

THE ABSORPTION SPECTRUM OF THE QUASAR PHL 1222

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ABSTRACT

Intermediate dispersion spectroscopy of the quasar PHL 1222 ($z_{\text{em}} = 1.91$) has revealed the presence of C II and Si II absorption lines arising from the ground state in a system with $z_{\text{abs}} = 1.934$. The absence of absorption lines arising from the excited fine-structure levels of these ions enables limits to be placed on the physical conditions in the absorption cloud. The gas must have a density $n_e \leq 15 \text{ cm}^{-3}$, and must be at least $4 \times 10^5 \text{ pc}$ from the continuum source. If inward gravitational acceleration is responsible for the existence of the absorption system with $z_{\text{abs}} > z_{\text{em}}$, and if the cosmological distance of the QSO is adopted, then the mass producing the acceleration must be $\geq 3 \times 10^{14} M_{\odot}$. We take this as suggestive evidence that the $z_{\text{abs}} = 1.934$ system represents an intergalactic gas cloud moving in a cluster of galaxies which contains a quasar. In addition, we have discovered three new redshift systems based upon the C IV doublet, for which $z_{\text{abs}} \ll z_{\text{em}}$.

Subject headings: galaxies: intergalactic matter — galaxies: redshifts — quasars

I. INTRODUCTION

The quasi-stellar object PHL 1222 has been observed at intermediate dispersion as part of a program we have undertaken to study objects which have previously been reported to have an absorption redshift which exceeds the emission redshift, $z_{\text{abs}} > z_{\text{em}}$. Spectra have been obtained of a number of such objects, and the results of this program are in preparation. The object PHL 1222 was found to have a spectrum of sufficient interest that a separate short communication concerning this particular object was felt warranted.

PHL 1222 has previously been observed spectroscopically by Burbidge (1968) and Schmidt (1974). Both used relatively low dispersion ($\geq 200 \text{ \AA mm}^{-1}$), and reported the presence of a number of emission lines and one absorption line. The emission lines identified by both investigators were $\text{L}\alpha$, N V $\lambda 1240$, Si IV $\lambda 1400$, and C IV $\lambda 1550$, yielding a redshift of $z_{\text{em}} = 1.91$. Both Burbidge and Schmidt reported observing one strong absorption line in the spectrum at $\sim 3570 \text{ \AA}$, which they identified as $\text{L}\alpha$, yielding $z_{\text{abs}} = 1.94$. In 1975 November we reobserved PHL 1222 with the RCA C33063 two-stage image tube and Cassegrain spectrograph of the Steward Observatory 2.3 m telescope, obtaining three separate spectra of the object at a dispersion of 47 \AA mm^{-1} and widened 0.4 mm. Two of the spectra (plates 1785 and 1802) cover the blue portion of the spectrum, from 3400 to 4200 \AA , while the remaining spectrum (plate 1803) covers the region 4100–5000 \AA .

II. RESULTS

The measured wavelengths of the absorption lines appearing on plates 1802 and 1803 are presented in Table 1, together with our suggested identifications and resulting redshifts. Those lines on plate 1802 which were

TABLE 1

ABSORPTION LINES IN PHL 1222

Line	Measured λ (\AA)	Identification	z_{abs}
<i>a</i> *	3507.8
<i>b</i> *	3539.0	Si III 1206.51	1.9332
<i>c</i> *	3551.5
<i>d</i> ₁ *	3561.1	$\text{L}\alpha$ 1215.67	1.9293
<i>d</i> ₂	3566.7	$\text{L}\alpha$ 1215.67	1.9339
<i>d</i> ₃ *	3570.2	$\text{L}\alpha$ 1215.67	1.9368
<i>e</i> *	3697.4	Si II 1260.42	1.9335
<i>f</i> *	3820.0	C IV 1548.20	1.4674
<i>g</i>	3826.1	C IV 1550.77	1.4672
<i>h</i> *	3915.2	C II 1334.53	1.9338
<i>i</i>	3964.7	C IV 1548.20	1.5608
<i>j</i>	3970.8	C IV 1550.77	1.5605
<i>k</i> *	4053.3	C IV 1548.20	1.6181
<i>l</i> *	4060.4	C IV 1550.77	1.6183
<i>m</i>	4541.4	C IV 1548.20	1.9333
<i>n</i>	4548.6	C IV 1550.77	1.9331

NOTES.—An asterisk denotes that the lines on plate 1802 (*a-l*) were also measurable on plate 1785. Identification wavelengths are vacuum wavelengths; observed wavelengths have not been reduced to vacuum values.

also seen on plate 1785 (which is somewhat overexposed and poorer in quality) are marked with an asterisk. Absorption lines at 3493, 3513, 3519, and 3531 \AA appear to be present on 1785 but were not present with any certainty on 1802. Figure 1 shows a density tracing of plate 1802, covering the region 3500–4100 \AA .

The most striking features in the spectrum are the very strong absorption line centered around $\lambda 3567$, which we observe to be split into three components, and four sets of closely spaced doublets. The identification of the $\lambda 3567$ features as $\text{L}\alpha$ is confirmed by the very

good redshift agreement for single lines identified with Si II, Si III, and C II, and the C IV doublet at $\lambda\lambda 4541, 4549$. The identification of the three remaining doublets as C IV $\lambda 1550$ in three separate redshift systems seems quite certain in view of the close agreement between the theoretical doublet wavelength ratio (1.00166) and the observed values of 1.00159, 1.00155, and 1.00175 for the systems with $z_{\text{abs}} = 1.467, 1.561, \text{ and } 1.618$, respectively. [We note in passing that the ratio of $(1 + z_{\text{em}})/(1 + z_{\text{abs}})$ for these three systems is 1.111, 1.136, and 1.179. Two of these values correspond to the line-locking ratios discussed by the Burbidges (1975), while the third (1.136) does not.] We have not identified one strong line, $\lambda 3508$, and one line of moderate strength, $\lambda 3551$. The Si II lines at $\lambda\lambda 1190.4$ and 1193.3 should be present at $\lambda 3492$ and $\lambda 3500$ in the same redshift system as the Si II $\lambda 1260$ line. The former may be present on plate 1785, but the wavelength discrepancy is too large to identify it with the strong observed line at $\lambda 3508$. Both unidentified lines may therefore simply represent $L\alpha$ in additional redshift systems. We shall not comment further on the 1.467, 1.561, and 1.618 systems except to note that the absence of C II (which is accessible in the latter two systems) suggests that the ionization in these systems is substantially higher than in the 1.934 system.

The absence of detectable C II $\lambda 1335.7$ and Si II

$\lambda 1264.7$ absorption lines arising from excited fine-structure levels in the $z_{\text{abs}} = 1.934$ system is noteworthy. The expected positions of these lines are denoted by h' and e' in Figure 1. The expected separation of the C II pair is a bit larger than our resolution limit, being comparable to the separation of the two $L\alpha$ components marked d_2 and d_3 . We estimate that the equivalent widths of the excited-state absorption lines are no more than about one-third of the corresponding ground-state lines in each case.

III. DISCUSSION

It has been suggested that one mechanism for producing absorption systems with $z_{\text{abs}} > z_{\text{em}}$ involves the inward acceleration of a cloud of gas by a central mass. This gravitational infall could occur either by the accretion of material not previously associated with the quasar (Williams 1970), or as the result of a cloud which was ejected from the quasar by radiation pressure, which expanded and then fell back toward the continuum source (Kippenhahn, Perry, and Röser 1974). There are other mechanisms possible which can produce $z_{\text{abs}} > z_{\text{em}}$, but virtually all of them interpret the redshifts of the emission and absorption systems as indicating the relative velocities of the emitting and absorbing gas. The various theories differ only in explaining the cause of the inward cloud velocity. If it

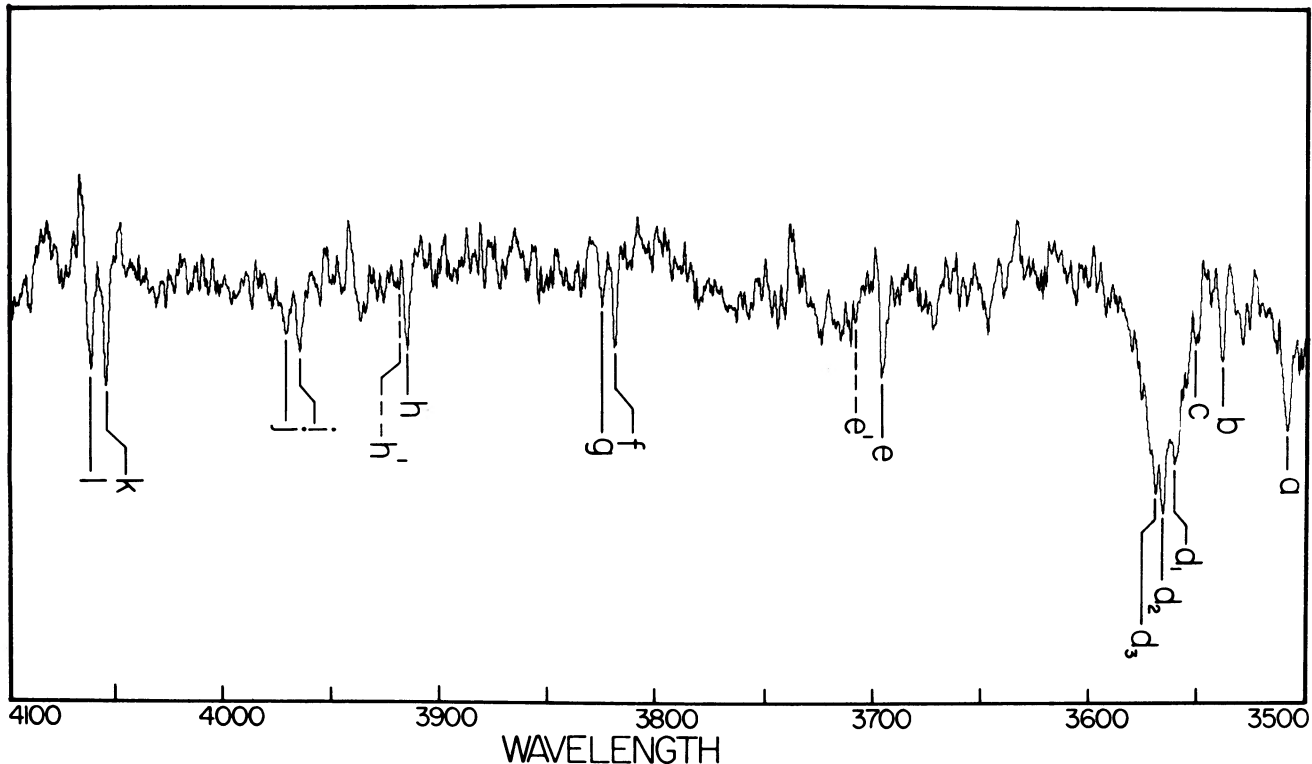


FIG. 1.—Density tracing of plate 1802 of PHL 1222. The lines marked $a-l$ correspond to the lines measured in Table 1. The points marked e' and h' correspond to the expected positions of the excited fine-structure lines of Si II and C II, respectively. The wavelength scale is approximate.

is caused by gravity, as we shall initially assume below, certain constraints can be put on the parameters of the absorbing cloud by our data.

The observed strengths of the Si II, Si III, C II, and C IV lines, in addition to the absence of any detectable Si IV or N V absorption, provide an indication of the level of ionization in the absorbing cloud. A series of ionization equilibrium calculations with normal solar abundances and plane-parallel slabs has been carried out which show that the observed line strengths in the 1.934 redshift system can be reproduced quite well by photoionization of a cloud in which the level of ionization is prescribed by the parameter $n_e r^2 \approx 3 \times 10^{49} \text{ cm}^{-1}$, where n_e is the electron density and r is the distance of the cloud from the ionizing continuum source. For these calculations, we have assumed the continuous radiation to have a spectral index of $\gamma = 1$, and the monochromatic luminosity at the Lyman limit to be $L_{\nu_0} = 5 \times 10^{30} \text{ ergs s}^{-1} \text{ Hz}^{-1}$. This latter assumption depends, of course, upon the assumption of the cosmological distances for the QSOs which we shall adopt in the remainder of the discussion. The calculations also show that the temperature throughout the region producing the C II and Si II ions does not differ much from 10^4 K , and that the hydrogen ionization is sufficiently high that electron collisions will be the dominant mechanism for excitation of the C II and Si II fine-structure levels (Bahcall and Wolf 1968). Using the expressions given by these authors for the radiative rates and collision cross sections, together with the limit inferred from the relative line strengths for the population ratio of the excited level to the ground level of C II, leads to the result that $n_e \leq 15 \text{ cm}^{-3}$. This limit on the gas density and the value of the ionization parameter $n_e r^2$ necessary to explain the relative line equivalent widths require the cloud distance from the continuum source to be $r_0 \geq 460 \text{ kpc}$.

If we adopt an emission redshift of 1.910 for PHL 1222 and a value of 1.9335 for the absorption redshift, then the resulting infall velocity for the cloud is 2400 km s^{-1} . The simplest, most straightforward model of a cloud of gas falling from rest at infinity toward a point mass requires a mass of $M \geq r_0^3/(2G) = 3 \times 10^{14} M_\odot$ to produce such a velocity at a distance of $r_0 \geq 460 \text{ kpc}$. While admitting to the uncertainty in these values, if the $z_{\text{abs}} > z_{\text{em}}$ system in PHL 1222 is a representative example of such systems in quasars, the parameters deduced for the absorbing cloud are of some consequence. If gravity is causing the inward acceleration of gas toward the continuum source, either the masses of QSOs must be far greater than the $\sim 10^8 M_\odot$ figure sometimes cited (cf. Burbidge and Perry 1976), or the mass causing the acceleration is not directly related to the quasar.

We believe that the fact that the inferred minimum mass of $\sim 3 \times 10^{14} M_\odot$ and the velocity and distance of the cloud are similar to the masses, velocity dispersions, and sizes of large clusters of galaxies (Rood *et al.* 1972) is suggestive evidence that $z_{\text{abs}} > z_{\text{em}}$ systems are clouds of gas moving in the gravitational

field of large clusters of galaxies. The cloud velocity of 2400 km s^{-1} is greater than the velocity dispersions of the nearer, well-studied clusters; however, it is known that individual galaxies near the apparent center of the Coma cluster have peculiar velocities of $\sim 2500 \text{ km s}^{-1}$ (Tift and Gregory 1976). The cloud velocity could be due to direct infall from outside the cluster, or it could represent the random motion of a bound intra-cluster gas cloud. The fact that carbon and silicon are observed in the cloud argues for the previous association of the gas with galaxies, from which it has perhaps been expelled by explosive phenomena in galactic nuclei. There is weak independent evidence that may support this interpretation. The ionization calculations used to predict column densities for the $z_{\text{abs}} = 1.934$ system correctly accounted for all of the relative absorption line strengths, with the possible exception of $\text{L}\alpha$. The model giving the best fit to the carbon and silicon lines predicts a neutral hydrogen column density of $\sim 3 \times 10^{18} \text{ cm}^{-2}$. This result, obtained using solar element abundances, appears to be inconsistent with our observed $\text{L}\alpha$ profile (cf. Fig. 1), which indicates the presence of a damping wing extending $\sim 10 \text{ \AA}$ longward of the line core. If the damping wing is real, the column density of H^0 required to produce this feature is $\sim 2 \times 10^{20} \text{ cm}^{-2}$, a value larger than our predictions by almost two orders of magnitude, and we would probably have to conclude that the metals are underabundant in the cloud by a factor of 100 from solar values, comparable to extreme Population II objects in our Galaxy. One would expect that the metal abundance of an intergalactic cloud should be low, if metals are even present at all. If the metal abundance is indeed low, our ionization calculations would no longer be representative of the gas. The increased column density of H^0 relative to other elements would require decreasing $n_e r^2$ by a factor of ~ 16 in order to maintain the observed heavy-element ionization. This would reduce the derived cloud distance and cluster mass by a factor of 4.

It is interesting to note that a cloud with a density $n_e \approx 10 \text{ cm}^{-3}$ and electron temperature of $\sim 10^4 \text{ K}$ would be in approximate pressure equilibrium with the hot ($\sim 10^8 \text{ K}$), tenuous ($n_e \approx 10^{-3} \text{ cm}^{-3}$) gas postulated to exist in clusters of galaxies which show extended X-ray emission (Lea *et al.* 1973).

Finally, we must mention the fact that our conclusions concerning PHL 1222 are tentative, subject to an accurate determination of the emission redshift. The system we used in obtaining our data is unsuitable for this purpose, and we have therefore used the value obtained by Burbidge (1968) and Schmidt (1974). According to Schmidt (1974), the error in z_{em} is at least ± 0.01 . Hence, it is important to obtain accurate profiles of the broad emission lines to obtain an accurate value of z_{em} , since the inferred mass is proportional to $(z_{\text{abs}} - z_{\text{em}})^2$.

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REFERENCES

- Bahcall, J. N., and Wolf, R. A. 1968, *Ap. J.*, **152**, 701.
 Burbidge, E. M. 1968, *Ap. J. (Letters)*, **154**, L109.
 Burbidge, E. M., and Burbidge, G. R. 1975, *Ap. J.*, **202**, 287.
 Burbidge, G. R., and Perry, J. J. 1976, *Ap. J. (Letters)*, **205**, L55.
 Kippenhahn, R., Perry, J. J., and Röser, H.-J. 1974, *Astr. and Ap.*, **34**, 211.
- Lea, S. M., Silk, J., Kellogg, E., and Murray, S. 1973, *Ap. J. (Letters)*, **184**, L105.
 Rood, H. J., Page, T. L., Kintner, E. C., and King, I. R. 1972, *Ap. J.*, **175**, 627.
 Schmidt, M. 1974, *Ap. J.*, **193**, 509.
 Tift, W. G., and Gregory, S. A. 1976, *Ap. J.*, **205**, 696.
 Williams, R. E. 1970, *Nature*, **228**, 269.

Note added in proof.—Dr. R. Carswell has kindly shown us a scan of PHL 1222 obtained by W. Sargent, A. Boksenberg, and him with the Hale Observatories 5 m telescope, from which we have determined the emission redshift from the $L\alpha$ and Si IV lines to be $z_{\text{em}} = 1.903 \pm 0.008$. This implies a velocity for the absorbing cloud with respect to the quasar of -3190 km s^{-1} .

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