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OPTICAL VARIABILITY OF QUASARS: STATISTICS AND COSMOLOGICAL PROPERTIES

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ABSTRACT

The long-term optical variability of a composite, complete sample of quasars is investigated. While no correlation with luminosity is detected, a positive correlation with redshift is found ($\rho = 0.25$). These results are reconciled with previous opposite findings of other authors, arguing that the analysis of variability can be biased by the combined effect of the structure function of light curves and of cosmological time dilation. Such bias becomes negligible if variability is measured by a magnitude difference at a fixed and large time lag (4 yr). Interpretation of this cosmological trend is given in terms of spectral variability. Statistical biases on the estimate of the evolution rate for the quasar population are discussed.

Subject headings: cosmology — quasars

1. INTRODUCTION

Previous studies on the long-term optical variability of quasars have shown them to vary on different time scales and with different amplitudes (see, e.g., Barbieri et al. 1988 and references therein; McGimsey et al. 1975; Usher, Warnock, & Green 1983). Extreme variability of a magnitude or more over weeks or days is characteristic of the small subclass of optically violently variable objects (OVVs) where relativistic beaming is commonly believed to occur (Blandford & Rees 1978), while other objects vary by a few tenths of magnitude on time scales of months to several years. Thus any statistical analysis depends on the kind of objects included in the sample, namely on the selection criterion.

A correlation of variability with absolute magnitude could in principle provide a test of whether quasars are single coherent sources or made up of many independent subunits (see Pica & Smith 1983 and references therein). The most extensive study of optical variability of quasars is the survey of the Rosemary Hill Observatory (Pica & Smith 1983; Pica et al. 1988), consisting of a continuous monitoring of ~ 200 objects over ~ 20 yr. They found a negative correlation with luminosity and redshift. We note, however, that if radio-loud quasars are definitely more variable than radio-quiet ones (see Cristiani 1986), their distribution in the optical luminosity-redshift plane could affect the correlation of variability with these parameters. It is preferable to use flux-limited samples, where selection effects can be more easily taken into account and the fraction of radio-loud objects is in any case very small.

Uomoto, Wills, & Wills (1976) found a negative correlation of variability with luminosity in a complete subset of the radio 4C catalog. Bonoli et al. (1979), using the complete optically selected sample of Braccesi, Formiggini, & Gandolfi (1970), found no correlation with redshift nor with absolute magnitude. Netzer & Sheffer (1983) found the same result in a spectroscopically selected sample.

More recently, Cristiani, Vio, & Andreani (1990) have found a negative correlation with redshift and/or luminosity for the optical complete sample of the SA 94. On the contrary, we find a positive correlation with redshift and no correlation with luminosity (Giallongo, Trevese, & Vagnetti 1990).

Discrepancies in the correlation of variability with luminosity and redshift previously remarked might be ascribed to differences in the analysis procedures. Taking into account the structure function (see Trevese & Kron 1990), we show how the different statistical results can be reconciled; we propose an interpretation of the redshift dependence in terms of spectral variability, and we suggest possible implications for the cosmological evolution of the quasar population.

2. DATA ANALYSIS

In a complete flux-limited quasar sample, the majority of objects lie near the limiting flux, and this causes a strong correlation between redshift and luminosity. Hence, we cannot say to what extent the correlation of variability with either quantity is due to the other.

We use therefore two complete optical samples with different magnitude limits to reduce this effect and to increase the significance of the statistics.

We consider first the variability data of the Koo, Kron, & Cudworth (1986, hereafter KKC) sample in SA 57 by Trevese et al. (1989), which gives photometry of 27 quasars with $B \lesssim 22.5$ at seven epochs spanning 11 yr. Photometric accuracy is within 0.05 mag (rms) up to the magnitude limit. The second sample is extracted from the variability data of Bonoli et al. (1979), considering confirmed quasars from the complete sample of Marshall et al. (1984). It consists of 28 objects with $B < 19.2$ repeatedly measured during 4 yr with a photometric accuracy ranging from 0.05 to 0.1 mag.

The correlation coefficient between absolute magnitude and redshift is -0.5 and is to be compared with the value of -0.95 of Cristiani et al. (1990).

Different indexes have been used to analyze variability. Pica & Smith (1983) use the differences between brightest and faintest recorded magnitudes for each object; Netzer & Sheffer

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(1983) and Uomoto et al. (1976) adopt a magnitude difference at two distant epochs (20 and 30 yr, respectively); Trevese et al. (1989) and Cristiani et al. (1990) adopt the rms magnitude variations and the average of the absolute values of the variations about the mean, taken over the whole time base.

The intrinsic autocorrelation of the light curves, combined with the cosmological time dilation, affects in a different way each of the above variability indexes, depending on the adopted time sampling.

The behavior of variability can be described by the rms magnitude differences as a function of the time lag τ between the observations:

$$\sigma(\tau) = \sqrt{\langle [m(t+\tau) - m(t)]^2 \rangle - \sigma_n^2} \, , \qquad (1)$$

where σ_n^2 is the variance of the noise and the angular brackets indicate the ensemble average over the whole sample (Bonoli et al. 1979). This is equivalent to the structure function (see Simonetti, Cordes, & Heeschen 1985) for $\sigma_n = 0$, but is to be preferred when the noise becomes comparable to the variability, since it refers to an intrinsic property of the objects. Bonoli et al. (1979) show that $\sigma(\tau)$ can be represented by a function of the type $\sigma_{\rm max}[1 - \exp(-\tau/T)]$, with $\sigma_{\rm max} = 0.22$ for the radio-quiet objects and $T = 0.83$ yr. Trevese & Kron (1990) find a similar result on the fainter sample of SA 57 with $\sigma_{\rm max} = 0.37$ and $T = 1.03$ yr. It is to be remarked that, scaling the time lags of each quasar according to the $(1 + z)$ factor, both the above analyses become consistent with $T_{\rm rest} \simeq 0.45$. Trevese & Kron also find some evidence of correlation up to ~ 10 yr, consistently with two time scales found by Smith (1990) the longer extending beyond 20 yr.

Although Cristiani et al. (1990) find a steady increase of variability up to 7 yr, their data are consistent with a decay of a substantial fraction ($\gtrsim 50\%$) of the correlation within $\lesssim 0.5$ yr (rest-frame).

The structure function can be considered nearly constant for rest-frame time lags $\gtrsim 2$ yr (Hawkins 1983). Thus we adopt as variability index the asolute value of the magnitude difference at a fixed observed time lag $= 4$ yr:

$$\delta m_k = \langle | m_{ik} - m_{jk} | \rangle \qquad (2)$$

at $\Delta t = t_i - t_j$, where k indicates the object, i and j specify the fixed epochs, and the average is over all the epoch pairs corresponding to the same time lag. In this way we can neglect the reduction of variability of high-redshift objects caused by cosmological time dilation.

In Figure 1 δm_k is plotted versus absolute magnitude for each object of the composite sample. K-corrections based on a power-law spectrum with slope $\alpha = 0.5$ have been applied. A standard linear regression analysis shows no correlation; the correlation coefficient is $\rho = -0.1$, but the probability of being random is $P = 0.5$.

In Figure 2 δm_k is plotted versus redshift. In this case we find a positive correlation $\rho = 0.25$ significant at the 95% confidence level. Exclusion of objects fainter than $M_B = -23.5$ does not change the results appreciably.

The absence of significant correlation with magnitude, despite the correlation with redshift, can be understood by considering the wider spread of the composite sample in the M_B-z plane with respect to samples used in previous analyses, having strong M_B-z anticorrelation.

We believe the δm-z correlation to be real for the following reasons.

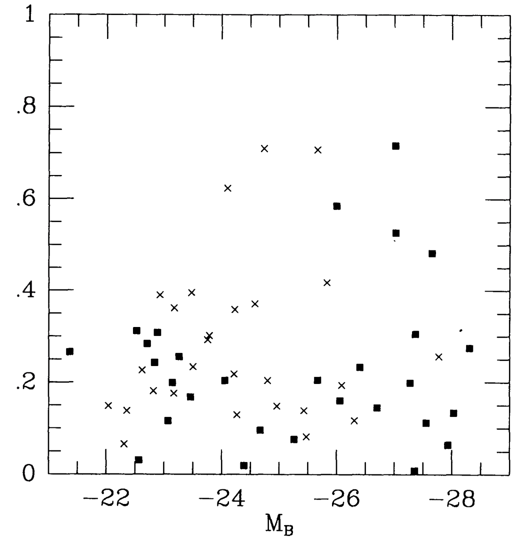

FIG. 1.—Variability as a function of absolute magnitude. Squares indicate data points from Bonoli et al. (1979), and crosses from Trevese et al. (1989).

Although the redshift ranges of the Braccesi and KKC samples are different, the average δm of the two samples in the overlapping redshift interval is statistically the same. Different noise levels in the two samples could in principle produce an artificial correlation of variability with apparent magnitude. In our case the correlation coefficient is $\rho = 0.15$ but with a probability of being random $P = 0.25$. Moreover, the noise is smaller in the KKC sample containing the higher redshift, more variable objects (cf. Bonoli et al. 1979; Trevese et al. 1989) and this should, in any case, reduce the variability-redshift correlation. Finally the δm-z correlation coefficients are similar in the two samples (0.28 and 0.21 in the KKC and Braccesi samples), although the significance is low when the samples are considered separately.

Our result appears in contrast with previous analyses where higher variability is found at lower redshifts. However, this

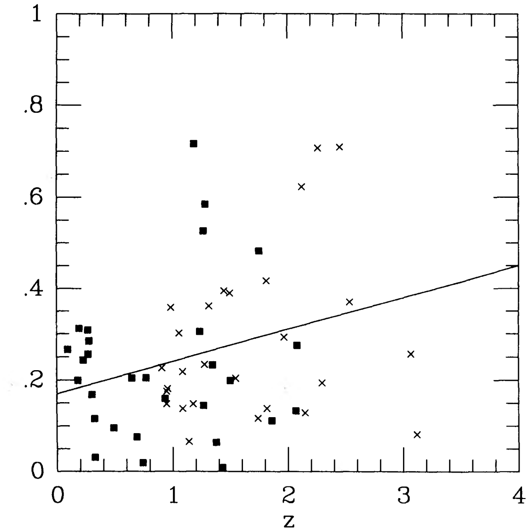

FIG. 2.—Variability as a function of redshift. Straight line indicates the least-squares fits of variability as a function of redshift of the type $\delta m = bz + a$ with $b = 0.07$ and $a = 0.17$. Data points as in Fig. 1.

could be due to the different kinds of variability indicators adopted and to the different time sampling.

The Q statistics, defined as the difference between the maximum and minimum of the light curve, normalized to the photometric noise, is specially suited for detecting variability (Usher 1978). If larger magnitude variations are progressively less probable (see, e.g., Usher et al. 1983), then they will be observed, on average, at progressively longer time lags. Cosmological time dilation reduces the total rest-frame duration of the survey by a factor $(1 + z)$, thus unfavoring large magnitude differences for the high redshift objects. This effect may generate a negative correlation. This could explain the negative correlation found by Pica & Smith (1983), although the incompleteness of their sample makes the interpretation problematical.

Cristiani et al. (1990) use $\Lambda_k = \sum_{i=1}^{N} |m_{ki} - \mu_k|/n$, where m_{ki} is the magnitude of the kth object at the ith observation and μ_k is its median magnitude. Time dilation increases the sampling frequency in the quasar rest-frame and changes the median value, reducing Λ_k for high redshift objects. To check this effect we have interpolated the light curves of KKC objects and resampled them with the time lag distribution of Cristiani et al. (1990). The resulting Λ_k exhibits a negative correlation with redshift. A negative $\Lambda_k - z$ correlation is also obtained using the Bonoli et al. light curves, which however cannot be sampled with the above time sequence since they span a shorter time.

Therefore our claim is that variability is not correlated with luminosity while it is positively correlated with redshift.

3. INTERPRETATION AND CONSEQUENCES

The absence of correlation with absolute magnitude favors models with a single coherent source rather than randomly flaring subunits (see Angione 1973).

The positive correlation of variability with redshift could reflect a real cosmological evolution of the quasar activity, in the sense of a stronger instability at early epochs.

However we suggest a possible explanation in terms of an observational effect. In fact, all quasars are observed in the same optical band, thus we sample higher redshift objects at shorter rest-frame wavelengths. On the other hand, there is evidence (Edelson, Krolik, & Pike 1990) that Seyfert galaxies are more variable in the UV than in the visual, which corresponds to a steepening of the spectral energy distribution during the less luminous phase. A similar evidence has been found for quasars by Kinney, Bohlin, & Blades (1991). A positive correlation of variability with z follows.

A rough estimate of the effect can be obtained under the simple assumption of a power-law spectrum ($\log f_\nu = -\alpha \log \nu +$ const), whose spectral index α decreases when the object becomes brighter in the blue, leaving the flux unchanged at a fixed rest-frame frequency ν^* somewhere in the red part of the spectrum. In this way the amplitude of variability is

$$\delta m = 2.5 \log [(1 + z)\nu_{\rm obs}/\nu^*]\delta\alpha\ . \qquad (3)$$

Using archival *IUE* data of low-z active galactic nuclei, Edelson et al. (1990) studied the change of the spectral index as a function of the UV flux. From their Figure 2 we estimate $\delta\alpha/\delta m_{\rm UV}$, and from equation (3) we obtain that $\lambda^* = c/\nu^*$ is in the range 6000–8000 Å. For our average $\delta B \simeq 0.25$ at the mean redshift $z = 1$, a typical $\delta\alpha \simeq 0.2$ is found again using equation (3), Differentiating respect to the redshift we obtain $\partial(\delta B)/\partial z = 1.086\ \delta\alpha/(1 + z)$, corresponding to a slope $\simeq 0.1$ for the linear regression of δB versus redshift, consistent with our observed value of 0.07. Our result is also consistent with the color variations found by Hawkins & Woltjer (1985).

The picture emerging from the above analysis is that optically selected quasars have the same average intrinsic variability at all redshifts and luminosities. Within this framework the quasar-to-quasar dispersion of the spectral index represents an upper limit to the average spectral variability of individual objects. An estimate of the rms dispersion of the spectral index can be found e.g. in Sargent, Steidel, & Boksenberg (1989), who report a value of 0.3 for a sample of 59 high-z quasars, consistent with the more recent finding of Schneider, Schmidt, & Gunn (1989). This value is only slightly higher than the one associated with variability. It appears attractive to consider the exteme possibility that the light curves of all the optically selected quasars are statistically the same on long enough time scales (e.g., > 100 yr); of course, this does not prevent the occurrence of different patterns of variability (e.g., flares, flickering, or slow trends), which may represent different phases of quasar life, rather than "genetically" different quasar types.

Variability can also be used as a selection criterion for finding quasars (van den Bergh, Herbst, & Pritchet 1973; Usher 1978), and complete samples have been constructed on this basis (Hawkins 1983; Trevese et al. 1989). In principle, candidates selected on the basis of variability should not be biased in redshift for cosmological time dilation, if they are observed at long (e.g., $\gtrsim 4$ yr) time lags, where the structure function can be considered nearly constant. However, the correlation found in the present analysis implies a bias even at long time lags, favoring in particular the discovery of high-redshift objects. This could explain the lack of variability of the objects studied by Huang, Mitchell, & Usher (1990) which are mainly at low z.

In any case, this bias is complementary to those of the color selection criterion. The completeness of samples selected through variability depends essentially on the signal-to-noise ratio of the data. For example, high-quality plates from the KPNO 4 m telescope allowed Trevese et al. (1989) to adopt a variability threshold of 0.1 mag, reaching a completeness level of $\gtrsim 70\%$. An indication of the redshift dependence of the completeness level can be obtained from Figure 2, where all the objects with $\delta m > 0.3$ have $z \gtrsim 1$, while the redshift bias becomes negligible for a threshold $\delta m = 0.1$ mag.

The increase of variability with redshift also implies a larger uncertainty on the apparent magnitude of high-redshift objects, affecting the estimate of the evolution of the luminosity function, as discussed by Cavaliere, Giallongo, & Vagnetti (1989). In particular, if δm is uncorrelated with absolute magnitude, a power-law luminosity function would maintain the slope, but the object number, in a given luminosity interval, would be enhanced with respect to the intrinsic value. This effect increases with redshift and, in a framework of pure luminosity evolution, results in an underestimate of the characteristic time-scale. However, a reliable evaluation of the decrease of the evolutionary rate requires extension of the present analysis to a larger sample of quasars observed at long time lags.

4. SUMMARY

We have investigated the optical variability of a composite complete sample of optically selected quasars. The main results of our analysis are as follows:

1. Variability dependence on redshift and luminosity is biased by the combined effect of the structure function and cosmological time dilation. This bias is negligible if variability is determined by a magnitude difference at a fixed, long enough time lag ($\gtrsim 4$ yr).

2. There is no evidence of correlation with absolute magnitude. This favors models with a single coherent source rather than randomly flaring subunits.

3. Variability increases, on average, with redshift. This result is reconciled with the negative correlations found by previous analyses on the basis of the different variability indexes and time samplings.

4. We propose an interpretation of the positive correlation in terms of variability of the spectral index, implying larger magnitude variations at higher rest-frame frequencies, which correspond to the fixed observing band at higher redshifts. This effect accounts quantitatively for the observed correlation, suggesting that a real cosmological evolution of the quasar variability is absent or negligible.

5. Quasar samples selected on the basis of variability could be biased against low-z objects. The importance of this bias is a function of the variability threshold adopted, which depends on the signal-to-noise ratio of the data and becomes unimportant in low-noise surveys.

6. The correlation can also effect the luminosity function of quasars, in the sense of a larger uncertainty of the apparent magnitude of high-redshift objects which may cause an overestimate of the evolution.

Confirmation of the above trends on larger variability data bases and a better evaluation of the implied biases would be desirable.

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