QSO LUMINOSITY FUNCTIONS AND EVOLUTION

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DEDICATION. This article is dedicated to the teams at the UK Schmidt Telescope, at the photographic plate library in Edinburgh, with the APM in Cambridge and the COSMOS in Edinburgh; their many years of unselfish support work, maintaining the highest professional standards, have contributed much to the field covered in this review.

CONTENTS.

1. INTRODUCTION

There has been substantial progress in the last three years (since the Bangalore IAU Symposium #119 "Quasars") in deriving the optical and radio luminosity functions for quasars as a function of redshift. Improved definition of the optical luminosity function at various redshifts has permitted a more certain identification of the effects of luminosity and density evolution, from redshifts of about 2.2 to the present, although the subject remains somewhat controversial (c.f. Fig.1, and Weedman 1986, p124). Graphs of numbers of QSOs versus look-back time (e.g. Fig.2) show an apparent peak in numbers near redshifts z=2 to 3 for both optical and radio wavelengths; large uncertainties about unquantified selection effects in the presence of steep luminosity functions and/or use of very small samples made this

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conclusion much less reliable a few years ago (see, e.g., Smith 1981).

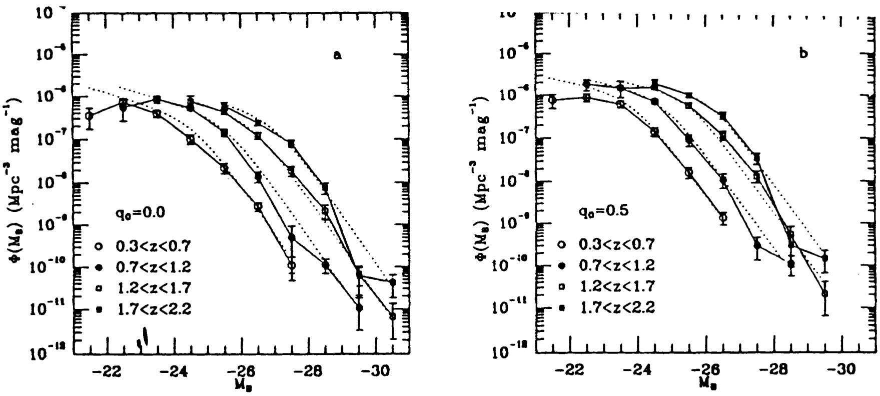

Figure 1. The QSO luminosity function derived for (a) q=0 and (b) q=0.5 universes. Dotted lines represent luminosity evolution fits to bright (M(B)<-23) QSOs. Diagram taken from Boyle, Shanks & Peterson (1988).

Progress on an unambiguous physical interpretation of the data on evolution in the properties of the quasar population has been less striking. It is still far from clear whether the decline in the luminosity of the quasar population with cosmic time means (on conventional hypotheses - see also Rees 1984):

(a) that a relatively small number of long-lived (10exp10 yr) individual quasars with very massive central black holes (10exp9 - 10exp10 $M_\odot$) have poured out vast amounts of energy throughout most of the history of the universe but are now dying out - these very massive black holes being found at low redshift in quasars and Seyfert galaxies, but not in normal galaxies (see, e.g. Boyle et al. 1987), or

(b) that most galaxies harbour currently inactive quasars, which have been short lived (10exp8 yr) or flare up - possibly more than once - and have less massive black holes (10exp8 $M_\odot$, see, e.g. Dressler and Richstone 1988). Luminosity evolution in this scenario is a gradual reduction in the mean intensity of the QSO cycles, and may depend critically on the environment of the quasar (see, e.g., Roos 1985a, b).

Even these basic popular scenarios may have difficulties. Wandel and Petrosian (1988) find it difficult to see how a luminous quasar with the requisite high mass and accretion rate can evolve into a low-luminosity Seyfert or QSO - see also the discussions by Begelman (1988) and by Blandford (1988) at this conference.

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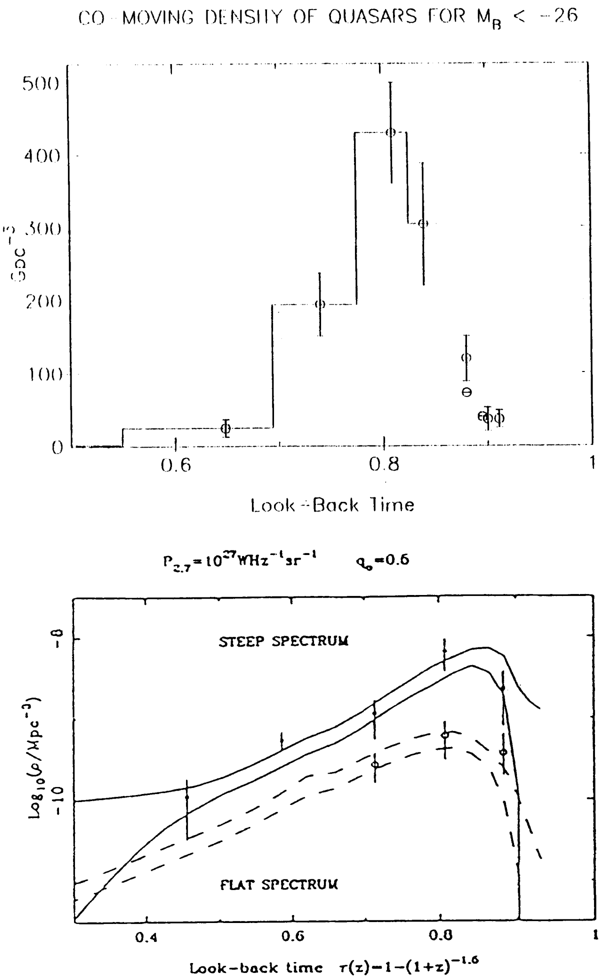

Figure 2. The evidence for a turn over in the co-moving space density of QSOs in (a) the optical - based on a diagram supplied by Richard Green and (b) the radio - based on a diagram taken from Peacock and Miller (1988; see also Dunlop and Peacock 1989).

It is quite likely that an improved physical understanding of quasar luminosity evolution will have to come from careful studies of the central regions of nearby galaxies - including our own (e.g. Rieke 1988; Kormendy 1988; Dressler and Richstone 1988; Dressler 1988). It is clear that surveys for low-luminosity quasar activity merit attention similar to that usually afforded the more luminous classical quasars (see, e.g., Cheng et al. 1985; Filippenko and Sargent, 1985; Marshall 1987,1988; Filippenko, 1988; Khachikian 1988; Miller, 1988; Netzer, 1988; Krolik & Begelman 1988).

Significant challenges to cosmological models for the early evolution of galaxies may as readily come from studies of the ages and masses of stellar populations in very high redshift galaxies as from studies of QSO statistics; the known redshifts of resolved galaxies are now approaching 4, including at least one object with a massive population of old stars (e.g. Lilly 1988a; Chambers & Miley 1988). "The formation redshift of this 'old' population depends strongly on the assumed cosmological geometry, but is in excess of z = 4.5 even for an open, low q cosmology, and would be much higher for the popular 'flat' cosmological models favored by inflationary scenarios for the early Universe" (Lilly 1988b). A high space density of luminous QSOs at redshifts z>5 would nevertheless provide significant constraints on the cold dark matter model (e.g. Efstathiou and Rees 1988). Studies of absorption lines in QSOs are of importance in understanding the formation history of disk galaxies (see, e.g., Sargent 1988; Pettini 1988); "metal" lines (e.g. silicon) in absorption systems near z=4 confirm the existence of evolved stars even at that redshift. Deep galaxy redshift surveys (e.g. Ellis 1988) show that galaxy evolution is luminosity dependent; the bright end of the galaxy luminosity function is fixed, whereas low-luminosity galaxies exhibit sporadic bursts of star formation activity (see also Roos 1985b).

The evolution of the luminosity function is also important in determining the contribution of QSOs to the X-ray background and to the UV ionising field at high redshift. Further clues concerning the evolution of quasars may come from the study of the environment of quasars (see e.g., Yee 1987; Fricke and Kollatschny 1988); the local galaxy density, frequency and type of interactions with other galaxies and the state of the intracluster medium may all affect the formation and fuelling of quasars.

In this article, redshift is assumed to be an indicator of distance as given by standard Friedmann cosmologies.

2. FINDING QUASARS - RECENT SURVEY WORK

In order to begin to understand the data on luminosity functions for quasars, it is necessary first briefly to review recent work on quasar surveys. I last gave a review of quasar surveys at IAU Symposium 119 and covered the results of searching for QSOs at a variety of wavelengths from X-ray to radio (Smith 1986). A valuable comprehensive summary of quasar surveys is contained in the proceedings of the recent Tucson conference (e.g. Osmer, 1988; Foltz & Osmer 1988). I shall therefore highlight only a few of the most significant areas of development in survey techniques and results in this review.

Most recently discovered quasars have been found from automated optical searches of multicolour plates taken with Schmidt telescopes (most notably with the U.K. Schmidt); these searches have been performed most successfully with the high-speed measuring machines APM (at Cambridge - see e.g. Hewett et al 1985; Foltz et al. 1987; Warren 1988; Demers et al. 1988; Warren, Hewett and Osmer 1988; MacAlpine et al. 1988; Chaffee et al. 1988) and COSMOS (at Edinburgh, see e.g. Boyle et al. 1987; Boyle, Shanks and Peterson 1988; Miller and Mitchell 1988). These multicolour searches of direct plates have been supplemented by automated searches of objective-prism plates. A major new feature of such searches is that there is now much greater control over selection criteria and associated biasses (e.g. Miller and Mitchell 1988). The multicolour separation technique is effective on a wide variety of quasar spectra. One of the major reasons for the greater success rate at high redshifts compared with earlier searches is the care being taken to calibrate and measure accurately (e.g. Warren 1988). In a single field in the region of the South Galactic Pole, Warren, Hewett and Osmer (1988) have now identified 24 QSOs with z>3, three of which have z>4 (these numbers include previously known objects). A promising development for future work at the faint end of the luminosity function is the development of a very accurate CCD-based automated multicolour survey by Anderson and Schechter (1988).

Miller and Mitchell (1988) have succinctly summarised the automated multicolour search procedures developed by Warren et al.: "Basically the technique involves measuring the broad-band colours of every stellar image on UBVR and I band Schmidt plates with a fast measuring machine and looking for those objects whose colours are peculiar. The selection is achieved by calculating for each object in turn the distance in the 4-dimensional multicolour space to the nth nearest other object, that distance being a measure of how isolated the object is in multicolour space.....Quasars can have very extreme colours, and they may be undetected in one or more bands. It is thus important to include objects which only have limits on their colours in the quasar search....."

An example of this last point occurs in the methods being adopted by Hewett, Warren and the author in a search for objects with redshifts around 5. This is proceeding in two phases. The first, is already complete. It was based on the observation by Dunlop et al. (1986) of the "blue" optical-infrared colour of the z=3.71 QSO PKS1351-018. The method we used basically involved searching for faint optically very red objects (R-I>1.5), which do not lie close to the densely populated locus of M stars in UBVRI space (see, e.g. Fig. 3). This selection included many objects not present on the U, B(J), V and I plates. Because the optical colours of M stars with R-I>1.5 are so extreme - typically 4 to 5 magnitudes in V-K - compared to the IR colours for a QSO spectrum of typical continuum slope, we found that the M-stars could be eliminated reliably in only a few minutes each through photometry in the K-band (2.2 microns). In the single

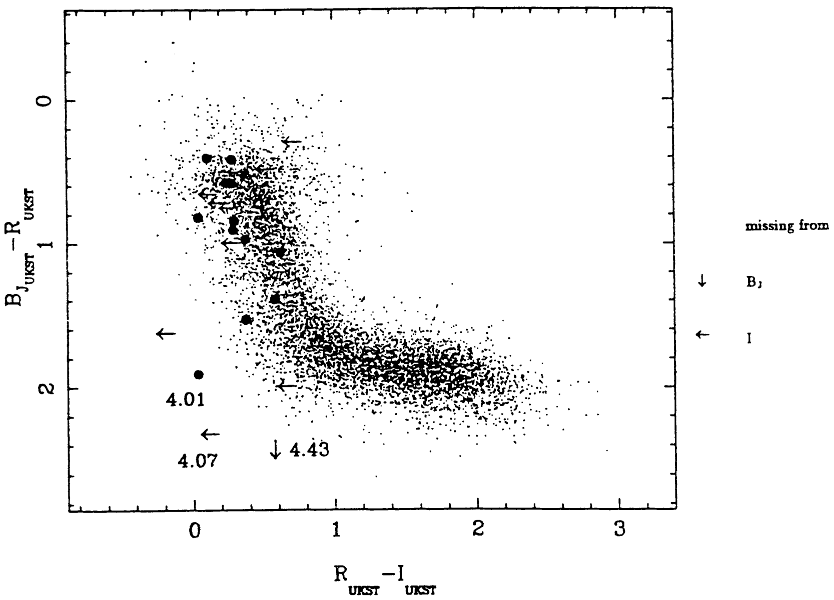

Figure 3. The B(J)RI 2-colour diagram for stellar images in a U.K. Schmidt South-Galactic-Pole field brighter than m(R)=20.0, showing the 24 quasars of redshift z>3. The large number of normal stars missing from the B(J) and I passbands have been omitted for clarity. Searches for QSOs near redshift 5 are currently concentrating on objects with 1.0<R-I<1.5. Diagram taken from Warren, Hewett and Osmer (1988).

40 sq. deg. Schmidt field studied in detail (centred near the South Galactic Pole - SGP) we found no quasars with R-I > 1.5.

The second phase is to consider the predicted colours of QSOs with various properties, and see where we should best look for objects similar to those known, but with redshifts near 5. Such quasars are red in B-R and will not appear on the B(J) plates at the magnitude limits we are considering - B(J)-R is around 2.5 to 3.5. As the Lyman-alpha emission line moves out of the R band, our model quasars all transit very rapidly across the R-I diagram, and the most suitable candidates appear to end up with 1.0<R-I<1.5 (Fig. 3). The important point is that stars and quasars with R-I colours in this range have significantly different I-J and J-K colours; infrared photometry can be used to distinguish between them. We intend therefore to obtain J (1.2 micron) magnitudes of our candidate objects to form an R-I vs I-J diagram, then to observe at K the bluest objects in I-J to form an I-J vs J-K diagram. There should be a clear distinction between the quasars and the stars in such a diagram.

Miller and Mitchell (1988) have addressed the question of completeness in the multicolour UBVRI searches. They find that the addition of the extra colours to the traditional UVX technique (e.g. their U-B, B(J)-I diagram) can reduce contamination by stars in bright samples, and improve completeness, even at redshifts z<2.2. They have tested the effectiveness of the multicolour surveys at higher redshifts by (a) checking against QSO samples assembled by objective-prism techniques (a test which will probably be valid only for strong-lined objects) and (b) checking against simple models of quasars. As they point out, these models "cannot tell us the completeness fraction of our surveys, since we don't know the relative numbers of any particular spectral type, but they can tell us if there is a particular class of quasars (such as weak-lined objects) which may be missed by the technique." They find that in the range 2.2<z<3.5, the redshift sub-range which is least well covered by the UBVRI selection process is 2.7<z<3; particular trouble is experienced with the stronger-lined quasars with red continua, but for such objects the objective-prism selection process can be used as an efficient supplement.

At redshifts z>3.5, there are not yet enough objects with measured UBVRI colours, so model quasars must be used to provide guidance; no estimate can therefore be given of completeness. It has been found to be best to restrict the selections from the Schmidt plates to R<18.5; the U.K. Schmidt telescope plate limits are such that the technique becomes ineffective at R>18.5 Modelling of quasars for testing the efficiency of optical surveys has naturally covered only the known kinds of quasars - e.g. objects with central sources having relatively unobscured optical spectra; as interactions, intrinsic dust etc. are likely on many scenarios to become more important at high redshifts, such tests alone are unlikely to be conclusive. One may hope to start finding a few highly reddened quasars with high redshifts.

Following the launch of IRAS, a population of infrared galaxies with luminosities similar to those of quasars has been found at low redshifts in greater numbers than classical quasars of similar luminosity. A complete sample of objects with IR luminosities L(8-1000microns) > 10exp12 L_{o} were all found to be extremely rich in molecular gas, most appeared to be advanced mergers of two spiral discs, 9 out of 10 exhibited optical emission-line ratios characteristic of active nuclei, and the near-IR colours showed a mixture of starburst and AGN energy sources (e.g. Sanders et al. 1988; Baan, 1988; but see also Rieke 1988; Norris 1988). Depoy, Becklin and Geballe (1987) have observed broad Brackett-alpha emission in Arp 220.

Some of the most significant recent work at radio wavelengths has been the work on a database of 522 sources complete to 0.1 Jy at 2.7 GHz. This database is based on 4 complete samples (e.g., Dunlop 1987). The resultant data set consists of 172 flat-spectrum sources and 350 steep spectrum sources, and is summarised by Dunlop and

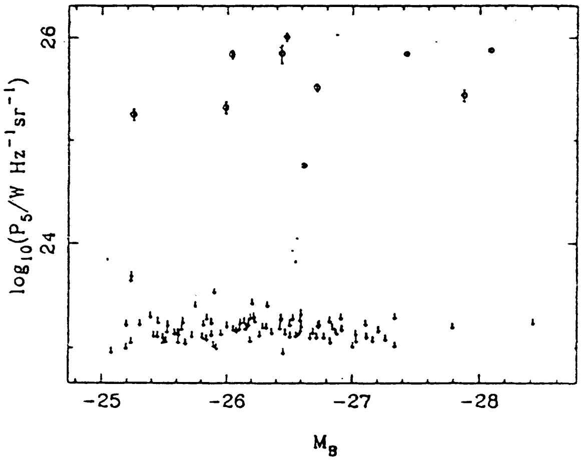

Figure 4. Radio quiet and radio loud quasars appear to form two distinct populations. Diagram taken from Peacock and Miller (1988).

Peacock (1989). Of these 522 radio sources, only 3% are unidentified, though a further 14% lack any reliable redshift information.

Optically faint QSOs (B=20mag) are detected by the VLA in only a few percent of cases (e.g. Kellerman et al. 1983); this has led Peacock, Miller and Longair (1986) and Peacock and Miller (1988) to conclude that there are two distinct classes of QSO which can be separated in radio luminosity at P=10exp24 W/Hz/sr at 2.7GHz. They note that the radio-loud class has properties similar to those of radio-loud elliptical galaxies. Fig. 4 shows the bimodal nature of the radio power and the lack of any obvious radio-optical correlation for a sample of prism-selected QSOs observed with the VLA. Peacock and Miller find that radio-loud quasars and elliptical radio galaxies have identical radio luminosity functions above P=10exp25 W/Hz/Sr, with a "redshift cutoff" near z=2. It is likely that the host galaxies of radio-loud quasars are giant ellipticals (see, e.g. Malkan 1984). The next major step will be to determine the high redshift evolution of radio sources at lower luminosities, as discussed in more detail by Peacock and Miller.

3. THE LUMINOSITY FUNCTION FOR QUASARS AND ITS EVOLUTION AT LOW REDSHIFTS (z<2.2).

Surveys carried out most notably by the Durham group (e.g. Boyle et al 1987) and by Marshall et al. (1983a,b) appear to show that the luminosity function for quasars has a distinctive form, which remains roughly the same for a wide range of redshifts. Using a

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characteristic bend in the quasar luminosity function (see, e.g., Fig. 1) Boyle et al. reported that the function at redshifts $z<2.2$ appears to evolve in a manner which can be described by pure luminosity evolution of the form $L(z)=L_o(1+z)\exp(3.2\pm 0.1)$ (see also Heisler & Ostriker 1988a; Weedman 1986, p124). At all redshifts over the range $0.3<z<2.2$ and for values of $q_o=0$ and 0.5, the luminosity function changes from a steep power law at bright magnitudes to a flatter slope at faint magnitudes. This bend in the luminosity function was earlier thought to be a "break" between two power laws - see e.g. Dunlop and Peacock 1989 and Fig. 1. The break has become less clear as the data and the fitting have been examined more carefully. Boyle et al. conclude that for QSOs with $M(B)<-23$, any evolution in density at $z<2.2$ is at least 50 times slower than the corresponding evolution in luminosity.

The luminosity function for Seyfert nuclei in the range $-23.5 < M(B) < -18.5$ has been derived by Cheng et al. (1985); it matches that for optically selected low-redshift QSOs at $M(B) = -24$ by Schmidt and Green (1983).

A more recent analysis by Green (1988) shows less convincing evidence for shape preservation or for any distinctive break or bend in the luminosity function that can be used as a reliable tracer of density or luminosity evolution. He threw out one-line redshifts from the sample in Figure 1 and made other fairly conservative selections from the lists of objects then available to him. Green argues that a significant component of density evolution is still consistent with the data, i.e. vertical movement and tilt (luminosity dependent density evolution) of functions like those in Fig. 1(b) is as good an approximation as horizontal movement (pure luminosity evolution).

Yee and Green (1987) have reported discovery of a change of quasar environment with redshift (see also Green & Yee 1988). Assuming that interaction with close companions is reponsible for triggering activity, evolution of the quasar luminosity function would not be interpreted as a direct result of the steady decay of long-lived quasars - following an initial single burst of QSO formation - but rather as a change in the interaction rate with cosmic time. Peacock and Miller (1988) have noted that Yee and Green's sample is however largely based on radio-selected quasars; the objects at high redshift happen also to be the most luminous, so the environmental changes might more naturally correlate with luminosity than with redshift. Prestage and Peacock (1988) have suggested that some low-power sources are not seen in dense environments because they cannot supply enough ram pressure to overcome the static pressure of the intergalactic medium; the more luminous quasars and galaxies have no such difficulties. Green (personal communication) has checked his sample carefully and finds the correlation with redshift to be much stronger than with luminosity.

4. THE LUMINOSITY FUNCTION FOR QUASARS AND ITS EVOLUTION AT HIGHER REDSHIFTS (z>2.2).

Since 1985 the search for high redshift QSOs has proceeded at a greatly accelerated pace, using a variety of techniques (e.g. Hazard and McMahon 1985; Hazard, MacMahon and Sargent 1986; Anderson and Margon 1987; Schmidt, Schneider and Gunn 1986, 1987, 1988; Warren et al. 1987a, b; Warren, Hewett and Osmer 1988; Webb, et al. 1988). The most obvious conclusion from this recent work is that QSOs with z>4 do exist and can have spectra similar to their counterparts at lower redshift. Details of the form of the evolution at z>2.5 are only just beginning to emerge (see, e.g., Koo and Kron 1988; Warren,

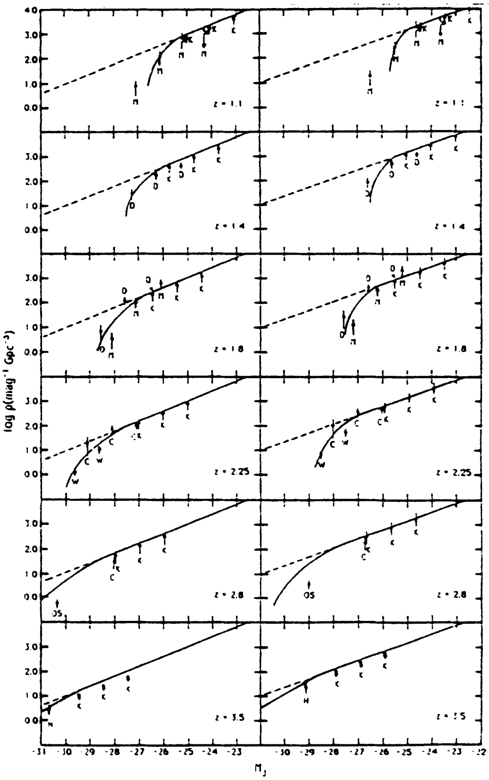

Figure 5. Luminosity functions as derived by Koo and Kron (1988). The units on the ordinate are the logarithm of the number of QSOs per cubic gigaparsec per unit interval of absolute J magnitude. The left hand side is for q(o) =0 and the right-hand side is for q(o)=0.5. The solid line is the model presented by Koo and Kron. The bottom left panel shows no detections of objects fainter than M(J)=-30, presumably because of the limited area of sky surveyed.

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Hewett and Osmer 1988). This kind of information is of significance to a number of questions relating to the formation of galaxies and QSOs; it is necessary to confirm and quantify any decline in the co-moving space density of QSOs and address questions of incompleteness.

Efstathiou and Rees (1988) conclude that "At redshifts z>2.5, the quasar luminosity function is poorly known. There are strong indications that the prodigious rise in the comoving number density of luminous quasars seen at low redshifts does not continue beyond z>2.5....but the quantitative details of the change in evolutionary behaviour (e.g. the luminosity dependence) are controversial. There seems to be no firm evidence for a decline in the density of luminous quasars ..... at redshifts z<3.5."

Koo and Kron (1988) have investigated the evolution of the QSO optical luminosity function from z=1.1 to z=3.5. They conclude that "We do not see any evidence for a feature in redshift that could be called a 'cutoff', and certainly not one that depends on luminosity." Kron (1988) adds that "the emissivity due to QSOs is continuing to increase with redshift out to the highest redshifts yet sampled."

Warren, Hewett and Osmer (1988) find that "the data from the multicolour survey confirm and in a preliminary manner quantify the apparent decline in comoving space density of quasars at high redshifts implied by the null detections of previous surveys. Indeed despite the seemingly large number of high redshift quasars in our sample the derived luminosity function is broadly compatible with the majority of the earlier searches." Examination of their preliminary luminosity functions (which unfortunately do not show individual points with error bars) in comparison with those derived by Boyle et al. for lower redshift (which do have individual points with error bars) suggests a remarkable lack of low-luminosity objects (MB>-27) at redshifts above about 3.5. Warren et al. find evidence for a pronounced flattening of the luminosity function for QSOs at z>3. It is difficult for me to compare the apparently conflicting conclusions of Koo and Kron vs Warren, Hewett and Osmer, as the latter group has not yet published luminosity functions with any discrete data points and error bars in the critical regions of interest. What is worse, many of the groups have not yet published the basic surveys on which all this data rest!

Koo (personal communication) has suggested that modified K-corrections could shift the high-redshift luminosity functions to the right in Figure 6, and noted that the slope is not very different from the flatter slopes found for the lower-luminosity objects at low redshifts. He speculates that if a larger region of sky were to be surveyed for z = 4 quasars, the high luminosity part of the luminosity function may continue to the right in Figure 6 to objects brighter than m (B) = -28. A steepening of the luminosity function could then occur, similar to the curves in Figure 5.

At this stage I would be inclined to concur with the cautious summary quoted above from Efstathiou and Rees (1988). On the other hand, Schmidt, Schneider & Gunn (1988) find from their spectroscopic

CCD survey that "the co-moving space density of quasars with Lyman-alpha line luminosity exceeding 10exp45 erg/sec at redshift 3.3 is about 7 times smaller than at redshift 2.2." They add that "there is not much doubt that the redshift cutoff does exist". It should be noted by the doubters that the emission-line limits used by Schmidt, Schneider and Gunn are quite conservative.

More luminous objects (e.g. M(B) = -28) in Fig 6 show no evidence for any turnover in their co-moving space density out to at least z=4, but data on such objects at these high redshifts is still very sparse. Any such luminosity dependence in the evolution could have important implications for optimising search techniques for QSOs at very high redshifts; luminous objects have low surface densities on the sky. Wide-field search techniques - using Schmidt plates and fast measuring machines - will still be needed to find them (although

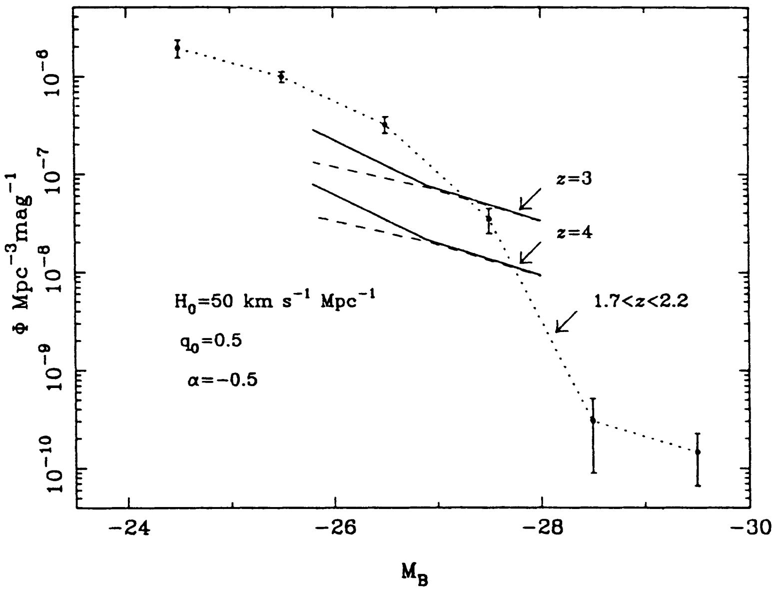

Figure 6. The luminosity function as derived by Warren, Hewett and Osmer (1988) at z=3 and z=4, compared to the result of Boyle et al. (1988) for 1.7<z<2.2. The dashed line is the result of the calculation by Warren et al. with no allowance for incompleteness. The solid line is allowing for incompleteness as described in their paper. The highest-redshift QSOs appear to have a flatter luminosity function than that for QSOs of redshift near 2. There is no evidence in this diagram for a turnover in the comoving space density for QSOs with M(B) brighter than about -27.5.

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remarkable statistical events can happen, as demonstrated recently in the serendipitous discovery of a QSO at z=4.4 by McCarthy and Dickinson 1988). It will be very interesting to see at what redshift the comoving space density of these very luminous objects does start to turn over.

The apparent lack of faint objects at the higher redshifts must raise questions in the mind of the experienced observer about selection effects and incompleteness. Until the careful simulation work on model spectra by Warren, Hewett, Miller and Mitchell, quantitative work on selection efficiency inherent in the multicolour technique itself was lacking (c.f. the discussion by Carswell and Smith, 1978, of such effects in grism spectroscopy with photographic plates and by Clowes, 1981, covering objective-prism surveys; the Palomar CCD grism survey is relatively free of many of these effects, and involves very conservative emission-line limits). Similar careful model simulations had not been published for other search techniques at high redshifts; the initial lack of any positive detections further undermined confidence that these techniques were really working on known types of QSO at redshifts much beyond 3.5. For example, concerning the widely held view that quasars were fewer but brighter in the past, Dunlop et al.(1986) commented "This conclusion may indeed be correct but at present does not seem fully justified".

One must also look more carefully at effects intrinsic to the optical spectrum used to discover the objects. Photographic slitless surveys for quasars have in the past used methods of selection whose efficiency probably varies with intrinsic luminosity (Baldwin effect) and with redshift (the shift in the spectrum seen) - not the ideal way to set about an investigation of evolution in the luminosity function unless it is very carefully controlled! The multicolour technique may be less severely affected. Faint objects are missing from the surveys at high redshifts - why? Selection effects are at last beginning to overlap with the astrophysics rather than being buried in the boring techniques of QSO surveys themselves. After all these years, we may be on the verge of being able to look at the physical reasons underlying a reliably established shortage of high-redshift objects, rather than having to root around for shortcomings in the search methods or sample sizes for an explanation.

An example is the suggestion (e.g. Rowan-Robinson 1984; Smith 1985; Sanders et al. 1988; Baan 1988) that the ultra-luminous IRAS galaxies are newly active quasars still shrouded in a cocoon of dust; Sanders et al. write "A model has been presented for the formation of ultraluminous infrared galaxies through the strong interaction, or merger of two molecular gas-rich spirals. The funneling of molecular gas clouds toward a merger nucleus accounts for both a nuclear starburst and provides fuel in the form of gas and stellar remnants for an active nucleus. In the ultraluminous infrared phase it is assumed that the active nucleus dominates the starburst which may already have begun to fade. Once the combined forces of radiation pressure and supernovae explosions begin to sweep dust clear of the nuclear region these objects will take on the appearance of optical quasars. Current observations of quasars and infrared galaxies in the local universe are consistent with the idea that the majority of quasars are formed through galaxy collisions and that all quasars may start in an ultraluminous infrared phase." It is of interest to recall experiments at other wavelengths showing the frequent presence of galaxies as companions to quasars (e.g. Stockton 1982; Stockton and MacKenty 1983; Hutchings et al. 1982; Hutchings 1983; Gehren et al. 1984; Dahari 1984; Malkan 1984; Heckman et al. 1984; Hintzen 1984; Yee and Green 1984; Smith et al. 1986; Yee 1987). Baan (1988) has constructed models to illustrate the evolution of the superluminous FIR and OH megamaser galaxies as the nuclear activity decays. He concludes that quasars, BL Lac's and Seyfert 1's could be "the final products of FIR evolution and were once superluminous thermal FIR sources. During the onset of nuclear activity, the source uses or blows away some of its dust covering. At that early stage the nucleus may show both Seyfert and starburst characteristics. Prominent examples like Mkn 231 and IC4553 belong to this special group...During the FIR evolution of the source, the nucleus may change from an obscured source to an almost naked active nucleus. In the course of this evolution the strongest luminosity contribution shifts from the infrared to the UV and optical".

In contrast to this, Norris (1988) has compared the radio properties of southern ultra-luminous IRAS galaxies with a control sample of optically selected Seyferts and narrow-lined objects. In his sample, he finds that most of the luminous IRAS galaxies are dominated by starbursts. Soifer's set of 10 objects is based on a flux-limited sample at 10μm; Norris used colour selection - F(100μm) > F(60μm) - as an additional criterion, which tends to discriminate against some AGN. Norris finds compact radio cores only among those luminous IRAS objects in his sample which have broad optical emission lines. Rieke (1988) has found that the hard-X-ray luminosities of the superluminous IR galaxies are much weaker relative to their total luminosities than would be expected for Seyfert galaxies or quasi-stellar objects, so although there may be "a causal connection between exceptionally powerful star formation and the presence of an active nucleus, ... it need not take the form suggested by Sanders et al." However, Soifer (personal communication) has pointed out that hard x-rays have not been detected from Mkn 231, the archetype of this class of ultra-luminous composite galaxy. Furthermore, Elvis and Lawrence (1988) conclude that the hard x-rays they detect from the observed Seyfert 1 nucleus of NGC1068 are seen only as scattered radiation. I have presented an illustrated review (Smith 1985) which includes a descriptive catalogue of a series of composite nuclei, ordered according to the degree of dominance of the non-thermal activity.

Data on ultraluminous galaxies at z=2 do not exist;observations of IRAS sources out to z<0.5 show that highly infrared-luminous sources do exist (e.g. Kleinmann and Keel 1987; Neugebauer, Soifer and Miley 1985). We know essentially nothing about their evolution; establishing the presence of any non-thermal activity in the nucleus can be a difficult task even in the low-redshift cases (see, e.g., DePoy 1987; DePoy, Becklin & Wynn-Williams 1986; Condon et al. 1982; Lester, Harvey & Carr 1988). However, one may speculate that at earlier epochs galaxy interactions were sufficiently common that the fueling of black holes was more effective; such cocoon-like quasars may therefore have quite different (possibly more pronounced) statistical evolution properties than the ones we know about. Sanders et al. (1988) have gone as far as to speculate that the observed evolution in the optical luminosity function could be caused by the increased frequency of interactions that would have occured between galaxies in the smaller, early universe (see, e.g. Roos 1985b; Wright et al. 1988).

Green (personal communication) has suggested instead the opposite evolution scenario, namely that QSOs shroud themselves in dust during a late stage of their evolution, which is why there are more of the ultra-luminous IRAS sources than conventional quasars (of similar luminosity) at the present epoch. At present, one must conclude that the proportion of very luminous IRAS sources which can be considered to be cocoon quasars is an open question, particularly as Norris did not make 100% radio detections of his control sample of Seyferts.

Heisler and Ostriker (1988b) consider the possibility that dust in intervening galaxies may produce significant distortions in the observed luminosity function at high redshifts. They found that the typical observed quasar has "suffered only one third to one half as much extinction as the mean extinction to a given redshift and so may be relatively unreddened. The net result is a picket fence obscuration where a larger and larger fraction of the quasar population is simply removed from a magnitude limited sample as z increases". Unfortunately, this picket-fence effect makes it difficult to obtain any direct observational indications of significant dust obscuration, or to check directly that the assumed properties of dust in the intervening galaxies are reasonable. Fall and Pei (1988) have compared the spectra of quasars that have damped Ly-alpha with those that do not in order to obtain statistical information about the reddening by dust. They find much lower values for dust obscuration than the values used by Ostriker and Heisler, and conclude that the apparent cutoff in the counts of quasars near z=3 is probably not caused by dust in the damped Lyman-alpha systems. Radio data could be used as a check, but there are already indications of a cutoff at similar redshifts in the distribution of radio sources (e.g. Peacock and Miller 1988; Dunlop and Peacock 1989); the radio cutoff cannot be attributed to dust absorption in intervening galaxies. Finally, in the discussions following the paper given by Heisler and Ostriker (1988b) in Tucson, Surdej pointed out that if the dust absorption has an important effect on the observed properties of quasars, one might expect a correlation between dust and the number of absorption lines.

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Turner (1988) has reviewed the present state of evidence that distortion of the derived luminosity functions and evolution could be introduced by undetected gravitational lensing effects; there are considerable uncertainties. Ostriker and Vietri (1986) concluded that there is probably no important effect; Schneider (1987) made a number of plausible asumptions and concluded that lensing is likely to be a dominant effect. Turner concludes by supporting Ostriker and Vietri's point that that "the optical luminosity function for quasars and its evolution derived from observations do not resemble those which would be expected to result from lensing distortions", but concedes that the calculations are still somewhat uncertain (see also Kayser and Refsdal 1988). In particular, multiple strong scatterings have been ignored in standard calculations of micro-lensing statistics. Setti and Zamorani (1983) have pointed out that because the ratio of x-ray flux to optical flux decreases as luminosity increases, only a small fraction of luminous QSOs could be produced as an artifact of lensing.

5. PHYSICAL CONSEQUENCES OF OBSERVED QUASAR EVOLUTION.

Rees (1984) has emphasised the highly tentative nature of any theoretical conclusions that can be drawn about the central engines of AGN, and their evolution. Nevertheless he adds "Even if AGNs are precursors on the route toward black hole formation.....rather than structures associated with black holes that have already formed, it seems hard to escape the conclusion that massive black holes must

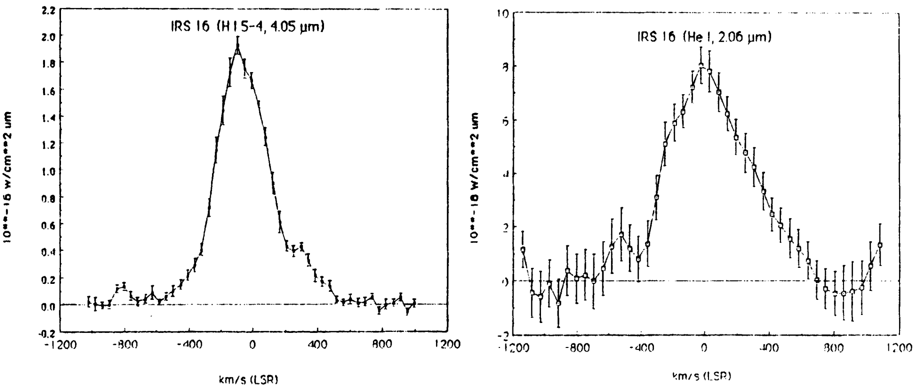

Figure 7. Is there a massive black hole at the centre of our galaxy? Although the gas motions are very rapid as shown in these line profiles obtained recently by Geballe et al. at UKIRT, the stars do not share such rapid motions. Recent evidence by McGinn (1988) does indicate an increase in the stellar velocity dispersion in the central 0.8pc.

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exist in profusion as remnants of past activity; they would be inconspicuous unless infall onto them recommenced and generated a renewed phase of accretion-powered output or catalyzed the extraction of latent spin energy. Estimates of the masses and numbers of "dead" AGNs are bedeviled by uncertainty about how long individual objects live and the evolutionary properties (i.e. the z-dependence) of the AGN population....we are still a long way from having much astrophysical understanding of why the luminosity function evolves [in the manner observed]."

Penrose (1969) was the first to suggest the possibility of extracting the rotational energy of a black hole. A realistic process for doing this was first suggested by Blandford and Znajek (1977). More details, including references covering reformulations and extensions of this process are discussed by Park and Vishniac (1988). They conclude that if the Blandford-Znajek mechanism is a correct description of the coupling between the black hole and the surrounding plasma, then "the evolution of AGNs must be driven by a rapid decrease in the mass flux [accreted from the surrounding disk].....Our results suggest.....that AGNs evolve from QSOs to the nuclei of Seyfert or radio galaxies. It does not follow from this that all Seyfert's (sic) and radio galaxies were once QSOs, although that possibility does exist."

Wandel and Petrosian (1988) emphasise that disks with a constant or increasing accretion rate will evolve towards a steeper UV spectrum at a roughly constant or increasing luminosity. They conclude that "It is difficult to see how a luminous quasar with the requisite high mass and accretion rate will evolve into a low-luminosity object (Seyfert galaxy or quasar)." Begelman (1988) and Blandford (1988) have reviewed the physics of the central engine in much more detail at this conference.

Cavaliere et al (1987, 1988) have considered the various commonly invoked scenarios to account for the observed evolution of quasars. They conclude that in order for a single object to dim down from a luminous QSO to a Seyfert 1-1.5 in our local environment, a time scale of about 3 Gyr is required. This is a small fraction of the age of the oldest known galaxies, yet is much longer than the natural time scale associated with an accreting black hole. Thus the observed luminosity evolution would have to be a co-ordinated population evolution, rather than the reflection of each distant QSO dimming down almost uniformly to become a Seyfert galaxy. This would require that black holes exist in many galaxies which do not currently exhibit obvious Seyfert activity.

The centre of our own Galaxy is the first place to look for a massive black hole, but it suffers about 30 magnitudes of visual extinction (Becklin et al. 1978). Recent IR measurements by Geballe and collaborators on UKIRT (e.g. Geballe et al. 1984; Geballe 1988) have revealed broad HI and HeI lines with FWZIs of 1500 km/s within a central region less than 0.1pc across (see, e.g., Fig. 7 - also Hall, Kleinmann and Scoville 1982). The rotation curve derived from gas velocities increases rapidly towards Sgr A* and is consistent with an

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rexp(-1/2) dependence over a range of radius 1pc<r<2pc (Genzel and Townes 1987; Serabyn et al. 1988).

The existence of rapid gas motions does not necessarily indicate the presence of a massive black hole. The existence of a ring of dust and gas including shocked molecular hydrogen, around the outside of a cavity of 2 pc radius centred on IRS16, may instead indicate the presence of a powerful outflow source (e.g. Gatley et al. 1984); in that case the gas motions are non-gravitational, and the indicated mass (assuming gravitationally driven velocities) will be an over-estimate (see, e.g. Sellgren et al. 1987).

HCN maps of the ring overlaid on images made with UKIRT's infrared camera show a paucity of stars where HCN is strongest; stellar objects are seen in regions corresponding to a pronounced lack of HCN (Genzel, 1988). It is possible that very heavy obscuration in the ring is hiding a much larger central cluster of stars in our own galaxy. Sellgren et al. (1987) and Rieke and Rieke (1988) have investigated the velocities of individual bright stars that are seen in the near infrared and find essentially no change in velocity dispersion over a radius range from r<0.5 pc to 1<r<2pc. The stellar velocity dispersion remains near 72-75 km/s (c.f. the gas motions illustrated in Figure 7).

Rieke and Rieke (1988) conclude that "It is unclear whether the stellar velocity dispersion requires an increase in M/L in the central parsec. If the stellar distribution has a core radius of the order of 0.1pc, as has been suggested in the past and used in modeling the gas motions, then the stellar velocities are compatible with constant M/L over the entire range of our measurements. If, however, the core radius is significantly larger...then an additional nonluminous mass of 2x10exp6 $M_\odot$ is indicated. This mass need only lie within the central 2pc diameter; there is no requirement that it be concentrated into a central black hole." Sellgren et al. (1987) had earlier reached almost identical conclusions, based on a smaller data set.

Very recently, however, McGinn (1988) - who used UKIRT to make large-beam measurements of the stellar component - has reported evidence for an increase in the stellar velocity dispersion, with values of 120-130 km/s in the central 0.8pc. There appear to be of order a million solar masses of unseen material in a very compact central region. The apparent discrepancy between her results and those of Rieke and Rieke (1988) are probably because they are sampling different stellar populations.

Tonry (1987), Dressler and Richstone (1988) and Kormendy (1988) have independently presented recent evidence for a dark central mass in both M31 and M32. As Kormendy points out, at D=0.7Mpc "....1pc resolution is attainable with the best conditions at the CFHT...We can resolve M31 and M32 better from the ground than we can resolve the next-nearest early-type candidates even with the Space Telescope". He finds that the the nucleus of M31 rotates much more rapidly than the bulge, with a maximum apparent rotation velocity of 149 km/s. When combined with high-resolution (Stratoscope II)

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photometry, Kormendy's results imply a central mass-to-light ratio of M/L(V) > 100 and a nuclear mass concentration of >10exp7 $M_\odot$. Dressler and Richstone also find that the most straightforward interpretation of their data "is that M31 and M32 harbour central black holes of 3-7x10exp7 and 8x10exp6 solar masses, respectively." These galaxies are the closest galaxies with dense spheroidal stellar components. Rieke and Rieke comment that "Despite the much higher level of activity apparent in the Galactic center, it has no more and probably less unseen nuclear mass...[than M31 or M32]". Jones (1986) reports the presence of an X-ray point source co-incident with the centre of M32.

Dressler (1988) has presented a much more detailed review of observational evidence for supermassive black holes, at this conference.

CONCLUSIONS

In addition to the cautious words for theorists quoted earlier from Martin Rees concerning modelling existing data, I am reminded also of some remarks for observers in Dan Weedman's (1986) book: "Understanding the data in hand is where artistry enters astronomy.....All samples in astronomy are arbitrary and approximate to some degree. As a result, all deductions concerning luminosity functions will have major associated uncertainties. As long as one can gain a feeling for the level of those uncertainties and the reasons for them, honest astronomy is being done. I think a distinguishing characteristic of a 'good' astronomer is to know when the data are adequate for the assumptions, so that no further effort at the telescope is justified". Unfortunately, I know a number of people, all of whom I would normally consider to be good astronomers, who believe their own data are already adequate for the assumptions, yet still disagree with others on their conclusions.

Perhaps I risk trouble by calling for yet more data to be carefully analysed and published. We now have as many quasars in the range 2 to 4 as we had below 2 a few years ago (Hewitt and Burbidge 1987; Veron-Cetty & Veron 1985); it is becoming realistic to embark on tracing the luminosity function in that interval, particularly with the spread of multi-object fibre-optic spectroscopic facilities. Quasars are being discovered in significant numbers at redshifts above 4 (see, e.g., Shaver 1987) and specific observational plans are being followed to try to find quasars around redshift 5. I believe the methods now being used are a vast improvement over earlier work, and that substantial further progress can be made by the next IAU Symposium on AGN.

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DISCUSSION

VÉRON In view of the high success of the survey by Surdej *et al.* for gravitationally lensed objects among highly luminous quasars, do you think that gravitational lensing could significantly affect the quasar luminosity function at high redshift?

SMITH There are considerable uncertainties. Turner (1988) reviewed the evidence during the Tucson conference and concluded by supporting Ostriker and Vietri's (1986) view that not much distortion of the luminosity function should arise from gravitation lensing. Schneider (1987) had come to the opposite conclusion. However, effects like multiple strong scatterings have been ignored in the calculation of micro-lensing statistics.