Outflow in Overlooked Luminous Quasar:
Subaru Observations of AKARI J1757+5907*

Kentaro AOKI,1 Shinki OYABU,1,2 Jay P. DUNN,3 Nahum ARAV,3 Doug EDMONDS,3 Kirk T. KORISTA,4 Hideo MATSUHARA,5 and Yoshibu TOBA5

1Subaru Telescope, National Astronomical Observatory of Japan, 650 North A’ohoka Place, Hilo, HI 96720, USA
2Graduate School of Science, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8602
3Department of Physics, Virginia Tech, Blacksburg, VA 24061, USA
4Department of Physics, Western Michigan University, Kalamazoo, MI 49008-5252, USA
5Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, 3-1-1 Yoshinodai, Chuo-ku, Sagamihara 252-5210

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Abstract

We present Subaru observations of the newly discovered luminous quasar AKARI J1757+5907, which shows an absorption outflow in its spectrum. The absorption consists of 9 distinct troughs, and our analysis focuses on the troughs at $-1000\,\text{km}\,\text{s}^{-1}$ for which we could measure accurate column densities of HeI, FeII, and MgII. We used photoionization models to constrain the ionization parameter, total hydrogen column density, and number density of the outflowing gas. These constraints yielded lower limits for the distance, mass-flow rate, and kinetic luminosity for outflows of $3.7\,\text{kpc}$, $70\,M_{\odot}\,\text{yr}^{-1}$, and $2.0\times10^{43}\,\text{erg}\,\text{s}^{-1}$, respectively. Such a mass-flow rate value can contribute significantly to metal enrichment of the intra-cluster medium. We found that this moderate velocity outflow is similar to those recently discovered in massive post-starburst galaxies. Finally, we describe the scientific potential of future observations targeting this object.

Key words: galaxies: active — quasars: absorption lines — quasars: emission lines — quasars: individual (AKARI-IRC-V1 J1757000+590759)

1. Introduction

Roughly 20% of all quasars exhibit Broad Absorption Lines (BALs) in their spectra (Knigge et al. 2008; Hewett & Foltz 2003), which are indicative of outflows with velocities of $\sim10^{3}$–$10^{4}\,\text{km}\,\text{s}^{-1}$. The kinetic energy and mass emanating from quasars have become key elements in the theoretical modeling of the evolution of supermassive black holes (SMBH) and their host galaxies (e.g., Di Matteo et al. 2005; Hopkins et al. 2008), the suppression of cooling flows in clusters (e.g., Ciotti et al. 2010; Brüggen & Scannapieco 2009), and enrichment of the intra-cluster and inter-galactic media with metals (e.g., Moll et al. 2007). Collectively, harnessing quasars’ mechanical energy to help in driving the above processes is known as “AGN feedback”.

To assess the contribution of BAL outflows to AGN feedback scenarios, it is (at least) necessary to determine their mass-flow rate ($M_{\text{out}}$) and kinetic luminosity ($\dot{E}_{k}$). Early attempts to do so were done by de Kool et al. (2001, 2002), Hamann et al. (2001), and Wampler, Chugai, and Petitjean (1995). Recently, using improvements in analysis methods and in target selection (see discussions in Arav et al. 2008; Dunn et al. 2010), we published several more accurate determinations of these quantities (Moe et al. 2008; Dunn et al. 2010; Bautista et al. 2010; Arav et al. 2010). Here, we present a similar analysis of an outflow in a luminous overlooked quasar.

We use the term “BAL outflow” to designate intrinsic absorption detected in the spectrum of a quasar [i.e., originating from outflowing material in the vicinity of the AGN, see Barlow and Sargent (1997)]. The original BAL definition (Weymann et al. 1991) was created to differentiate, in low-resolution spectra, AGN outflow absorption systems from intervening absorbers that do not have a dynamical connection to the AGN, and is now physically obsolete. A significant number of narrower absorption lines show intrinsic natures, i.e., time variability and partial coverage of the background light source. The frequency of intrinsic absorption lines is discussed and summarized in Ganguly and Brotherton (2008). We therefore use “BAL outflow” to designate the physical nature, rather than the observational definition, of the phenomenon.

AKARI-IRC-V1 J1757000+590759 (hereafter AKARI J1757+5907) was discovered during follow-up observations of the AKARI mid-infrared (MIR) All-Sky Survey. The infrared (IR) satellite AKARI performed an all-sky survey at 9 and 18 $\mu$m as well as at four far-IR bands (Murakami et al. 2007; Ishihara et al. 2010). The initial identification of the AKARI MIR All-Sky Survey sources involved association with the Two Micron All Sky Survey (2MASS) catalog (Skrutskie et al. 2006). This search identified some AKARI MIR sources with $F(9\,\mu\text{m})/F(K_S) > 2$ in the high Galactic latitude ($|b| > 20^\circ$) after excluding the sample in the Large and Small Magellanic Clouds. AKARI J1757+5907 has a large ratio of MIR to near-IR flux density $[F(9\,\mu\text{m})/F(K_{S}) = 11.1]$. This MIR source is also coincident with a bright near-UV and optical
source. We present photometries of AKARI J1757+5907 in Table 1. The photographic magnitudes are from the USNO-B1.0 catalog (Monet et al. 2003), and were converted to $g$, $r$, and $i$ magnitudes using equation (2) of Monet et al. (2003). We found that the radio source NVSS J175659.82+590801.5 (6.5 ± 0.5 mJy at 1.4 GHz) (Condon et al. 1998) is coincident with AKARI J1757+5907. The ratio of the radio (5 GHz) to optical (4400 Å) flux density is 1.4, assuming that the radio spectral index is −0.5. This ratio indicates that the quasar is radio quiet (Kellermann et al. 1989).

Follow-up spectroscopy using the KPNO 2.1 m telescope revealed that AKARI J1757+5907 is a $z = 0.615$ quasar that shows HeI$^+$ and MgII absorption lines as well as H$\beta$ and strong FeII emission lines (Y. Toba et al. in preparation). The spectrum resembles that of QSO 2359−1241 (Brotherton et al. 2001; Arav et al. 2001). Both quasars show rare HeI$^+$ absorption as well as MgII absorption. They also have redder continua and strong FeII emission lines. The high-resolution spectroscopy of QSO 2359−1241 by Arav et al. (2001) revealed FeII absorption lines. Thus, FeII absorption lines are expected to exist in AKARI J1757+5907. Following Korista et al. (2008), by measuring the ionic column densities ($N_{\text{ion}}$) of FeII and HeI$^+$, we can constrain the ionization parameter ($U_{\text{H}}$) and hydrogen density ($N_{\text{H}}$). The high brightness of this quasar permits us to perform high-resolution spectroscopy of HeI$^+$ absorption lines and search for FeII resonance and excited state absorption lines. The $N_{\text{ion}}$ ratio of FeII$^+$ to FeII ($E = 0$) yields the hydrogen number density $n_{\text{H}}$, which in turn yields the distance of outflowing gas from the central source $R$, $E_k$, and $M_{\text{out}}$, by using $n_{\text{H}}$, $U_{\text{H}}$, and $N_{\text{H}}$.

The plan of this paper is as follows. In section 2 we describe the observations and data reduction. In section 3 we determine the redshift of the object. The outflow absorption troughs are discussed in section 4, and the spectral energy distribution in section 5. In section 6 we describe our photoionization modeling, and in section 7 the resultant determination of the mass-flow rate and kinetic luminosity for the outflow. In section 8 we discuss our results, and in section 9 we describe the scientific potential of additional Subaru/HDS and HST/COS observations targeting this object. Throughout this paper we assume $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.3$, and $\Omega_{\Lambda} = 0.7$. Note that the wavelengths of any transition in this paper are those in a vacuum, and the observed wavelength scale is converted to that in a vacuum.

2. Observations and Data Reduction

2.1. High-Resolution Spectroscopy

The high-resolution spectroscopy of AKARI J1757+5907 [RA = 17$^h$57$^m$00$^s$.24, Dec. = +59°08′00″.3 (J2000.0)] was performed with the High Dispersion Spectrograph (HDS: Noguchi et al. 2002) attached to the Subaru 8.2 m telescope (Iye et al. 2004) on 2010 June 17 (UT). The weather conditions were poor with thick cirrus, and the seeing was unstable (> 1′/0). The slit width was set to be 1′/0. The HDS setting was Yd, covering between 4054 and 6696 Å. This resulted in a resolving power of $R \sim 36000$. The binning was 2 (spatial direction) × 4 (dispersion direction). Although we obtained eight exposures of 1800 s each, one of them was unusable due to a low signal-to-noise ratio.

The data were reduced using IRAF$^1$ for the standard procedures of overscan subtraction, dark subtraction, cosmic-ray removal, and flat-fielding, where a wavelength calibration was performed using a Th−Ar lamp. The rms wavelength calibration error was 0.011−0.013 Å. The one-dimensional spectra were extracted from each exposure. A heliocentric correction was applied. After that, all of the spectral exposures were combined, and all orders were connected to one spectrum. We normalized the spectrum using spline fits. Finally, we converted to the vacuum wavelength scale.

2.2. Spectrophotometry

The low-resolution spectrophotometry of AKARI J1757+5907 was performed on 2010 June 30 (UT) with FOCAS (Kashikawa et al. 2002) attached to the Subaru telescope. New fully depleted-type CCDs developed by NAOJ/ATC and fabricated by Hamamatsu Photonics K. K. were installed and commissioned at that time. We obtained six spectra of 5 min integration under a clear-sky condition and good seeing (0′′.6−0′′.9). A 2′/0 width slit was used for the purpose of spectrophotometry. We used two configurations: an R300 grism with an OS8 filter (“red”), and a B300 grism without any order-cut filters (“blue”). The first three 300 s spectra were red, which covers between 5700 Å and 10200 Å. The last three 300 s spectra were blue, which has an uncontaminated range between 3500 Å and 7000 Å. An atmospheric dispersion corrector was used. The slit position angle was 0°, and the binning was 2 (spatial direction) × 1 (dispersion direction). A spectrophotometric standard star, BD +28°4211, was observed for sensitivity calibration.

The data were reduced using IRAF for the standard procedures of bias subtraction, wavelength calibration, and sky subtraction, except for flat-fielding. AKARI J1757+5907 is so bright that its counts on the CCD are comparable to the flat frames, and are much higher at shorter wavelength (<4000 Å). The flat-fielding procedure significantly reduced its signal-to-noise ratio. We therefore skipped the flat-fielding procedure. Wavelength calibration was performed using OH night-sky

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$^1$ IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
emission lines for the red spectra and a Cu–Ar lamp for blue ones. The rms error of the wavelength calibration was 0.2 Å. The seeing was much smaller than the slit width, and thus the resolution was determined by the seeing disk size. The resulting He I $^+$ 3889 absorption line was 13 Å width at 6260 Å. This value corresponds to a resolving power of 480 ($\sim 620 \text{ km s}^{-1}$), which is similar to the resolution obtained with the 0.8 width slit, and is consistent with the seeing size during our observations. The sensitivity calibration was performed as a function of the wavelength. The flux of the blue and red spectra at the same wavelength agree within 1.6%. The foreground Galactic extinction of $E(B-V) = 0.043$ mag (Schlegel et al. 1998) was corrected.

3. Results of Spectrophotometry

Figure 1 displays the low-resolution optical spectrum of AKARI J1757$^+$5907. The spectrum shows strong absorption lines of Mg II and He I$^+$ as well as emission lines of Mg II, Fe II, Hγ, Hβ, [O III]. In order to determine the systemic redshift of the quasar, we deblend the [O III] emission lines from the Hβ and Fe II emission lines. As can be seen in figure 1, AKARI J1757$^+$5907 has strong Fe II emission lines. However, the Fe II emission template around Hβ derived from the spectrum of I Zw 1 (Aoki et al. 2005) is not a good match to the Fe II emission in AKARI J1757$^+$5907 (figure 2a). The intensity ratios among Fe II emission lines are different between these objects. Thus, we cannot use the Fe II emission template derived from the spectrum of I Zw 1.

Instead, we fit the spectrum between 7662 Å and 8204 Å with a combination of Fe II $\lambda\lambda$4925, 5020, Hβ, and [O III] after subtracting a power-law continuum. This power-law continuum was constructed by fitting at 6526–6544 Å and 8842–8891 Å. The Hβ emission line was fitted with a combination of three Gaussians. We fit the [O III] doublet $\lambda\lambda$4960.3, 5008.2 with two sets of two Gaussians. The width and redshift were assumed to be the same for each set, and the intensity ratio was fixed to be 3.0. Fe II $\lambda\lambda$4925, 5020 were modeled by two Lorentzians with the same width and redshift. Their redshift was fixed to be the same as the strongest Gaussian component of Hβ. The result of the fitting is shown in figure 2b. We need a separate “red wing” of Hβ to obtain a satisfactory fit. This component may be an [O III] emission line. The derived redshifts and FWHMs are tabulated in table 2. The FWHM was corrected for instrumental broadening by using a simple assumption: $\text{FWHM}_{\text{true}} = (\text{FWHM}_{\text{obs}}^2 - \text{FWHM}_{\text{inst}}^2)^{1/2}$, where FWHM$_{\text{obs}}$ is the observed FWHM of the line and FWHM$_{\text{inst}}$ is an instrumental FWHM (620 km s$^{-1}$). The redshift of the red component of [O III] was 0.6150 $\pm$ 0.0001. The rest equivalent width of [O III] including both components was 9.9 $\pm$ 0.3 Å. This value is consistent with the [O III] strength in majority (> 50%) of Mg II BAL quasars reported by Zhang et al. (2010). We also detected weak [O II] emission at 6023.4 Å, which corresponds to a redshift of 0.6155.
Fig. 2. Hβ--[O III] region of AKARI J1757+5907. (a) Continuum-subtracted spectrum. The dotted line is the Fe II template produced from I Zw 1. The Fe II template is broadened and scaled at 5170 Å. Note that the Fe II template is clearly different from the Fe II emission line of AKARI J1757+5907 at 4600–4700 Å and 5260–5400 Å. (b) Fit of the spectrum. Hβ, [O III] doublet, and Fe II λλ 4925, 5020 are fitted with three Gaussians (blue, violet, and red lines), two sets of two Gaussians (green lines), and two Lorentzians (magenta lines), respectively.

Table 2. Properties of emission lines of AKARI J1757+5907.

| Line    | λ_{obs} (Å) | z        | FWHM_{true} (km s\(^{-1}\)) |
|---------|-------------|----------|-----------------------------|
| Hβ      | 7872.0      | 0.6189   | 5080                        |
| [O III] 5008.24 | 8088.3     | 0.6150   | 710                         |
| [O III] 5008.24 | 8063.3     | 0.6100   | 480                         |

We thus adopted 0.61525 ± 0.00025 as the systemic redshift of the quasar. The blue component of [O III] is blueshifted by 980 km s\(^{-1}\) relative to the systemic redshift.

4. Absorption Lines

In the HDS spectrum of AKARI J1757+5907, the absorption lines are not heavily blended. Identification is thus a straightforward task. We identified Mg II λλ 2976, 2803, HeI* λ 2945, λ 3188, λ 3889, Fe II λ 2600, λ 2586 as well as weaker absorption troughs from Mg I λ 2852, HeI* λ 2829, and Ca II λλ 3934, 3969. The strong absorption lines, such as the Mg II doublet and HeI* λ 3889, clearly show 9 distinct troughs, which span a velocity range from −660 to −1520 km s\(^{-1}\). The trough at −1000 km s\(^{-1}\) has the same outflow velocity as the blue component of the [O III] emission line. We show the absorption troughs from Mg II λλ 2976, 2803, HeI* λ 2945, λ 3188, λ 3889, and Fe II λ 2600, λ 2586 in figure 3. We did not detect an Fe II* λ 2612 absorption trough from the \(E = 385 \text{ cm}^{-1}\) excited level, which has the largest oscillator strength of the Fe II* lines from this energy level, in our spectral range. We show the spectral region of Fe II* λ 2612 in the lower panel of figure 3.

4.1. Column Density Determinations

Both the Mg II and HeI* troughs span the full velocity range from −660 to −1520 km s\(^{-1}\), and appear in all 9 distinct troughs (see figure 3). There is self-blending in the Mg II troughs at the velocity extremes, which does not affect the majority of troughs. The HeI* and Fe II troughs are free of any self-blending. Of the 9 troughs, only three have corresponding absorption in Fe II. These are in the range of −1050 to −800 km s\(^{-1}\) (see figure 3). Thus, we concentrated on this velocity range for our measurements, since the best photoionization constraints are achieved by contrasting the HeI* and Fe II column densities (see section 6; Korista et al. 2008; Arav et al. 2010).

To determine the ionic column densities, we rebinned the data to 10 km s\(^{-1}\), and used the velocity-dependent apparent optical depth (AOD), covering factor \([C(v)]\), and power-law fitting
methods from Dunn et al. (2010; methods 1, 2, and 3 in their subsection 3.2) across the range of $-1050$ to $-800$ km s$^{-1}$.

The AOD method assumes that the emission source is completely and homogeneously covered by the absorber, so that the optical depth $\tau(v)$ at a given velocity is related to the normalized intensity via: $I(v) = \exp(-\tau(v))$. The covering factor method assumes that at a given velocity, a fraction, $C(v)$, of the emission source is covered with a constant value of optical depth, while the rest of the source is uncovered. In order to obtain both $\tau(v)$ and $C(v)$, we used at least two absorption lines from the same energy level of the same ion, and solved for $I(v)_j = 1 - C(v) + C(v)\exp[-\tau(v)_j]$, where $I_j$ is the normalized intensity of the absorption due to the $j$ transition at the same energy level. The ratio of different $\tau(v)_j$ values are known from atomic physics, and therefore the set of equations is solvable. The power-law model assumes that the absorption gas inhomogeneously covers the background source. The optical depth is described by $\tau_s(x) = \tau_{\text{max}}(v)x^a$, where $x$ is the spatial dimension in the plane of the sky, $a$ is the power-law distribution index, and $\tau_{\text{max}}$ is the highest value of $\tau$ at a given velocity. In the case of the power-law model, $\tau$ is averaged over the spatial dimension, $x$.

In order to convert $\tau$ in each model to a column density we used $N(v) = 3.8 \times 10^{14} \times [1/(f\lambda)]\tau(v)$ (cm$^{-2}$ km$^{-1}$ s), where $\lambda$ is the wavelength of the line in Å, and $f$ is the oscillator strength. We used the oscillator strengths from Fuhr and Wiese (2006) for the Fe II lines and values from the NIST Atomic Spectra Database\textsuperscript{2} for Mg II and He I$^*$.\n
In figure 4, we show the He I$^*$ troughs and column-density determinations from the three lines of He I$^*$ present in the HDS spectrum. The He I$^*$ lines are well separated and have no self-blending; we obtained consistent results with all three column-density extraction methods. There are two velocity points where $C(v)$ becomes nonphysical (i.e., negative or larger than 1.0), near $-930$ km s$^{-1}$ and at velocities lower than $-850$ km s$^{-1}$. This occurs because the two weaker lines are very shallow at these velocities, and are thus consistent with the continuum level and are dominated by the noise.

We show in figure 5 the trough profiles and column-density results for Mg II. Both the red and the blue doublet troughs are quite deep, and therefore their level of saturation is model-dependent. The $C(v)$ solution suggests a small level of saturation (only 40% larger column density than the AOD estimate), while the power-law result is three-times higher. This is an inherent feature of the absorption models, where in order to fit deep doublet troughs the power-law model requires a much greater column density than the $C(v)$ solution [see the case of the O VI doublet in the spectrum of Mrk 279: Arav et al. (2005)]. Since we do not have data for troughs from additional Mg II lines, we cannot determine which model is more physical.

There is a possibility that a narrow Mg II emission line fills the trough. As already noted early in this section, the blue

\textsuperscript{2} http://www.nist.gov/pml/data/asd.cfm.
The component of [O III] has a velocity of $-1000 \text{ km s}^{-1}$. The Mg II emission line from the same gas probably exists. We estimated the flux of the Mg II emission line using the flux ratio of [O III] $\lambda 5008$ to Mg II in Seyfert 2 galaxies, NGC 1068 (Kraemer et al. 1998) and Mrk 3 (Collins et al. 2005). The ratios vary along the physical position in the galaxies between 0.03 and 0.15, and the averages of the extinction-corrected ratios are 0.09, and 0.07 in NGC 1068 and Mrk 3, respectively. We also assumed a 1:2 ratio for the Mg II doublet, and Gaussians of the same width ($\sigma = 205 \text{ km s}^{-1}$) as that of the [O III] emission line. This width corresponds to 3.0 Å at the Mg II observed wavelength of 4500 Å. The HDS spectrum before normalization was scaled to the low-resolution spectrum. The expected height of the Mg II emission line would be $\sim 13\%$ and $\sim 4\%$ of the residual intensity at the Mg II $\lambda 2796$ and $\lambda 2803$ troughs, respectively. Thus, the real residual intensity may be smaller than the observed one. Therefore, we conclude that the Mg II column density can be much larger than the AOD or $C(v)$ determined values.

Finally, we show the result for Fe II troughs in figure 6. Unlike Mg II and He I, the Fe II troughs are both shallow and in a much lower signal-to-noise region of the spectrum (towards the short-wavelength end of the detector). Due to this, we found that the weaker Fe II $\lambda 2587$ line is only detected across three velocity bins. Using both the Fe II $\lambda 2600$ and the Fe II $\lambda 2587$ lines we calculated $N_{\text{Fe II}}$ for both the $C(v)$ and power-law methods for the three bins, and included them in the integrated total. Due to a lack of detection of the $\lambda 2587$ line, we used the $\lambda 2600$ line to calculate the column density from the AOD method for the remaining points. We also checked the column density for Fe II using the covering factor of Mg II. The column density calculated in this fashion changed by only $\sim 10\%$, since Mg II nearly fully covers the source $[C(v) \approx 0.9]$ in this velocity range.

### 4.2. Column-Density Limits on Fe II* Excited State Lines

In order to help constrain the photoionization models described in section 6, we estimated the column density limits for the Fe II* $\lambda 2612$ and $\lambda 2757$ lines from the 385 and 7955 cm$^{-1}$ energy levels, respectively. Neither line shows a detectable trough in the data. Therefore, we can use the trough profile of Fe II $\lambda 2600$ to determine the relative optical depth and column density of these two energy levels (see subsection 3.3 of Dunn et al. 2010). We found upper limits on the ionic column densities of $(3.7 \pm 0.5) \times 10^{12} \text{ cm}^{-2}$ for the 385 and 7955 cm$^{-1}$ energy levels, respectively.
5. Determination of the Spectral Energy Distribution

Our FOCAS spectrophotometry data and the GALEX photometry clearly show the flux drops at shorter wavelengths (<2000 Å in the rest frame), and indicate reddening by dust (figure 7). We must consider extinction for deriving the intrinsic spectral energy distribution (SED). First, we measured the continuum flux at four points where there are less Fe II emission contaminants. These four points and the GALEX photometry points are then shifted to the rest frame. We fit a reddened power-law to the continuum points. We adopted the index of the power-law continuum (α reddened by the SMC-type extinction law. The best fit gave us the color excess E(B - V) of 0.18. The best fit of the reddened power-law continuum is shown in figure 7.

To estimate the distance to the outflow from the central source (R), we needed to determine the flux of hydrogen ionizing photons that irradiate the absorber [see equation (1) below]. Using the Mathews and Ferland (1987) SED, reddened to match the observed spectrum, we found that the number of hydrogen ionizing photons emitted per second by the reddened central source (Q_H) is \(2.2 \times 10^{37} \text{ photons s}^{-1}\). Here, we assumed that the reddening occurred between the central source and the outflow, as is the case where the photons are attenuated by the edge of the putative AGN obscuring torus (see full discussion in Dunn et al. 2010). This assumption will also give us smaller values for the inferred R, and therefore conservative lower limits for \(M_{out}\) and \(\dot{E}_{k}\). The bolometric luminosity \(L_{bol}\) for the dereddened, intrinsic spectrum is \(3.7 \times 10^{47} \text{ erg s}^{-1}\).

6. Photoionization Modeling

Through photoionization modeling, reliable measurements of He I and Fe II column densities provide accurate constraints on the total hydrogen column density, \(N_{H}\), and the hydrogen ionization parameter,

\[
U_{H} \equiv \frac{Q_{H}}{4\pi R^{2}n_{H}c},
\]

where R is the distance from the central source, \(n_{H}\) is the total hydrogen number density, and c is the speed of light. We used version c08.00 of the spectral synthesis code Cloudy, last described by Ferland et al. (1998), to model a plane-parallel slab of gas with a constant hydrogen number density irradiated by a source continuum. We focused on the kinematic components spanning a velocity range from \(-800 \text{ km s}^{-1}\) to \(-1050 \text{ km s}^{-1}\), where we detected Fe II(0). In this velocity range, measurements of the upper limits on Fe II(\(E = 385 \text{ cm}^{-1}\)) and Fe II(\(E = 7955 \text{ cm}^{-1}\)) yielded upper limits of the electron number density, \(n_{e}\), of \(10^{6}\) and \(10^{13} \text{ cm}^{-3}\), respectively. We adopted the conservative value of an upper limit of \(n_{e} \leq 10^{13} \text{ cm}^{-3}\), and assumed \(n_{H} \approx n_{e}\), which is valid within the ionized zone we are discussing. While the electron number density is well constrained from above, there are no diagnostics for a lower limit on \(n_{e}\) in the data.

We begin investigating the parameter space by using the Cloudy’s optimization mode to determine \(N_{H}\) and \(U_{H}\) for \(n_{H} = 10^{3.8} \text{ cm}^{-3}\). The parameters \(N_{H}\) and \(U_{H}\) were varied...
and the ionic column densities were computed for each set of parameters. Best-fit values were determined by \( \chi^2 \) minimization for given tolerances at the measured ionic column densities. We adopted measured ionic column densities determined by the partial covering method, and optimized to \( N_{\text{He}^+} \) and \( N_{\text{He}^+} \), since these are the more robust measurements. The measured and model-predicted column densities are presented in table 3. For solar abundances and the MF87 SED, as implemented by Cloudy,3 we found that \( \log N_{\text{H}} = -2.15 \) and \( \log N_{\text{H}} = 20.82 \) yielded good fits to the column densities of \( \text{He}^+ \) and \( \text{Fe}^+ \), while \( N_{\text{Fe}^+} \) was overpredicted. However, as discussed in section 4, the Mg II troughs may be more saturated than the partial covering model suggests. A hydrogen ionization front, which we define as the position at which half of the total hydrogen is neutral (approximated by \( N_{\text{H}} = 10^{23} U_{\text{H}} \)), does not form in this solution, although we are very close to it with \( \log (N_{\text{H}}/U_{\text{H}}) = 22.96 \).

Since the data do not provide a lower limit on the electron number density, we found other valid solutions by reducing \( n_{\text{H}} \). When the hydrogen number density was reduced, the \( \text{He}^+ \) population dropped. This is due to the fact that \( \text{He}^+ \) is populated by recombination of \( \text{He}^+ \) and \( \text{He}^+ \), and the number of recombinations per unit time depends linearly on \( n_e \). Therefore, \( N_{\text{H}} \) must increase in order to provide enough \( \text{He}^+ \) to be consistent with the measured value. \( \text{Fe}^+ \) becomes dominant near the hydrogen ionization front, while \( \text{He}^+ \) drops off drastically at the front. Thus, solutions in this region of the slab have \( U_{\text{H}} \) fixed by \( N_{\text{H}}/U_{\text{H}} \) and the ratio \( N_{\text{H}}/U_{\text{H}} \) fixed by \( N_{\text{Fe}^+} \). Due to the tight correlation of \( N_{\text{H}} \) and \( U_{\text{H}} \), all valid solutions have a similar ratio laying (nearly) on a straight line in the \( N_{\text{H}}-U_{\text{H}} \) plane for number densities greater than \( \sim 100 \text{ cm}^{-3} \). At these densities, the slabs do not form a hydrogen ionization front. As we go to densities lower than \( \sim 100 \text{ cm}^{-3} \), a front forms, behind which \( \text{Fe}^+ \) and \( \text{Mg}^+ \) increase linearly with \( N_{\text{H}} \).

In order to determine what effects the choice of SED may have on \( N_{\text{H}} \) and \( U_{\text{H}} \), we compared results of the MF87 SED with results of a softer SED. The soft SED has an optical to X-ray spectral index of \( \alpha_{\text{ox}} = -1.5 \), compared to the MF87 SED with \( \alpha_{\text{ox}} = -1.4 \) (with the convention \( F_x = \nu^\alpha \)). It was generated using the Cloudy command `agn 375000 -1.5 0.125 -1.00`, where the numbers are the temperature of the UV bump, \( \alpha_{\text{ox}} \), \( \alpha_{\text{uv}} \), \( \alpha_{\text{e}} \), respectively. We found the resulting \( N_{\text{H}} \) and \( U_{\text{H}} \) are nearly identical, and concluded that changing the SED only affects the energetics through \( Q_{\text{H}} \), a finding consistent with an analysis of QSO 1044+3656 reported in Arav et al. (2010).

Another assumption in our models was the solar abundances. To check the sensitivity of our results to metallicity changes, we used the abundances given in table 2 of Ballero et al. (2008) for metallicity \( Z = 4.23 \) with the MF87 SED and \( \log n_{\text{H}} = 3.8 \). While the helium abundances are expected to increase with the oxygen abundances (e.g., Olive & Scully 1996), the amount of increase varies for different galaxies. Therefore, to be conservative, we increased the helium abundance significantly to 15% above solar. We found that \( \log U_{\text{H}} \) is approximately 0.02 dex lower and \( \log N_{\text{H}} \) is approximately 0.15 dex lower for the increased metallicity model with \( \log (N_{\text{H}}/U_{\text{H}}) = 22.83 \). We discuss the effect of these changes on the energetics of the outflow in the next section.

7. Energetics of the Outflow

Of particular interest for any outflow are its mass \( (M_{\text{out}}) \), the average mass-flow rate \( (\dot{M}_{\text{out}}) \), and the mechanical work output or kinetic luminosity \( (\dot{E}_k) \). Assuming the outflow is in the form of a thin partial shell moving with a constant radial velocity \( (v) \), at a distance \( R \) from the source, the mass of the outflow is

\[
M_{\text{out}} = 4\pi \mu m_p \Omega R^2 N_{\text{H}},
\]

where \( N_{\text{H}} \) is the total column density of hydrogen, \( m_p \) is the mass of a proton, \( \mu = 1.4 \) is the plasma’s mean molecular weight per proton, and \( \Omega \) is the fraction of the shell occupied by the outflow. The average mass-flow rate is given by dividing the outflowing mass by the dynamical time scale of the outflow \( R/v \) (see full discussion in Arav et al. 2010); therefore,

\[
\dot{M}_{\text{out}} \sim \frac{M_{\text{out}}}{R/v} = 4\pi \mu m_p \Omega R N_{\text{H}} v \quad \text{and}
\]

\[
\dot{E}_k = \frac{1}{2} \dot{M}_{\text{out}} v^2 \sim 2\pi \mu m_p \Omega R N_{\text{H}} v^3.
\]

For the troughs that we consider in AKARI J1757+5907, the median velocity of the system is \( -970 \text{ km s}^{-1} \). We assumed

\footnotesize

\(^3\) This SED differs from the MF87 SED by the addition of a sub-millimeter break at 10 \( \mu \text{m} \).
$$\Omega = 0.2,$$ which is the percentage of quasars showing BALs in their spectrum (see discussion in Dunn et al. 2010).

To determine the distance, we solved equation (1) for $$R,$$ which depends on $$U_H$$ and $$n_H.$$ The lack of Fe$$^{+1}$$ detection yielded an upper limit of $$n_H < 10^{3.8} \text{ cm}^{-3}$$ (see section 6), and therefore, as shown below, a lower limit on $$R.$$ For the range $$10^{3.8} < n_H < 10^{4.8} \text{ cm}^{-3},$$ our photoionization solutions obey the relationships $$N_H \propto U_H$$ and $$U_H \propto n_H^{1/2},$$ where $$0.4 < \alpha < 1$$ ($$\alpha$$ decreases as $$n_H$$ increases). The first relationship arises from the requirement of being close to a hydrogen ionization front, and the second is due to the decreasing electron population at the He$$^{+1}$$ meta stable level for lower number densities. Therefore, equation (1) yields $$R \propto n_H^{(\alpha - 1)/2}.$$ We used the solar abundances photoionization solution values from section 6 ($$\log(U_H) = -2.15,$$ $$\log(N_H) = 20.82 \text{ cm}^{-2}$$ for $$n_H = 10^{3.8} \text{ cm}^{-3}$$ and $$\mathcal{Q}_H$$ from section 5. Inserting these values into equation (1), we derived a lower limit on the distance, $$R > 3.7 \text{ kpc}$$ for $$n_H = 10^{3.8} \text{ cm}^{-3},$$ which only increases to 6.6 kpc for $$n_H = 10^{3.8} \text{ cm}^{-3}$$ due to the weak dependence of $$R$$ on $$n_H.$$ From equation (3) we observed that $$M_{\text{out}}$$ and $$E_k$$ depend linearly on the product $$R N_H,$$ which is proportional to $$n_H^{-1/(\alpha - 2)}.$$ Therefore, the upper limit for $$n_H$$ provides lower limits to $$M_{\text{out}}$$ and $$E_k.$$ Using $$N_H$$ and $$R$$ derived for $$n_H = 10^{3.8} \text{ cm}^{-3},$$ we found lower limits of $$M_{\text{out}} > 70 \mathcal{Q}_{0.2} M_\odot \text{ yr}^{-1}$$ and $$E_k > 2.0 \times 10^{41} \mathcal{Q}_{0.2} \text{ erg s}^{-1},$$ where $$\mathcal{Q}_{0.2} \equiv \Omega/0.2.$$ In the previous section, we discussed changes in $$N_H$$ and $$U_H$$ due to metallicity and SED changes. Using the Ballero et al. (2008) abundances for $$Z/Z_{\odot} = 4.23$$ reduces the mass flow rate by $$\sim 30\%.$$ Changing to the soft SED described in the previous section in very small changes in $$N_H$$ and $$U_H,$$ but $$Q_H$$ increases by a factor of $$\sim 2,$$ increasing the mass-flow rate by a factor of $$\sim \sqrt{2}.$$ The mass of the black hole ($$M_{\text{BH}}$$) of AKARI J1757+5907 was derived to be $$4 \times 10^9 M_\odot$$ based on the width of the H$\beta$ emission line of $$\sigma = 2160 \text{ km s}^{-1}$$ and the dereddened optical luminosity $$\lambda L(5100 \AA)$$ of $$3.8 \times 10^{46} \text{ erg s}^{-1}.$$ We used a formula in Bennett et al. (2010) based on calibrations of a broad-line region size–luminosity relation (Bentz et al. 2006) and the virial coefficient taken from Onken et al. (2004). The derived $$\log(L_{\text{bol}}/L_{\text{Edm}}) = -0.13$$ was used to calculate the mass-accretion rate ($$M_{\text{ac}}$$) based on the accretion-disk model by Kawaguchi (2003), which takes into account the effects of electron scattering (opacity and disk Comptonization) and relativistic effects. $$M_{\text{acc}}$$ is $$110 M_\odot \text{ yr}^{-1},$$ which is similar to the lower limit of $$M_{\text{out}}.$$ We note that $$\Omega = 0.2$$ that we used was based on the percentage of quasars showing CIV BALs. In a recent work, Dai, Shankar, and Sivakoff (2010) have shown that in near-IR surveys the low-ionization BALs (LoBALs) fraction is 4%, considerably higher than that deduced from optical surveys (probably due to obscuration effects in the optical band). A more appropriate comparison in our case is to include somewhat narrower outflows with $$1000 \text{ km s}^{-1} < \Delta v < 2000 \text{ km s}^{-1}.$$ For these LoBALs based on the “Absorption index” (Trump et al. 2006), Dai, Shankar, and Sivakoff (2010) found a 7.2% fraction. The frequency of He$$^{+1}$$ outflows is much less known. The strongest He$$^{+1}$$ line in the optical ($$\lambda 3889$$) is shifted outside the optical range for objects where we can detect CIV $$\lambda 1550$$ from the ground ($$e.g., z = 1.5$$ for SDSS spectra), so a meaningful census of these outflows is difficult to come by. Anecdotally, we found that in most cases where we detected Fe$$^{+2}$$ absorption troughs, we also detected He$$^{+1}$$ troughs, provided we had a clear spectral coverage of the latter ($$e.g.,$$ Arav et al. 2008, 2010).

We also point out that AKARI J1757+5907 as well as QSO 2359–1241 do not have measurable Fe$$^{+2}$$ absorption in their low-resolution spectra. Also, their outflow velocities ($$\sim 1200 \text{ km s}^{-1}$$) and widths of troughs are moderate. Quasars with similar moderate outflows are more numerous than extreme FeLoBALs ($$e.g.,$$ SDSS J0318–0600: Hall et al. (2002)), and as we show here, can have similar mass-flow rates and kinetic luminosity as the more extreme ones. This fact suggests that the mass-flow rate and kinetic-luminosity values found here are more common among quasars, than judged by the rarity of extreme FeLoBALs. If we assume as a conservative limit that $$\Omega$$ of the outflow seen in AKARI J1757+5907 is similar to the 7.2% LoBALs fraction found by Dai, Shankar, and Sivakoff (2010) then $$\Omega_{0.2} = 0.36,$$ which will reduce the values for the mass-flow rate and kinetic luminosity, accordingly.

8. Discussion

In table 4 we show our $$M_{\text{out}}$$ and $$E_k$$ determinations in quasar BAL outflows to date ($$e.g.,$$ Table 10 of Dunn et al. (2010)). While the lower limit

| Object          | $$\log L_{\text{bol}}$$ (erg s$$^{-1}$$) | $$R$$ (kpc) | $$\log N_H$$ (cm$$^{-3}$$) | $$\log U_H$$ (erg s$$^{-1}$$) | $$\log E_k$$ (erg s$$^{-1}$$) | $$M_{\text{out}}$$ (M$$\odot$$ yr$$^{-1}$$) | Reference† |
|-----------------|-----------------------------------------|-------------|-----------------------------|-------------------------------|-------------------------------|-----------------------------------------|------------|
| AKARI J1757+5907 | 47.57                                   | > 3.7       | 20.82                       | −2.15                         | 43.30                         | > 70                                    | 1          |
| QSO 1044+3656   | 46.84                                   | 1.7 ± 0.4   | 20.84 ± 0.10                | −2.19 ± 0.10                  | 44.81 ± 0.09                  | 120 ± 25                                | 2          |
| QSO 2359–1241   | 47.67                                   | 3.2$^{+1.1}_{-1.0}$ | 20.56 ± 0.15                | −2.40 ± 0.15                  | 43.36 ± 0.27                  | 90$^{+35}_{-20}$                        | 3          |
| SDSS J0838+2955 | 47.53                                   | 3.3$^{+1.5}_{-1.0}$ | 20.80 ± 0.28                | −1.95 ± 0.21                  | 45.35$^{+0.23}_{-0.32}$        | 300$^{+210}_{-120}$                     | 4          |
| SDSS J0318–0600 | 47.69                                   | 5.9 ± 0.4   | 19.90 ± 0.17                | −3.08 ± 0.05                  | 44.55$^{+0.10}_{-0.15}$        | 60 ± 20                                 | 5          |

* Calculated using equation (3) assuming $$\Omega = 0.2.$$ The values for the last three objects are half of those found in the reference due to the use of an improved estimate for $$M_\odot$$ and $$E_k$$ given by equation (3), over those given by equations (9) and (10) in Dunn et al. (2010).
† 1-This Work, 2-Arav et al. (2010), 3-Korista et al. (2008) and Bautista et al. (2010), 4-Moe et al. (2009), 5-Dunn et al. (2010).
on $E_k$ for the AKARI J1757+5907 outflow is rather low for AGN feedback purposes, we note that the corresponding $M_{\text{out}}$ value is large enough to yield a significant contribution for the metal enrichment of the intra-cluster medium around the parent galaxy (see Hallman & Arav 2010).

We also note that this moderate velocity outflow is similar to those discovered in post-starburst galaxies at $z \sim 0.6$ (Tremonti et al. 2007). Those galaxies show an outflow with Mg II absorption and a velocity of 1000 km s$^{-1}$. Their stellar masses are as high as $(0.7\sim4.8) \times 10^{11} M_\odot$ (calculated from stellar population synthesis modeling fit to their spectra). For a comparison, $M_{\text{BH}}$ of AKARI J1757+5907 is $4.0 \times 10^9 M_\odot$, therefore based on the $M_{\text{BH}}$-M$_{\text{bulge}}$ relation (Haring & Rix 2004), the bulge of its host galaxy is estimated at $M_{\text{bulge}} = 1.8 \times 10^{12} M_\odot$.

In addition, our derived $N_\text{H}$ is similar to that of Tremonti, Moustakas, and Diamond-Stanic (2007), derived for outflow in massive post-starburst galaxies ($N_\text{H} = 2 \times 10^{20}$ cm$^{-2}$).

They also pointed out that AGNs probably exist in those post-starburst galaxies because they get a better fit to the spectra with a featureless blue power-law continuum, and they detected high-excitation emission lines, such as [O III] and [Ne V]. Thus, the outflows seen in massive post-starburst galaxies may be the same phenomena as outflows in quasars. These facts may be one of the indications that the outflow is a common phenomenon among massive galaxies. Tremonti, Moustakas, and Diamond-Stanic (2007) had to make several assumptions to derive the physical quantities of the outflow, because high resolution spectroscopy for such faint targets is difficult and non-detection of the important diagnostic absorption lines from Fe II (both ground and excited states) and He I*. In contrast, our high-resolution spectroscopy of BAL outflows in quasars can constrain the total hydrogen column density and the distance of outflowing gas from the nucleus, which yield less model-dependent estimates for $M_{\text{out}}$ and $E_k$.

9. Scientific Gains with Additional Observations

9.1. Additional Subaru HDS Data

We expect data with a much higher signal-to-noise ratio using Subaru/HDS under good weather conditions. A half-hour exposure should have a signal-to-noise ratio of 35 per pixel at 3800 Å, where Fe II$^+$ λ2396 is shifted to. Our current upper limit to Fe II$^+$ λ2612 was derived from data with a signal-to-noise ratio of 30 per pixel. Fe II$^+$ λ2396 is 2.3-times stronger absorption than Fe II$^+$ λ2612. With two hours (4 × 1800 s) of exposure time, we expect a five-times more strict upper limit of the column density for the excited state of Fe II(385 cm$^{-1}$).

Such an upper limit would translate to a hydrogen number density of $n_\text{H} < 10^{-9}$ cm$^{-3}$. For this value of $n_\text{H}$ and our best model at that density (log $U_\text{H} = -1.66$ and log $N_\text{H} = 21.32$), we found $R > 5.9$ kpc, $E_k > 1.2 \times 10^{-15} \Omega_{02}$ erg s$^{-1}$, and $M_{\text{out}} > 340 \Omega_{02} M_\odot$ yr$^{-1}$. It is of course possible that we’ll be able to detect Fe II$^+$ λ2396 absorption, which will give us a determination of $n_\text{e}$, and therefore measurements (instead of lower limits) for $M_{\text{out}}$ and $E_k$.

In this paper our analysis focused on troughs for which we can measure the Fe II column density. The other six troughs have only upper limits for the Fe II column density, given the current signal-to-noise ratio. In order to study the relationship between the troughs, and to obtain integrated values of $M_{\text{out}}$ and $E_k$ for the full outflow, it is important to measure the Fe II column density in all troughs. Combined with our other measurements, this will constrain the ionization parameter and total hydrogen column density in each individual trough. We detected He I$^+$ absorption from 3 different lines in almost all of the troughs (figure 3). The current data at He I$^+$ 2945, 3188 have a signal-to-noise-ratio of 65 per pixel. In order to obtain a similar or better signal-to-noise ratio at Fe II resonance lines (2383, 2586, and 2600) we need two additional hours of HDS integration.

9.2. Imaging of Outflowing Gas

The blue component of the [O III] emission line has the same outflow velocity as the trough at ~1000 km s$^{-1}$. Furthermore, the derived density and ionization parameter values for the trough are typical for the narrow-line regions of AGNs (see, e.g., Groves et al. 2004). The scale of 3.7 kpc in AKARI J1757+5907 corresponds to 0.55. The extended nebular gas associated with the outflow can be observed by the [O III] emission line by HST or the [S III] λ9533 emission line by integral filed spectroscopy coupled with adaptive optics observations from large ground-based telescopes. Currently, the solid angle subtended by the outflow is the parameter with the largest uncertainty. Imaging the outflowing gas will directly determine this parameter.

9.3. HST Cosmic Origins Spectrograph (COS) Observations

The near-UV side of COS offers two important gains for a scientific investigation of the outflow in AKARI J1757+5907. First, using the G230L grating we can cover the full range of 1333–2800 Å (observed frame) with a resolution of ~3000, and obtain data with $S/N \sim 30$ per resolution element using a total of six HST orbits. Such data will allow us to connect the low ionization absorption studied in this paper with the higher ionization phase seen in Si IV, C IV, and N V. In addition, this spectral range covers 3 pairs of Si II/Si II* lines that can determine a number density considerably lower than is possible with Fe II $E = 385$ cm$^{-1}$ (essentially the critical density of the Si II$^*$ level is an order of magnitude lower than that of Fe II $E = 385$). In the unlikely event that we will detect Si II, but not Si II$^*$ absorption, which means that the gas density is substantially below the critical density for the Si II$^*$ level, we will have C II/C II$^*$ transitions covered that can determine the number density down to $n_e \sim 10$ cm$^{-3}$. These diagnostics practically guarantee that we will be able to determine $n_e$, and therefore the distance of the outflow, as long as $R < 100$ kpc.

In addition, we can target the strongest pair of Si II/Si II$^*$ lines (1260 Å, 1265 Å) for a higher resolution ($R \sim 20000$) in order to obtain a fully resolved trough where we can obtain $n_e$ as a function of velocity for all 9 outflow components. With 6 HST orbits using the COS 225M grating we can obtain a sufficiently high signal-to-noise ratio to determine $n_e$ for 25–50 resolved velocity points across the full width of the outflow for a dynamical range in $n_e$ ($100 < n_e < 3000$ cm$^{-3}$). This will allow sensitive tomography of the outflow and a precise determination of the distance to each kinematic component.
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