PART 11

VARIABLE QUASI-STELLAR OBJECTS AND NUCLEI OF GALAXIES

VARIABLE QUASI-STELLAR SOURCES WITH PARTICULAR EMPHASIS ON OBJECTS OF THE BL LAC TYPE

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Abstract. The optically variable quasars tend to have steep optical spectra and to show variable polarization; they tend to be associated with compact radio sources which have flat radio spectra at GHz frequencies. Objects are known which have continuous spectra (like BL Lac and OJ 287), but whose other properties closely parallel those of the variable quasars and *N* galaxies; in fact no sharp distinction can be drawn between them. The variation in the visibility of emission lines in quasars and *N* galaxies could be due to variations in the strength and spectral index of the radiation from the non-thermal source and from the differences in the amount and disposition of the material around it; it does not seem unlikely that a combination of these factors accounts for the observed range in emission line strength. The systematic difference in optical spectral index between continuous-spectrum objects (and OVV variables) on the one hand and those with emission lines on the other will produce a difference in *K* term between them, which may be expected to affect their relative distributions with respect to apparent magnitude.

1. Introduction

There is wide acceptance of the statement (Schmidt, 1969) that quasars are characterized by their star-like optical appearance and by emission-line spectra. For some purposes (e.g. for a study of their distribution; Schmidt, 1973), more exact definitions are needed to perform the analysis. More generally, however, sharp definitions of terms such as quasar, *N* galaxy, etc. tend to be eroded with time as objects are found which do not fit well into older classifications, or the classifications are found to correspond more to appearance than physical distinction. Thus, Sandage (1970) and Kristian (1973) have given evidence that quasars are like *N* galaxies except that they have a stronger non-thermal source, or are so far away that the extended part cannot be seen. The similarity between the spectra of quasars and Seyfert galaxies was noted long ago by Burbidge *et al.* (1963), while Morgan (1972) noted the possibility of confusing a Seyfert galaxy (primarily a spectroscopic classification) with an *N* galaxy (a form classification). In this review, particular emphasis will be placed on objects which have continuous spectra and are sometimes called Lacertids. They do not qualify as quasars on Schmidt's definition, but their properties so resemble those of quasars that it seems more sensible to expand the meaning of the term quasar to include them than to regard them as a separate class. It may be noted that no distinction has been made in the past between radio galaxies which have emission lines and those which do not – presumably because it was apparent that a whole range of emission-line strengths is present.**

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** In a compilation of radio galaxies (Moffett, 1973) of types E, DE, ED, SO, D, and DB, 42 show only absorption lines, 15 show only λ 3727 with or without absorption, and 29 show emission other than λ 3727.

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In all these objects, the common factor is the non-thermal source and the absolute brightness of this source is a matter of contention. This brightness can either come from a distance which is derived from the redshift of the spectral lines (the cosmological hypothesis) or in some cases from the distance derived from the properties of a presumably associated galaxy. On the other hand, one may obtain upper limits to the brightness for specific types of non-thermal radiation (usually electron synchrotron radiation) for specific models where the dimensions are derived from considerations of the rapidity of the fluctuations of the radiation. A recent discussion of the problems involved is given by Jones *et al.* (1974). The fact that these nonthermal sources vary in both flux and in polarization is therefore of considerable importance.

In this review, we shall be concerned mainly with *optical* variability. Significant variations on time scales of as short as a day are fairly well established. The dimensions implied (3×10^{14} cm) and the power output (10^{41} erg s^{-1}) – on the cosmological hypothesis – lead to a brightness temperature of the order of 10^8 degrees and imply magnetic fields in excess of 10^3 gauss if relativistic streaming is not present (Rees and Simon, 1968). It must be remembered, however, that not all quasars vary in this way. Thus, according to Peach (1969), less than 10% of his sample of quasars showed variations with amplitudes greater than 1 mag. and even in these, very rapid variations are not always present. This frequency of variability in quasars is for the kind that were originally selected as radio sources; there is little information available on the variability of those whose selection depended on optical methods alone.

The term non-thermal radiation is used here without precise definition. It seems likely that this radiation is electron synchrotron radiation, but this is still not certain. The presence of significant amounts of non-thermal radiation seems to be the single most important criterion for distinguishing quasars and related objects from other galaxies. Unfortunately, a quantitative scheme of classification based on the amount and quality of this radiation is difficult to achieve at optical frequencies and we are forced to continue with the older aspectual definitions for the present.

2. General Properties of Variable Quasars

Many of the most active optically variable quasars also vary at radio wavelengths. The radio variability is most pronounced at the higher radio frequencies where the radiation comes from compact sources. Such sources have relatively flat spectra at the higher radio frequencies and so it is also found that the larger amplitude optical variables tend to be associated with radio sources with flat spectra at GHz frequencies (Penston and Cannon, 1970). The early radio surveys were made at meter wavelengths and did not reach to very faint flux limits; they therefore preferentially discovered objects which are bright at longer wavelengths. The variable sources found in these surveys therefore tend to contain extended, steep-spectrum components in addition to the compact, high-frequency sources (e.g. 3C 273, 3C 279, and 3C 345; Kellermann and Pauliny-Toth, 1968). More recent surveys have reached lower flux levels at higher frequencies and these have revealed objects which do not have extended, steep-spectrum components.

A number of typical light curves for optically variable quasars were given in an earlier review paper (Kinman, 1968). Most of the generalizations based on the data then available are still valid. The variations still appear to be more in the nature of outbursts than fluctuations about a mean value and the rates of brightening and fading seem to show no pronounced systematic difference. Large variable polarizations (see Figures 3 and 8) are found in the radiation of the most active variables; as high as 20 to 30% in some cases. The polarization has not been found to vary with wavelength (Visvanathan, 1974) except where there is evidence for a significant contamination of the non-thermal radiation by light from an accompanying galaxy (e.g. NGC 1068). The variation of polarization with wavelength and with the size of the measuring aperture can be used to determine the relative proportions of non-thermal and galaxy radiation in a number of sources, as was done for NGC 1068 by Visvanathan and Oke (1968).

3C 446 is a quasar which has been studied for a number of years and which is of particular interest because of the amplitude and rapidity of its variations. A partial light curve is shown in Figure 1 both in terms of *B* magnitude and intensity units of 10^{-26}W m^{-2} Hz^{-1}. The intensity at 2.8 cm given by Medd *et al.* (1972) is also given. It is seen that the character of the variations at the two wavelengths is quite different.

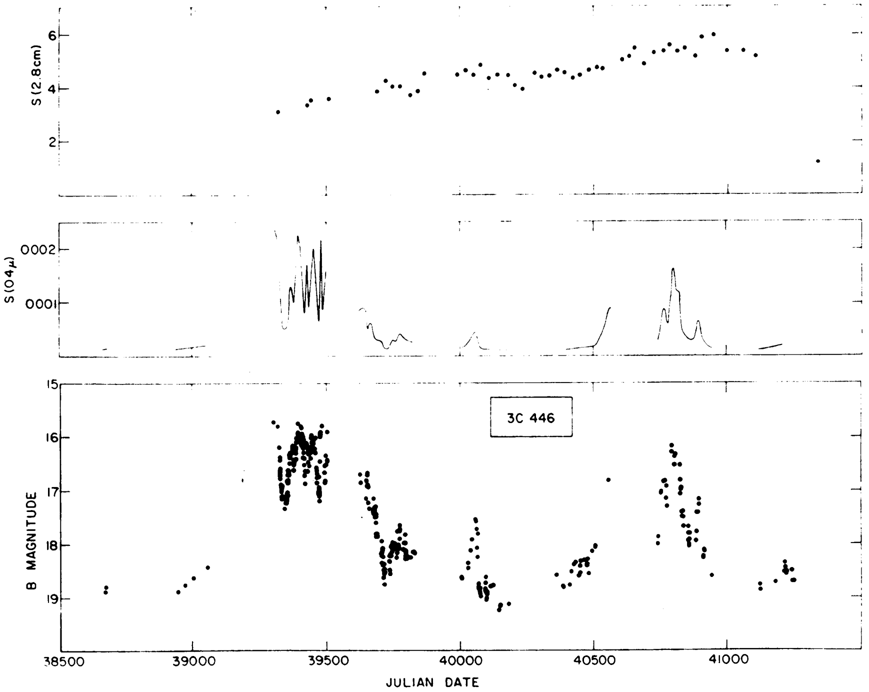

Fig. 1. The intensity variations of the quasar 3C 446: (top panel) at a wavelength of 2.8 cm from Medd et al. (1972); (middle panel) in the optical *B* waveband (0.44 μ). The lower panel gives the *B* magnitudes (nightly means) mostly from unpublished observations by the author. For other comparisons between radio and optical variations, see Kellermann (1972) for 3C 345 and Kinman *et al.* (1974) for OJ 287.

We have already noted that the radio spectra of sources such as 3C 446 are complex and it is likely that the 2.8 cm radiation is made up from the emission from a number of sources in different stages of evolution. The time scale for evolution (in the expanding cloud model (Shklovsky, 1960; van der Laan, 1966)) will differ from that at optical wavelengths and this, together with the multiplicity of radio sources, will produce different types of variation at the two wavelengths even if a common source of relativistic particles is responsible for the radiation at both wavelengths.

Oke *et al.* (1970) gave the energy distributions for 28 quasars in the wavelength range 0.3 to 2.2 μ, and showed that the continuum radiation from these objects (freed from the effects of the strong emission lines) could generally be represented by power-law spectra with exponents in the range -0.2 to -1.6. It should be noted that when very broad emission lines are present it may be difficult in some cases to establish whether the continua are really power-laws or are curved – a comparison of the continuum spectra of 3C 446 given by Oke (1967) and Wampler (1967) illustrates this point. It may also be difficult in scans of limited resolution to distinguish between a change in the slope of the continuum and the presence of unresolved absorption lines; this may be a practical problem in the neighborhood and to the blue of Lα. It is evident that the power-law exponents do change quite markedly on a short time scale; in 3C 446, Wampler (1967) found spectral indices in the range -1.84 ± 0.04 to $-1.56 \pm$ ± 0.04 in August and September, 1966. Oke *et al.* concluded that those quasars which showed large amplitude variations showed no sensible change in their energy distribution during their variations. Earlier, both Oke and Wampler noticed that 3C 446 was bluer in 1965 and became redder during its 1966 outburst. However, Visvanathan (1973) found that 3C 446 became bluer during its 1969 outburst. When rather large, short-term variations are present, it is certainly difficult to be sure of long-term trends unless one has a lot of data. We shall return to this question in the next section.

An important point, which became apparent when a large sample of continuum spectra became available, was that the large amplitude variables with large polarization have steep optical spectra (Figure 2). In discussing various variable quasars which they had monitored, Penston and Cannon (1970) introduced the term 'optically violent variable' or OVV variable for what they regarded as a well-defined subset of variables with an amplitude of more than one photographic magnitude. They were influenced by the lack of variables of intermediate amplitude (say about 0.75 mag.) in their original survey. No adequately homogeneous set of data has been published which allows the real frequency of different amplitudes to be established. Objects with intermediate amplitudes (e.g. 3C 351) certainly exist and their polarizations are noticeably lower than the variables of larger amplitude. The situation is confused by the fact that the more active variables seem to show periods of relative quiesence so that misclassifications can occur with limited data. However, although it is not very precise, the term 'OVV variable' is useful for qualitative statements; e.g. "such variables tend to have steep optical spectra and be associated with compact variable radio sources which have flat radio spectra at GHz frequencies". It will be used in this way in this paper.

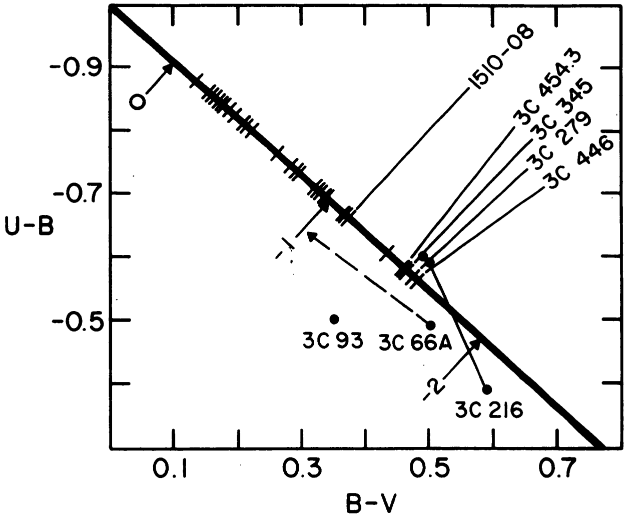

Fig. 2. The thick line gives the locus of points with power-law spectra $F(\nu) = \nu^n$ and the points where $n = 0$, -1, and -2 are shown in the $U-B$ vs $B-V$ diagram. The distribution of these spectral indices (n) in the sample of quasars observed by Oke *et al.* (1970) and Oke (1974) are shown by short bars on the power-law line: OVV variables are indicated by name. The colors of 3C radio sources with continuous optical spectra are shown by filled circles; the dashed line shows a possible correction for the interstellar reddening for the source 3C 66A given by Wills and Wills (1974a), but a reddening of about half this amount is more likely.

The question of the variability of the emission lines in quasars is a very important one and deserves more attention. There is no strong evidence that quasar emission lines have varied. Visvanathan (1973) found no evidence for variability or for polarization in the Mg II line in 3C 345. Burbidge and Burbidge (1966) judged that they saw variations in this line. No evidence for variation of the emission lines in 3C 446 was found by Sandage *et al.* (1966), Oke (1967) and Wampler (1967). It seems likely that the emission lines are produced in a volume of several parsecs radius and that the primary excitation mechanism is photoionization (Davidson, 1972; MacAlpine, 1972; Greenstein and Schmidt, 1964) – in general, rapid changes in emission lines generated in this way would not be expected. Long-term variations might be expected, however, in sources where the ionizing radiation has undergone marked changes over relatively long time scales.

3. Continuous Spectrum Objects

Not all the star-like objects which have positional coincidences with radio sources show emission lines. A few objects identified from the early, low-frequency 3C survey (3C 93 and 3C 216, Schmidt, 1968; 3C 66A, Wills and Wills, 1974a) have continuous spectra. Only 3C 216 and 3C 66A seem to have been checked for optical variability; in 3C 216 Sandage (1966a) found a range in B of 0.56 mag. from three observations and he also found significant color changes. In the $U-B$ and $B-V$ diagram, sources with power-law spectra $F(\nu) \propto \nu^n$ lie on a straight line (Matthews and Sandage, 1963) although the situation is clearly complicated by the presence of emission lines. The *UBV* colors of continuous-spectrum objects can, however, be used without correction to see whether the objects have a power-law spectrum and to determine the spectral index *n*. In the present review, interstellar reddening has been neglected unless it is specifically mentioned. The colors of 3C 216 (Figure 2) scatter around the power-law line, while the single measures of colors of 3C 93 and 3C 66A lie reasonably close to it. It is seen that the optical spectral index is high, like the OVV variables, and at least sometimes is variable as in the case of 3C 446. The radio spectral index is, however, steeper at high frequencies than for OVV objects: between 0.75 and 5 GHz, 3C 93 and 3C 216 have indices of -0.85 ± 0.04 and -0.65 ± 0.06 (Kellermann *et al.* 1969), although the scintillation observations at 178 MHz by Little and Hewish (1968) of 3C 216 indicate a complex source with 20% of the flux within a diameter of $0\rlap{.}''7$. 3C 66A also has a steep spectral index of -1.1 between 0.4 and 1.4 GHz, but shows a flux of $(6.0 \pm 2.5) \times 10^{-26}$ Wm^{-2} Hz^{-1} at 141 GHz indicating the presence of a strong high-frequency component (Wills and Wills, 1974a). If we are to assume that these objects like the OVV quasars have high-frequency, compact radio components, they must be weak relative to the steep spectrum components in 3C 93 and 3C 216 and so obscured by them.

Recently, Wills and Wills (1974b) examined a sample of 62 optical objects, chosen on the basis of positional coincidence with radio sources, from the 365 MHz Texas survey (Douglas *et al.*, 1973). Six of these objects were found to have no stellar features or definite emission lines on well-exposed spectra (240 Å mm^{-1}, 10–15 Å resolution). In view of lack of bias in the selection of these objects, except the bias against extended radio sources, this is probably the best available figure for the frequency of sources having either continuous spectra or very weak lines.

Higher frequency radio surveys have produced more identifications of radio sources with continuous-spectrum objects. One of the first to be discovered this way, and much studied since, is BL Lac. The radio source VRO 42.22.011 was first identified with an optical object by MacLeod and Andrew (1968) and by Schmitt (1968) with the variable 'star' BL Lac (which Hoffmeister (1929) had discovered). The older photographic observations of BL Lac have been discussed by Shen and Usher (1970), who give its range of brightness as $12.4 < m_{pg} < 16.3$. A compilation of recent photometry (together with a bibliography of earlier observations) is given by Bertaud *et al.* (1973). There is no question that this object shows rapid variations at both optical and radio wavelengths. Nevertheless, care should be taken when using optical magnitudes of this object derived from fast photographic systems (e.g. Schmidt telescopes), since the object has an extended image which can produce very significant errors in astrophotometry. High ($\leqslant 19\%$) and variable linear polarization is shown by its optical continuum (Figure 3).

Wlérick (1974) has shown from electronographic observations that the 25 mag per square sec of arc contour of BL Lac extends $33'' \pm 3''$ in the northeast-southwest direction and $21'' \pm 1\rlap{.}''5$ in the northwest-southeast direction. He assumes an interstellar

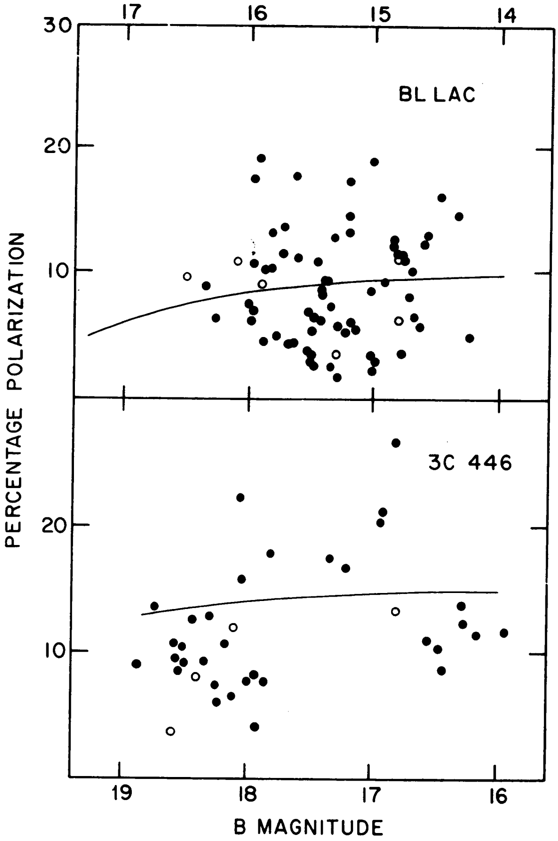

Fig. 3. The variation of percentage linear polarization with apparent optical magnitude for BL Lac and 3C 446. Open circles are observations by Visvanathan (1973) and filled circles are by the author. The curve for BL Lac is for a nonthermal source with a constant 10% polarization combined with a galaxy of 18.0 apparent B magnitude. The curve for 3C 446 is for a non-thermal source with constant 15% polarization and unpolarized emission lines equivalent to a 21.0 B-mag. source.

extinction of $A_V = 1.2$ (after Bertaud *et al.*, 1969) and deduces a V_{25} magnitude of 16.7±0.2 for the extended part of BL Lac; i.e., omitting the contribution of the nucleus. Identifying the extended part with a bright galaxy, Wlérick derives a redshift of $z = 0.05 \pm 0.015$. Oke and Gunn (1974) claim to have detected absorption lines with a redshift of 0.07 in the extended part; they used an annular aperture to exclude the nucleus and observed when the nucleus was faint. They assumed a non-thermal source with spectral index −1.55 and found that their observations could be fitted to those of a standard, bright galaxy with redshift 0.07, an extinction $A_V = 0.85$, and a varying contribution from the non-thermal source. The extinction is hard to determine precisely. DuPuy *et al.* (1969) found $E_{B-V} = 0.31$ by comparing the spectral type and colors of a star 20″ from BL Lac; this is presumably a lower limit. The photograph of Penston and Penston (1973), however, shows very irregular, bright and dark nebulosities in this low latitude field ($b = 10°$) so that it would be desirable to observe more stars near BL Lac. Very clearly, more observations are needed to confirm Oke and Gunn's result – preferably with higher resolution so that the line identifications can be made with greater certainty. Adams (1974) has attempted to derive the brightnes of the extended part of BL Lac from $U-B$ and $B-V$ variations as a function of V, and derived a redshift of 0.022 assuming the extended part was a bright galaxy. His result is unlikely to be correct since his mean value for the galaxy magnitude is 15.26 ($B-V=1.39$ and $U-B=1.00$), whereas BL Lac has been observed to have had colors $V=15.32$, $B-V=1.06$, $U-B=-0.05$, and Oke and Gunn observed a V magnitude as low as 15.6.

Even though the scatter in the $U-B$ and $B-V$ variation with V is too large to derive a redshift for BL Lac by Adams' method, these colors should be consistent with those predicted by Oke and Gunn's model. These predicted values are compared with the observations in Figure 4. The comparison is uncertain when the object is faint, because the colors then depend quite strongly upon the size of the measuring aperture

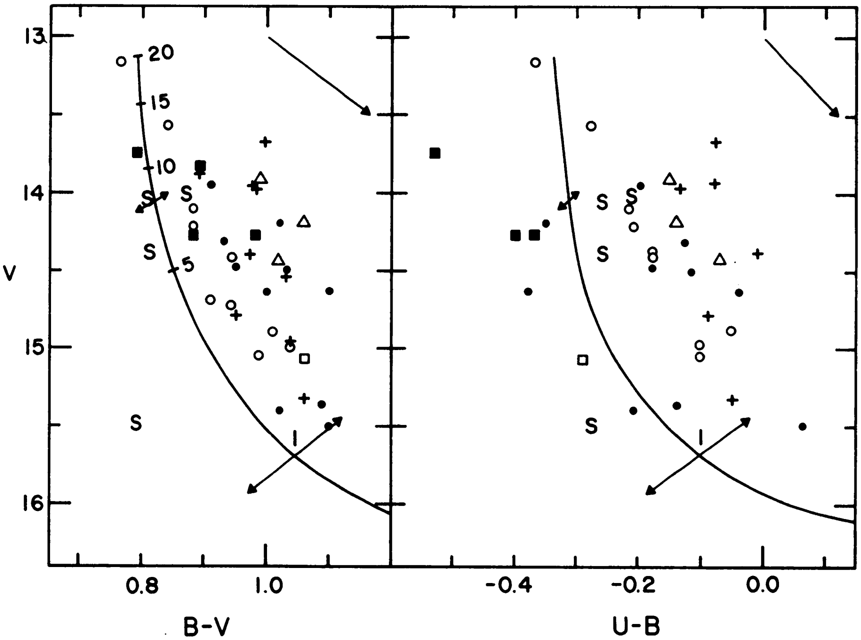

Fig. 4. Color magnitude diagrams for BL Lac. The symbols represent the following sources of data: open circles, 1.5-, 2.1-, and 2.5-m data of DuPuy *et al.* (1969) and Racine (1970); filled circles, 0.9-m data of Du Puy *et al.* (1969); open triangles, data of Bertaud *et al.* (1969); open square, data of Visvanathan (1969); S, scanner data of Visvanathan (1973); filled squares, data of Milone (1972); and crosses, unpublished data by Kinman. The arrow at the top left corner of each panel is the reddening line. The curves are those derived from the Oke and Gunn model of BL Lac when a 10″ measuring aperture is used; a galaxy with $V=15.60$, $B-V=+1.17$, and $U-B=+0.49$ together with a variable, non-thermal source of spectral index -1.55 and a reddening of $E_{B-V}=0.28$. The numbers opposite the curve give the relative intensity of the non-thermal source to the galaxy in the V passband. The arrows (which are roughly orthogonal to the curve) show, toward the left, the effect of decreasing the measuring aperture to 5″ diameter and, toward the right, the effect of increasing this aperture to 20″ diameter.

and this is not often quoted. Nevertheless, the predicted colors are clearly too blue, although the general trend of the variation with V seems in reasonable agreement. Possibly the assumed reddening is too low and also the mean spectral index of the non-thermal source may be steeper than Oke and Gunn assume. Clearly, the energy distribution of the non-thermal source becomes increasingly variable towards higher frequencies. The rms variations in $B-V$ and $U-B$ (after removing the systematic trend due to the galaxy) are ±0.075 and ±0.125 mag., respectively. These correspond to ±0.31 and ±0.56 in the spectral index. Similar figures for the source OJ 287 are ±0.05 (in $B-V$) and ±0.09 (in $U-B$) corresponding to spectral index variations of ±0.21 and ±0.40. It is clear, however, from Figure 5 that the variations are not just changes in the slope of a power law distribution, but that there is variable curvature in the energy distribution of these objects.

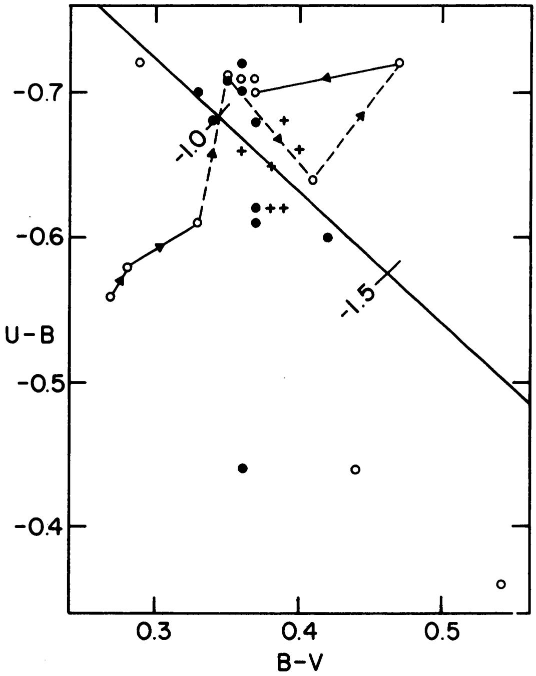

Fig. 5. $U-B$ and $B-V$ colors of OJ 287 from sources listed by Rieke and Kinman (1974). Filled circles are for $V<13.1$, open circles are for $13.2<V<13.8$, and crosses are for $15.3<V<15.7$; each point represents the mean for one night. For observations by Kikuchi *et al.* (1973), a full line joining two points indicates an interval of one day and a dashed line an interval of two days. It is seen that the variations do not represent simple changes in the spectral index, although the mean color is close to that expected from a source with a power-law energy distribution.

Better results might be obtained if the observations were extended to 10 μ where the stellar contribution from the galaxy might be expected to be missing, although a component produced by radiation from grains is still a possibility as Knacke and Capps (1974) suggest for NGC 1068. Notwithstanding these criticisms, it seems very likely that BL Lac is an *N*-type galaxy with a highly variable non-thermal component at a distance of a few hundred Mpc as Wlérick and Oke and Gunn suggest. As Wlérick points out, a redshift of 0.07 gives BL Lac an absolute magnitude range of -26.8 to -23.4 in M_V which is comparable to that deduced for many OVV quasars on the cosmological hypothesis.

In comparing the variability of different sources, allowance must be made for the effects of time dilation; this is only possible when the redshift is known. In the case of BL Lac, we presume that time dilation is negligible, but for 3C 446 ($z=1.4$), a time interval of one day in the rest frame of the object corresponds to 2.4 days in the observer's rest frame. It is seen in Table I that the rms, magnitude changes (σ) in a 2- to 3-day interval in 3C 446 are comparable with those observed in a one-day interval with BL Lac, although σ is not constant in either object.

TABLE I

Rms magnitude variations (σ) in time interval (Δt)

Object	Epoch	Δt (Days)	σ^a (Mag.)
0735 + 178	1971–73	1	±0.087
OJ 287	1971–73	1	±0.104
BL Lac	1968–70	1	±0.286
BL Lac	1970–72	1	±0.153
3C 446	1966–67	1	±0.121
3C 446	1966–67	2	±0.157
3C 446	1966–67	3	±0.174

[a] Corrected for the effects of observational error.

The radio spectrum of BL Lac is relatively flat at frequencies above 1 GHz and falls off at lower frequencies. Blake (1970) made optical identifications with a number of radio sources with similar spectra. One of these – OJ 287 – has a continuous spectrum and shows rapid variations both at radio and optical frequencies in both flux and polarization. In early 1972, it was particularly bright in the optical ($B\sim 12.5$) and also in the radio and a detailed study was made of its variations (Kinman *et al.*, 1974). Significant radio flux changes in time scales of ~1 day were found at 4.5 cm and shorter wavelengths. No correlation was found between the radio and optical wavelengths, although the time scales were similar, and the radio variations were difficult to explain on the simple expanding cloud model. Since 1972, OJ 287 has decreased in brightness by a factor of 15, but the ratio of the fluxes at wavelengths 0.44 and 10.5 μ showed no systematic change and the mean value of the *UBV* colors showed no change either (Rieke and Kinman, 1974). There is therefore a strong presumption that the optical and infrared radiation is all generated by the same mechanism; the spectral index of OJ 287 becomes flatter toward the infrared and the source may become optically thick at wavelengths ~20 to 30 μ. Although there may be a common particle supply for both radio and optical, radiation at *these* two wavebands is probably generated in different places.

Unlike BL Lac, OJ 287 shows no obvious signs of nebulosity on Sky Survey plates, and the absence of any significant trend in its colors suggests that any associated galaxy is probably at least as faint as $V \sim 17.8$, which corresponds roughly to 3C 28 with a redshift of 0.20 (Sandage, 1972). When OJ 287 was faint, a deep red plate was taken at the prime focus of the Kitt Peak 4-m reflector (Figure 6). A possible faint 'nebulosity' can be seen which has a radial extension to the North of about 5″, or about one-quarter the radial extent of that about BL Lac. It must be emphasized, however, that there is a significant chance that this 'nebulosity' could be due to the superposition of a field galaxy. We only wish to point out that the properties of OJ 287 are consistent with such a redshift; its brightest absolute luminosity would then be somewhat greater than that of 3C 273 in the optical and perhaps somewhat less at centimeter wavelengths.

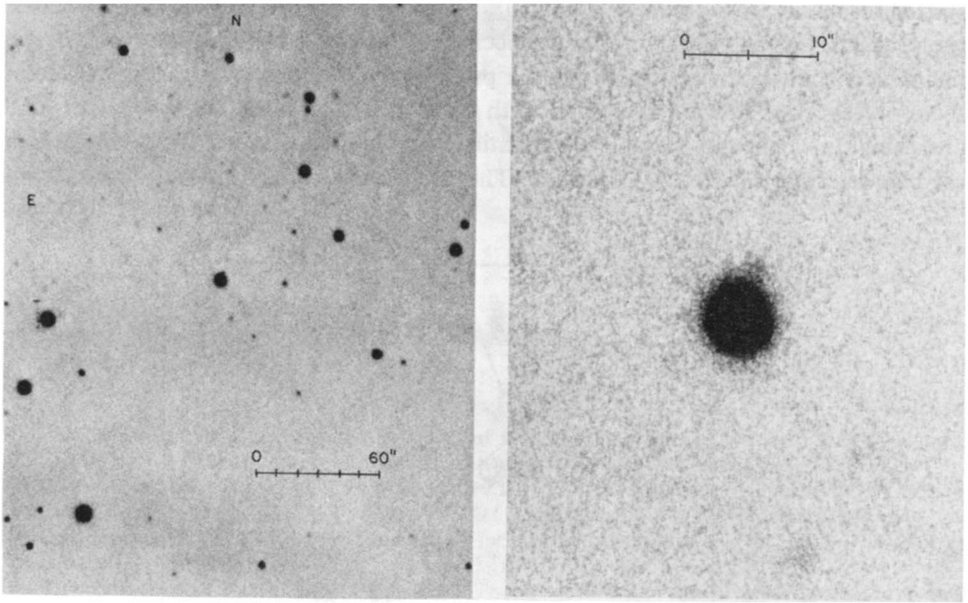

Fig. 6. Both the above prints of OJ 287 are from the same 111-min exposure on Eastman Kodak 127 − 02 emulsion through an RG-610 Schott filter at the prime focus of the 4-m reflector on 1974, February 28 UT. The approximate magnitude and colors of the object were then $V = 15.65$, $B - V = 0.39$, and $U - B = -0.68$.

Another example of a continuous-spectrum object that was also first identified by Blake (1970) is the source 0735+178. Its rapid variations in both optical flux and polarization have been described by Carswell *et al.* (1974). They showed that its otherwise continuous optical spectrum contained two absorption lines, which could be identified with the Mg II λ 2798 doublet, with a redshift of 0.424. The absorption lines in quasars generally have a lower redshift than the emission lines, so one might expect that the redshift associated with the continuum source of 0735+178 is at least as great as 0.424. The evidence from BL Lac, OJ 287, and 0735+178 therefore suggests that these objects are similar to *N* galaxies or quasars except for the absence of emission lines. They are in particular similar to the variable quasars, and it is to be remembered that when variable quasars are bright, their emission lines appear to be weakened because they are swamped by the continuum. An extreme example of variability in a continuous-spectrum object is 0537−441 for which a visual range of nearly 4 mag. has been found by Eggen (1973).

Blake identified continuous-spectrum objects by selecting objects which had radio spectra with maxima at GHz frequencies. They can also be found among objects identified with radio sources which have a 'neutral' color; i.e., images of equal strength on the red and blue Sky Survey plates. Strittmatter *et al.* (1974), among others, have recently obtained spectra of a number of these sources and found some of them either to be continuous or to have quite weak emission lines. A program was therefore started to obtain *UBV* colors and optical polarization for these objects to test whether the properties of all these continuous-spectrum objects are similar. The work is still incomplete, but it can be seen from the preliminary results shown in Figure 7 that these objects have power-law spectra with spectral indices more negative than −0.8 and a high incidence of variable polarization (Figure 8). These are properties which are characteristic of the OVV quasars. The correlation of 'neutral color' with con-

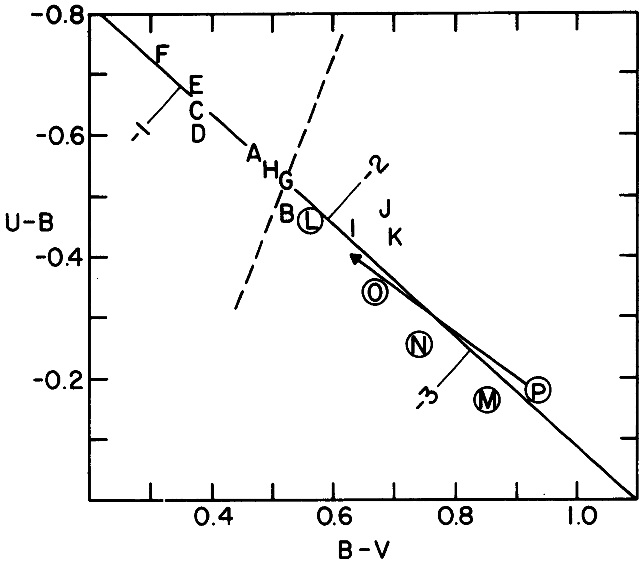

Fig. 7. Mean $U-B$ and $B-V$ colors of sources which have either continuous spectra or weak emission lines. The full line gives the locus of sources with a power-law spectrum and the dashed line shows the boundary between quasars and *N* galaxies (after Sandage, 1970). The sources are as follows: A, 0537−441; B, 0735+178; C, 0808+019; D, OJ 287; E, 0912+29; F, 1057+10; G, 1147+24.5; H, ON 325; I, ON 231; J, 1514+19; K, OY 091; L, 1101+38; M, AP Lib; N, 1652++39; O, 1727+50; P, BL Lac. Circled letters indicate sources which are known to contain an extended optical component. The arrow shows a likely reddening correction for BL Lac.

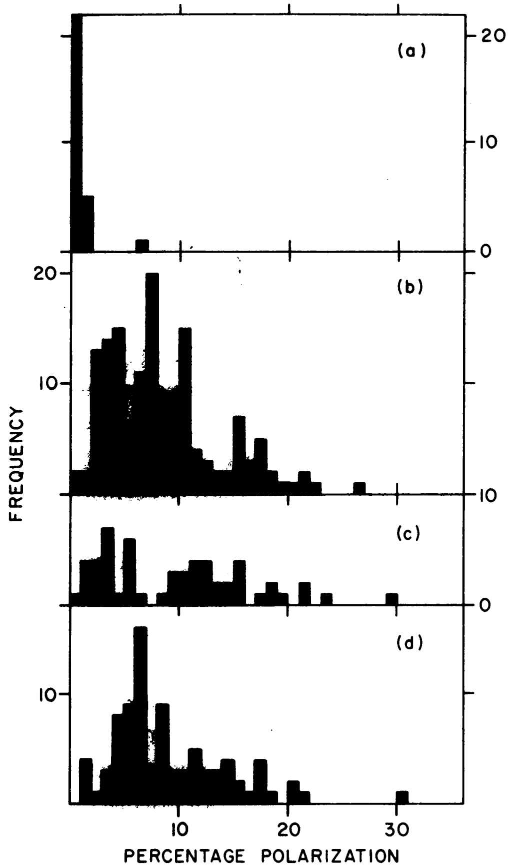

Fig. 8. Frequency of occurrence (in numbers of nights) for a given percentage linear optical polarization for: (a) Quasars with optically flat spectra: 0405 − 12 (−.25), PHL 957 (− 0.30), 1354 + 19 (− 0.31), 3C 380 (− 0.38), 3C 334 (− 0.45), 3C 249.1 (− 0.46), and 3C 351 (− 0.66); (b) OVV quasars with steep optical spectra: 3C 345 (− 1.50), 3C 279 (− 1.51), and 3C 446 (− 1.58); (c) The continuous-spectrum source OJ 287 (− 1.2); (d) Continuous-spectrum or weak-lined sources: 0735 + 178 (− 1.8), 0808 + 019 (− 1.2), 0912 + 29 (− 1.1), 1057 + 10 (−0.8), 1147 + 24.5 (− 1.7), ON 325 (− 1.6), ON 231 (− 2.1), 1514 + 19 (− 2.1), and OY 091 (− 2.4). The spectral indices shown in parentheses after each object in groups (a) and (b) were taken from Oke *et al.* (1970) and Oke (1974) while those of objects in groups (c) and (d) were derived from their *UBV* colors.

tinuous-spectrum objects is to be expected, since objects with spectral indices more negative than −0.8 have $B-V$ greater than +0.3.

Sandage (1970) noted that *N*-type galaxies have *UBV* colors which are intermediate between quasars and redshifted galaxies. Besides BL Lac, AP Lib (Rodgers, 1971), and I Zw 1727 + 50 (Zwicky, 1966; Pauliny-Toth and Kellermann, 1968) are examples of *N*-type galaxies with continuous spectra. In these objects, the non-thermal component is so strong and the objects so distant that it is difficult (as we saw for BL Lac) to obtain the redshift of the underlying galaxy from its absorption lines. Cases are known, however, where the galaxies are nearer and spectra can be obtained of the extended part. Thus, B2 1101+38 and B2 1652+39 were observed by Ulrich *et al.* (1975). No emission lines were found, but redshifts of 0.0308 and 0.0337, respectively, were found from the H and K lines and the G band in absorption. The *UBV* and 10.5 μ data for these galaxies are satisfied by assuming that these objects consist of a giant *E* galaxy and a non-thermal source of spectral index ~ -0.8.

A final example of a non-thermal source in a galaxy is the jet in M 87. This, like the objects considered above, has a continuous spectrum, is highly polarized (Baade and Minkowski, 1954; Baade, 1956) and is coincident with a compact, flat-spectrum radio source (Graham, 1970). A new determination of the energy distribution in the jet (Kinman *et al.* 1974) shows that it has a power-law distribution with a spectral index of -1.7 ± 0.2, which is similar to that of the OVV quasars and the continuous-spectrum objects. There is, however, no compelling evidence that the jet is variable. The jet has an absolute magnitude M_V of about -15.4, which is less than 1% of that of M 87 itself. In more distant systems, such a jet would be undetectable optically. The recognition of non-thermal sources of size intermediate between the M 87 jet and those in B2 1101+38 and B2 1652+39 (which are comparable in brightness with the parent galaxy at optical wavelengths) would be a matter of some interest. Presumably, following Heeschen (1973), the most likely candidates are relatively nearby galaxies containing compact, flat-spectrum radio sources. The non-thermal sources are best detected in the far ultraviolet and far infrared (10 μ) where the contrast of the source against the background galaxy will be maximized. If a source with continuous optical spectrum is also a compact radio source, there is clearly a reasonable probability that the optical source is also at least partly non-thermal. Besides radiation from stars, we must remember that bound-free and free-free radiation from hydrogen, two-photon emission, and infrared emission by hot dust may be present and the composite radiation from these sources can be modified by interstellar reddening (Oke, 1972). Little is known about 'optically selected' quasars (i.e. those not identified in the first place as radio sources), which have continuous spectra, although they are known to exist (Sandage and Luyten, 1967; Schmidt, 1975). In the case of such objects, confusion with stars such as DC white dwarfs is a possibility and it is very desirable that additional data, such as proper motions, colors, and polarization, be available.

4. Concluding Discussion

The evidence suggests that the continuous-spectrum objects have properties which closely parallel the variable *N*-type galaxies and quasars except for the absence of emission lines.

At 365 MHz, the Wills and Wills survey suggests that they could account for about 10% of the quasars. Their correlation with flat-spectrum radio sources (which become more frequent in surveys at centimeter wavelengths than in those at longer wavelengths (Kellermann, 1972)) indicates that they form a significant part of the total quasar population. It is, in fact, difficult to make a sharp, practical distinction between them even if this was thought to be necessary. Objects such as 0808+019 (Strittmatter *et al.*, 1974), Markarian 194 (Markarian, 1969; Arakelian *et al.*, 1970a, 1970b; Sargent, 1972) could at different times have been given different classifications – presumably because of intrinsic changes in the non-thermal component, although in the case of Markarian 194, differing spectral resolutions could have contributed.

We have seen that variability is a common property of the continuous-spectrum objects so that it is reasonable to suppose that the lack of emission lines is in some cases due to a temporarily abnormally strong continuum. Oke (1972) has noted that the visibility of the Ca II H and K absorption lines in a galaxy associated with a power-law source depends upon the spectral index of the power-law source. A parallel situation exists for emission lines. Another explanation of the lack of emission lines could be insufficient material of an appropriate ionization to generate the lines in the optical window available to the observer at a given redshift. The association of the continuous-spectrum objects with presumably young, compact radio sources and the general absence (except in cases like 3C 93 and 3C 216) of a steep-spectrum extended radio source, which would indicate past activity, suggests that these objects may all be in some early evolutionary state with a common lack of 'interstellar' material at an appropriate distance from the ionizing source. Finally, a lack of ionizing radiation could be the cause. The correlation between continuous spectra and steep, negative spectral indices would favor this explanation. It has been found in the case of OJ 287 that the spectral index appears to steepen toward higher frequencies (Rieke and Kinman, 1974). If OJ 287 is a relatively low redshift object, as some evidence suggests, it could be deficient in ionizing radiation near the Lyman limit. On the other hand, OVV quasars with optically steep spectra do have strong emission lines, although one case is known (3C 345) where Oke (1972) has shown that its spectrum flattens shortward of a rest wavelength of 4000 Å.

The strongest quasar emission lines have equivalent widths of a few hundred Ångströms and they are generally quite broad so that if they were reduced in strength by a factor of 100 or so, they would not be easy to detect. This factor would be significantly less for objects to appear continuous in surveys, such as that by Wills and Wills (1974b) where the resolution is ~10–15 Å. It does not seem unlikely therefore that a combination of all or some of the factors mentioned above conspires to produce the range in emission line strengths that we see.

A correction must be applied to the observed fluxes from extragalactic objects to compensate for effects produced by the redshift. This K term includes a 'non-selective' term $(+2.5\log(1+z))$, which is independent of the energy distribution with wavelength, and also a 'selective' term which is so dependent (Sandage, 1966b). In the case of a power-law distribution, $F(\nu)\propto\nu^n$, the selective term is $-2.5(n+2)\log(1+z)$ so that the total correction is $-2.5(n+1)\log(1+z)$. If two objects have the same V magnitude at very low redshift and if one has an optical spectral index -0.5 and the other -1.5, then at redshifts 1, 2, and 3, the object with the flatter spectrum will appear, respectively, 0.75, 1.2, and 1.5 V magnitudes brighter than the object with the steep spectrum. It is clear therefore that in any survey, to a given optical apparent magnitude, the flat-spectrum objects will be favored at the expense of the steep-spectrum objects which, as we have seen, mostly consist of OVV variables and continuous-spectrum quasars. These latter objects may therefore constitute a larger fraction of the total quasar population than is apparent from current surveys. There are also implications for estimates of the spatial density distribution and for the luminosity functions of quasars.

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Addendum

Recently Disney *et al.* (1974) have shown that AP Lib has both absorption and emission lines of varying visibility with a redshift of 0.0486. AP Lib thus consists of a galaxy with $M_v \sim -21.4$ and a variable non-thermal component. Baldwin *et al.* (1975) made spectrophotometric observations of the BL Lac nebulosity which do not confirm the absorption lines with redshift 0.07 found by Oke and Gunn (1974): neither do they confirm that this nebulosity has the energy distribution of a redshifted *E* galaxy. Kinman (1975) made *UBV* observations of BL Lac through apertures of different