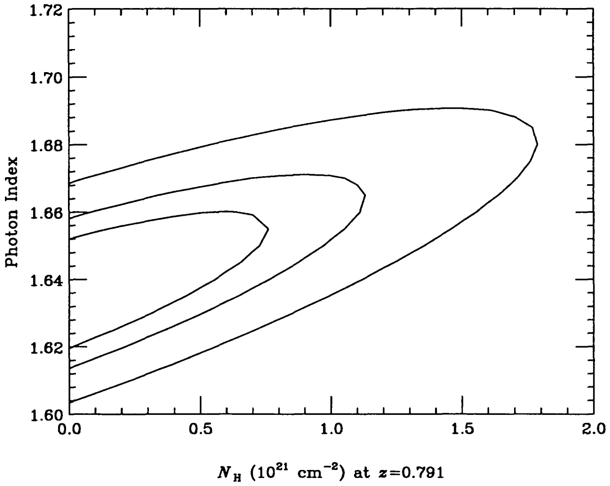

Fig. 2. Contour plot of the photon index Γ vs. the absorption column density $N_{\rm H}$ at $z=0.791$. The absorbing gas is assumed to have a metal abundance of 1 solar. Lines show 67%, 90%, and 99% confidence levels.

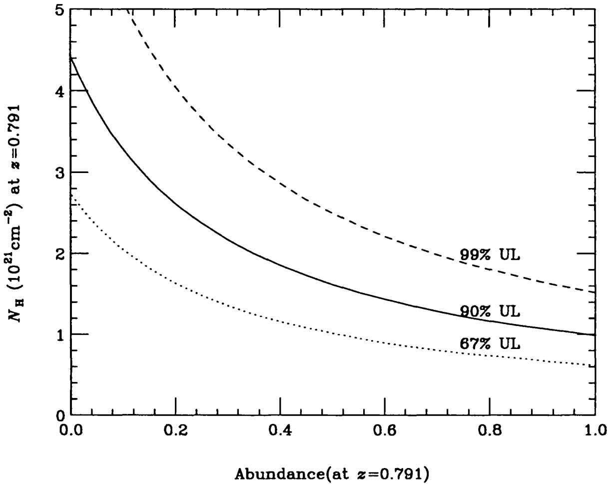

Fig. 3. Upper limit of the absorption column density at $z=0.791$ for different metal abundances. The dashed, solid, and dotted lines show 99%, 90%, and 67% confidence levels, respectively.

tral matter with an abundance of 1 solar. In this fit, we fixed the redshift of "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 8.5×10^{20} cm^{-2}. A contour plot of the photon index Γ vs. the absorption column density $N_{\rm H}$ 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 "zvphabs" (Balucinska-Church, McCammon 1992); therefore, the model spectrum is described by wabs ($N_{\rm H}=4.8\times10^{20}$ cm^{-2} fixed) × zvphabs ($z=0.791$) × power-law. In this fit, all of the elements are assumed to have a common abundance except for He, which has an abundance of 1 solar. In figure 3, we plot the 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 1.6×10^{21} cm^{-2}. This does not contradict the two-phase model ($N_{\rm H}=1.7\times10^{20}$ 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 fit the energy spectra with an absorbed power-law and an edge-structure model given by wabs ($N_{\rm H}=4.8\times10^{20}$ cm^{-2} fixed) × "zedge" (redshifted K-edge) × 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 9.7×10^{17} cm^{-2} and 6.3×10^{17} cm^{-2} for Si III and Si VII ions (Verner et al. 1996), or assuming 0.5 solar abundances, the upper limits for the total hydrogen column density of 5.4×10^{22} cm^{-2} and 3.5×10^{22} cm^{-2}, respectively.

2.3. *Comparison with Previous X-Ray Observations*

We compared the flux of PKS 2145+067 with the previous X-ray results. Einstein IPC observed the quasar in 1980 May 5. Wilkes et al. (1994) have reported the flux between 0.16 and 3.5 keV to be 3.8×10^{-12} erg cm^{-2} s^{-1}, assuming a photon index of 1.5. This is about 1/3 of the level, $F_{\rm X:0.16-3.5keV} = 1.1 \times 10^{-11}$ erg cm^{-2} s^{-1}, estimated from the extrapolated spectrum of the ASCA observation (wabs × power-law) without excess absorption. ROSAT PSPC also observed the quasar on 1991 May 9 and the flux between 0.1 and 2.0 keV is 3.3×10^{-12} erg cm^{-2} s^{-1} (Perlman et al. 1998), which is about half of the extrapolated ASCA level ($F_{\rm X:0.1-2keV} = 7.1 \times 10^{-12}$ erg cm^{-2} s^{-1}).

These flux comparisons suggest two possibilities: the first is that the X-ray luminosity of PKS 2145+067 has become higher during the past 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 a small variation only 7% in rms (Salgado et al. 1999). Sambruna (1997) compiled ROSAT results, and reported that the 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 on the order of 10–30% with no accompanying spectral changes. If the X-ray flux of PKS 2145+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, spectral information from ROSAT and Einstein observations is not available. We added 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 1.6×10^{21} cm^{-2}. It thus 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 PKS 2145+067 has increased by a factor of 2–3 during these past 10 years.

3. Discussion and Conclusion

An ASCA observation of PKS 2145+067 shows that the 0.6–10 keV spectrum is well described by a power-law model ($\Gamma = 1.6$) absorbed by galactic interstellar absorption. An upper limit for the $z = 0.791$ absorbing cloud is $N_{\rm H} < 1.6 \times 10^{21}$ cm^{-2} (90% U.L.).

These results are consistent with the two-phase ionized cloud model by Bergeron et al. (1994). 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 assumed 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 was varied between 1.0×10^{-3} and 1.0×10^{-5} cm^{-3} and the calculation was stopped when the neutral hydrogen column density reached $N_{\rm H} = 3.2 \times 10^{17}$ 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 Å is assumed to be (0.3, 1, 3) $\times 10^{-22}$ erg cm^{-2} s^{-1} sr^{-1} Hz^{-1} (Okoshi, Ikeuchi 1996), and the energy index, α, is assumed to be -0.5 and -1.0 . Under these conditions, the ionizing parameter U ($= n_\gamma/n_{\rm H}$), takes values in the region $-2.72 < \log(U) < 0.28$. There are 4 cases of strong radiation fields: for the 912 Å intensity of 1 and 3×10^{-22} erg cm^{-2} s^{-1} sr^{-1} Hz^{-1} and the index α of -0.5 and -1. In these cases, the neutral-hydrogen fraction becomes too low and the inferred total hydrogen column density, $N_{\rm H}$, exceeds 1.7×10^{20} cm^{-2} for the fixed neutral hydrogen of $N_{\rm H} = 3.2 \times 10^{17}$ cm^{-2}. In weaker radiation field cases, the cloud size becomes smaller than 1 Mpc only when the hydrogen density is larger than 4×10^{-4} cm^{-3}, or $\log(U) < -1.9$. The electron temperature is $1.4 \times 10^4 < T_{\rm e} < 2.2 \times 10^4$ K and the dominant spices of oxygen are O III and O IV. Because the hydrogen density is larger than 4×10^{-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 takes place in the absorbing cloud, the fraction of highly ionized ions would become large, and could be detected as X-ray absorption structures.

A comparison with the previous Einstein IPC and ROSAT PSPC observations indicates that the X-ray luminosity of PKS 2145+067 has increased by a factor of 2–3 between 1991 and 1998, and that this discrepancy is not due to excess absorption. Sambruna (1997) studied the time variability of 10 FSRQs on timescales of months–years, and found that the maximum flux change was a factor of 2 drop in 0836+710 during ~ 8 months. The large flux change in PKS 2145+067 shows that the X-ray luminosity of FSRQs can vary by more than a factor of 2 in a long timescale on the order of 10 years.

The present ASCA observation has shown that an improved sensitivity for the X-ray absorbing matter would enable us to study the 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 Observatories 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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