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OBSERVATIONS OF HIGH-REDSHIFT QSOs FROM A MOLONGLO FAINT SOURCE SURVEY*

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ABSTRACT

We present spectrophotometric observations of four objects identified with the Molonglo radio sources 0758+120, 0824+110, 0830+115, and 0938+119. All are QSOs with $z > 2$. The sources 0758+120, 0824+110, and 0830+115 have previously unreported redshifts $z = 2.66$, 2.29, and 2.97, respectively. The optical and radio spectra of these objects are compared with the spectra of other known high-redshift QSOs.
Subject headings: galaxies: redshifts — quasars — radio sources: spectra

A faint red optical object identified with the Molonglo radio source 0938+119 has recently been shown by Beaver *et al.* (1976) to be a QSO with a redshift $z = 3.19$. We have made further optical and radio observations of this interesting object, and we have also found that the Molonglo sources 0830+115, 0758+120, and 0824+110 are coincident with new high-redshift QSOs with $z = 2.97$, 2.66, and 2.29, respectively. All four objects are from an unpublished Molonglo survey at 408 MHz which completes the right ascension coverage at the declination of the MC 2 survey (Sutton *et al.* 1974) and improves the sensitivity to a limiting flux density of 0.15 Jy in a restricted area and 0.2 Jy elsewhere. The identifications are based solely on positional agreement. An identification program restricted to blue objects would have missed 0938+119, which appears very red in color on the Palomar–National Geographic Sky Survey prints and was at first mistaken for a faint galaxy.

The optical and radio positions and radio flux densities are given in Table 1. The measurements at 2295 MHz have been made with the NASA 64 m telescope at Tidbinbilla, Australia, using left-hand circular polarization. The measurements at 5 GHz have been made with the C.S.I.R.O. 64 m telescope at Parkes, Australia, using orthogonal linear polarization and the results quoted represent the mean of the two polarizations. The optical positions have been obtained with the Sydney University XY coordinate machine (Hunstead 1971) and are accurate to 0".5. The positions for 0938+119 were given by Beaver *et al.* but are repeated here for completeness. Figure 1 (Plate L6) is a finding chart for the three new QSOs. A finding chart for 0938+119 has been given by Beaver *et al.*

The optical observations were made with 7 and 15 Å

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TABLE 1

RADIO INFORMATION AND OPTICAL POSITIONS

SOURCE	RIGHT ASCENSION (1950)		DECLINATION (1950)		FLUX DENSITY (Jy)		
	Radio	Optical	Radio	Optical	408 MHz	2295 MHz	5 GHz
0758+120	07^{h}58^{m}14^s.0	14^s.49	12°01′57″	43".3	0.44	0.10	0.05
0824+110	08 24 21.9	22.39	11 02 19	19.4	0.55	0.233	0.24
0830+115	09 30 30.6	29.94	11 33 58	52.9	0.59	0.33	0.22
0938+119	09 38 32.2*	31.75	11 59 21†	12.6	0.30	0.265	0.19

† Radio position slightly amended due to revised calibration.

1976ApJ...206L..83B

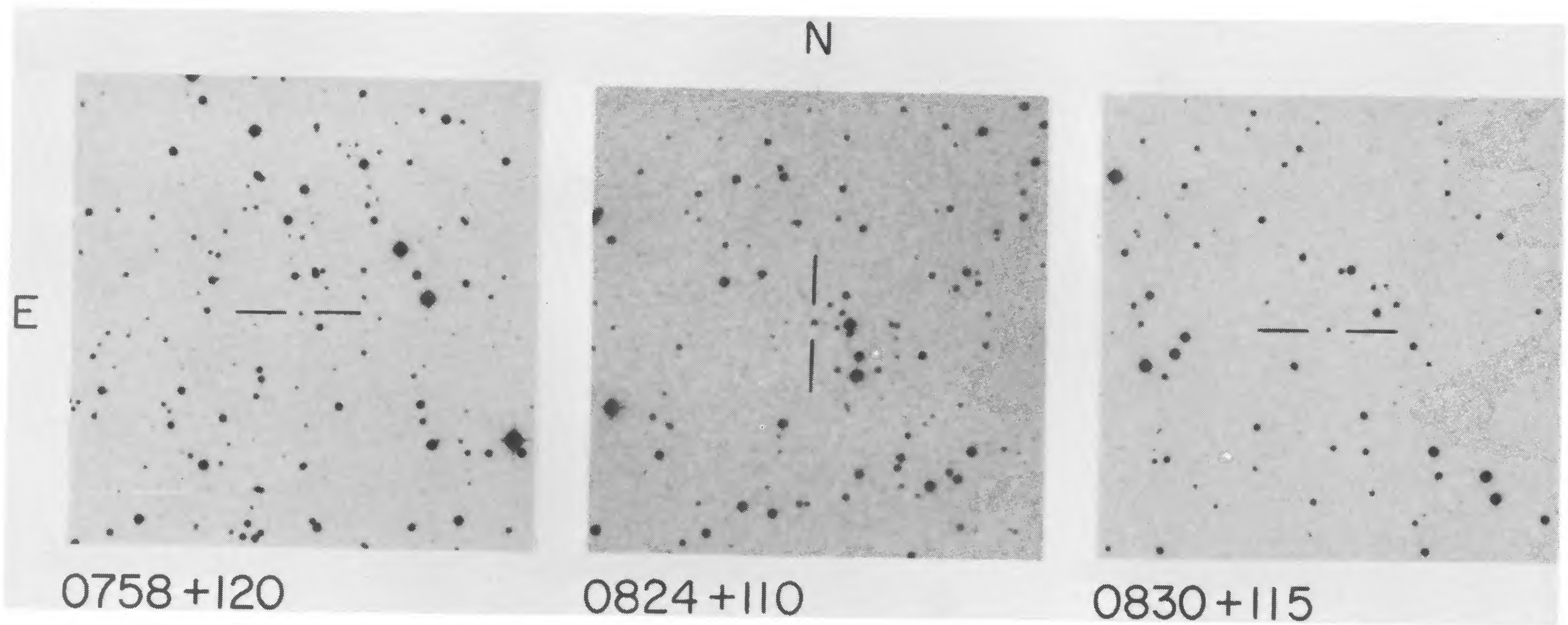

FIG. 1.—Finding charts for three of the QSOs listed in Table 1 for which there are no previously published identifications. The charts are 10.7 arcmin square; they are reproduced from the Palomar Sky Survey O-prints (© National Geographic Society–Palomar Observatory Sky Survey).

BALDWIN *et al.* (*see* page L83)

resolutions at Lick Observatory with the image-tube scanner (Robinson and Wampler 1972) at the Cassegrain focus of the 3 m telescope. Table 2 lists the dates, integration times, and wavelength coverage of our observations. Table 3 lists data for the emission lines detected in the spectra of these QSOs. The measurements for Lα also include any blended N V λ1240 lines. The redshift given for 0938+119 by Beaver *et al.* was based on the O VI λ1034 and Lα emission lines and on the absence of radiation in the Lyman continuum. Our scans also show C IV λ1549, thus confirming the redshift (our mean redshift for 0938+119, giving zero weight to the O VI line, is 3.183). We find a redshift for 0830+115 of $z = 2.976$, based on the O VI, Lα, C IV, and C III] λ1909 lines. A broad Si IV + O IV λ1400 emission feature is also present. For 0758+120 we see strong Lα and C IV with C III] λ1909 only weakly present. With our redshift of 2.66 the O VI feature falls at λ3780 where our signal-to-noise ratio is extremely poor. Our mean redshift for 0824+110, $z = 2.280$, is based on Lα and C IV. The Si IV + O IV band and a line which is possibly N II λ1085 are also visible, but there is no sign of the O VI line (the relative intensity must be less than about 4). Carswell *et al.* (1975) have previously identified the O VI λ1034 line in the spectrum of 0642+44 (OH 471), but there it is possibly blended with Lβ. Almost all of the flux in the corresponding features in the spectra of 0938+119 and 0830+115 must certainly come from the O VI doublet.

The optical as well as the radio continua of these new QSOs are comparatively faint, even when the large redshifts are allowed for. The measured AB_ν at 5000 Å, shown in Table 3, range from 18.5 to 20, and should be compared with $AB_\nu \approx 17$ for 1442+101 (OQ 172) with a redshift of 3.53 (Wampler *et al.* 1973). Spectral indices[1] for the optical region are also given in Table 3. The continuum slope of 0938+119 is fairly steep for a QSO and is more typical of BL Lacertae objects (Strittmatter *et al.* 1972). This probably accounts in part for the fact that it does not appear blue on the Palomar Survey. The occurrence of the strong C IV emission line close to the center of the rather narrow passband of the Palomar E filter also contributes to the red color.

The radio spectra are plotted in Figure 2. Three objects in the present sample, including the two with highest redshift, belong to the class of radio sources loosely referred to as "flat spectrum sources," which are characterized by having at least a significant section of their radio spectrum with a spectral index $\alpha < 0.5$. As both of the known objects with higher redshift, 1442+101 and 0642+44, are also flat-spectrum objects, all four objects with $z > 2.95$ belong to this class. It is somewhat surprising to find these weak sources with flat spectra, both because of the low frequency used in the Molonglo survey and because Condon and Jauncey (1974) have shown that there is a smaller proportion of flat-spectrum sources among weak radio sources. The preponderance of flat-spectrum sources among high-z objects is probably due in part to the radio K-correction. For example, the spectrum of 0938+119 (like that of 1442+101) peaks in the vicinity of 1 GHz which repre-

[1] Defined by spectral index α; $f_\nu = k\nu^{-\alpha}$.

TABLE 2

JOURNAL OF OBSERVATIONS

Object	Date of Observation	Wavelength Coverage	Integration Time (minutes)
0758+120...	1974 Nov. 12	λλ4400–8500	48
	1974 Nov. 17	λλ3300–6800	28
	1975 Nov. 5	λλ3700–8400	48
0824+110...	1974 Dec. 16	λλ3400–5500	16
0830+115...	1974 Dec. 16	λλ3400–5500	16
	1975 Jan. 13	λλ4400–8000	48
0938+119...	1975 Jan. 13	λλ4400–8000	48
	1975 Jan. 13	λλ3600–5600	20

TABLE 3

SPECTROPHOTOMETRIC PROPERTIES

Object	AB_ν (5000 Å)	Spectral Index	λ_{obs} (Å)	ID	λ_0 (Å)	z	W_λ (Rest Frame) (Å)	FWHM	Relative Intensity
0758+120...........	20±.5	0.5	4515	Lα	1216	2.713	30	60	100
			5642	C IV	1549	2.642	18	42	45
			6990	C III]	1909	2.661	8:		10:
0824+110...........	19±1	0.5	3575	N II	1085	2.295	7	11	7
			3991	Lα	1216	2.282	70	23	100
			4609	Si IV, O IV	1400	2.292	13	20	17
			5081	C IV	1549	2.278	55	43	70
0830+115...........	18.5±.5	0.8	4110	O VI	1034	2.975	13	10	12
			4834	Lα	1216	2.975	84	16	100
			5522	Si IV, O IV	1400	2.944	10	68	11
			6160	C IV	1549	2.974	57	24	56
			7599	C III]	1909	2.981	10:	14:	10:
0938+119...........	20±1	2.0	4400	O VI	1034	3.255	100:	22	50:
			5096	Lα	1216	3.191	180	14	100
			6472	C IV	1549	3.175	32	17	24

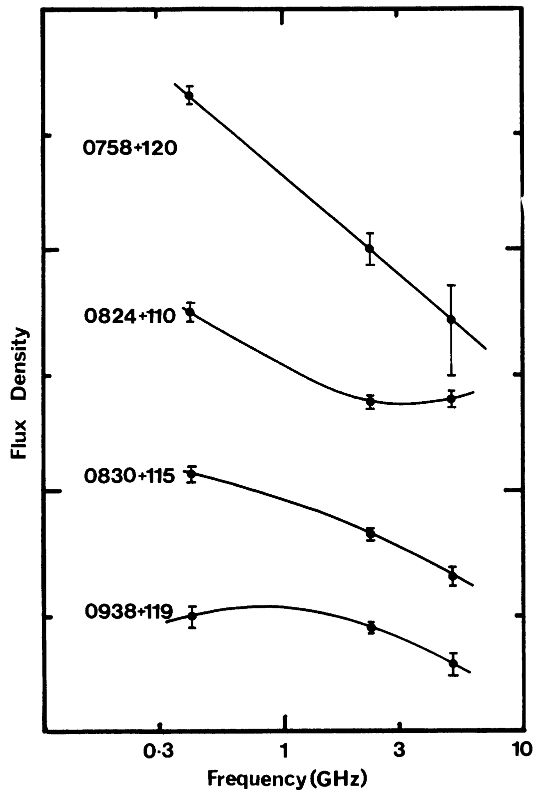

FIG. 2.—Radio spectra for the four sources. The flux density scale is arbitrary.

sents a frequency in excess of 4 GHz in the emission system. The existence of this high-frequency peak (common in compact QSOs) together with the high redshift lifts the 408 MHz flux density from what would otherwise be below the survey limit. It is also surprising that four objects with $z > 2.2$ have so far been found among the small number (about 15) for which optical spectra have so far been attempted from the unpublished Molonglo survey in the region 07^h50^m–11^h30^m right ascension.

An interesting contrast between the optical spectra of these QSOs is the absence of any obvious absorption in the Lyman continuum of 0830+115, while there is a clear discontinuity in the continuum of 0938+119. Beaver *et al.* found, and our data confirm, that the continuum break in the spectrum of 0938+119 comes at a wavelength distinctly below the expected position of the Lyman break in the emission-line redshift system. This is also true in the spectra of 0805+047 (4C 05.34) and 0642+44 (Carswell *et al.* 1975), while there is no discontinuity in the continuum of 1442+101 (Baldwin *et al.* 1974). Thus of the five highest redshift QSOs, none have complete absorption in the Lyman continuum of their emission-line redshift systems. Where there is absorption, it comes at a lower redshift and is presumably associated with some of the numerous absorption line systems found in the spectra of these objects (both 0830+115 and 0824+110 have rich absorption-line spectra which will be discussed in detail elsewhere [Burbidge, Smith, and Caldwell 1976], and it is also likely that there is absorption in the spectrum of 0758+120). The presence of the low-ionization collisionally excited Mg II λ2800 emission line in the spectra of all of the low-redshift QSOs and the absence of Lβ emission in the spectra of these high-redshift QSOs strongly suggest that the emission-line regions associated with most QSOs are optically thick. The interpretation of this lack of continuum absorption in optically thick gas requires either a model in which the line-emitting gas is arranged in clouds which cover only a small portion of the total solid angle seen from a small continuum source at the center of the QSO (cf. Oke 1974), or one in which the continuum radiation originates between ourselves and the emission-line region (MacAlpine 1974).

Referring again to Table 3, it is interesting to note the deviation in three of these spectra of the C IV/Lα intensity ratio from the often used "normal" value of ~0.25. One possible explanation of the unusually large C IV/Lα ratios found here is that the ionizing spectra are less cut off than is normal at high frequencies, so that there is a greater heating per photoionization with the resulting requirement for more cooling through the C IV line. One would also expect generally higher ionization in this situation, but the observed presence of the high-ionization O VI line in the spectra of 0830+115 and 0938+119, but not in the spectrum of 0824+110, does not correlate at all well with the C IV/Lα ratio. Another plausible cause of the differences in the C IV/Lα ratio is a change in the ratio of the ionizing flux to the electron density (the parameter U_1 used by Davidson 1972). Models showing these effects have been calculated by Davidson (1972, 1973), MacAlpine (1972), and Chan (1974). Differences between real QSO spectra are presumably due to some combination of variations in U_1, the shape of the ionizing spectrum, and the general geometry of the gas and the ionizing radiation source. More observations of high-redshift QSOs will be required to get enough data to sort out general correlations between observable parameters.

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