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SPECTROSCOPIC OBSERVATIONS OF NINETEEN QUASI-STELLAR RADIO SOURCES*

Redshifts have been determined for seventeen quasi-stellar radio sources, thirteen of which have not been previously determined, while four are confirmations of redshifts already measured by other observers. Observations of two additional objects, for one of which we have found a discrepancy with previously published observations, are also described here.

The objects are listed in Table 1 in order of increasing right ascension together with references for the identifications. Most of the objects are taken from the Parkes catalogues of radio sources, three are from the 4C catalogue, and one is an occultation position measured with the Arecibo radio telescope. Although most of the identifications are now published, our observations were begun while many of them were in the preprint stage, and we are grateful to Drs. J. G. Bolton, C. Hazard, P. A. G. Scheuer and D. Wills, and J. D. Wyndham for sending us identifications ahead of publication.

The spectrograms were obtained at the prime focus of the 120-inch reflector using both the conventional spectrograph (with a thick-mirror Schmidt camera) and the new spectrograph that incorporates an R.C.A. image tube kindly supplied by the Carnegie Tube Image Committee. The latter spectrograph was described by Burbidge and Kinman (1966). The instrumental arrangements were the same as those described in that paper, except that most of the present spectrograms were taken on baked Kodak IIaO emulsion while the remainder were taken on the coarser-grained and faster Kodak 080-01 emulsion.

The wavelengths of the emission lines which were measured are given in Table 1, together with an indication of the strengths and widths of the lines, using the same notation as Burbidge and Kinman (1966). These subjective estimates of line strengths are at best approximate. Broad lines, for example, tend to appear stronger on the image-tube spectrograms than on those at higher dispersion and the reverse is true for narrow lines. The identifications of the emission lines were made by the same method as was used before.

The redshifts $z = (\lambda - \lambda_0)/\lambda_0$ and the computed rest wavelengths of the lines are given in Table 2, where the objects are listed in order of increasing redshift. Further remarks on individual sources are given below:

PKS 0837−12: This object was identified by Bolton (see Kinman 1967), and he has found the coordinates $08^h37^m27^s.95$, $-12°\ 03'\ 54''.2$ (1950.0). The redshift is based on measures of a broad line at 5214 Å and a strong narrow line at 5995 Å which were identified with Hγ and [O III] λ5007. Hδ was measured as a weak feature at 4939 Å and Hβ and Hα were measured as strong broad features that were badly confused with the night-sky spectrum at 5841 Å and about 7850 Å. [O III] λ4959 may be faintly visible, but was not measured.

PKS 2135−14: Hα, Hβ, Hγ, and Hδ were measured as broad features, although Hα and Hβ were confused with night-sky features. A weak narrow feature which was measured at 4654 Å is probably [Ne III] λ3869. It may be noted that 0837−12 and 2135−14 have similar optical and radio properties in addition to having the same redshift.

PHL 1093 = 4C 1.04: Lynds (1967) obtained $z = 0.262$ for this object, based on the lines Mg II λ2798 at 3542 Å, [Ne V] λ3426 at 4314 Å, and [O III] λ5007 at 6325 Å. Our plate covering the blue and ultraviolet was too underexposed to show a line near 3542 Å, but the [Ne V] λ3426 line could be seen although it was not measured. A difference of

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26 Å in the wavelength of [O III] λ5007 measured by us and by Lynds can probably be accounted for by the broad fuzzy nature of the line, and possibly by its blending with [O III] λ4959.

PKS 1049−09: No Balmer lines were observed with certainty. Hβ may be present as a weak broad feature that is confused with a night-sky feature.

PKS 1229−02: The broad line at 3889 Å (identified as Mg II λ2798) has a narrow but quite strong absorption component 13 Å on the long-wavelength side of the emission maximum. A rather indistinct feature measured at 5180 Å may be [O II] λ3727. Neither Hγ nor Hβ nor [O III] λ5007 were seen, although the last of these would be confused with a weak night-sky feature.

TABLE 1

SOURCES IN ORDER OF INCREASING RIGHT ASCENSION AND WAVELENGTHS OF EMISSION LINES

Source	References*	λ (Å) †
PKS 0056−17	3, 9	3800, Sw, 4175, Mw; 4841, Sw
PKS 0119−04	3, 9	3600, Sw, 4150, Ww; 4568, vSw; 4842, Wm; 5635, Ww
PHL 1093=4C 1.04	11	4868, Mw; 6299, Mw
PKS 0229+13	9	3726, Sm; 4749, S 40 Å
PHL 1377=4C−4.06	11	3767, S 95 Å; 4652, Sw
PKS 0405−12	2, 5, 10	4405, Sw; 6240, Ww; 6463, Ww; 6830, Mw
PKS 0812+02	6, 5	3923, vSw; 4492, W 20 Å; 4690 Wn; 4807, M 20Å
PKS 0837−12	10	4939, Ww; 5214, Mw; 5841, Sw; 5995, Sn; 7850, Sw
AO 0952+17	7, 8	3829, S 110 Å; 4087, Ww; 4719, Mw
PKS 1049−09	3, 4	3765, S 50 Å; 3831, Wm; 4600, Wm; 6670, Wn; 6735, Mn
PKS 1136−13	2, 4	4349, Sm; 4434, Wm; 4459, Wm
PKS 1229−02	3, 4	3889, Mw; 4751, Mw; 5180, Wm
PKS 2135−14	3, 9	4654, Wn; 4940, Ww; 5208, Mw; 5829, Sw; 5951, Mn; 6011, Sn
PKS 2251+11	1, 9	3701, Mn; 4240, Wm; 5767, Mw; 6425, S 85 Å; 6560, Mn; 6632, Sn
4C 29.68=CTD 141	12	3841, W 95 Å; 4675, Wm; 5645, Ww
PKS 2344+09	1, 9	3911, Mm; 4681, S 45 Å
PKS 2354+14	1, 9	3416, vSw; 4355, Mw

* References:

1. Bolton and Ekers (1966*a*);
2. Bolton and Ekers (1966*b*);
3. Bolton and Ekers (1966*c*);
4. Bolton and Kinman (1966);
5. Bolton, Shimmins, Ekers, Kinman, Lamla, and Wirtanen (1966);
6. Clarke, Bolton, and Shimmins (1966);
7. Hazard (1965);
8. Hazard, Gulkis, and Bray (1967);
9. Kinman, Bolton, Clarke, and Sandage (1967);
10. Kinman (1967);
11. Scheuer and Wills (1966);
12. Wyndham (1966).

† vS, S, M, and W denote strengths of lines (very strong, strong, medium, weak); w, m, n (wide, medium, narrow) or an actual width (in Å) refer to estimates of line width.

PKS 0812+02: The broad line at 3923 Å (identified as Mg II λ2978) is asymmetrical. Broad indistinct absorption features appear to be present at 3760 and 3872 Å and also possibly at 3820 and 3990 Å.

PKS 1136−13: The strong line at 4349 Å is not seen on one spectrogram, although it is present on two others of the blue and ultraviolet taken with the conventional spectrograph. Of several weak indistinct features mentioned by Bolton and Kinman (1966), that at 4900 Å is not confirmed but that at 6020 Å might be [Ne III] λ3869. A possible explanation of the absence of the 4349 Å line on one spectrogram (apart from a misidentification of the object) would be that the strength of the continuum is variable. However, a few direct photographs taken with the Lick 20-inch Astrograph give no evidence of variability. Further observations of this object are desirable.

PKS 0405−12: A rather weak feature at 6463 Å and an even weaker one at 6240 Å are identified with Hδ and the blend of Hε with [Ne III] at λ3968. Hβ would be expected at 7650 Å, but its violet wing would coincide with the atmospheric A-band of O_2. A broad feature at approximately 7700 Å is taken to be the red wing of Hβ.

PKS 2344+09: The wavelength agreement is not very good, but the suggested identifications give a better fit than other possibilities. Thus the ratio of the rest wavelengths C III] λ1909/C IV λ1549 is 1.232, while Mg II λ2798/[C II] λ2326 is 1.203 and the observed ratio is 1.197. Two other broad emission features, measured at 4014 and 4351 Å, may be real; if so, the redshift of 0.677 would give rest wavelengths of 2394 and 2594 Å, respectively. None of the features usually seen fall here, but in view of the identification by Wampler and Oke (1967) of Fe II lines in 3C 273 it is interesting to note that the ultraviolet ground-level multiplets (1) and (2) of Fe II consist of lines grouped near these two wavelengths.

TABLE 2

REDSHIFTS, LINE IDENTIFICATIONS, AND COMPUTED REST WAVELENGTHS

Source	z	Mg II λ2798	[Ar IV] λλ2854, 2869	He II λ3203	[Ne V] λλ3346, 3426	[Ne III] λ3869	Hγ λ4340, [O III] λ4363	Hβ λ4861	[O III] λλ4959, 5007
0837−12	0.200	......	......	......	......	......	4345	4867	5000
2135−14	.200	......	......	......	......	......	4340	4857	4959, 5008
PHL 1093	.258	......	......	......	......	3869	......	......	5007
2251+11	.323	2798	......	3205	......	......	4359	4857	4959, 5013
1049−09	.344	2801	2851	......	3423	......	......	......	4963, 5011
1229−02	.388	2801	......	......	3422	......	......	......	......
0812+02	.402	2798	......	3203	3344, 3428	......	......	......	......
1136−13	.554	2798	2853 2869	......	......	......	......	......	......
0405−12	0.574	2799	......	......	......	......	4339	......	......

Source	z	Ly-α λ1216	C IV λ1549	He II λ1640 [O III] λ1663	[C III] λ1909	[C II] λ2326	Mg II λ2798
2344+09	0.677	......	......	......	......	2332	2791
4C 29.68	1.013	......	......	......	1908	2322	2804
PHL 1377	1.434	......	1548	......	1911	......	......
0952+17	1.472	......	1549	1654	1909	......	......
2354+14	1.810	1215	1550	......	......	......	......
0119−04	1.955	1218	1546	1639	1907	......	......
0229+13	2.065	1216	1549	......	......	......	......
0056−17	2.125	1216	1549	......	......	......	......

4C 29.68: This source, identified by Wyndham (1966), had been identified earlier by Wyndham as CTD 141, and as such Schmidt (1966) published a redshift for it of $z = 1.015$. Lynds (1967) independently measured the redshift of the object, as 4C 29.68, and obtained $z = 1.009$; he noted that 4C 29.68 and CTD 141 were probably the same object. [C II] λ2326, seen by us at 4675 Å, was not measured by either Schmidt or Lynds.

PHL 1377 = 4C − 4.06: Hiltner, Cowley, and Schild (1966) observed this object and gave the most probable redshift as 1.439. Two doubtful weak emission features measured by them at 4243 and 4421 Å did not have satisfactory identifications. We do not confirm either of these features; on the other hand, our spectrogram shows a definite absorption component at 3747 Å, 20 Å on the short wavelength side of the center of the very broad emission at 3767 Å. Since an absorption component is often seen in C IV λ1549, we feel that this is a satisfactory identification and confirm the redshift of Hiltner *et al.*

AO 0952+17: This is a rather weak source, identified by Hazard, and its structure has been determined by lunar occultation (Hazard, Gulkis, and Bray 1967).

PKS 0119−04: Two strong broad emission lines were measured at about 3600 and 4568 Å. The former is cut up by several absorption components, and the latter has a strong asymmetrical absorption in its red wing; the wavelength centroids of these emission lines are therefore uncertain. They are identified as Ly-α and C IV λ1549 with a redshift of 1.955. Fainter features were measured at 4150, 4842, and 5635 Å (the last being heavily confused with the wing of a night-sky line) and were identified with a Si IV blend at λ1398, He II λ1640, and C III] λ1909. These lines are too indistinct, however, to give much weight to the redshift determination. The redshift of the emission lines has an uncertainty of about ± 0.005. A list of seven absorption features measured

TABLE 3

ABSORPTION LINES IN PKS 0119−04

Measured λ (Å)	Identification and λ (Å)	z	Note*
3579.8	Si III 1206.5	1.9671	(1)
3607.2	Ly-α 1215.7	1.9672	(1)
3672.9	N V 1238.8	1.9649	(2)
3685.8	N V 1242.8	1.9657	(2)
4132.0	Si IV 1393.7	1.9648	(3)
4159.6	Si IV 1402.7	1.9654	(3)
4594.6	C IV 1549.1	1.9660	(4)

* (1) Very weak. (2) Resolution difficult; lines are contaminated by the red wing of a night-sky feature. (3) Extremely weak. (4) An asymmetrical line (steeper on the short wavelength side) which may be partially resolved.

on a blue spectrogram is given in Table 3. Most of these lines are quite weak or difficult to measure but the redshifts obtained from them are consistent and larger (1.966) than that found for the emission lines.

PKS 0229+13: Kinman, Bolton, Clarke, and Sandage (1967) noted that Schmidt has obtained a spectrum giving $z = 2.07$. Our measured z is in good agreement with this. On our plate the Ly-α emission has a narrow core and there is a narrow absorption component 9 Å shortward of this.

PKS 0056−17: Three broad and indistinct emission features were measured on a single image-tube spectrogram at $\sim$ 3800, 4175, and 4841 Å. The first of these was very indistinct and confused with features from an overlapping order. The 4841 Å feature has an absorption component in its red wing at 4870 Å. The three lines are tentatively identified with Ly-α, C II λ1335, and C IV λ1549 with a redshift of 2.125, while the redshift of the single absorption component is 2.144. The relatively good agreement between the redshifts obtained from the three emission features is surprising in view of their indistinctness on the spectrogram.

Two further objects for which we have obtained spectrograms are PKS 2145+06 and PKS 2216−03. Lines at 3824 and 4682 Å were measured in 2145+06, and these are probably Mg II λ2798 and [Ne V] λ3426, with a redshift $z = 0.367$. However, Hβ should then appear at 6643 Å, and we have not seen this line on spectrograms taken in the red with the image-tube spectrograph. This possible redshift needs confirming.

Lynds (1967) obtained $z = 0.901$ for PKS 2216−03, from lines measured at 3628 and 5323 Å, identified with C III] λ1909 and Mg II λ2798. We have two image-tube spectrograms and on both of these we see an emission line at 5170 Å, with a much weaker feature possibly present at 5350 Å. We did not obtain spectrograms in the ultraviolet. Further work on this object is needed; conceivably the wavelength of the feature in the green spectral region has varied.

We draw attention to the absorption components seen in Mg II λ2798 in PKS 1229−02 and 0812+02. The only previous observation of absorption in this line was for PKS 1510−08 (Burbidge and Kinman 1966).

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