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OBSERVATIONAL EVIDENCE FOR COSMOLOGICAL EVOLUTION

QUASARS AND COSMOLOGICAL EVOLUTION

Maarten Schmidt
Hale Observatories
Pasadena, California, U.S.A.

The first evidence that quasars exhibit a non-uniform distribution in the universe was obtained ten years ago from a sample of 33 quasars in the 3CR catalogue. Much larger samples of radio quasars are now available and we will discuss the results in terms of an exponential decrease of quasar numbers with cosmic time. Only a few samples of optically selected quasars exist. We will show that their counts indicate a non-uniform space distribution, even if the redshifts are non-cosmological.

1. RADIO QUASARS

For samples that are complete to given limits of optical flux and radio flux one can test the hypothesis that the objects have a uniform distribution in space. For each object one can derive V/V_{max}, where V is the volume of the Universe out to the distance of the object, and V_{max} the volume corresponding to the maximum distance at which the object could still be observed within the sample limits.

Table I lists values of $<V/V_{max}>$ obtained for five complete samples. The 3CR sample (Schmidt 1968) is now complete to about 20-th

Table I

Radio Quasar Samples

Catalog	Sample	ν	n	$<V/V_{max}>$	
3CR		178 MHz	44	0.64	
4C	Olsen, Schmidt	178	51	0.64	
4C	Wills, Lynds	178	117	0.69	
PKS±4°	Masson, Wall	2700	57	0.56	0.62
	Wills, Lynds	2700	60	0.65	
S1,S2,I	Schmidt	5000	51	0.61	

M. S. Longair and J. Einasto (eds.), The Large Scale Structure of the Universe, 289–293. All Rights Reserved.

magnitude. The Olsen (1970) 4C sample between declinations 20^o-40^o has been investigated to about the same optical limit (Schmidt 1974). Wills and Lynds (1978) have studied several 4C samples represented by one entry in Table I. The PKS±4° quasar sample has been discussed by Masson and Wall (1977) and Wills and Lynds (1978) with rather different results. Dr. D. Wills has attempted a reconciliation between the two studies (private communication) from which I estimate $<V/V_{max}> = 0.62$ for $q_o = 0$. The last sample (Schmidt 1976, 1977) is based on the S1, S2, and I parts of the NRAO 6-cm survey.

The $<V/V_{max}>$ values shown in Table I have mean errors of around 0.03 - 0.05. Each of the entries is significantly larger than the value 0.50 expected for a uniform space distribution. This constitutes the evidence for cosmological evolution of radio quasars.

Flat-spectrum radio quasars appear to have smaller values of V/V_{max}. Table II gives relevant results for four complete samples. The final value given for the PKS±4° sample is again an estimate,

Table II

Quasars with Flat Radio Spectrum

Sample	Spectral Index	n	$<V/V_{max}>$	
3CR, 4C, S1, S2, I (Schmidt)	$\alpha > -0.2$	28	0.52+0.05	
PKS±4° (Masson, Wall)	$\alpha > -0.5$	42	0.52	0.58±0.04 ($\alpha > -0.5$)
PKS±4° (Wills, Lynds)	$\alpha > -0.23$	30	0.61	
S4 (Kuhr, Schmidt)	$\alpha > +0.2$	29	0.58±0.05	

for $q_o = 0$, based on a discussion by D. Wills. The last entry is the result of an unpublished study of quasars with inverted spectra between 6 and 11 cm in the NRAO-Bonn S4 catalogue.

Flat-spectrum quasars exhibit $<V/V_{max}> \approx 0.57$ while steep-spectrum quasars have $<V/V_{max}>$ around 0.67. The corresponding density laws are $\rho = e^{3\tau}$ and $\rho = e^{10\tau}$ respectively, where $\tau = z/(1+z)$ is the light-travel time in a $q_o = 0$ cosmology. We have assumed here that the density depends exponentially on cosmic time. Larger radio quasar samples will be required if we want to determine, rather than assume, the shape of the density law eventually.

2. OPTICALLY SELECTED QUASARS

Radio quasars constitute only a small fraction (around one percent) of quasars selected by optical means. The initial optical selection is based on the ultraviolet excess, i.e., the criterion $U-B < -0.4$ which is fulfilled by almost all radio quasars at high galactic latitude with redshifts less than 2.5, or on evidence for emission lines on objective prism exposures. The two techniques tend to complement each other since the objective prism should be effective for redshifts of 2 and more since Lα emission is usually strong. All candidates selected by color or objective prism spectra require slit spectroscopy to confirm the quasar nature and to measure the redshift.

Table III

OPTICALLY SELECTED QUASARS

	Area	Mag. Limit	Surface density
Braccesi	36 sq. deg.	$B < 18.0$	0.47 $(\text{sq deg})^{-1}$
Green, Schmidt	1434 sq. deg.	$B < 15.7$	0.0035 $(\text{sq deg})^{-1}$
Sandage, Usher	40 sq. deg.	$B < 18.5$	1.3-1.6 $(\text{sq deg})^{-1}$

We list in Table III results of surface densities for three studies. For the Braccesi survey (Braccesi, Formiggini, and Gandolfi 1970) we have used a somewhat conservative magnitude of completeness $B = 18$ to derive the surface density. The result by Green and Schmidt is based on a discussion of part of the Palomar Bright Quasar Survey (Green 1976) designed to detect all quasars brighter than $B = 15 - 16$ in an area of 10,000 square degrees on the basis of their ultraviolet excess. The last entry concerns an as yet unpublished result of a study by Sandage and Usher.

The values for the surface density shown in Table III vary very steeply with magnitude. In fact, the numbers increase by a factor of about 8.5 per magnitude. The expected increase for a uniform distribution of quasars is only a factor of around 2.2 per magnitude (Green and Schmidt 1977). This discrepancy constitutes solid evidence for cosmological evolution of optically selected quasars. The numbers given in Table III lead to a density law even steeper than $\rho = e^{10\tau}$, found for steep-spectrum radio quasars. The results from the entire Green survey will eventually allow a determination of the cosmological evolution as a function of optical absolute luminosity.

The very steep slope of the optical counts has a bearing on the local hypothesis of quasars, which assumes that their redshifts are non-cosmological and that their distances are relatively small. In this case the distribution of quasars would presumably be similar to that of galaxies, i.e., approximately uniform. A uniform distribution in space yields counts that rise by a factor of 4 per magnitude, regardless of the shape of the luminosity function. Green and Schmidt (1977) show that such a slope is definitely incompatible with the surface densities given in Table III. Hence, quasar counts do not allow a uniform space distribution in the local hypothesis of quasars. Rather, the space density has to increase approximately as $r^{1.6}$ (where r is the distance). Any version of the local hypothesis that does not incorporate such an increase of space density with distance will be unable to reproduce the counts as given in Table III.

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DISCUSSION

Peterson: It has been known for some time from the work of Bolton and his co-workers at Parkes that the source counts of quasi-stellar radio sources with flat radio spectra differ from the source counts of the steep spectrum quasi-stellar sources. In order to see whether or not the difference in counts implied a difference in their space distribution, Jauncey, Wright, Condon and myself, during the past two years, have obtained redshifts with the 4-metre Anglo-Australian telescope of Parkes quasi-stellar sources with flat radio spectra. We have more than 100 redshifts, of which about 1/3 form a complete sample. These give a $\langle V/V_m \rangle$ for quasi-stellar sources with $\alpha > -0.5$ of 0.56 ± 0.05, which is similar to Prof. Schmidt's result.

Ostriker: How does the slope of your log N versus B relation for optically selected quasars compare with that found by Sandage and Luyten?

Schmidt: The early Sandage-Luyten slope of 0.75 was based on incomplete observations of their 1-hour field and on very incomplete observations of a preliminary version of the Braccesi list of objects with ultraviolet excess. This slope may well be approximately correct over the magnitude range (B = 19 - 19.5) for which it was originally derived.

Zeldovich: What is the effective z to which the $e^{10\tau}$ law is valid? How does it change if $q_o = 1/2$ instead of 0?

Schmidt: The $e^{10\tau}$ law is probably valid at least to z = 1 or 2. The exponent would probably differ by only 1 or 2 units for $q_o = 1/2$.

Silk: Are there any other morphological differences for sources with different values of V/V_m, for example, radio structure and frequency of optical absorption systems?

Schmidt: There is the well known correlation between small radio size and flat radio spectrum. I am not aware of anyone having investigated correlations with absorption line systems.

Petrosian: Is there any difference between the redshift distribution of steep and flat spectrum radio quasars?

Schmidt: At an optical magnitude of around 18 or 19 the redshift distribution of steep and flat spectrum radio quasars are indistinguishable at the present time.