INVESTIGATION OF THE PROPERTIES OF LARGE-REDSHIFT QSOs USING SLITLESS SPECTROSCOPY

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1. INTRODUCTION

The use of natural spectral-form groups (Morgan, 1951) on low-dispersion slitless survey plates efficiently isolates rather pure samples of intrinsically interesting extragalactic objects (e.g. Smith, 1975, 1976; Smith, Aguirre and Zemelman 1976; MacAlpine, Smith and Lewis 1977a, b; MacAlpine, Lewis and Smith 1977, MacAlpine and Lewis 1978, Cooke et al. 1977, Hoag and Smith 1977, Sramek and Weedman 1978, Bohuski, Fairall and Weedman 1978, Osmer and Smith 1979). One of these groups (illustrated for various telescopes by Smith 1975, Hoag and Smith 1977, Bolton et al. 1977 and Smith 1978) has been found to include a very large set of high-redshift QSOs. Definition of the group (e.g. Smith 1976) rests on the direct detection of the QSO emission lines on the survey plates. Objects already selected from the group range in redshift from 0.32 (PKS 2227-399 - see also Peterson and Bolton 1978, Browne, Savage and Bolton 1976, Bolton et al. 1977) to 3.45 (Q2227.6-3928 - Smith et al. 1977, Osmer 1978a) and in apparent magnitude from 21 (Osmer 1977, Smith 1978) to 16 (including the apparently brightest high-redshift object known, Q1101-264 - Osmer and Smith 1976, Smith 1978, Carswell et al. 1979 and the most luminous object known, Q0420-388 - Osmer and Smith 1977b; Wright and Kleinmann 1978). 15 of the 21 objects known with confirmed redshifts $z > 3$ have been discovered this way.

2. OVERALL SPACE DISTRIBUTION

From these samples, a lower limit of $z > 3$ has been set for the cut-off redshift in the space distribution of emission-line QSOs (Osmer and Smith 1977c); the comoving space density of QSOs out to

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this redshift is at least uniform and may be increasing. Data on QSOs or the lack of them at redshifts beyond $z \sim 3.3$ (the redshift at which Lyman-alpha is redshifted beyond the green wavelength limit of the IIIaJ emulsion response) are still surprisingly limited (Hoag and Smith 1977, Smith et al. 1977). Density evolution laws as steep as $\rho(z) \sim (1+z)^6$ can probably be ruled out by the failure to detect Lyman-alpha in large numbers of objects on red-sensitive emulsions (Carswell and Smith 1978), but there is no evidence at present for any cut-off in the redshift distribution. More quantitative statements based on this material should be regarded with caution, because the definition of the natural group is based on the detection of emission lines, which presumably introduces selection effects additional to the apparent magnitude limit (Smith 1978). Work is just beginning on quantitative spectrophotometry of QSOs directly from the Schmidt spectra.

3. PROJECTED SURFACE DISTRIBUTION

The projected surface density of QSOs on the sky as a function of apparent magnitude and redshift σ (m,z) is of interest not only for determining the space density of QSOs, but also (i) for investigating any anisotropy in this distribution, (ii) for evaluating the luminosity function of QSOs, and later for investigating any evolution (variation with redshift) of this function, and (iii) for assessing the significance of apparent associations (e.g. pairing) of QSOs and galaxies, especially where such groupings involve objects with very different redshifts. Now the equivalent widths of the strongest emission lines (needed to recognise a QSO as a member of the natural group) are usually not much less than $\sim$ 30 to 50 Å (in the observer's frame). Thus the highest current estimates ($\sim$ 15 deg^{-1} at 19.5 mag for all QSOs - Osmer 1977) may only be lower limits (Smith 1978). However, it should also be understood that many of these QSOs would not have appeared in the (ultraviolet excess) samples used in most recent discussions of the significance of QSO-QSO or QSO-galaxy pairs (Savage, personal communication); thus the higher surface densities derived from the recent slitless work do not necessarily affect those earlier arguments. Furthermore, the very steep luminosity function (an increase in numbers of QSOs by a factor of somewhere between 3 and 8 per magnitude interval) demands fairly accurate magnitudes if estimates of σ are required to better than a factor $\sim$ 2. Over 300 QSOs have now been found on a single UK Schmidt plate. A preliminary power-spectrum analysis (Coleman, 1978, unpublished) of another UK Schmidt field, involving over 200 high-redshift candidates, yields no statistically signficant evidence for clustering of QSOs on scales of order one degree down to one minute of arc.

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4. ABSOLUTE SPECTROPHOTOMETRY OF EMISSION LINES AND CONTINUA

As is particularly well appreciated at a meeting like this, the discovery of different luminosity classes in the spectra of red stars had a colossal impact on our present knowledge of the properties and evolution of stars, and has aided in the determination of the structure of our galaxy. It was hoped that quantitative information on QSOs might similarly shed light on their physical properties and evolution, and aid in the determination of the large-scale structure of the universe. Luminosity differences are immediately apparent if redshift is taken as an indicator of distance; objects of similar redshifts have a wide range of apparent magnitudes ($\Delta m \gtrsim 5$ magnitudes at $z \sim 2$ for example). Extensive, absolute, photoelectric spectrophotometry of emission lines and continua for the optically-selected high redshift objects has been performed (Osmer and Smith 1976, 1977a, b; Osmer 1978a). The recent indirect observation (Baldwin 1977a), and direct verification (e.g. Davidsen, Hartig and Fastie 1977; Hyland, Becklin and Neugebauer 1978; Boksenberg et al. 1978b), of the intensity ratio $r = I(Ly\text{-}\alpha)/I(H\beta) \sim 2\text{-}8$, is in contrast to the results of straightforward application of recombination theory (which suggest $r \sim 20\text{-}40$); this new result has considerably modified the constraints set on theoretical models of the emission-line regions in QSOs (see e.g., McKee and Krolik 1978).

As regards application to cosmology, it is unfortunate that unlike the correlation between the equivalent width of C IV 1549 Å emission and the absolute continuum luminosity reported for flat-spectrum radio sources (Baldwin 1977b, Baldwin et al. 1978), no such correlation appears valid for the optically selected objects (Osmer 1978b, Smith 1978). This is in spite of the fact that a similar range in equivalent width and luminosity has now been covered. It is rather disappointing that the most significant cosmological result to emerge so far from these very large new samples is a slight increase in the lower limit to the redshift cut-off (Smith 1978; Osmer and Smith 1977c: Carswell and Smith 1978). However, because the UK Schmidt telescope provides $\sim 10^5$ spectra of objects down to beyond 20^{th} magnitude (Smith 1978) in a single, 1 hour, high-latitude exposure, the advent of a full-aperture prism for that telescope, with dispersions suitable for QSO selection up to redshifts $z \sim 4.7$ or perhaps even more, offers more exciting prospects for the future.

5. THE LYMAN LIMIT AND THE STRUCTURE OF THE EMISSION-LINE REGION

At very high redshifts, the Lyman limit at 912 Å becomes accessible within the visible region of the spectrum. Observational data is now available for about 20 objects (see e.g., Baldwin et al. 1976, Osmer 1978a, Smith 1978). The majority show no depletion of radiation near the Lyman continuum limit at the emission-line redshift. Osmer finds a few objects with strong continuous absorption in the vicinity of 912 Å in the emission-line frame, but in every well-documented case, there are strong Ly-α absorption features close to the Lyman-alpha emission; blending of higher-order absorption lines (an analogue of the effect discussed for Balmer lines in stars by Divan at this conference) probably accounts for the drop in the continuum. There are therefore no unambiguous cases of continuous absorption below the Lyman limit caused by material in the emission-line region. How is it then that Ly-β emission is not observed in view of the fact that for an optically thin gas, the expected ratio Ly-α/Ly-β is 5 (Bahcall 1966, Burbidge 1977)? The model most widely accepted invokes optically thick clouds in the emission-line region with a small covering factor - i.e. we usually expect to be able to see the QSO continuum source shortwards of 912 Å shining through between the emission clouds; we simply have no **definite** observation corresponding to one of those clouds getting into the line of sight between us and the continuum source. However, in the majority of cases, a more distant absorber (an intervening galaxy?) at lower redshift than the quasar, is encountered; this cuts off the light, but usually at a wavelength significantly below 912 Å in the emission-line frame. I am not expecting to see very much blue optical continuum in QSOs at redshifts $z \sim 4$.

6. SPECTRAL CLASSIFICATION OF OPTICALLY SELECTED QSOs OUTSIDE THE OPTICAL DOMAIN

The detection of x-rays by Elvis et al. (1978) from almost all Type 1 Seyfert galaxies with nuclear magnitudes $m_V < 14^m$ (see also Ward et al. 1977, 1978) has led to a realisation of the important future role of x-ray astronomy in the study of Seyfert galaxies and quasars. In particular, the rapid variations in the x-ray flux from NGC 4151 (Tananbaum et al. 1978) suggest that one may be observing directly into an extremely compact source. Discovery of QSOs by purely x-ray methods has already begun (e.g. Ricker et al. 1978), while Ward et al. (1978) point out that HEAO-B, to be launched late this year, will probably be able to detect most quasars brighter than $m_V \sim 19$ mag. We can thus expect that considerable activity in spectral classification of QSOs in the x-ray region will begin in the near future; proposals have been submitted to use HEAO-B to examine samples of QSOs with various common physical properties, selected from the slitless surveys. Similar samples have recently been observed at various radio frequencies (see, e.g. Condon, Buckman and Smith 1978), and work has also begun in the infrared region (Wright and Kleinmann, 1978); this will provide the widest possible coverage of the continuum shapes.

7. HIGH-RESOLUTION STUDIES OF SHARP ABSORPTION LINES

As expected, the brighter objects from these surveys are proving valuable targets for detailed follow-up studies at high spectral resolution. The brightest object, Q1101-264, has been studied at the highest spectral resolution ever used on a QSO, 20 km s^{-1}. In deriving absorption redshifts to 5 decimal places, corrections for the earth's orbital velocity have become highly significant, even though the relative velocities between the earth and the QSO exceed 80 percent of the velocity of light (on the conventional Doppler interpretation of redshifts). This high accuracy has permitted, for the first time, positive identification of some sharp absoprtion features in the forest of lines usually found at wavelengths shortwards of Lyman alpha (Smith 1978, Carswell et al. 1979). The identification of magnesium and iron lines in three systems with absoprtion redshifts $z_{abs} \sim 0.36$ yields the largest velocity difference yet found between an absorption and emission redshift in a single object; if the material were ejected from the QSO, the velocity of ejection would have to be close to 0.7c, yet with an internal velocity dispersion $\lesssim$ 30 km s^{-1}. Such a degree of velocity collimation is considered improbable by many (but not all) who are active in this area of research; relatively nearby intervening galaxies seem a more natural explanation. However, the numbers of these low-redshift absorption systems containing metals is proving to be embarrassingly large (Wright, personal communication; see also Burbidge et al. 1977; Whelan, Carswell and Smith 1977, Carswell, Smith and Whelan 1977).

8. A NEW NATURAL GROUP - QSOs WITH VERY BROAD ABSORPTION FEATURES

A new natural group, probably consisting mainly of QSOs, has been discovered on objective-prism plates. In this case, however, the members are not a common type of QSO, but rather those objects with broad absorption troughs. If indeed the objects are very broad-lined QSOs, the absorption troughs may be two wide (typically $\sim 10^4$ km s^{-1}) to have been produced by any known intervening material unless it was ejected from the QSO; the line widths far exceed the range of velocities expected in a cluster of intervening galaxies. On the other hand, Boroson et al. (1978) have speculated that the distribution in redshift of sharp C IV absorption doublets for PKS 0237-23, (the distribution has a width $\sim$ 5,000 km s^{-1}) could be produced by an intervening cluster of clusters of galaxies (a supercluster). The most well known object from this natural group is Q1246-057 (Osmer and Smith 1976, Boksenberg et al. 1978a - see also Fig. 1), but others are shortly to be studied. By far the most extreme object yet known of this type is Q1309-056 (Osmer and Smith 1976), which has evidence for what is probably ejected material moving in excess of a tenth of the velocity of light with respect to the QSO; the C IV absorption trough occupies the entire spectral region between the C IV 1549 Å emission to at least the Si IV 1400 Å emission (and perhaps to even shorter wavelengths). It appears that absorbing material can be ejected at very high velocities from at least a few QSOs like Q1246-057 (this natural group containing the high-redshift - i.e. $z > 2$ - emission-line objects).

Clearly the next steps are (i) to locate and confirm other QSOs from this group, and (ii) to obtain higher-resolution observations to see if the very widest troughs break up into multiple sharp-lined components. No case has been found so far in which a sharp-lined absorption system must be associated with a QSO, that is to say as far as one knows at present, all sharp-lined systems could arise from material at cosmological distances from the QSO (e.g. in intervening galaxies or intergalactic clouds). If, however, the absorption troughs in objects as extreme as Q1309-056 do break up into sharp-lined systems, they may provide the best evidence so far to associate at least some sharp-lined systems with material ejected from the QSO; one might thus demonstrate that such systems could retain the high degrees of velocity collimation required, even when travelling near a tenth of the velocity of light. By producing a reasonably large sample of very broad-lined objects, we can test to see how often the broad troughs remain smooth as is the case for Q1246-057 (Boksenberg et al. 1978a). Such a sample of these very rare objects is once again most efficiently obtained by using objective-prism Schmidt plates. Indeed, though we have seen that the sharpest and widest absorption lines ever seen at optical wavelengths in QSOs have been identified from objects within these natural groups, more will probably be learned from the statistical properties of a uniform sample of objects. One of the major advantages of the slitless technique is proving to be the ability efficiently to assemble samples suited to given astrophysical problems.

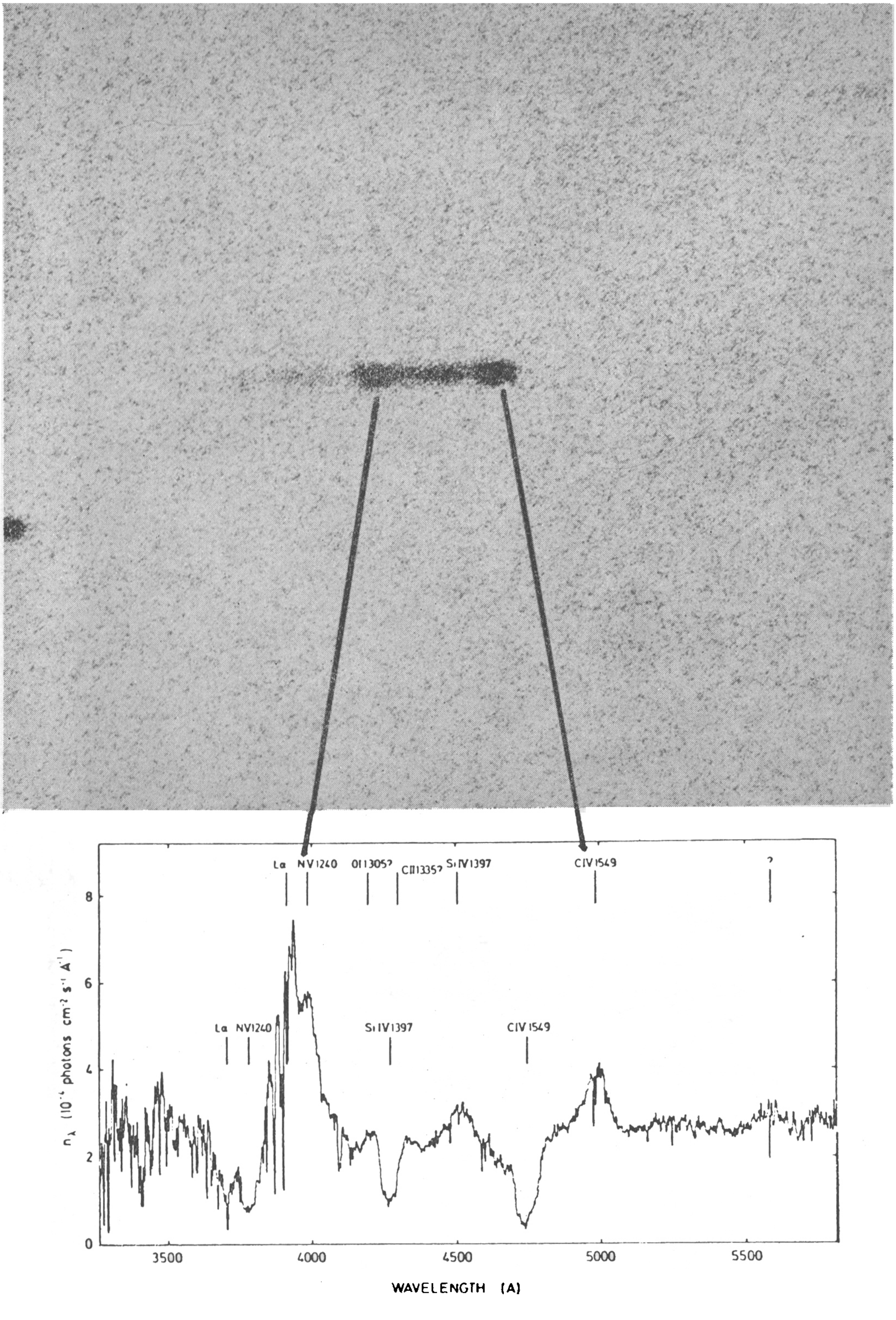

Fig. 1. UK objective-prism spectrum of Q1246-057. A slit spectrum (Boksenberg *et al*, 1978) of this object is shown for comparison. This object illustrates the natural spectral form group on these plates which is thought to consist mainly of this very rare class of QSO having broad absorption troughs.

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DISCUSSION

Nandy: You have not detected any quasars with red shift, Z > 3.5. Doesn't this imply a cut off of quasars at this value?

Smith: No. For further discussion of this, see Carswell, R. F. and Smith, M. G. (1978, M. N. R. A. S., in press).

Blanco: I would like to comment on Nandy's remark in regard to a possible limit of Z = 3.5 for quasars. Most of the survey work carried out so far is with IIIaJ plates. The long wavelength spectral sensitivity cut-off of this emulsion is such that if Z $\gtrsim$ 3.3 Lyman α cannot be seen. We are only now starting to use red and infrared plates. The surveys will be difficult because the field of view is small and the number of QSO's with high red shifts is expected to be small.

Smith: That is correct. An advantage of the UK Schmidt is its unique combination of faint limiting magnitude and wide field. The field is 120 times that of the AURA Grisms.

Abati: Did you find any correlation between the strength of the Lyman α and the radio energy in order to see if there are physical differences between objective prism QSO and QSS?

Smith: At the Santa Cruz, California, QSO workshop (July, 1978), Jim Condon, Pat Osmer, Alan Wright and I will be combining all our radio and optical data to search for correlations like this. Our overall (perhaps naive) aim is to try to understand why most QSOs are radio quiet. Is the radio emission absorbed out or are the fundamental emission mechanisms different in radio-quiet and radio-loud QSOs? We are basing our efforts on the Curtis-Schmidt -40° (declination) zone, which produced 140 or so luminous QSO candidates. Absolute, optical spectrophotometry for most of these has now been obtained at CTIO. All these objects have been surveyed at each of four frequencies (0.408 GHZ < ν < 15 GHZ) — to avoid bias — and detections have been examined with the VLA. I will send you our results as soon as possible.

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