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COSMOLOGICAL STUDIES, CLUSTERING, ISOTROPY ETC.

"The fact that a conference on quasars cannot find more than two percent of total available time for a discussion of the question as to how far these objects are located, indicates that most astronomers have already made up their minds about the answer."

- Jayant Narlikar (p.463)

Giancarlo Setti appears unconvinced by Richard Green's arguement

EVOLUTION OF THE LUMINOSITY FUNCTION

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ABSTRACT. In this review, the currently published, complete, spectroscopically identified samples of quasars are assembled to produce a composite luminosity function, independent of evolutionary assumptions. Two interpretations of the change with cosmic time provide reasonable fits to the data. Luminosity evolution implies a fixed population of host objects, with nuclear luminosity that fades with advancing cosmic time; some dependence of the timescale on intrinsic luminosity is required. Density evolution traces objects of comparable luminosity to find the change in space density, without a requirement of long lifetime. The change in co-moving volume density depends on luminosity; newer data suggest that somewhat stronger evolution is required at the low luminosity end than the models of Schmidt and Green allowed. Caution is advised in drawing direct physical conclusions about the evolution of individual quasars from mathematical representations of ensemble properties.

The aim of this review is to examine the methodology of deriving the quasar luminosity function and its change with cosmic time, as well as the current data and the success of various model fits. A caveat is offered about taking the step from mathematical model to physical interpretation. Illustrative examples are presented from the extensive work in this area; therefore, the review will not be entirely comprehensive.

A fundamental question underlying the validity of a luminosity function exercise is whether the redshifts of quasars can be used as cosmological distance indicators. There are two general arguments in favor of the cosmological interpretation. The first is the steep count slope, by which the integral surface density of quasars changes by a factor of eight per magnitude in the brighter magnitude range (Schmidt and Green 1983; hereafter SG83). If quasars were relatively local, this result implies a steep radial gradient of objects, with a local deficit centered on the Galaxy, in violation of Copernican notions of uniformity. The other general argument is based on the association of quasars with normal galaxies for which the redshift is assumed to be a valid distance indicator. In their imaging survey,

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Yee and Green (1984) found that fields centered on quasars showed an excess of faint galaxies over the background, and that those objects are radially concentrated around the quasars. This excess was detected only for quasars with redshifts that would place normal luminous galaxies within the survey limiting magnitude; beyond that redshift no excess was found. Narlikar (these proceedings) gives an extensive review of the arguments against acceptance of a cosmological interpretation of quasar redshifts. The most compelling involve objects of significantly different redshifts in close angular proximity on the sky, with very low probability of chance occurrence. For the purpose of this discussion, the conclusion is drawn that most quasars are at the cosmological distances implied by their redshifts, which will be used for calculations of luminosities and volumes.

A second major question is whether gravitational lensing so distorts the distribution of apparently high luminosity objects in a magnitude-limited sample that correct conclusions cannot be drawn about that end of the luminosity function. The Palomar Bright Quasar Survey would be particularly susceptible to this effect, and provides an interesting example. Only 1 of 15 of the most luminous objects in the BQS was found to be lensed, the triple quasar PG 1115+08, so the fraction of objects affected is small. The slope of the luminous end is proportional to the luminosity to the -3.5 power, somewhat too shallow to be produced entirely by a reasonable distribution of lensing material (see, e.g., Turner _et al._, 1984).

At this point, I make the claim that we have insufficient physical understanding of the quasars themselves to test a cosmological model and the change in the collective properties of quasars simultaneously. For example, Segal and Nicoll (1986) compare the size of cosmological volume elements in the chronometric and Friedman cosmologies on the assumption of no number density evolution for the quasar probes. The present discussion will assume a Friedman cosmological model, in order to investigate the changes in the luminosity function with cosmic time. It must be recognized that this world model is an assumption, and involves at least three parameters.

It is important to distinguish the luminosity function and its change with cosmic time from the source and evolution functions. The luminosity function is the instantaneous distribution of quasar space densities as a function of luminosity, while the source and evolution functions describe the birthrate and change of luminosity with time of individual objects (Petrosian 1986, Cavaliere _et al._ 1985). The derivation of the source and evolution functions are the ultimate goal of luminosity function research, but that step is a difficult one to make. Ideally the entire magnitude-redshift plane would be filled with counts from complete samples. Slices in redshift would then yield the luminosity function directly as a function of look-back time. The purpose of mathematical modeling of the luminosity function itself has been primarily to fill in deficiencies in the m-z plane coverage and to make testable predictions for surveys with new limits in magnitude or redshift. Discrepancies with new observational results then teach us about the ensemble properties of the quasar population.

A critical aspect to this investigation is the completeness of the samples used. A summary of the discussion by Green et al. (1986) about the completeness of the BQS highlights the critical issues in color-selected samples. Since the count slope for all objects shows no inflection down to the instrumental magnitude limit, completeness to that limit is not in doubt. The photometric transformations show no scale or zero-point shifts when compared to a photoelectrically measured sample of white dwarfs, so systematic problems are also small. There remain three sources of error: measuring inaccuracies near the magnitude limit and near the color limit, and accidental errors. The measuring errors are large for the BQS, with one standard deviation being 0.29 mag in the B magnitude and 0.38 mag in the U-B color. With a steep count slope, more objects will be included in the survey in error for being measured to be brighter than the magnitude limit than are lost for appearing too faint. This effect leads to an overcounting of 18% for the BQS. An assessment of the color error is more complicated because the intrinsic colors of quasars are a strong function of redshift, in particular, in response to the passage of the 3000 A bump through the B filter. From assuming a Gaussian error distribution, we can compute the fractional losses as a function of the actual U-B colors of the objects. From a large independent sample of (mostly radio selected) quasars the distribution of U-B vs. redshift is constructed. The losses as a function of redshift then follow from the BQS detections, producing an average value of 15% for the whole sample, but ranging from 8% at high and low redshifts to 30% in the redshift range 0.6 - 0.8. Accidental losses of 8% were derived from a sample of 120 previously known white dwarfs, by computing analytically the color and magnitude losses based on the photoelectically measured colors and magnitudes. The net result is an average undercounting by 5%, with a redshift dependence. The Medium Bright Quasar Survey (Mitchell et al. 1984) shows a count slope similar to that of the BQS, but a 20% upward displacement in surface density. The cause could be a lower measuring error in magnitude for the BQS, which is unlikely, substantially higher color and accidental errors, or a scale mismatch between the two surveys.

A different set of considerations operates for slitless spectroscopic surveys. In this case, the limiting magnitude is a function of limiting equivalent width. It is necessary to know the intrinsic distribution of equivalent widths, found from a sample selected by an independent criterion, in order to estimate the incompleteness of the slitless survey. Wampler (1985) points out a significant systematic difference between color-selected and slitless spectroscopic samples in the way that magnitudes are derived. The color-selected samples use total magnitudes, while the slitless samples use continuum magnitudes in well-defined intervals. As an example, Wampler gives the distribution of C IV equivalent widths for flat spectrum radio sources, which shows a median value of ~60 Å in the rest frame. The addition of this line to a broad-band magnitude can brighten it by 0.1 to 0.2 mag. In the steep count slope regime, this systematic effect can lead to an overestimate of the numbers of color-selected objects with respect to spectroscopically selected quasars by as much as 50%.

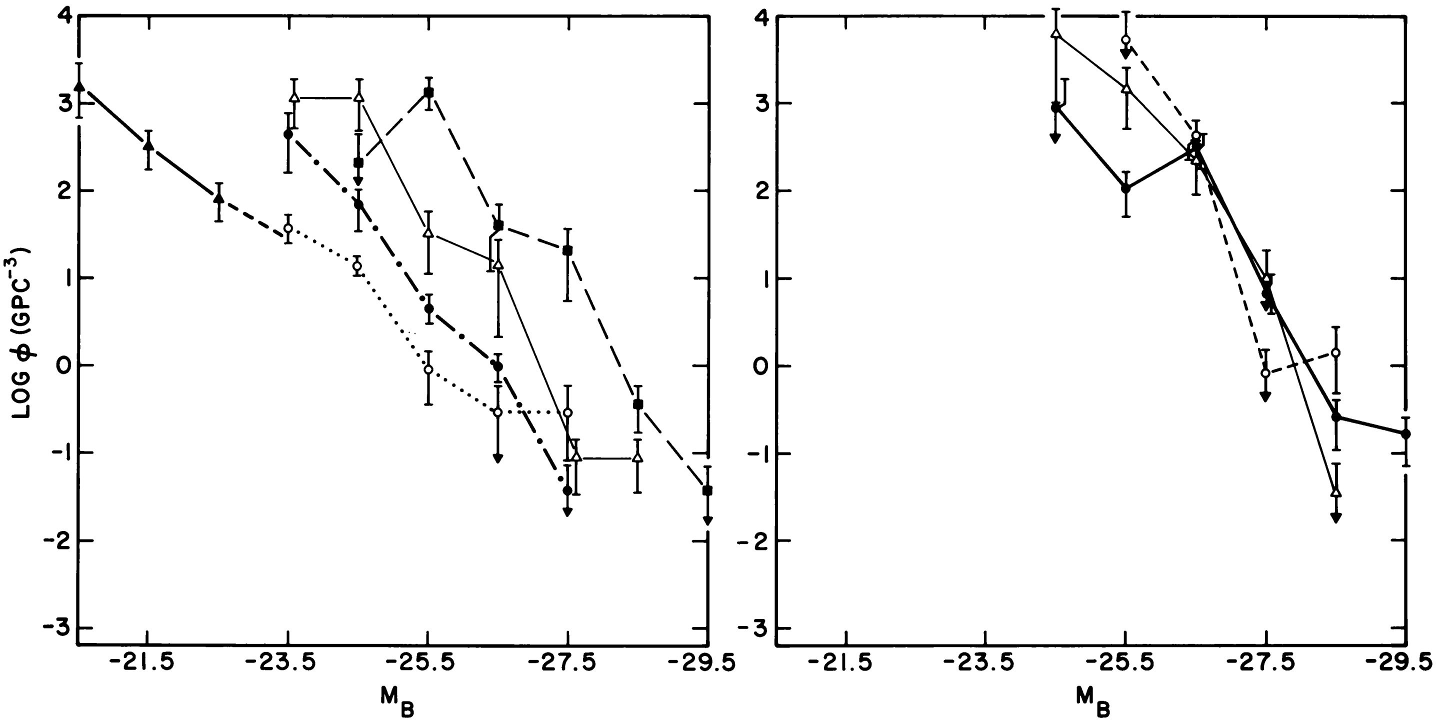
To examine the luminosity function itself, the redshift-magnitude diagram was populated with objects drawn from those complete samples available to me at the time of this meeting. The value of the work of Shanks and his collaborators (this volume and Boyle et al., 1986) soon becomes apparent. In deriving the luminosity function, no assumptions were made about evolution; H_0 = 50 km/s/Mpc, q_0 = 0.5, and a spectral index of −0.5 were assumed. Spherical shells were defined by redshift intervals, and the contribution of each object from the various surveys to the volume density within its shell was computed. When objects from more than one sample appeared in the same redshift-luminosity bin, the contributions from each survey were combined in a weighted average, with the weighting inversely proportional to the Poisson error of the counting statistics. The result is independent of the binning in luminosity, but does depend in detail on the choice of redshift boundaries. The quasar samples are listed in Table 1; they are all statistically complete, fully spectroscopically identified, and contain objects with absolute B magnitudes brighter than −23.0. An additional sample is that of Seyfert galaxies from the CfA redshift survey by Cheng et al. (1985).

Table 1
Complete Quasar Samples

Name	Number	B lim	Area(sq.deg.)	z	Ref.
BQS	92	16.16	10,714	0 - 2.15	SG83
AB	16	18.0	36	0 - 2.15	1
US - SA 29	12	18.5	7.67	0 - 2.15	2
Curtis Schmidt	15	18.0	340	1.8 - 2.5	SG83
4-M Grism (Hoag-Smith, Sramek-Weedman)	19	19.5	7.8	1.8 - 2.5	SG83
BF	31	19.8	1.72	0 - 2.15	1
Koo-Kron SA 57	8	20.53	0.27	0 - 2.5	3

References for Table 1
1) Marshall, et al. 1984
2) Usher, et al. 1983
3) Koo, et al. 1986.

The results are shown in the Figures. All the redshift intervals except the lowest represent equal volume shells in the q_0 = 0.5 cosmological model. It can be seen that there is a marked change in the luminosity function between redshifts 0.2 and 1.3, after which the functions remain essentially identical. In this world model, the fractional look-back time is 0.75 for z=1.5, while it is 0.85 for z=2.5, so evolutionary effects over that small time interval are negligible within our means to discriminate them. Note also that there is rather good agreement between the Seyfert galaxy luminosity function and that of the low redshift quasars.



The Luminosity Function of Quasars. The figures show the comoving volume density vs. absolute blue magnitude for different epochs. In the left-hand panel, filled triangles are the local Seyfert galaxy function of Cheng et al. (1985). Open circles are quasars from redshifts of 0.1 to 0.3; filled circles show the LF from z of 0.3 to 0.8; open triangles are 0.8 to 1.2; and filled squares show the range from 1.2 to 1.5. In the right-hand panel, open triangles represent redshifts from 1.5 to 1.8, filled circles from 1.8 to 2.2, and open circles show the redshift range from 2.2 to 2.5.

Two different mathematical representations of the change in the luminosity function have been investigated. A luminosity evolution treatment arises from a natural description for the galaxy luminosity function, in which there is a population of objects with constant comoving space density that fades in brightness with advancing cosmic time. Pure luminosity evolution requires a luminosity function of constant shape and normalization that slides (in the Figures, horizontally) to higher luminosity with increasing look-back time. In this case, the decay of brightness with cosmic time is independent of the intrinsic luminosity of the source. The application of this technique to the quasar luminosity function has been investigated by Mathez (1978), Braccesi et al. (1980), Cheney and Rowan-Robinson (1981), and more recently by Weedman (1986), Koo (1986) and Marshall (1985). Marshall approximates the high luminosity portion with a power-law, then cuts off at the inflection with an epoch-dependent luminosity cut-off. He finds that for an exponential representation of source dimming with cosmic time, the e-folding time is about 1/6 of the Hubble time. The major test of the validity of this simple model is whether the characteristic luminosity or inflection point translates at constant density with look-back time. Extensive deep surveys are required to address this point.

An argument in favor of pure luminosity evolution is that it gives an adequate fit to a portion of the data with a single evolutionary parameter. If the mathematical description were interpreted physically, it would imply long lifetimes for quasar activity in a constant population of hosts. Some evidence in favor of this picture is offered by Crampton et al. (1986), who find from a CFHT blue grens selected sample of spectroscopically confirmed quasars that there is no evidence for a changing nearest neighbor distance with increasing look-back time. Some stronger trend would have been expected if there were much higher quasar space densities at earlier epochs. Objections to the pure luminosity evolution picture arise from the large power consumption required for a quasar which fades from an absolute B magnitude of -29.5 at redshift 2.5 to -24.0 at the present epoch. A luminosity-independent propagation of the luminosity function also creates difficulties with the zero-redshift Seyfert luminosity function over-shooting the counts at the faint magnitude end, as pointed out by Koo (1986). A luminosity-dependent luminosity evolution, as suggested, for example, by Cavaliere et al. (1985) is required for a fit consistent with all the data.

An alternative view of the problem is to apply the concept of density evolution. This approach is motivated by galactic structure investigations, in which the space density as a function of distance is derived for a population of tracer objects of constant luminosity. In the presentation of the Figures, density evolution means a vertical propagation of the luminosity function with increasing look-back time. It was originally found by Schmidt (1968, 1974), Lynds and Wills (1972), and Wills (1974) that the co-moving space density of quasars increases with redshift. On the basis of much more complete redshift-magnitude plane coverage, SG83 and then

Marshall (1985) noted that pure density evolution is not an adequate representation of the data, because the space density of lower luminosity objects increases much less rapidly than that of high luminosity objects. In the Figures, we see a factor of 30 increase in the space density at MB = -23.5, while there is a factor of over 1000 increase at MB = -25.5 between z = 0.2 and z > 1.2. Before the availability of the Koo and Kron or BF samples, SG83 saw even less increase at the low-luminosity end in constructing their models of luminosity-dependent density evolution. The composite luminosity functions derived here suggest that a small revision in the SG83 parameters would be required to fit this data set, but that the sense of the original models is still an adequate description of the data.

The physical implications of this mathematical model are much less stringent than those of luminosity evolution, because short lifetimes are allowed, and there need not be the identical set of host objects from epoch to epoch. Some evidence in favor of this interpretation is presented by Yee and Green (these proceedings) from their imaging survey. Radio quasars with z > 0.55 are often found in a rich cluster environment that is never observed at lower redshifts. The availability of new sites for quasar activity at earlier cosmic times implies that there is definitely some number density evolution for one sub-population of quasars. Objections to the luminosity-dependent density evolution model are based primarily on the choice of the functional form and fit parameters of the SG83 models; these predictions can be improved with increasing availability of high-quality survey data.

The promised caveat in interpretation is based on a well-known luminosity function. It has a steep high-luminosity portion, flattening off at the low-luminosity end. There is a sharp, well-defined feature at a rather bright absolute magnitude. The faintest end of the function is poorly determined observationally, while the luminous end is sparsely populated. As we look back in cosmic time, the characteristic luminosity propagates toward higher values, while the bump-like feature stays roughly constant in amplitude and position, and the faint end normalization remains constant. The change in the shape of the more luminous end of the luminosity function can be interpreted successfully by either luminosity or density evolution, with a non-evolving component populating the bump. However, I have just described the luminosity function of a globular star cluster; from the physics of stellar evolution, we know that stars move through that function with cosmic time in a non-monotonic way, including a stay in the bump feature, which is the horizontal branch. Until we reach a deeper understanding of the physical evolution of quasars, we should be very cautious in drawing physical conclusions from successful mathematical representations of the quasar population ensemble properties.

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DISCUSSION

Shanks : The fact that you observe more galaxies around high redshift QSOs than around low redshift QSOs; could this alternatively be interpreted as evidence for non-cosmological redshifts ?

Green : As was the case with our first sample, when we observe quasars with redshifts for which the magnitudes of brightest cluster members would be beyond our limiting magnitude, we see no excess. The magnitudes of the "excess" galaxies are considerably fainter for the higher redshift objects.

Segal : A statistical study of the Seyfert I sample of Cheng et.al. indicates that the luminosity evolution model has a problem fitting observations with $z < 0.1$ as well as at high redshifts. Could you comment on the situation at low redshifts ?

Green : It seems that both the optical counts and the X-ray background would be exceeded by a direct brightening of the faint end of the Seyfert I luminosity function. Cavaliere and his collaborators have fit the data by using a luminosity-dependent luminosity evolution with more success.

Narlikar : If redshifts are not cosmological but intrinsic to the objects, then a luminosity that depends on z is not unexpected. This is because both L and z are intrinsic to the object and would be related. Do you agree with this alternative interpretation of an evolving luminosity function ?

Green : The steep source counts certainly imply some kind of evolution in the luminosity function. I would have to understand how to compute the intrinsic luminosity in this interpretation, before evaluating whether the data support it.

Machalski : Do you have any comment on evolution of the radio luminosity function ?

Green : We would like to use the radio material presented by Ken Kellermann to answer that question. One difficulty with our individual object method calculation is that the very few most luminous radio sources dominate the counts at faint flux levels, so that we have poor leverage on the evolution of the faint end of the radio/optical flux ratio distribution.

Shanks : Does the Cheng Seyfert luminosity function not turn over at fainter luminosities ?

Green : It does; those points were not plotted on the figure. The peak amplitude for that function is somewhat higher than the densities shown for lower luminosity quasars.

Margon : You have commented that you find that L_x/L_{opt} must decrease with redshift to avoid overpredicting X-ray counts. Does this imply that you claim to unambiguously distinguish a redshift dependence from a luminosity dependence ? As you know, in a flux limited sample this is quite difficult to do.

Green : Our technique is to tag each member of the Bright Quasar X-ray sample with its observed f_x/f_{opt} ratio, then to evolve the sources according to the prescription of the optical evolution model. Any dependence of L_x/L_{opt} on L_{opt} is implicitly taken into account. To reconcile our predictions with the counts and redshift distribution in the EINSTEIN Medium Sensitivity Survey, we then parameterize L_x/L_{opt} as a decreasing function of increasing z.

Sapre : Can you comment on the search for standard candles and distance indicators in quasars with a view to determining q_o ?

Green : Work by Baldwin, Wampler and collaborators has shown a correlation between CIV equivalent width and luminosity for certain classes of quasars. It remains difficult to distinguish source (spectral) evolution from cosmological effects.