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O VIII RESONANT ABSORPTION IN PKS 2155−304: A HOT WIND

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ABSTRACT

The broad X-ray absorption feature in PKS 2155−304 could be due to O VIII Lyα resonant absorption in a wind with outflow speeds up to $\sim$30,000 km s^{-1}. The properties of such a wind are calculated. A homogeneous spherically symmetric wind would involve a mass flux of $\sim$1000 $M_\odot$ yr^{-1}, but this estimate could be greatly reduced if the outflow were beamed, and/or the absorbing gas were clumped into small clouds. In the latter case, the O VIII absorption offers clues to the physical state of thermal material closer to the central energy source than the clouds which produce optical emission lines in quasars.

Subject headings: BL Lacertae objects — quasars — radiation mechanisms

I. INTRODUCTION

Canizares and Kruper (1984) have reported the detection of a sharp absorption feature at about 600 eV in the X-ray spectrum of the BL Lac object PKS 2155−304. The absence of any other X-ray or ultraviolet spectral features and a measured optical redshift for the object of 0.117 (Bowyer *et al.* 1984) led Canizares and Kruper (1984) to identify the feature with resonant absorption of O VIII Lyα, which has a rest energy of 654 eV. The width of the absorption line indicates a velocity spread of $\sim$30,000 km s^{-1}.

The absorbing material may either be part of an outflow close to the source, or it may be in the form of an enriched intergalactic medium along the line of sight. This last possibility creates more cosmological problems than it solves (Bowyer *et al.* 1984), but we note here that any oxygen in a diffuse hot intergalactic medium (such as may contribute to the X-ray background) need not be in ionization equilibrium. In this paper we consider the first possibility and show that the steep soft X-ray spectrum of PKS 2155−304 photoionizes surrounding gas in such a way that O VIII is a dominant absorber.

II. PHOTOIONIZATION IN PKS 2155−304

a) The Continuum Spectrum

The intensity of the X-ray emission from PKS 2155−304 appears to be variable. The spectrum is usually approximated by a sequence of power laws which are particularly steep in the soft X-ray region. Canizares and Kruper (1984) fitted their *Einstein Observatory* objective grating spectrometer (OGS) data between 0.7 and 1.5 keV with an energy index $\alpha \approx 1.8$ (flux $F_\nu \propto \nu^{-\alpha}$). Simultaneous ultraviolet spectra were taken with the *International Ultraviolet Explorer* (*IUE*) by Urry *et al.* (1982). The overall spectrum of PKS 2155−304 is shown in this last paper and in their report of *HEAO 1* X-ray spectra (Urry and Mushotzky 1982). Earlier spectra have been reported by Agrawal and Riegler (1979). We choose a continuum spectral shape of

$$F_\nu \propto \begin{cases} \nu^{-0.6}\,, & 0.4 \text{ eV} \le \epsilon \le 4.1 \text{ eV} \\ \nu^{-1.8}\,, & 4.1 \text{ eV} \le \epsilon \le 1.3 \text{ keV} \\ \nu^{-1.5}\,, & 1.3 \text{ keV} \le \epsilon \le 13 \text{ keV} \\ \nu^{0}\,, & 13 \text{ keV} \le \epsilon \le 45 \text{ keV} \\ \nu^{-0.7}\,, & 45 \text{ keV} \le \epsilon \le 500 \text{ keV} \end{cases} \quad (1)$$

for input to the photoionization code. There is an unusually hard segment from 13 to 45 keV as reported in the work of Urry and Mushotzky (1982) but unconfirmed by the simultaneous harder X-ray observations of R. Rothschild (1984, private communication). As we note below, our conclusions are not substantially affected by the spectral shape above a few keV. The total observed luminosity is $9 \times 10^{46}\, h^{-2}$ ergs s^{-1}, where h is the Hubble constant in units of 100 km s^{-1} Mpc^{-1}, and assuming that the effects of nonsimultaneity of observation in the different energy bands are negligible.

b) Equilibrium Ionization

We have used the photoionization code which is described elsewhere by Kallman and McCray (1982) and Krolik and Kallman (1984) to determine the physical conditions in gas irradiated by the above spectrum. The equilibrium temperature as a function of the ionization parameter $\Xi = L_{\rm ion}/(4\pi c r^2 n_{\rm H} kT)$ is shown in Figure 1, and the oxygen ionization fraction, n(O VIII)/n(O), in Figures 2 and 3. The fraction $L_{\rm ion}/L$ as given by the spectrum (eq. [1]) is 0.12, so that $L_{\rm ion} = 1.1 \times 10^{46}\, h^{-2}$ ergs s^{-1}.

The unusually steep UV and soft X-ray spectrum means that any multiple-equilibrium region, in which zones at different temperatures coexist in pressure equilibrium, is small (cf. Guilbert, Fabian, and McCray 1983). Also, as a result of the unusually steep ionizing spectrum, the maximum Ξ which permits a "cool" equilibrium (Ξ^*) is almost 100, at which $T \approx 1.4 \times 10^5$ K, while for a more typical active galaxy spectrum $\Xi^* \approx 10$ and $T \approx 5 \times 10^4$ K. The fractional abundance of O VIII is greater than 0.1 for $10 \le \Xi \le 90$ and $3 \times 10^4 \le T \le 1.6 \times 10^5$ K. Along the marginally stable branch (the section of the curve in Fig. 1 that rises almost vertically in T) the O VIII abundance falls approximately as

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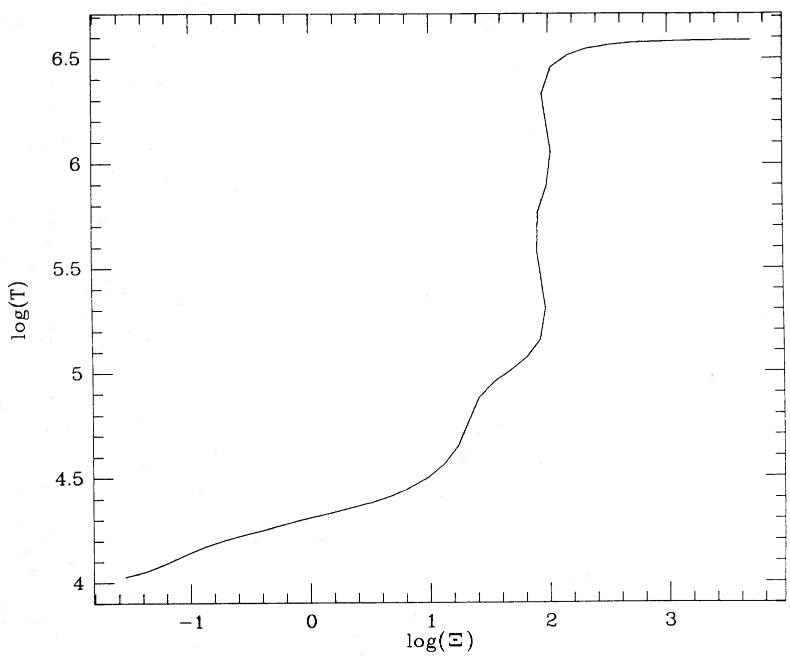

FIG. 1.—Temperature as a function of the ionization parameter $\Xi = (L_{\rm ion}/4\pi c r^2 n_{\rm H} kT)$ for a radiation spectrum of the form (1). Because this spectrum is rather steep, there is no genuine two-phase equilibrium, but only a "neutrally stable" regime at $\Xi \approx 100$; the limiting temperature for high Ξ, set by Compton equilibrium, is only $\sim 3 \times 10^6$ K.

$T^{-1.8}$; along the high-temperature Comptonization equilibrium the O VIII abundance falls roughly as $\Xi^{-1.2}$.

In the range of Ξ and T in which the O VIII abundance is greatest, neither Si nor S is fully stripped (Si XII, Si XIII and S XIV, S XV predominate at the high-Ξ end, less ionized species at the low end), and Fe always has L-shell electrons. The relative strengths of the lines that they will produce are given in Table 1. They are not detectable if the optical depth in O VIII Lyα is not large. If n(O VIII)/n(O) is reasonably close to unity, only Fe L has substantial opacity. No features are reported (Urry *et al.* 1982) from the *Einstein Observatory* solid state spectrometer data which cover the range from 0.8 to 4.5 keV.

As the temperature rises along the marginally stable branch, the abundances of unstripped Si and S increase relative to that of O VIII. Once the Comptonization equilibrium is reached, the ratios of the abundances of H-like Si and S relative to that of O VIII saturate at 50 and 120, respectively. Consequently, any model which produces an observable O VIII feature in which the temperature is greater than $\sim 2 \times 10^5$ K will predict substantial opacity in the Si and S K lines. Although Fe L opacity disappears above 2×10^6 K, Fe K opacity remains strong to higher values of Ξ than we have calculated here.

We have repeated the photoionization calculation for several other continuum spectra for which (1) the hard X-rays above 13 keV were absent or (2) the steep X-ray spectrum from 4.1 eV to 1.3 keV was continued to higher energies and/or (3) an extreme ultraviolet component was added. The Compton temperature was reduced in all cases to $\sim$(3–5) $\times 10^5$ K, but the curves of fractional oxygen abundance versus T or Ξ (Figs. 2 and 3) are not substantially changed.

c) O VIII Lyα *Resonance Absorption*

The O VIII Lyα cross section at line center, assuming only thermal broadening, is $4 \times 10^{-16}\ T_6^{-1/2}$ cm^2. Hence the column density as a function of optical depth $\tau(v)$ ($\tau < 1$) is

$$\Delta N_{\rm tot}(v) = 4 \times 10^{18} \tau(v) T_6^{1/2} \frac{n({\rm O})}{n({\rm O\ VIII})}\ {\rm cm}^{-2}\ , \qquad (2)$$

i.e.,

$$\Delta N_{\rm tot}(v) = 8 \times 10^{20} \tau(v) T_6^{2.3}\ {\rm cm}^{-2} \qquad (3)$$

TABLE 1

LINE OPACITIES

Parameter	O VIII Lyα	Si Kα	S Kα	Fe L
ϵ	654 eV	1.8–2 keV	2.4–2.6 keV	0.74–1.15 keV
X	7×10^{-4}	3×10^{-5}	1.2×10^{-5}	3×10^{-5}
$\sigma_{\rm th}$ (relative)	1.0	1.3	1.4	0.5–6.5
$X\,\sigma_{\rm th}$ (relative)	1.0	0.056	0.024	0.02–0.3

NOTE.—In this table, ϵ is the photon energy, X the abundance of the element relative to hydrogen, $\sigma_{\rm th}$ (relative) the line-center cross section relative to O VIII Lyα assuming thermal Doppler broadening, and $X\sigma_{\rm th}$ (relative) the line-center opacity relative to O VIII Lyα if all the atoms of each element are in the ionization stage (or stages) which contribute to line opacity. The cross sections for Si and S Kα are for the hydrogen-like stage; increased numbers of electrons increase them slightly.

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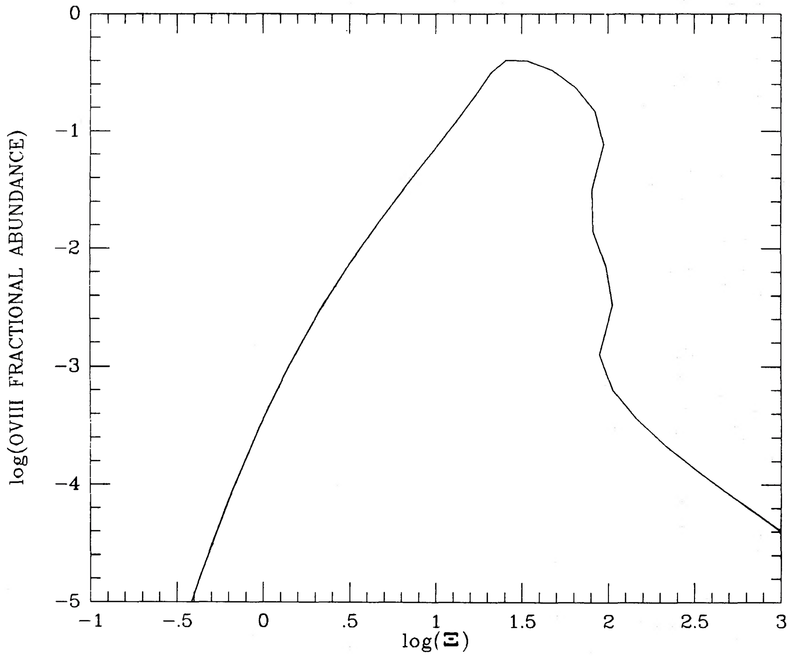

FIG. 2.—The fraction of oxygen in the O^{+7} state, as a function of Ξ

along the marginally stable equilibrium up to 3×10^6 K, or

$$\Delta N_{\rm tot}(v) = 1 \times 10^{22} \tau(v) \left(\frac{\Xi}{100}\right)^{1.2} \text{ cm}^{-2} \quad (4)$$

on the Comptonization equilibrium track.

The observed absorption feature is about 1000 times wider than that expected by thermal broadening alone, $\Delta v_{\rm th}$. The total column density summed over all velocities in the outflow is therefore at least this factor larger than the above $\Delta N_{\rm tot}(v)$, or, for typical parameters, $\sim 10^{24}$ cm^{-2}. Iron K-shell photoelectric absorption then has an optical depth $\tau_K \approx 0.5$, reducing to 0.001 if $T \approx 10^5$ K. Measurement of this edge is important in determining the gas temperature. A broad emission feature is expected below 600 eV in a manner analogous to the P Cygni profiles observed from stellar mass loss. The strength of this feature depends upon the geometry and any central opacity. It is not expected to be apparent in the steeply rising spectrum of Canizares and Kruper (1984).

The outflow must give velocities of 0 to $\sim 3 \times 10^4$ km s^{-1} at

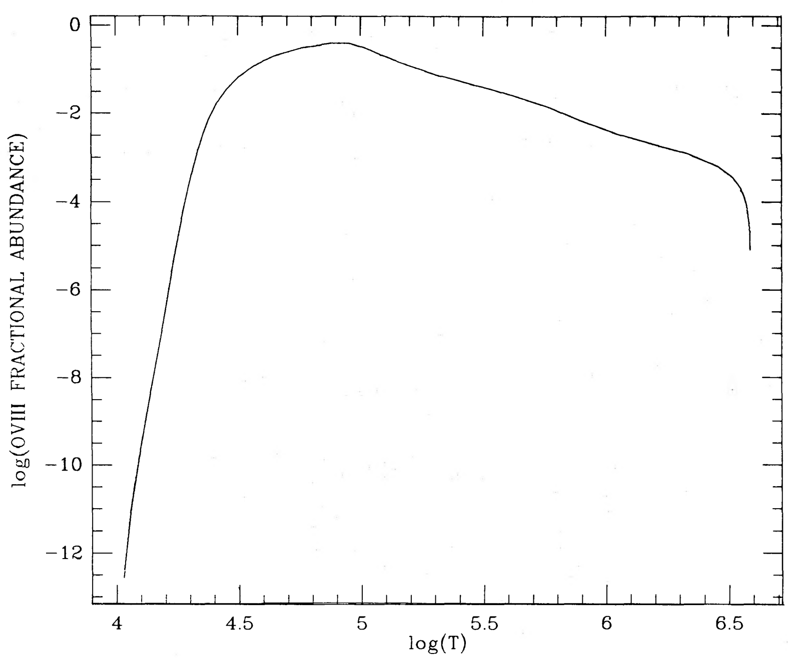

FIG. 3.—The fraction of oxygen in the O^{+7} state, as a function of T

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1985ApJ...295..104K

radii where O VIII is abundant, as well as the required column density.

$$r(v) = \frac{L_{\rm ion}}{4\pi c \Delta N_{\rm tot}(v) kT\Xi} \frac{\Delta v_{\rm th}/r}{dv/dr} . \tag{5}$$

If

$$d \log v / d \log r = \alpha(v) \approx 1 ,$$

then

$$\frac{\Delta v_{\rm th}/r}{dv/dr} \sim \frac{\Delta v_{\rm th}}{\alpha v} \sim \frac{10^{-3} T_6^{1/2}}{\alpha} , \tag{6}$$

for a total line width of 3×10^4 km s^{-1}. The radius and gas density are then evaluated as

$$r(v) = \begin{cases} 2.4 \times 10^{18} \tau^{-1}(v) L_{\rm ion,46}\, \alpha^{-1} T_6^{-2.8} \left(\frac{\Xi}{100}\right)^{-1} \text{ cm} \\ 3.3 \times 10^{17} \tau^{-1}(v) L_{\rm ion,46}\, \alpha^{-1} \left(\frac{\Xi}{100}\right)^{-2.2} \text{ cm}, \end{cases} \tag{7}$$

where $L_{\rm ion} = 10^{46} L_{\rm ion,46}$ ergs s^{-1}, and

$$n{\rm H} = \begin{cases} 3.3 \times 10^5 T_6^{4.6} (\Xi/100) \alpha^2 \tau^2 L_{\rm ion,46}^{-1} \text{ cm}^{-3} \\ 1.8 \times 10^7 (\Xi/100)^{3.4} \alpha^2 \tau^2 L_{\rm ion,46}^{-1} \text{ cm}^{-3} \end{cases} \tag{8}$$

for the marginally stable branch and the Comptonization equilibrium, respectively.

An additional uncertainty is introduced if $\tau \gtrsim 10$: because the absorbing bandwidth $\Delta v_{\rm obs} \approx 0.1c$, the oxygen K edge would then become thick, altering the ionization equilibrium.

d) Nonequilibrium Effects

The photoionization time scale, $t_{\rm ion} = 1.0 \times 10^4 r_{\rm pc}^2$ s, where the radius is measured in parsecs. This is much less than the dynamical time scale, $t_{\rm dyn} = 10^9 r_{\rm pc}$ s, unless the matter is $\gtrsim 100$ kpc away from the continuum source. Oxygen in matter close to the source cannot therefore be underionized unless the X-ray flux varies by a large factor on a time scale $< t_{\rm ion}$. This is unlikely, since there is no evidence for variation of more than a factor of 6 (M. Urry 1984, private communication). The recombination, heating, and cooling time scales,

$$t_{\rm rec} = 4.2 \times 10^6 T_6^{1/2} (n/10^5 \text{ cm}^{-3})^{-1} \text{ s} ,$$

$$t_{\rm heat} = 4.1 \times 10^8 T_6 r_{\rm pc}^2 \text{ s} ,$$

$$t_{\rm cool} = 8.0 \times 10^8 T_6^{0.7} (n/10^5 \text{ cm}^{-3})^{-1} \text{ s} ,$$

are less than $t_{\rm dyn}$ for typical values and mean that the gas is likely to be close to its photoionization and temperature equilibrium.

III. THE MASS FLUX

The mass loss rate, for a uniform spherically symmetric outflow, is

$$\dot{M} = \frac{\mu_{\rm H} v L_{\rm ion}}{ckT\Xi} = 2.7 \times 10^3 L_{\rm ion,46}\, T_6^{-1} \left(\frac{v}{3 \times 10^4 \text{ km s}^{-1}}\right) \times \left(\frac{\Xi}{100}\right)^{-1} M_\odot \text{ yr}^{-1} . \tag{9}$$

It is independent of almost all detailed quantities, including the optical depth of the absorption. The ionization parameter carries all the information about the density of material, while the greater the column density, the smaller the radius at which the characteristic value of Ξ is found.

If $\dot{M}$ is conserved, v must rise linearly with Ξ. In order for the wind to accelerate outward, we must have $d(\tau\alpha)/dr < 0$. From the data, τ does appear to decrease with increasing velocity, but the uncertainties do not allow for any quantitative estimate.

The ratio of the momentum flux in a smooth flow to the photon momentum flux is

$$\frac{\dot{M} vc}{L} = 1.8 \times 10^2 T_6^{-1} \left(\frac{\Xi}{100}\right)^{-1} \left(\frac{L_{\rm ion}}{0.12L}\right) \left(\frac{v}{3 \times 10^4 \text{ km s}^{-1}}\right)^2 , \tag{10}$$

while its kinetic power compared with the photon luminosity is

$$\frac{\dot{M} v^2}{2L} = 9.1 T_6^{-1} \left(\frac{\Xi}{100}\right)^{-1} \left(\frac{L_{\rm ion}}{0.12L}\right) \left(\frac{v}{3 \times 10^4 \text{ km s}^{-1}}\right)^3 . \tag{11}$$

Driving such a wind appears to be a problem. The power ratio can be reduced below unity if Ξ is increased by a factor of 10, which in turn means that the absorption takes place at $\lesssim 10^{15}$ cm or $\sim 100 R_{\rm S}(L_{\rm ion,46}/L_{\rm E})$. ($R_{\rm S}$ and $L_{\rm E}$ are the Schwarzschild radius and the Eddington limit of the central mass: gravitational redshift is then important.) We could also invoke a supersolar oxygen abundance.

Beaming, in which the outflow is directed along our line of sight, provides an alternative explanation. Moreover, the kinetic power, L_w, can be reduced below the photon luminosity if the outflow is collimated to within $\pm 40°$ but the photon luminosity is not similarly beamed. $\dot{M}$ is still $\sim 300\ M_\odot$ yr^{-1}. The ratio of L_w/L matches that inferred for some radio galaxies, i.e., $L_w \approx 10L$ (Dreher 1981).

Clumping is another possibility. The typical radius at which a smooth flow provides the necessary absorption, r_0, is $\sim T_6^{-2.8}$ pc (for $0.1 \lesssim T_6 \lesssim 3$). If smaller radii are considered for the same ionization parameter, then too much column density is produced. The gas can then produce the observed feature even if it does not occupy the entire volume $\sim r^3$. The volume filling factor, f_v, produced by n clouds of radius s within a shell of fractional radius a, corresponding to a velocity change of $v_{\rm th}$, is

$$f_v = \frac{n}{3a} \left(\frac{s}{r}\right)^3 . \tag{12}$$

The covering factor,

$$f_A = \frac{n}{4} \left(\frac{s}{r}\right)^2 = f_v \frac{3a}{4} \frac{r}{s} , \tag{13}$$

must be ~ 1 to produce an observable feature. Requiring a constant ionization parameter and a fixed column density means that $nr^2 = n_0 r_0^2$ and $ns = n_0 a r_0$, respectively, so that when $f_v \ll 1$, $r = \frac{3}{4} r_0 f_v$, or

$$r = 2 \times 10^{18} T_6^{-2.8} f_v \text{ cm} . \tag{14}$$

The kinetic power of an isotropic outflow could be reduced below the photon luminosity if $f_v + (T_c p_c / T_h p_h) \lesssim 0.1$, where

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$T_{c,h}$ and $p_{c,h}$ are the temperature and pressure of the clumps and the hotter surrounding material; to provide sufficient column density, the absorption would then have to occur at $r \lesssim 10^{20}$ cm for $T = 10^5$ K (or $r \lesssim 10^{17}$ cm for $T \approx 10^6$ K). The corresponding cloud sizes s are $\lesssim 10^{16}$ and $\lesssim 10^{13}$ cm, respectively. The sound crossing time for a cloud, $t_s = 3 \times 10^5 s_{13}^{1/2} T_6^{-1/2}$ s, is much less than $t_{\rm dyn} \approx 3 \times 10^7 r_{17}$ s. The clouds then need to be confined (unless they can be repeatedly re-formed in the outflowing material). Because the gas is neutrally stable over the temperature range 5×10^4–3×10^6 K (see Fig. 2), it is marginally possible to have clouds with T at the bottom of this range confined by the pressure of a hotter intercloud medium up to ~ 60 times less dense. This allows a mass flux 60 times lower than that given by equation (9). A larger density contrast could arise if the ions in the confining medium were hotter than the electrons. Magnetic confinement would require fields of only $1.5 T_6^{1/2} r_{16}^{-1}$ G. The clouds may be thin filaments magnetically embedded in a plasma outflow. The accelerating force may provide extra confinement, at least in the radial direction.

Radiation pressure on the O VIII ions is inadequate to accelerate even a clumpy wind. The observed absorption feature removes only about 10^{-3} of the source luminosity (from eq. [1]). $\dot{M}vc/L$ (eq. [10]) must then be reduced below that value if radiation pressure on O VIII ions is important. However, since the frequency-averaged cross section per hydrogen atom for O VIII resonance scattering in the spectrum of PKS 2155−304 is at most only comparable to the Thomson scattering cross section (when $T \approx 10^5$ K), radiation pressure is important only when $L > L_{\rm E}$. In a clumpy wind, radiative acceleration will be greater for the clouds than for the hotter medium between them. Even though it cannot provide the main acceleration, it can generate supersonic velocities, and may thereby confine and maintain clouds under conditions which would otherwise only be marginally stable.

IV. DISCUSSION

The soft X-ray absorption feature in PKS 2155−304 can be produced by resonant scattering by O VIII in a manner similar to that producing the P Cygni profiles observed in hot stars. Simple models suggest that the associated mass flux is extremely large ($> 10^3\ M_\odot$ yr^{-1}) unless the outflow is beamed toward us. The power in the jet would exceed the photon luminosity unless the latter were unbeamed. PKS 2155−304 would then be an example of an object with a subrelativistic jet. It is possible that there is also a relativistic jet in PKS 2155−304 if the material we see is entrained matter. However, for this to be true, two conditions must be met: the relativistic jet must be narrow enough and the entrained matter wide enough that most of the X-ray emitting region can be obscured; and the ratio $(\Omega_b/4\pi e)(L/L_j)$ must be $\sim 5 \times 10^{-3}(\Xi/100)$ min $(T_6, 1)$, where Ω_b is the solid angle of the entrained matter with respect to the source of the ionizing continuum, L_j is the luminosity of the relativistic jet, and e is the efficiency of momentum transfer from the relativistic jet to the entrained matter (cf. eq. [10]). These conditions may be difficult to satisfy, in which case PKS 2155−304 would provide evidence against a "relativistic jet" model for BL Lac objects.

Clumping of the gas can reduce the inferred mass flux by a factor ~ 100, but it introduces a further requirement for confinement of clumps. Variability of the depth of the absorption feature is expected on time scales of days to years, depending upon the temperature of the gas and whether it is clumped or not. Observations of Si, S, and Fe features can limit the fractional abundance of O VIII and thus the temperature of the absorbing gas.

Such a large mass outflow in a quasar could lead to substantial optical and ultraviolet absorption, similar to that in broad absorption-line quasars (Canizares and Kruper 1984). These show large velocity absorption troughs with outflow velocities 2×10^4 km s^{-1} (Weymann, Carswell, and Smith 1981; Turnshek 1984) and involve mass fluxes of at least $3 r_{\rm pc} f_v^{-1}\ M_\odot$ yr^{-1} and perhaps up to $\sim 40\ M_\odot$ yr^{-1} (Drew and Boksenberg 1984). If the X-ray spectrum of PKS 2155−304 were to change into that of a typical Seyfert galaxy, the lowest density gas would be Compton heated to $\sim 10^8$ K, and may then expand to create an intercloud medium with a hundredfold increase of pressure. Any remaining denser clouds would then become more dense, cool, and generate strong optical and ultraviolet emission lines. The source would effectively become a quasar (cf. Guilbert, Fabian, and McCray 1983). Broad absorption lines would be observed while the outflow continued, or at least for $t_{\rm dyn}$.

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