THE SURFACE DENSITY OF QUASARS

J.G. Bolton
Division of Radiophysics, CSIRO, Sydney, Australia

Ann Savage
Royal Greenwich Observatory, Hailsham, Sussex, U.K.

A knowledge of the surface density of quasars as a function of magnitude is important for two reasons. Firstly it is necessary in order to assess the possible statistical significance of close pairs of quasars or the association between quasars and bright galaxies. Secondly it is a necessary step in the determination of the space density or luminosity function of QSOs. We have carried out what we believe to be currently the most comprehensive investigation into the surface density of quasars. Three techniques have been used in this investigation. These are -

(1) A search for ultra-violet excess stellar objects and their subsequent classification.

(2) A search for emission-line stellar objects on objective prism plates.

(3) Identification of radio sources from deep radio surveys.

The investigation has made use of five optical and one radio telescope: the SRC and Palomar 1.2-m Schmidt telescopes, the Anglo-Australian 3.9-m telescope, the 1-m and 0.5-m telescopes at the Sutherland Observing Station in South Africa, and the Parkes 64-m radio telescope.

The regions selected for study are two areas of 25 square degrees each centred at $22^{h}04^{m}$, -18°55', and $02^{h}00^{m}$, -50°00'. Pairs of blue and UV plates were taken for us by the UK Schmidt Unit in five areas near the south galactic pole and the final selection of two areas was based on plate quality. In the 22^{h} area a two-colour (blue and UV) plate which had been taken with the Palomar Schmidt in 1966 was available for comparison. The two-colour plates were blinked using a closed-circuit TV combined blink and coordinate measuring machine. Each plate is viewed through a TV camera and the outputs of the two cameras are combined electronically to present the two images of the same star side-by-side. The desired colour balance can be set in the electronic mixer. A target

M. S. Longair and J. Einasto (eds.), The Large Scale Structure of the Universe, 295-303.

https://doi.org/10.1017/S0074180900144742 Published online by Cambridge University Press

viewed through a third camera can be switched in for coordinate measurement using precision screws on the X-Y carriage which bears the plate-viewing cameras. Areas of 6' x 6' arc were inspected at a time and inspection of one set of plates took approximately nine days. Each plate pair was scanned by A.S. and again by A.S. and J.G.B.; thus for the 22^h field, where the additional Palomar plate was available, four independent examinations were made. About one-third of the UVX objects brighter than B = 19^m detected in the plate scanning were galaxies but about 250 apparently stellar objects with UVX were found in each area. (UVX was defined as U-B $\leqslant$ -0.4.)

Blue and ultra-violet magnitudes for these objects were established in three stages. Photoelectric magnitudes were measured for about 20 objects between 10^m and 17^m in the centre of each field using the South African 0.5-m and 1.0-m telescopes. A photographic sequence extending to 20^m was then obtained through the use of a 3^m objective grating built for use with the SRC Schmidt telescope. The grating is formed from 0.15 cm nylon lines 0.7 cm apart stretched across a circular aluminium angle frame. Several plates in both colours were taken of the two fields and iris photometry of these plates was used to form the extended photographic sequence. Finally, iris photometry of the two-colour plates provided the magnitudes for the UVX objects. R.M.S. errors in these magnitudes are $\sim 0^m.15$ in B and U and the major contribution to them arose from uncertainties in the final stage.

Low-dispersion spectra of about 30 objects in each field were obtained with the Robinson-Wampler image dissector scanner at the Cassegrain focus of the 3.9-m Anglo-Australian telescope. Half of the objects were brighter than B = 18^m and most of these proved to be stars, generally dwarfs or sub-dwarfs; most of the objects fainter than B = 18^m proved to be QSOs. Classification of the remaining UVX objects in the two fields was made from deep IIIa-J plates and objective prism plates taken with the SRC Schmidt telescope. Four classes of objects were distinguished:

(1) *Compact galaxies*. Although these appear to be stellar on the IIa-O or IIIa-O two-colour plates both the high resolution of the IIIa-J direct and objective prism plates clearly indicate that they were galaxies. These were almost all fainter than B = 19^m.

(2) *Galactic stars*. These could be recognized as such from the form of their continuous spectra on the objective prism plates by comparison with those confirmed as stars with the Anglo-Australian telescope.

(3) *Emission-line QSOs*. Examples of objective-prism spectra of some of these objects are shown in Figure 1. Comparison of objective prism spectra and the Anglo-Australian telescope scanner spectra of the same objects showed that lines with an equivalent width of as little as 15 Å could easily be seen on the objective prism spectra.

https://doi.org/10.1017/S0074180900144742 Published online by Cambridge University Press

(4) *Unknown.* These objects have continuous spectra similar to those of QSOs but no emission lines. Most of them are fainter than B = 19^m and although some may be QSOs we feel that the majority are very hot stars.

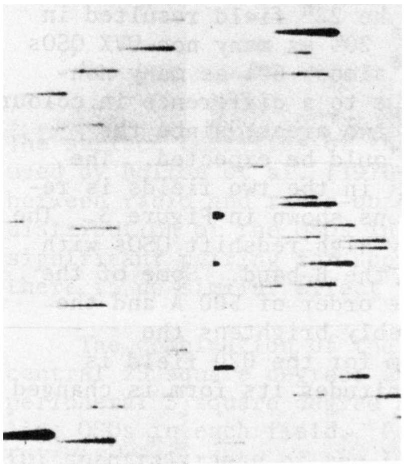

Fig. 1 - Reproductions of six QSO spectra from the SRC Schmidt objective prism plate of the 22^h field. Magnitudes and redshifts for the objects from top left to bottom right are:

B = $17^m.8$, z = 2.092

B = $18^m.3$, z = 2.28 or 0.43

B = $18^m.8$, z = 2.04

B = $18^m.9$, z not known

B = $18^m.9$, z = 2.31

B = $19^m.5$, z = 2.31

The distribution of UVX objects in the four classes as a function of magnitude for the 22^h field is shown in Figure 2. Galactic stars dominate the UVX population for objects brighter than 18^m; then the QSOs take over. However, compact galaxies make some impact near plate limit, and presumably this effect has also been present in earlier studies using similar plate material.

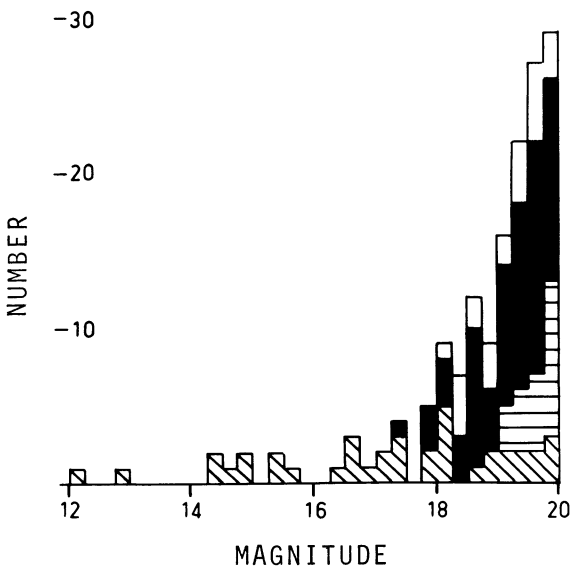

Fig. 2 - Number-magnitude distribution of UVX objects in the 22^h field. Stars are shown with diagonal hatching, compact galaxies with horizontal hatching, QSOs in black and unclassified objects clear.

https://doi.org/10.1017/S0074180900144742 Published online by Cambridge University Press

The objective prism plates were also scanned for emission line QSOs in an area of 30 square degrees. Some 70% of the UVX QSOs in the central 25 square degrees - generally the stronger-line objects - were rediscovered in this investigation. In the 22^h field only one UVX QSO was found which had been missed but in the 02^h field 10 such objects were found. Clearly the two plate pairs in the 22^h field resulted in greater completeness. In the 22^h field about 20% as many non-UVX QSOs were found as UVX QSOs but in the 02^h field almost 60% as many non-UVX QSOs as UVX QSOs. This result was not due to a difference in colour balance between the two-colour plates of the two areas, since the individual spectra clearly show whether UVX would be expected. The difference in the fraction of non-UVX objects in the two fields is reflected in their number-magnitude distributions shown in Figure 3. The 02^h field contains a large number of generally high redshift QSOs with very strong emission lines - fortuitously in the B-band. Some of the lines have equivalent widths which are of the order of 500 Å and the contribution from the emission line considerably brightens the B magnitude. If the number-magnitude diagram for the 02^h field is plotted using U magnitudes rather than B magnitudes its form is changed to resemble the B magnitude diagram for 22^h.

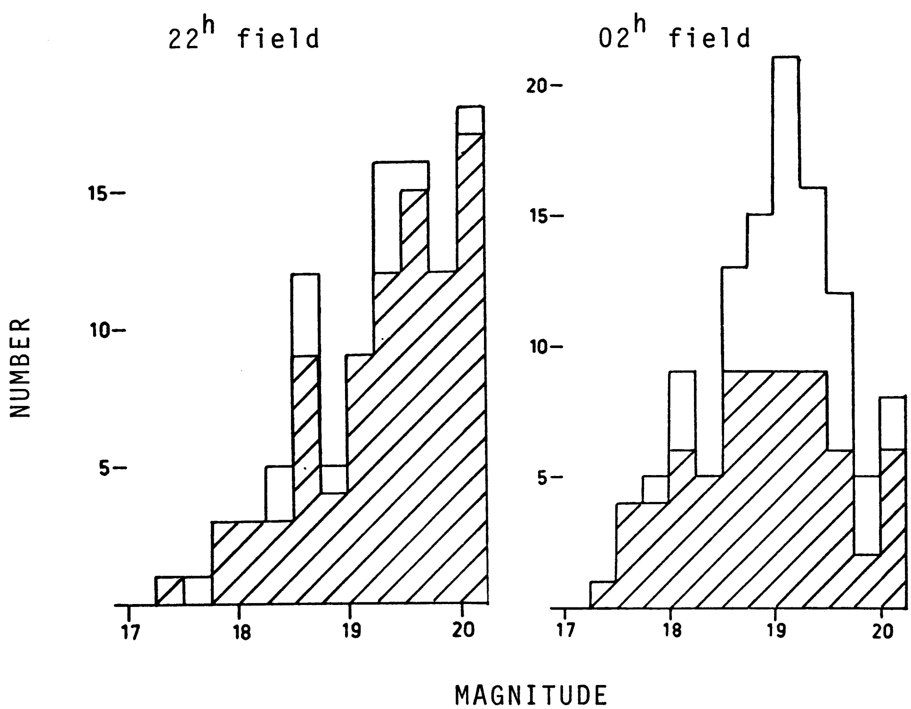

Fig. 3 - Number-magnitude distributions for QSOs in the 22^h and 02^h fields. UVX objects are shown cross-hatched and non-UVX objects clear.

The surface densities of UVX QSOs and UVX plus non-UVX QSOs (in parentheses) to magnitudes 19.5 and 19.75 for the two fields are as follows.

		$B \leqslant 19^m.5$	$B \leqslant 19^m.75$
No. per square degree	22^h field	1.8(2.2)	2.4(2.8)
	02^h field	2.2(3.6)	2.5(4.0)

The surface densities of the UVX objects are somewhat lower than those used by Bolton et al. (1976) in their claim of a significant pairing between radio and radio-quiet QSOs. A nearest-neighbour analysis of the distribution of the QSOs in the 22^h field (shown in Fig. 4) shows significant pairing for separations of the order of 2' arc; however, there is no similar effect in the 02^h field.

The combination of the UVX and objective prism searches of the central 25 square degrees and the objective prism searches in the peripheral 5 square degree areas yielded a total of about 120 emission-line QSOs in each field. For measurement of line wavelengths the useful spectral range of the IIIa-J objective prism plates is about 3300 to 5100 Å (the cut-off of the IIIa-J emulsion is close to 5200 Å but the

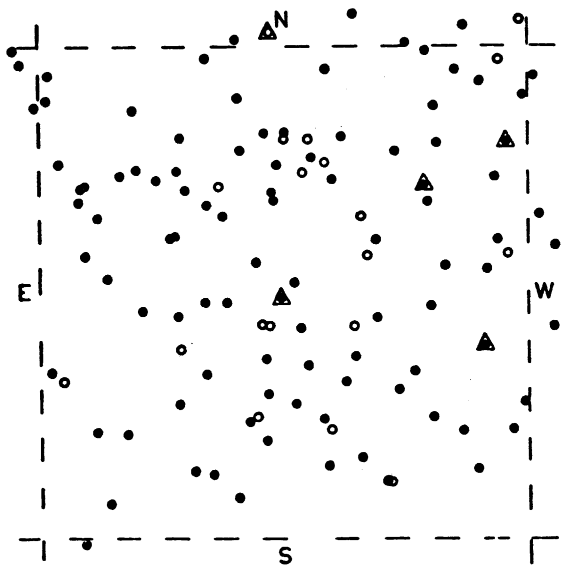

Fig. 4 - The distribution of QSOs in the 22^h field. The 5° square area of the search for UVX objects lies inside the dashed lines. UVX objects are shown as filled circles and non-UVX objects as open circles. Radio sources are indicated by triangles.

https://doi.org/10.1017/S0074180900144742 Published online by Cambridge University Press

resolution is so low at the red end that lines are very difficult to distinguish or measure). Wavelength calibration of the prism was determined by using the measured or deduced line wavelengths of QSOs which had been observed with the Anglo-Australian telescope. Unambiguous redshifts could be determined for most QSOs with two or more lines and for one-line objects where that line occurred at a wavelength where all but one line identification could be excluded by the absence of other lines. The combination of Anglo-Australian telescope and objective-prism spectra yielded redshifts for 90 QSOs in the 02^h field and for 60 QSOs in the 22^h field, and magnitude-redshift diagrams for the two fields are shown in Figure 5. The obvious gaps in certain redshift ranges occur where redshifts for single-line objects on the objective prism spectra are indeterminate. The diagrams reflect the familiar scatter of other QSO samples. Perhaps significant is the fact that the few radio emitters lie in the lower halves of these diagrams. The decrease in the number of QSOs with redshifts greater than ~2.5 is probably real, since the strong Ly-α line can be distinguished on the objective prism spectra up to a redshift slightly in excess of 3.

Two radio investigations were made in two fields. Deep radio surveys with a lower limit of detection of 100 mJy were carried out in both fields with the Parkes 64-m telescope at a wavelength of 11 cm.

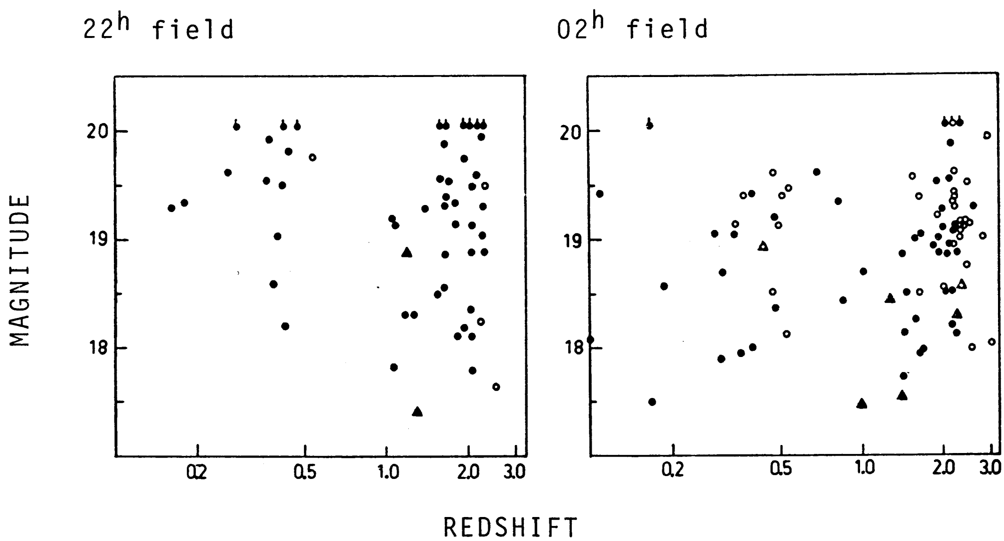

Fig. 5 - Redshift-magnitude diagrams for QSOs in the two fields. UVX objects are shown as filled circles, non-UVX objects as open circles and radio sources as triangles.

https://doi.org/10.1017/S0074180900144742 Published online by Cambridge University Press

Forty-three sources were found in the 02^h field and 37 in the 22^h field. Their positions were examined on the two-colour, the deep IIIa-J and the objective prism plates. Ten radio galaxies were identified in the 02^h field and six in the 22^h field. Six QSOs were identified in the 02^h field and four in the 22^h field. The four in the 22^h field had all been recognized as QSOs from the UVX or objective prism searches as had four in the 02^h field; the other two were objects with low UVX and very weak emission lines. One of the objects in the 22^h field - PKS 2203-18, long known as a QSO - has UVX but all attempts to detect emission or absorption lines have failed.

In the second radio investigation an attempt was made to detect radio emission at a very low level, at 6 cm, from all the UVX objects in the two areas. This was made in the hope that it would serve to distinguish between stars and QSOs. The 64-m telescope with the receiver switched between two feeds was used in a manner analogous to an optical telescope with a two-beam photometer. The system permits a very low signal to be detected - 20 mJy in only 100-s integration with an error of ±7 mJy; however, no position information is available. Very few possible detections were made and most of these were certainly chance detections of a radio source not coincident with the UVX object - the apparent detection rate for UVX objects subsequently found to be stars was as high as that for objects subsequently found to be QSOs! Additional observations at 6 cm were made on the non-UVX emission line QSOs with similar results. Finally all the QSOs in the 22^h field and half of those in the 02^h field were investigated using a new 2 cm receiver. Here the telescope beamwidth is much smaller, the confusion very much lower, and the detection limit 8±4 mJy for 300-s integration - but the results were again almost zero. To summarize: the fraction of optically selected QSOs which are radio sources shows almost no change as the radio detection limit is decreased by a factor of five or more below 100 mJy. This result is consistent with the explanation put forward by Bolton (1977) for the peak in the optical magnitude distribution for radio QSOs - QSOs either have radio emission which is fairly closely linked to their optical emission or none at all (though presumably free-free emission from the line-emitting region would exist, but at a level too low for detection).

A final interesting result from this investigation concerns the optical variability of QSOs. We had hoped that for the 22^h field where we had plates taken 10 years apart variability could be used to discriminate between stars and QSOs. In fact, only two variable QSOs were found: one is one of the four radio emitters in the field and the other one of the hundred radio-quiet QSOs. This result on radio-quiet QSOs is in strong contrast with extensive data on the optical variability of the radio QSOs. In a recent summary Heckman (1977) states '(radio) quasars are found to vary typically 1-3 magnitudes on time scales of tens of years'. Radio and radio-quiet QSOs, it would appear, can be distinguished statistically in two ways. Firstly there is a difference in the number-magnitude distribution and secondly there is a difference in the incidence of optical variability. Subjectively, we believe that there is a third distinction - the equivalent widths of the emission lines in the radio-quiet objects are greater than those in the radio sources. It would not be unreasonable to relate this effect to the difference in optical variability.

We acknowledge with great pleasure the assistance given to us in this investigation by Keith Tritton and all members of the UK Schmidt Unit.

References

Bolton, J.G., Peterson, B.A., Wills, Beverley J. and Wills, D.: 1976, *Astrophys. J. (Lett.)* 210, p. L1.
Bolton, J.G.: 1977, in *Proc. IAU Symp.* No. 74 (Ed. D.L. Jauncey), Reidel, Dordrecht (in press).
Heckman, T.M.: 1977, *Publ. Astron. Soc. Pac.* 88, p. 844.

DISCUSSION

Suchkov: Why is there a significant deficiency of objects on the red-shift magnitude diagram in the range of redshifts from 0.5 to 1.0?

Bolton: This is one of the redshift ranges in which only one line occurs in the spectral range (3300 to 5200 Å) of the objective prism spectra. It is not a real gap, just an artifact of our instrumentation. There are other small gaps but none between z = 1.7 and 3.1. At z = 3.1, we have an instrumental cut-off as Ly-α disappears beyond the red end of our spectra.

Tinsley: Have you a number for the density of galaxies at $19^{m}_{.}5$ on your IIIaJ plates?

Bolton: For UV excess galaxies it is approximately the same as that for the quasars.

Jones: I am particularly struck and surprised by the great differences between your two fields. According to usual cosmological ideas there should be no difference between such fields. Is the difference, in your opinion, significant and what may it be attributed to?

Bolton: The differences are undoubtedly real. We would have to look at a number of other fields to see whether these two are anomolous or not.

Tully: Allan Stockton at Hawaii has to my mind definitive new evidence regarding the cosmological nature of QSO's. He has now about eight red-shifts for galaxies near QSO's, which agree with the QSO redshift to within roughly 200 km s^{-1}, or one part in three hundred. Most of the redshifts are determined from the continuum break at 4000 Å and H+K absorption lines.

van der Laan: Would Dr Schmidt care to comment on the results of Green and himself in the light of Dr Bolton's results?

Schmidt: The steep gradient of optical counts of quasars with magnitude, between the Green-Schmidt ($B < 15^m.7$) and the Braccesi ($B < 18^m.0$) surveys, applies only to objects with ultraviolet excess, since quasars in both surveys fulfil $(U-B) < -0.5$. We can say nothing as yet about the quasars with redder (U-B) colours (with redshifts less than 2.5), if they exist.

Bolton: In our 2-hour field non UV excess objects with strong Mg II in the B band make an appreciable contribution to the low redshift numbers.

Tammann: I would like to add that Dr Stepe at Basle has been using UG as well as UV plates to search for ultraviolet excess objects. Using the UG plates which are taken with narrower filters than the UV plates, he finds 20% more ultraviolet excess objects than with the normal UV plates, in agreement with what you said.

Khachikian: I should like to point out that there are also strong differences between Markarian galaxies which have strong UV continuum and those which have not. The galaxies with strong UV continuum usually have active nuclei and most of them are the Seyfert galaxies.

A SURVEY PROGRAMME FOR QSO AND RELATED OBJECTS

H. Lorenz

I would like to give the first results of a survey programme for high redshift quasars and related objects on the Tautenburg-Schmidt plates. It is known that objective prism plates are very useful for detecting these objects. The smaller the dispersion of the spectra, the fainter are the objects that can be found. Our Schmidt correcting lens gives spectra with the dispersion of 2500 Å mm^{-1} at Hγ. The limiting magnitude is about 19^m in the B range. At this very low dispersion reliable classification of the objects requires the extraction of all the information stored on the plate. That means that a quantitative evaluation should supplement visual insepction.

First we detrmine the wavelength of spectral features in the suspected object using a wavelength scale, which has been determined by the position of reference stars on a direct Schmidt plate and the position of spectral features of these stars on the prism plate. The accuracy is sufficient to determine redshifts larger than 0.04. The main purpose is the determination of the intensity distribution in the spectra. The characteristic curve (as a function of λ) is derived from the known average intensity distributions in stars of the same spectral types as the references. The relatively crude estimate of the spectral

https://doi.org/10.1017/S0074180900144742 Published online by Cambridge University Press