The UVX quasar optical luminosity function and its evolution

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ABSTRACT

The recently finished Edinburgh UVX quasar survey at $B < 18$ is used together with other complete samples to estimate the shape and evolution of the optical luminosity function in the redshift range $0.3 < z < 2.2$. There is a significantly higher space density of quasars at high luminosity and low redshift than previously found in the PG sample of Schmidt & Green, with the result that the shape of the luminosity function at low redshifts ($z < 1$) is seen to be consistent with a single power law. At higher redshifts the slope of the power law at high luminosities appears to steepen significantly. There does not appear to be any consistent break feature which could be used as a tracer of luminosity evolution in the population.

Key words: galaxies: evolution - galaxies: luminosity function, mass function - quasars: general - cosmology: miscellaneous.

1 INTRODUCTION

One of the strongest pieces of evidence for an evolving universe has long been the observed evolution in comoving space density of the quasar population (Schmidt 1968). Until recently it had been thought that the shape of the quasar optical luminosity function and its evolution over the redshift range $0 < z < 2$ was well understood, and attempts to explain the physical causes of quasar evolution have relied on attempting to predict the observed evolution of the luminosity function (e.g. Haehnelt & Rees 1993). However, recent studies (Goldschmidt et al. 1992; Hewett, Foltz & Chaffee 1993; Hawkins & Véron 1993, 1995; Köhler et al. 1997) have cast doubt upon the completeness of the surveys used to define the luminosity function. In this paper we present an analysis of the quasar luminosity function and its evolution based on new observational data, and argue that knowledge of the luminosity function alone is insufficient to allow us to understand the physical causes of quasar evolution.

The most widely quoted study of the luminosity function to date has been that of Boyle, Shanks & Peterson (1988, hereafter BSP), who used the AAT sample of faint UVX quasars together with brighter samples such as the Palomar–Green survey (Schmidt & Green 1983) to determine the luminosity function in four redshift slices from $z = 0.3$ to $2.2$. BSP fit a variety of models to this function, and concluded that the best-fitting model was pure luminosity evolution (PLE) in which the shape of the luminosity function was parametrized by two power laws with a transition between them at a characteristic luminosity. The characteristic luminosity increased with redshift (we term this negative evolution, as the population appears to have become dimmer with increasing cosmic time):

$$d\phi (M, z) \propto \phi^* \left\{ 10^{0.4(z + 1)} [M - M^*(z)] + 10^{0.4(z + 1)} [M - M^*(z)] \right\},$$

(1)

in which $\alpha$ and $\beta$ are the indices of the power laws, and $M^*(z)$ describes the evolution:

$$M^*(z) = M^* - 2.5 \log_{10} (1 + z).$$

(2)

With the addition of two surveys extending to redshift $z < 2.9$ (Boyle, Jones & Shanks 1991; Zitelli et al. 1992) the above model has been slightly modified such that there is a maximum redshift beyond which no evolution occurs. The most recent parameters of this model have been presented by Boyle (1991) and are $\alpha = -3.9$, $\beta = -1.5$, $k = 3.5$, $M^* = -22.4$, $z_{\text{max}} = 1.9$.

BSP ruled out any need for additional density evolution for quasars with $M_B \leq -23$. PLE can be interpreted as either representing the actual evolution of individual objects in which a single population of quasars formed at a single epoch and have been growing dimmer ever since, or as the statistical evolution of the properties of successive populations. BSP noted that the latter interpretation implies a conspiracy between birth and death rates. However, the former interpretation, in which lifetimes are of the order
of the Hubble time, predicts massive remnant black holes in Seyfert galaxies at low redshift (Cavaliere & Padovani 1989).

The analysis by BSP relied on brighter quasar surveys, principally the Palomar–Green survey (Schmidt & Green 1983), in order to determine the most luminous part of the luminosity function. However, doubts have been raised about the completeness of this survey (Wampler & Ponzi 1985), and initial results from the Edinburgh Multicolour Survey (Goldschmidt et al. 1992) showed that the Palomar–Green survey underestimated by a factor of 3 the surface density of quasars with \( B < 16.5 \). In this paper we shall replace the Palomar–Green data with data from the Edinburgh survey.

Hewett et al. (1993) presented the first estimates of the space density of quasars from the recently completed Large Bright Quasar Survey (LBQS) (Hewett, Foltz & Chaffee 1993, and references therein), and compared those estimates with those predicted by the PLE model. They found that the PLE model overpredicts the number of quasars at high redshift, in contrast to PLE, and argue that modification of the luminous quasars appears to change shape with redshift, in contradiction to PLE, and that the model is needed: we shall see that our new results are in contradiction to PLE, and argue that modification of the luminous quasars appears to change shape with redshift, in contradiction to PLE, and argue that modification of the model is needed: we shall see that our new results are in accord with that conclusion.

Hawkins & Véron (1993, 1995) have used variability-selected samples of quasars to calculate the luminosity function in the same flux range as the AAT survey; they conclude that the latter survey is incomplete, and that the characteristic luminosity, or ‘break’, detected by BSP is simply an artefact of this incompleteness. If the luminosity function is a single power law with no break, then there is no way of discriminating between luminosity and density evolution.

This paper presents the results from the recently finished Edinburgh Multicolour Survey. A brief summary of this survey is given in Section 2, and in Section 3 we use this survey, together with fainter U V K X surveys, to estimate the luminosity function in redshift slices. In Section 4 we test whether the data can be adequately described by either the BSP model or even by any evolving power-law model in which the power-law index remains constant: a class of models which includes those of BSP and Hawkins & Véron (1995). Section 5 presents the results of fitting empirical models to the data.

## 2 The Edinburgh Quasar Survey

A full description of the construction of the survey is given by Mitchell (1989), Goldschmidt (1993) and Miller et al. (1997, in preparation); what follows is a brief summary.

The survey is based on the 130 UK Schmidt telescope (UKST) plates taken in 13 contiguous fields in five wavebands (the photographic bands u, b, v, r and i) at high galactic latitude covering 330 deg\(^2\). The coordinates of the field centres range from 12\(^h\) 40\(^m\) to 14\(^h\) 20\(^m\) (equinox 1950) in RA at Dec. \(-5\(^\circ\)\) (UKST fields 789 to 794), and from 12\(^h\) 40\(^m\) to 14\(^h\) 40\(^m\) at Dec. 0\(^\circ\) (UKST fields 861 to 867). The plates in each band were taken close together in time so that incompleteness and contamination due to variability should be insignificant.

The plates in each waveband were scanned and measured on the COSMOS machine (McCallin & Stobie 1984), and only those objects detected on both plates were included in the final data set. The resulting data set was calibrated with photospectroscopic and CCD sequences in every waveband in every UKST field (Mitchell 1989; Goldschmidt 1993), obtained at the ESO – Danish 1.5-m telescope, the University of Hawaii 88-inch telescope, the Steward Observatory 60- and 90-inch telescopes, and the JKT 1-m telescope.

The resulting quasar sample is complete in the redshift and magnitude ranges quoted above. The lower redshift limit arises because low-redshift quasars may have host galaxies that are visible and hence appear extended, or they may have redder colours due to the underlying host galaxy. However, this limit is poorly determined and is obviously a function of quasar luminosity.

## 3 The Differential Luminosity Function

We use the 120 quasars in the complete sample from the Edinburgh survey together with the AAT sample (Boyle et al. 1990), the SA 94 sample (La Franca, Cristiani & Barbieri 1992) and the MBQS sample (Mitchell, Warnock & Usher 1984) to estimate the luminosity function.

We transform the photographic magnitudes in the AAT \( B \)-band to the standard J ohnson B band using an average correction of 0.06 mag. This was derived from the transformation of Blair & Gilmore (1982), \( B = b + 0.34(b - v) \), and assuming the average \( b - v = 0.18 \) for the quasars in the Edinburgh survey.

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detected by a given survey, given its luminosity and the flux limit of the survey (note, however, that this method assumes that locally the comoving space density of quasars is uniform, and hence, if binned over large redshift ranges, strong evolution leads to a bias in the estimate of the luminosity function). We use the coherent method of Avni & Bahcall (1980) to maximize the information in the combined samples. In calculating the absolute magnitudes of the quasars we use K-corrections as defined by Schmidt & Green (1983), i.e., assuming a featureless power-law slope with a spectral index $\alpha = -0.5$. We compared this approximation to the K-corrections tabulated by Cristiani & Vio (1990), and found that there was no significant difference in the estimated luminosity function due to the difference in K-correction within the redshift range used in this paper.

The above method has been used to construct the differential luminosity function for the surveys (Fig. 1). The redshift slices have been chosen to be the same as those used in BSP. The first impression is that the luminosity function changes shape as a function of redshift, in direct contrast to the PLE model, and that the luminosity function in the lowest redshift slice looks like a featureless power law with no break at all for $M_B \lesssim -23$. We investigate the evolving shape of the luminosity function in the following sections.

We assume the Hubble constant $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$, zero cosmological constant, and the deceleration parameter $q_0 = 0.5$ unless otherwise stated.

4 COMPARISON WITH PURE LUMINOSITY EVOLUTION MODELS

In order to assess whether the observed luminosity function agrees with the PLE model, we carry out two tests. The first is a non-parametric test, comparing the observed cumulative distribution in luminosity with that predicted by PLE using the one-dimensional, one-sample Kolmogorov–Smirnov (KS) test (e.g. Conover 1980) to test the null hypothesis that both the observed and model distributions are drawn from the same parent population.

4.1 Comparison with the standard model

We bin the data into redshift slices as above, and calculate the observed cumulative distribution in absolute magnitude (note that we cannot simply compare observed and predicted cumulative luminosity functions as the KS test requires that each data point has equal weight, which is not true for the inverse volume-weighted luminosity function). The theoretical cumulative distribution is calculated from the PLE model of BSP for each object with absolute magnitude $M_B$ and redshift $z$:

$$N(< M_B) = \int_{z_1}^{z_2} \int_{M_{b, bright}}^{M_B} \phi(M'_B, z) \Omega(M'_B, z) \frac{dV}{dz} dM'_B dz,$$

where the redshift limits $z_1, z_2$ are determined by both the limits of the redshift slices and the distance limits for detection, given the apparent magnitude limits (both bright and faint) of the survey, and $M_{b, bright}$ is the luminosity corresponding to the bright flux limit at $z$. $\phi(M'_B, z)$ is determined from the model parameters, and $\Omega(M'_B, z)$ is the effective area searched to find that object.

We use three different subsets of the combined Edinburgh and AAT surveys.

(A) The whole of both surveys.

(B) The data from both surveys brighter than the absolute magnitude corresponding to the BSP break in each
redshift slice. This absolute magnitude was calculated from equation (2), with \( z \) taken to be the upper redshift limit of each redshift slice. Under the null hypothesis that we are testing, using this method should mean that the data used has the same shape distribution, regardless of redshift, if PLE is an adequate description of the data.

(C) The whole of the Edinburgh survey alone.

Fig. 2 shows the observed and model distributions for case C, i.e., for the Edinburgh survey alone. Table 1 shows the probabilities that the null hypothesis is true in each redshift slice for each of the three cases outlined above. In cases B and C the probability that the model describes the data in the lowest redshift slice is unacceptable at a significance level of 0.1 per cent. We also find that if we carry out a two-dimensional KS test (Peacock 1983) just on the Edinburgh sample over the entire range of redshifts, we obtain a probability of 2 per cent that the PLE model describes the data adequately. This rejection of the PLE model is not found when testing case A, a reflection of the fact that it is the high-luminosity quasars which are responsible for the effect. This is not surprising; the PLE model was developed to fit the fainter AAT data, which we continue to use in this analysis, plus the brighter data of Schmidt & Green (1983), which we have previously argued to be significantly incomplete (Goldschmidt et al. 1992) and which we have replaced by the Edinburgh quasar survey. We should therefore expect to see the most significant differences between the model and the Edinburgh data.

4.2 Comparison with general power-law models

We can extend our analysis to test whether the data can be fitted by any evolving power-law model in which the power-law index remains constant. Both the PLE model, at magnitudes more luminous than the BSP break, and the Hawkins & Véron model are examples of this class of model. In this section we fit a single-power-law model to the data in each redshift slice, but only at luminosities higher than the BSP break luminosity. We then test the null hypothesis that these bright-end power-law indices in each redshift slice have the same value.

The best-fitting values for the indices are calculated using maximum likelihood, assuming a single power-law fit to the data more luminous than the BSP break in each redshift slice,

\[
d\phi(M_B) = \phi^* 10^{(\hat{a} - 1)M_B} dM_B,
\]

where \( \hat{a} \) is the estimate of the index of the power law. The faintest absolute magnitude in each redshift slice used to fit the model to the data is calculated by taking a comoving space density \( \rho = 10^{-4.4} \text{ Mpc}^{-3} (\Omega_0 = 0.5) \) and finding the corresponding absolute magnitude in the BSP model at different redshifts. Under the null hypothesis this should
give a constant index for all redshifts. The answer should not be overly dependent on the value of $r$ chosen, although too low a value will result in too little relevant data being used to fit the model, thereby reducing the statistical significance. Too high a value will result in some of the data from the flat part of the luminosity function being used, again underestimating the true significance.

Errors on $\hat{a}$ are calculated by assuming a $\chi^2$ distribution for $S-S_{\text{max}} = -2 \log (L/L_{\text{max}})$, where $L$ is the likelihood function. For $q_0 = 0.5$ the best-fitting power-law index increases from $\hat{a} = 2.7$ in the lowest redshift slice to $\hat{a} = 4.1$ in the highest slice (Fig. 3). A single value for $\hat{a}$ is ruled out at a significance level of 0.1 per cent. For $q_0 = 0.1$ the index increases from $\hat{a} = 2.6$ to $\hat{a} = 3.6$, and a single value for $\hat{a}$ is unacceptable at a significance level of 2 per cent.

The evidence presented in this section shows clearly that the high-luminosity part of the luminosity function does not evolve according to the expectations of pure luminosity evolution. The slope of the luminosity function at $MB_x \leq -26$ displays significant steepening with redshift.

### 5 THE QUASAR LUMINOSITY FUNCTION AT LOW AND HIGH REDSHIFTS

The analysis in the previous section showed that the power-law index changed with redshift for quasars more luminous than the break. We have also previously remarked that there appears to be no evidence for a break in the luminosity function at low redshift. In this section we fit a single-power-law model to all the quasars brighter than $MB_x = -23$ in the lowest redshift bin with $0.3 \leq z \leq 0.7$.

\[
d\phi(M_B, z) = \phi^*(1+z)^{-3} \times \exp \left\{-0.4(M_B - M^*(z))\right\},
\]

where $M^*(z) = M_0 - 2.5; \log 10(1+z)$.

Using maximum likelihood as above, the best-fitting values for these parameters are $\alpha = -2.6 \pm 0.2$ and $\gamma = 9.1 \pm 2.0$.

To test the goodness-of-fit of the single power law we could use a binned chi-squared test. This is not the most efficient way of testing the model, as the chi-squared test cannot cope with incomplete bins. We prefer instead to use a KS test to estimate goodness-of-fit, following previous work such as BSP and Boyle et al. (1991). This procedure suffers from the problem that the slope of the power law is a free parameter in the model, and the value of the slope has been found by fitting to the data. Thus the significance level at which the model can be rejected is actually an overestimate: strictly speaking, in this application the KS test can only rule out models, but the fact that there is a value for a single-power-law model which does fit should indicate to us that there is no justification for the pursuit of a more complicated model at low redshifts. This is indeed the result we obtain. The KS test shows that this model is acceptable, with a significance level for rejection of 17 per cent.

Conversely, at redshifts $1.7 \leq z \leq 2.2$ it is clear that the luminosity function cannot be parametrized as a single-power-law. The data can be fitted by either a dual-power-law model as described previously or a variety of other functional forms. For example, we can fit a Schechter function with uniform luminosity evolution to the data at $1.7 \leq z \leq 2.2$, where the model is parametrized as

\[
\frac{d\phi}{dM_B}(M_B, z) = \phi^*10^{-0.4(z+2)(M_B - M^*(z))} \times \exp \left\{-10^{-0.4(M_B - M^*(z))}\right\},
\]

where $M^*(z) = M_0 - 2.5; \log 10(1+z)$. The best-fitting values of the parameters are $\alpha = -1.7 \pm 0.3$.

![Figure 3. Maximum-likelihood estimates of the power-law index of the luminosity function at absolute magnitudes more luminous than the BSP break, for $q_0 = 0.5$.](https://academic.oup.com/mnras/article-abstract/293/1/107/1012657)
6 DISCUSSION

From the above analysis we reach the following conclusions.

(i) The shape of the quasar luminosity function changes shape with redshift, in a manner that cannot be described as pure luminosity evolution. Specifically, the slope of the luminosity function at high luminosities is significantly steeper at redshifts z > 2 than it is at z = 0.5.

(ii) At redshifts z ≤ 1 the luminosity function may be described by a single-power-law, and there is no evidence for any feature in the luminosity function that may be used as a tracer of luminosity evolution. Conversely, at z > 1 the luminosity function cannot be described by a single-power-law, as previously found by BSP, and there is a break in the luminosity function at MB = −26.5. The luminosity function at high redshift may be described by a number of functional forms such as the two-power-law model of BSP, or indeed by a Schechter function.

The consequence of these conclusions is that it cannot be shown that the quasar population experiences luminosity evolution. It may be that quasars are long-lived, and that they do indeed dim with cosmic epoch in a luminosity-dependent manner so as to produce the observed evolution. However, it is equally possible that quasars are short-lived phenomena, and that the observed evolution is a more complex mixture of luminosity-dependent density evolution. In fact, recent models (Goldschmidt 1993; Percival, Miller & Goldschmidt, in preparation) suggest that such evolution might be expected if quasars are short-lived symptoms of galaxy mergers in a CDM-type (bottom-up) universe. In this case, it is possible to make progress in understanding quasar evolution only by constructing a specific model such as the one just described and then comparing the predictions of the model with the observed luminosity function. It is not possible to deduce model-independent conclusions about whether or not quasars undergo luminosity evolution from consideration of the observed luminosity function alone.

One piece of information which must be a powerful clue to the type of model that is required, however, is the observation that the amount of density evolution is greatest at intermediate luminosities (MB = −26), and appears to be less at higher quasar luminosities. Extrapolation of this result would indicate that at MB = −29 the comoving space density of quasars may have remained roughly unchanged since z = 2! The existing data are too noisy at high luminosities and low redshifts to demonstrate this unambiguously, and we must await larger area surveys to provide better statistical evidence for the most luminous quasars.

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