THE ASTROPHYSICAL JOURNAL, 226:L61–L64, 1978 December 1

PKS 0537−286: A HIGH-REDSHIFT QSO WITH AN EXTREME LYMAN-CONTINUUM CUTOFF

ALAN E. WRIGHT AND BRUCE A. PETERSON
Anglo-Australian Observatory, Sydney

DAVID L. JAUNCEY
Division of Radiophysics, CSIRO, Sydney

AND

JAMES J. CONDON*
National Radio Astronomy Observatory, Charlottesville, Virginia;† and
Department of Physics, Virginia Polytechnic Institute and State University
Received 1978 July 24; accepted 1978 August 17

ABSTRACT

Spectroscopic observations of the 20th mag object identified with the radio source PKS 0537−286 show it to have (i) an emission redshift of 3.11; (ii) a prominent absorption system at a redshift of 2.976; and (iii) a strong discontinuity at the Lyman-continuum edge in the absorption system.
Subject headings: galaxies: redshifts — quasars — radio sources: spectra

I. INTRODUCTION

The radio source PKS 0537−286 appears in the seventh part of the Parkes 2700 MHz supplementary catalog (Bolton, Shimmins, and Wall 1975), the fourth part of the Ohio 1415 MHz survey (Ehman, Dixon, and Kraus 1970, = OG 263), and the B1 Bologna 408 MHz catalog (Braccesi *et al.* 1965, = B1 0537−28). It was originally identified with a 19½ mag galaxy by Gearhart *et al.* (1972) but later as a 20 mag Q? (i.e., a stellar object on position but without confirmed UV excess), 1′ south of the galaxy, by Bolton *et al.*, who also give a finding chart. A more accurate radio position (Condon, Hicks, and Jauncey 1977) confirmed the latter identification, but the object is described by Condon *et al.* as a 20 mag red, possible galaxy, on the basis of a nonstellar image on the Palomar E plate. The positions (epoch 1950) from Condon *et al.* are: radio, $\alpha = 05^h\ 37^m\ 56^s.90 \pm 0^s.09$, $\delta = -28°\ 41'\ 26''.8 \pm 2''.6$; optical, $\alpha = 05^h\ 37^m\ 56^s.94 \pm 0^s.07$, $\delta = -28°\ 41'\ 28''.3 \pm 0''.9$. The radio spectrum of the source is shown in Figure 1, where the flux densities are taken from the references given above and supplemented by our own measurements.

II. SPECTROSCOPIC RESULTS

We obtained an optical spectrum of PKS 0537−286 on the night of 1978 February 11–12 using the Image Photon-Counting System on the RGO spectrograph of the 4 m Anglo-Australian Telescope during our program of low-dispersion spectroscopy of a complete sample of flat-spectrum radio sources drawn from the Parkes 2700 MHz Survey. The spectrum covered the wavelength region from about 3300 to 6800 Å with a resolution of approximately 10 Å. The data were taken under conditions of 2″ seeing with entrance apertures of 3″. The resulting spectrum is shown in Figure 2. The abscissa is observed wavelength and the ordinate is flux density, F_ν.

The most notable features of the spectrum shown in Figure 2 are (i) the strong emission line near 5000 Å which we identify with Lα λ1216; (ii) the many absorption lines, both shortward and longward of the Lα emission feature; and particularly (iii) the extremely sharp drop in the continuum level shortward of 3650 Å.

a) The Emission Redshift

Table 1 lists the wavelengths of the principal emission features. After the strongest line at 5000 Å had been identified with Lα, the other features could be identified with the normally occurring lines of C IV, N V, and Lβ/O VI at a mean redshift of 3.11. The close wave-

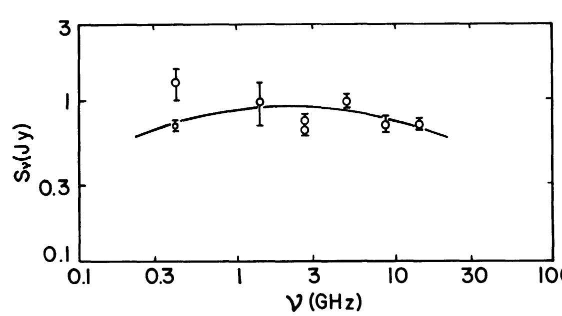

FIG. 1.—Radio observations of PKS 0537−286. The solid line represents our best estimate of the shape of the spectrum.

* Alfred P. Sloan Foundation Fellow.

† The NRAO is operated by Associated Universities, Inc., under contract with the National Science Foundation.

length agreement establishes the emission system beyond doubt. However, the presence of strong absorption features causes our mean emission redshift to be uncertain to about ± 0.01.

b) The Absorption Spectrum

Many absorption features are visible in Figure 2, particularly shortward of the Lα emission line. The wavelengths and identifications of several of these are given in Table 2. We tentatively identified the strong, black line at 4831 Å with Lα λ1215.7 at a redshift of about 2.97 and the strong continuum discontinuity near 3650 Å with the Lyman-continuum edge (912 Å) at the same redshift. It was then possible to identify

TABLE 1

PRINCIPAL EMISSION LINES IN PKS 0537−286

λ_{obs}	Ident.	λ_{rest}	z
4238......	Lβ/O VI	1030	3.115
5000......	Lα	1216	3.112
5100......	N V	1240	3.113
5760......	Si IV/[O IV]	1400	3.114
6302......	C IV	1549	3.068

TABLE 2

PRINCIPAL ABSORPTION LINES IN PKS 0537−286*

λ_{obs}(Å)	IDENT.	z System A	z System B
3728...........	Lϵ 937.8	2.975	...
3778...........	Lδ 949.7	2.978	...
3804...........	...	...	...
3869...........	Lγ 972.5	2.978	...
3883...........	C III 977.0	2.974	...
3922...........	...	...	...
4078...........	Lβ 1025.8	2.975	...
4103...........	O VI 1032.0	2.976	...
4129...........	O VI 1037.6	2.979	...
4289...........	...	...	...
4373 (blend?) ...	...	...	...
4446...........	N II 1084.0	...	3.101
4514...........	...	...	...
4567...........	...	...	...
4579...........	...	...	...
4650...........	...	...	...
4831...........	Lα 1215.7	2.974	...
4978...........	Lα 1215.7	...	3.095
5010...........	...	...	...
5310...........	C II 1334.5	2.979	...
6160...........	C IV 1549 blend	2.977	...
6340...........	C IV 1549 blend	...	3.093

* System A is certain; System B is believed only to be likely.

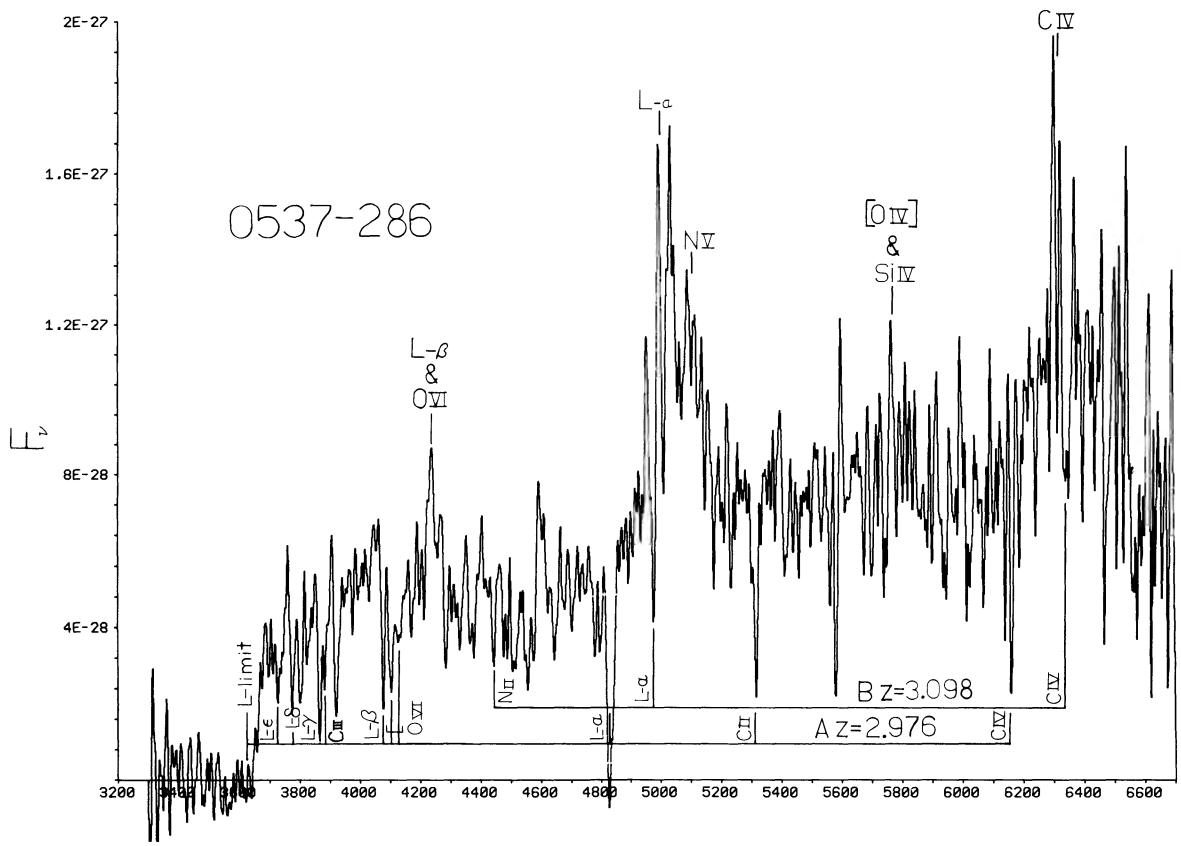

FIG. 2.—Scanner spectrum of PKS 0537−286. The ordinate is flux density F_ν in units of ergs s^{-1} cm^{-2} Hz^{-1}. The main emission and absorption features are marked.

many of the other lines in Table 2 with normally occurring QSO lines in a single redshift system at $z_{abs} = 2.976$ with a formal standard error of ± 0.001.

Another likely system can be found by identifying the 4978 Å line with Lα λ1215.7, the features at 4446 Å and 4650 Å with N II λ1084.0 and N I λ1134.5, respectively, and the strong, broad feature at 6340 Å with the blended C IV doublet. We note, though, that there is no evidence for a strong N I λ1200 line which would occur near 4916 Å. The N I λ1134.5 identification is therefore probably wrong. However, additional support for the reality of this system comes from other members of the Lyman series: Lβ appears to be present at 4200 Å, and a weak feature at 3980 Å may be Lγ. The overall mean absorption redshift of this system is 3.098 ± 0.003. The Lyman limit in this system would occur at an observed wavelength of about 3735 Å; however, it is not clear from our data whether continuum absorption is present at this wavelength. Clearly, higher-dispersion observations of this object are necessary; but these will not be easy, since PKS 0537−286 is presently at about 20th mag.

We note that the expected position of the Lyman-continuum edge at the *emission* redshift of 3.11 falls near 3750 Å. No appreciable absorption is seen there. The observed discontinuity near 3650 Å is clearly associated with the principal absorption system at a redshift of 2.976.

The presence of both a Lα absorption line and a Lyman-continuum discontinuity in the $z = 2.976$ absorption system allows two estimates to be made of the column density N_H of neutral hydrogen. If we assume that the Lα line, which we measure to have an equivalent width of about 30 Å, has a pure damping profile, we calculate a value for N_H of $\sim 1 \times 10^{20}$ cm^{-2}. Only if the hydrogen atoms have an rms velocity dispersion in the line of sight exceeding 250 km s^{-1} would the deviation from a damping profile reduce our value for N_H by more than a factor of 2.

Alternatively, from the observed discontinuity of greater than a factor of $\sim$15 due to Lyman-continuum absorption, we deduce an optical depth τ of $\gtrsim 2.7$. Using the value for the linear, continuum absorption coefficient (Allen 1973, p. 96), we obtain a column density of greater than $\sim 3 \times 10^{17}$ cm^{-2}. The two estimates are therefore consistent. We note that the value obtained from the Lα line (1×10^{20} cm^{-2}) is similar to that expected in the interstellar medium of an intervening galaxy.

III. DISCUSSION

In our *Letter* describing the high-redshift QSO PKS 2126−15 (Jauncey *et al.* 1978), we suggested that the search for other high-redshift QSOs on the basis of accurate radio positions and a red or neutral color selection criterion was likely to prove rewarding. This has been confirmed by the discovery of the red object PKS 1402+044 (Peterson *et al.* 1978) at an emission redshift of 3.20 and by the present data for PKS 0537−286. The result reported here for PKS 0537−286 brings to six the number of radio-selected QSOs known with emission redshifts in excess of 3. These are listed in Table 3. All of these objects except PKS 1442+101 show a Lyman-continuum absorption discontinuity in one of the absorption systems. In none of the six objects is there clear evidence for a Lyman-continuum discontinuity in either absorption or emission at the emission redshift. If these QSOs were situated in spiral galaxies with ordinary neutral hydrogen content, then the column density would probably be sufficiently high ($\gtrsim 10^{17}$ cm^{-2}, for a random orientation of the galaxy) that an absorption discontinuity would exist at the emission redshift. If the gas is ionized, the situation is more complex (Davidson 1976) but an emission discontinuity is then likely. The lack of a continuum discontinuity in either absorption or emission in *any* of the objects in Table 3 argues against them being situated in such galaxies.

It is also interesting to note that, of the six objects given in Table 3, three (0938+119, PKS 1402+044, and now PKS 0537−286) were originally identified from the Palomar Sky Survey plates as galaxies or probable galaxies on the basis of a nonstellar image, as well as a red color. Figure 3 (Plate L3) shows a reproduction of a recent IIIa-J plate of the field of PKS 0537−286 taken with the 1.2 m UK Schmidt telescope. The object is clearly stellar. The nonstellar image on the Palomar E-plate may result from poor chromatic aberration correction. But, whatever the explanation, there remains the urgent question as to how many more QSOs are misidentified as galaxies.

The red colors of 0938+119 and PKS 1402+044 result from strong absorption lines shortward of the

TABLE 3

RADIO-SELECTED QSOs KNOWN TO HAVE z_{em} 3.0

Name	z_{em}	Lyman-Continuum Discontinuity?	Ref.
PKS 0537−286	3.11	Yes	This *Letter*
0642+44 (OH 471)	3.40	Yes	Carswell and Stritmatter 1973
0938+119	3.19	Yes	Beaver *et al.* 1976
PKS 1402+044	3.20	Yes	Peterson *et al.* 1978
PKS 1442+101 (OQ 172)	3.53	No	Wampler *et al.* 1973
PKS 2126−15	3.27	Yes	Jauncey *et al.* 1978 and unpublished data

NOTE.—Objects in right ascension order. The Lyman-continuum discontinuity referred to is an absorption discontinuity in an *absorption* system.

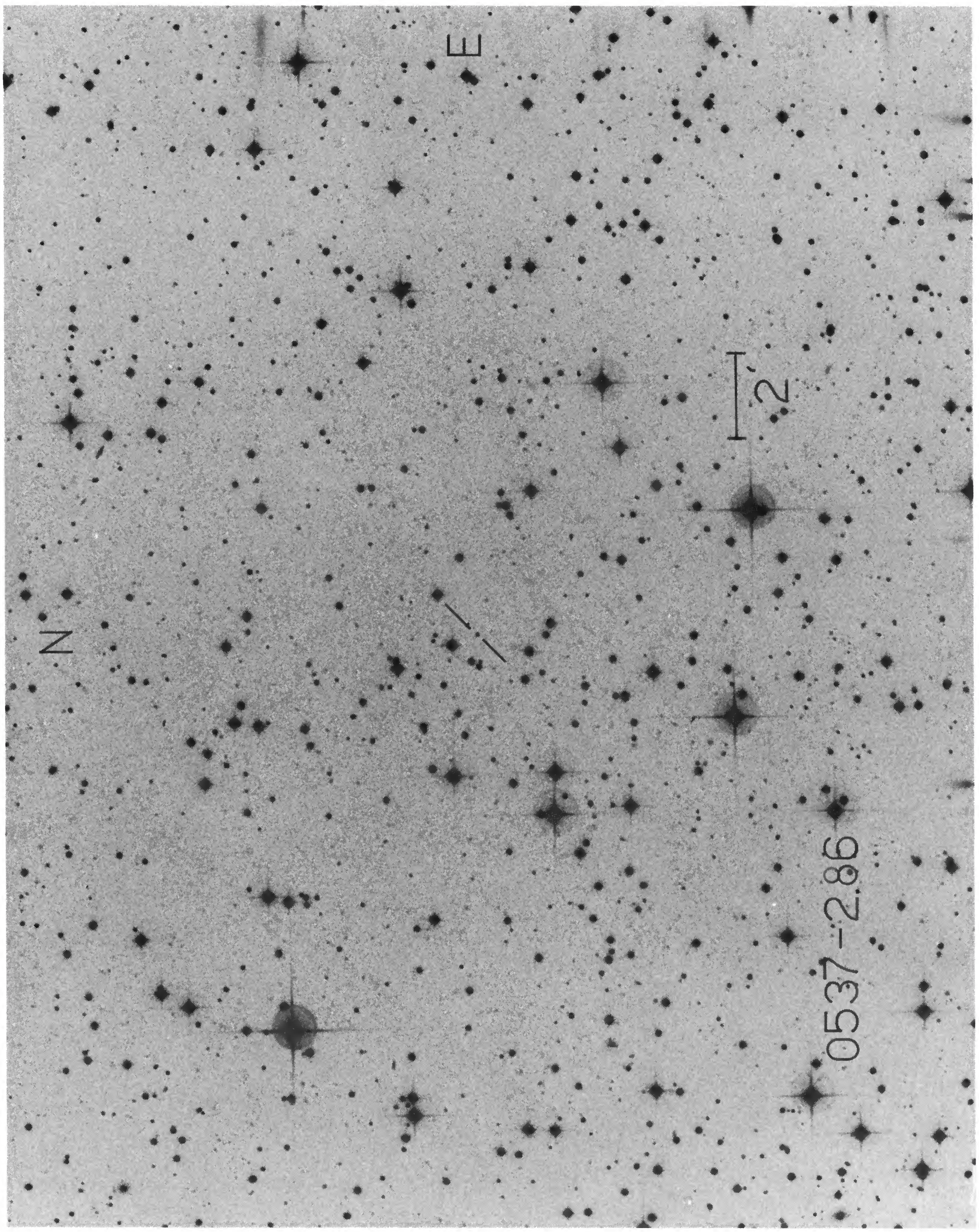

FIG. 3.—A 1.2 m UK Schmidt IIIa-J plate of the field of PKS 0537−286 taken in 1976 November through a Schott CG395 filter. The QSO is marked by bars. Note the stellar appearance of the QSO and the diffuse images of two galaxies 15″ SE and 20″ S.

WRIGHT *et al.* (*see* page L63)

$L\alpha$ emission line and Lyman-continuum absorption both falling within the extended ultraviolet response of the Palomar O-plate and also the strong C IV emission line falling in the narrow Palomar red filter. We note that these conditions also hold for PKS 0537−286 (except for the strong C IV line) and, in addition, the $L\alpha$ emission line is almost completely shifted out of the response curve of the O-plate.

Finally, it is interesting to speculate how QSOs at still higher redshifts ($z_{em} \sim 4$) may appear. If we assume (as now seems reasonable; see Table 3) that a strong Lyman-continuum cutoff in an absorption system at a redshift close to the emission redshift is the norm for radio-selected QSOs, then the Palomar O-plate image will be very faint. In addition, the $L\alpha$ emission line will be shifted out of the O-plate response curve and the C IV λ1549 emission line out of the narrow red filter. We therefore predict that such high-redshift objects will be very faint and also probably red, since at least the continuum emission will be present in the red filter. Such objects will be difficult to find. We believe the most promising method for their discovery will be by examining the optically faint ($m \gtrsim 19$) red objects identified with flat spectrum radio sources. From an examination of about 100 flat-spectrum objects for which we have accurate radio and optical positions (Condon *et al.*), we already have recently found three QSOs with z_{em} greater than 3.0.

We would like to thank the staff of the UK Schmidt telescope for making available a copy of the plate of the field of PKS 0537−286 and also D. C. Morton for several helpful discussions. This research was supported in part (J. J. C.) by National Science Foundation grant AST 77-08013.

REFERENCES

Allen, C. W. 1973, *Astrophysical Quantities* (3d ed.; London: Athlone Press).
Beaver, E. A., Harms, R., Hazard, C., Murdoch, H. S., Carswell, R. F., and Strittmatter, P. A. 1976, *Ap. J.* (*Letters*), **203**, L5.
Bolton, J. G., Shimmins, A. J., and Wall, J. V. 1975, *Australian J. Phys.*, *Ap. Suppl.*, **34**, 1.
Braccesi, A., *et al.* 1965, *Nuovo Cimento*, **40**, 267.
Carswell, R. F., and Strittmatter, P. A. 1973, *Nature*, **242**, 394.
Condon, J. J., Hicks, P. D., and Jauncey, D. L. 1977, *A.J.*, **82**, 692.
Davidson, K. 1976, *Ap. J.*, **207**, 710.
Ehman, J. R., Dixon, R. S., and Kraus, J. D. 1970, *A.J.*, **75**, 351.
Gearhart, M. R., Lond, J. M., Frantz, D. J., and Kraus, J. D. 1972, *A.J.*, **77**, 557.
Jauncey, D. L., Wright, A. E., Peterson, B. A., and Condon, J. J. 1978, *Ap. J.* (*Letters*), **223**, L1.
Peterson, B. A., Jauncey, D. L., Wright, A. E. and Condon, J. J. 1978. *Ap. J.* (*Letters*), **222**, L81.
Wampler, E. J., Robinson, L. B., Baldwin, J. A., and Burbidge, E. M. 1973, *Nature*, **243**, 336.

JAMES J. CONDON: National Radio Astronomy Observatory, Edgemont Road, Charlottesville, VA 22091

DAVID L. JAUNCEY: Division of Radiophysics, CSIRO, Sydney, Australia

BRUCE A. PETERSON and ALAN E. WRIGHT: Anglo-Australian Observatory, P.O. Box 296, Epping, NSW 2121, Sydney, Australia