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X-RAY AND UV OBSERVATIONS OF THE BL LACERTAE OBJECT 3C 66A[1]

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ABSTRACT

The energy distribution of the BL Lac object 3C 66A has been investigated in the soft X-ray range by means of repeated observations with the *Einstein Observatory* and in the UV range by means of the *IUE* satellite. The available optical photometry from 1979 to 1981 is reported. 3C 66A is characterized by violent X-ray activity over a time scale of 6 months, probably uncorrelated with optical variations. The featureless UV continuum is steeper than that deduced from infrared broad-band photometry, thus indicating a spectral break in the region 10^{14}–10^{15} Hz. The overall energy distribution is discussed in the framework of theoretical models proposed for BL Lac objects. The spectral properties indicate that synchrotron radiation is the dominant mechanism at all wavelengths, while the different optical and X-ray variability suggests different emission regions.

Subject headings: BL Lacertae objects — X-rays: sources

I. INTRODUCTION

The object 3C 66A is among the most luminous BL Lacertae objects ($L \sim 10^{46}$ ergs s^{-1}) if the distance estimated from its association with a cluster of galaxies ($z = 0.37^{+0.7}_{-0.1}$) (Butcher *et al.* 1976) and from the identification of an emission line with Mg II redshifted with $z = 0.444$ (Miller, French, and Hawley 1978) is correct.

It is moderately variable in the optical band with a variation of 1.2 mag recorded over 5 years (Pica *et al.* 1980) and of 0.5 mag on a time scale of about 2 weeks (Folsom *et al.* 1976).

The radio emission is characterized by a flat spectrum compact core surrounded by a steep spectrum halo (Stannard, Edwards, and McIlwrath 1981). VLBI measurements (Weiler and Johnston 1980; Stannard, Edwards, and McIlwrath 1981) revealed structure on a milli-arcsecond scale corresponding to a linear size of 13 pc. At 10.7 GHz, where the compact source dominates the emission, variations of 30% over periods of 3–4 yr have been observed (Andrew *et al.* 1978).

X-ray emission from 3C 66A was first detected with the *Einstein Observatory* (Feigelson and Berg 1982; Maccagni and Tarenghi 1981*a*). The source was observed three times in 1979 and once in 1980; on a time scale of 6 months, the data show a variation of a factor of 10, which is comparable to that observed in Mrk 421 by Ricketts, Cooke, and Pounds (1976) and exceptional among extragalactic objects (Cooke *et al.* 1978).

The X-ray light curve is reported here and compared with optical photometry by Pica *et al.* (1980), Pica (1982), and Barbieri, Cristiani, and Romano (1982). In 1981 the object was observed with *IUE* in the 1000–3000 Å range. The overall energy distribution obtained by combining nonsimultaneous measurements at different frequencies is discussed.

II. X-RAY OBSERVATIONS

a) *Variability*

The object 3C 66A was first observed with the *Einstein Observatory* in 1979 (Feigelson and Berg 1982; Maccagni and Tarenghi 1981*a*), and again on 1980 July 23 (Maccagni and Tarenghi 1981*b*). During the latter observation the 0.2–4.0 keV intensity was found to be $(7.22 \pm 1.00) \times 10^{-13}$ ergs cm^{-2} s^{-1}, a factor more than 10 lower than the maximum value observed in 1979 July and comparable to that observed by Feigelson and Berg (1982) in 1979 February.

Figure 1 shows the images of the X-ray field containing 3C 66A obtained in 1979 July–August (high state) and 1980 July (low state), respectively. On both images the X-ray source associated with the radio galaxy 3C 66B has constant intensity, comparable to that of 3C 66A at minimum.

The X-ray light curve is shown in Figure 2. The X-ray data of 1979 July–August are suggestive of a

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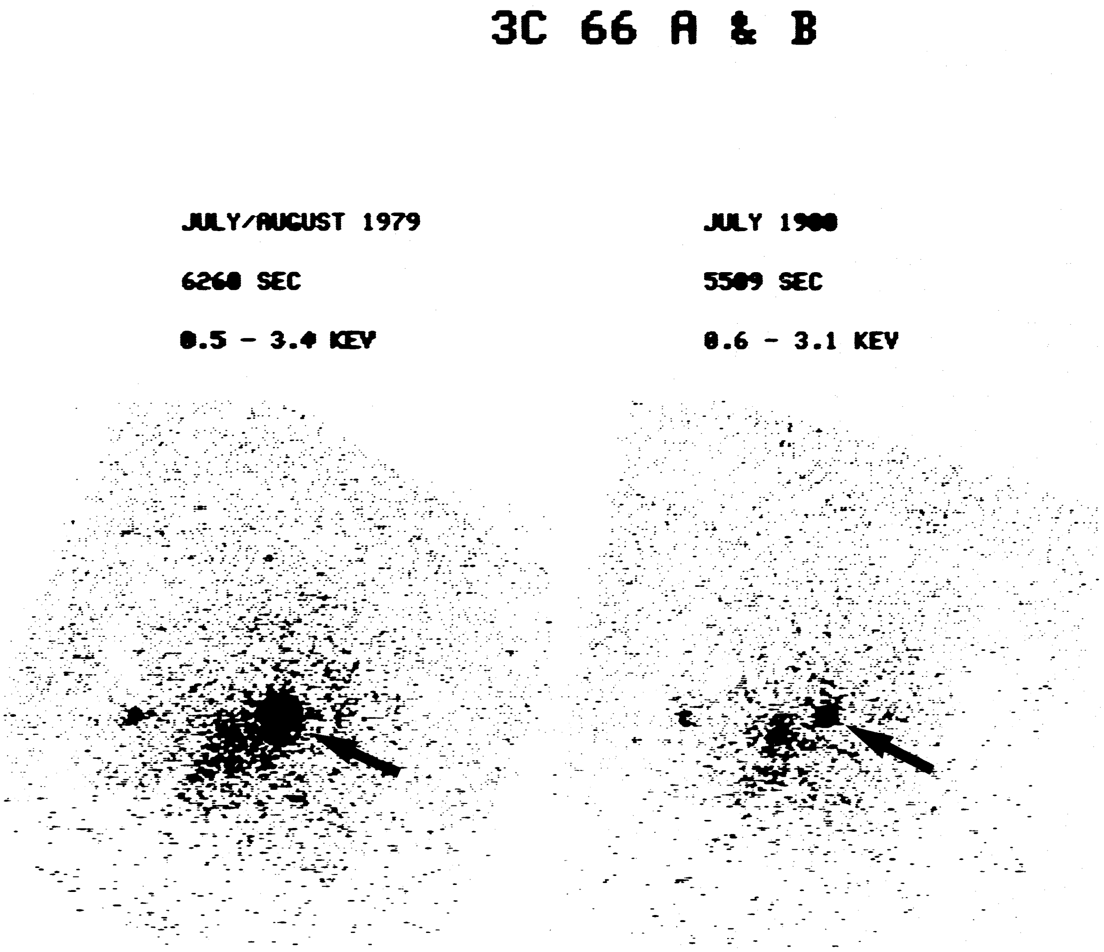

FIG. 1.—The X-ray images of the field of 3C 66A (*arrow*) taken 1 yr apart with the Imaging Proportional Counter of the *Einstein Observatory*. The data of the 1979 July and August observations have been merged together. Energy ranges have been chosen in order to maximize the signal-to-noise ratios.

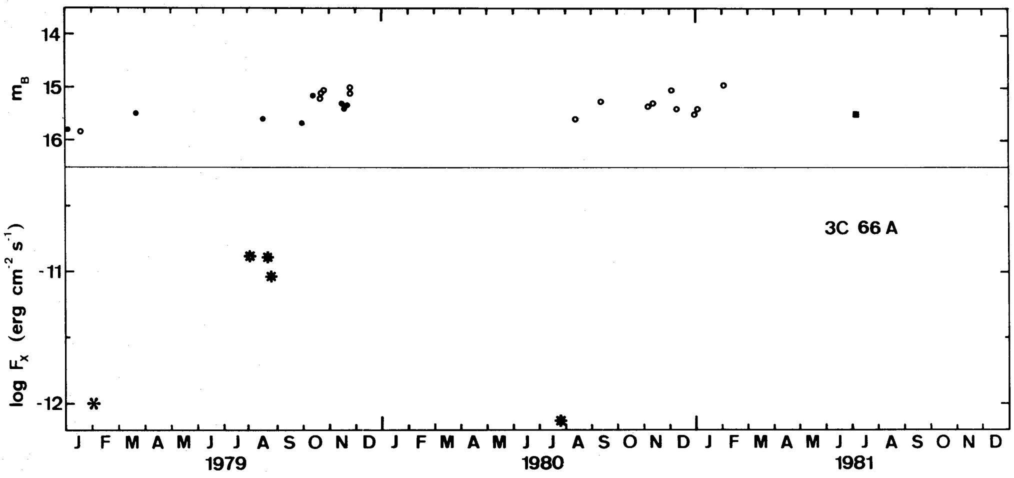

FIG. 2.—Optical (B magnitude) and X-ray (0.2–4.0 keV) time history of 3C 66A. ● Pica *et al.* 1980; ○ Barbieri, Cristiani, and Romano 1982; ■ Pica 1982, ∗ Feigelson and Berg 1982.

large outburst with peak luminosity (0.2–4.0 keV) $L_x \gtrsim 10^{46}$ ergs s^{-1} (assuming $z = 0.444$, $H_0 = 50$ km s^{-1} Mpc^{-1} and $q_0 = 0$), with a decay time scale of weeks. The energy radiated in X-rays during this outburst is in excess of 10^{52} ergs.

Also shown in Figure 2 is the optical light curve of the object as derived from the photometry of Pica *et al.* (1980) and Pica (1982) and from photographic magnitudes by Barbieri, Cristiani, and Romano (1982).

The optical variations recorded from 1979 to 1981 are within a magnitude with typical errors of 0.1 mag. In particular, the optical observation of 1979 August 16, which falls between two X-ray observations of the flare state, yields a magnitude similar to that of 1979 January and 1980 August when the X-ray flux (measured within 10 days) was a factor of 10 lower. An increase in the optical flux of ~0.5 mag is apparent between 1979 September and October. If the optical and X-ray brightenings are related, the delay time is about 3 months.

b) Energy Spectrum

The X-ray spectral analysis, due to the gain variations of the Imaging Proportional Counter (IPC), is not straightforward and is reported in detail in Maccagni, Maccacaro, and Tarenghi (1983).

For the observations of 1979 July 29 and August 25, both the IPC (0.2–4.0 keV) and the Monitoring Proportional Counter (MPC) (1.2–7.0 keV) data are compatible with a power-law energy spectrum with index $\alpha = 2.1 \pm 0.6$ and hydrogen column density $N_{\rm H} < 3.5 \times 10^{21}$ cm^{-2} (95% confidence level). The IPC data alone indicate a hydrogen column density of $(2.5 \pm 0.7) \times 10^{21}$ cm^{-2} close to the value derived by wide beam 21 cm line measurements in the direction of 3C 66A, $N_{\rm H} \sim 9 \times 10^{20}$ cm^{-2} (Heiles and Habing 1974).

During the observations of 1979 August 27 the IPC flux was lower by 30%, while the source was not detected by the MPC, indicating a substantial spectral steepening. In fact a power-law fit to the IPC data yields $\alpha \sim 4.0$ (Maccagni, Maccacaro, and Tarenghi 1983). The same spectral index is also obtained for the 1980 observation, when the source was in the low state, but with an extremely broad χ^2 distribution, and thus large errors are present in the derived parameters.

III. ULTRAVIOLET OBSERVATIONS

The object 3C 66A was observed with the short and long wavelength cameras of *IUE* on 1981 August 27 with exposures of 280 and 130 minutes, respectively. The object was acquired in the large aperture of the spectrograph with the blind offset technique with coordinates (Wills and Wills 1974): $\alpha(1950) = 2^{\rm h}19^{\rm m}30^{\rm s}.03$; $\delta(1950) = +42°48'29''.9$.

The data were analysed with the standard procedure developed at ESO using the 1980 May calibration curve (Bohlin and Holm 1981). The spectrum appears featureless (see Fig. 3). Also shown in Figure 3 are the average fluxes in 100 Å intervals; the error bars represent the standard deviations of the mean in the chosen intervals. A two-parameter fit to the data by the usual minimum χ^2 method with a single reddened power law $[F_\nu \propto f(A_v, \nu)\nu^{-\alpha}]$ gives best fit values of $\alpha = 1.75$ and $A_v = 0.01$. For this value of the interstellar reddening, the 95% confidence interval on α is ± 0.14. From the χ^2 grid one derives an upper limit on A_v of 0.20 with a corresponding lower limit on α of 1.48 at the same confidence level. The hydrogen column density, deduced from 21 cm line measurements and from the photoelectric absorption cutoff in the X-ray spectrum, $N_{\rm H} \sim 10^{21}$ cm^{-2}, and the low value of the extinction deduced from the UV continuum indicate an abnormally high gas-to-dust ratio (Savage and Mathis 1979).

IV. DISCUSSION

a) Energy Distribution

The overall energy distribution of 3C 66A obtained by combining nonsimultaneous measurements is shown

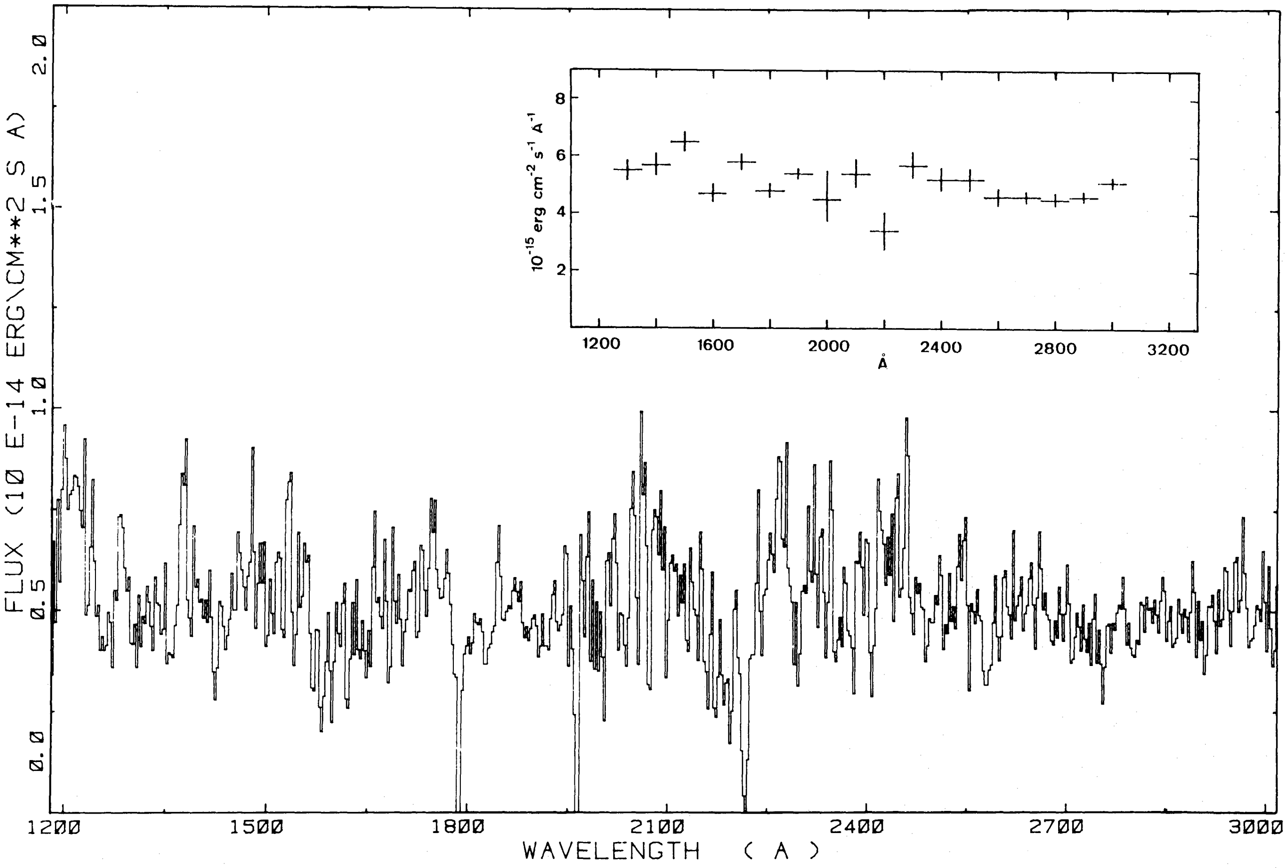

FIG. 3.—The UV spectrum of 3C 66A obtained with *IUE* on 1981 August 27. The insert shows the same spectrum averaged over 100 Å intervals.

in Figure 4. No correction for reddening or absorption has been applied to the data.

The UV continuum observed in 1981 connects well with that fitting the optical photometry obtained in 1975 January (Tapia, Craine, and Johnson 1976) and 1975 December (O'Dell, Puschell, and Stein 1977) when the source was in a relatively high state (Folsom *et al.* 1976). The slope of the optical continuum, however, differs significantly at the two epochs (cf. Fig. 4), being similar to the UV ($\alpha \sim 2$) in the first observation and similar to the infrared ($\alpha \sim 1$) in the second one. We consider this a strong suggestion that the spectrum of 3C 66A steepens between 10^{14} and 10^{15} Hz with a possibly variable break frequency ν_B within this range. This inference obviously needs to be confirmed by simultaneous observations from 10^{13} to 10^{15} Hz.

An extrapolation of the UV continuum to higher frequencies would yield an X-ray flux compatible, within the uncertainties, with that observed in the low state. This type of spectral behavior has been reported also for other BL Lac objects, in particular in the case of PKS 0548−322, when UV and X-ray observations were simultaneous (Urry *et al.* 1982).

In the high state the observed X-ray spectrum, together with the condition that the optical variation is small (see Fig. 2), suggests that there is a change in the energy distribution between optical and X-ray frequencies with respect to that of the quiescent state. If a single mechanism operates in the two bands, a substantial flattening of the UV continuum and a corresponding shift of ν_B to higher frequencies, $\nu_B \sim 10^{16}$ Hz, could be hypothesized.

b) *Theoretical Considerations*

It is generally believed that the radio to ultraviolet emission of quasars and BL Lacs is synchrotron radiation. The synchrotron mechanism could extend to the X-rays. However, in this energy band, other processes, in particular Compton scattering of the high energy electrons on the synchrotron photons (synchro-Compton), are also expected to play a rôle.

In the case of 3C 66A, the steep X-ray spectrum and the smooth connection between the UV and X-ray continua in the low state suggest that the synchrotron emission is dominant also in the X-ray band. This implies an upper limit on the Compton contribution which can be used to set limits on the synchro-Compton model (Jones, O'Dell, and Stein 1974; Mushotzky, Baity, and Peterson 1977). In fact, assuming that the entire spectrum from radio to X-ray

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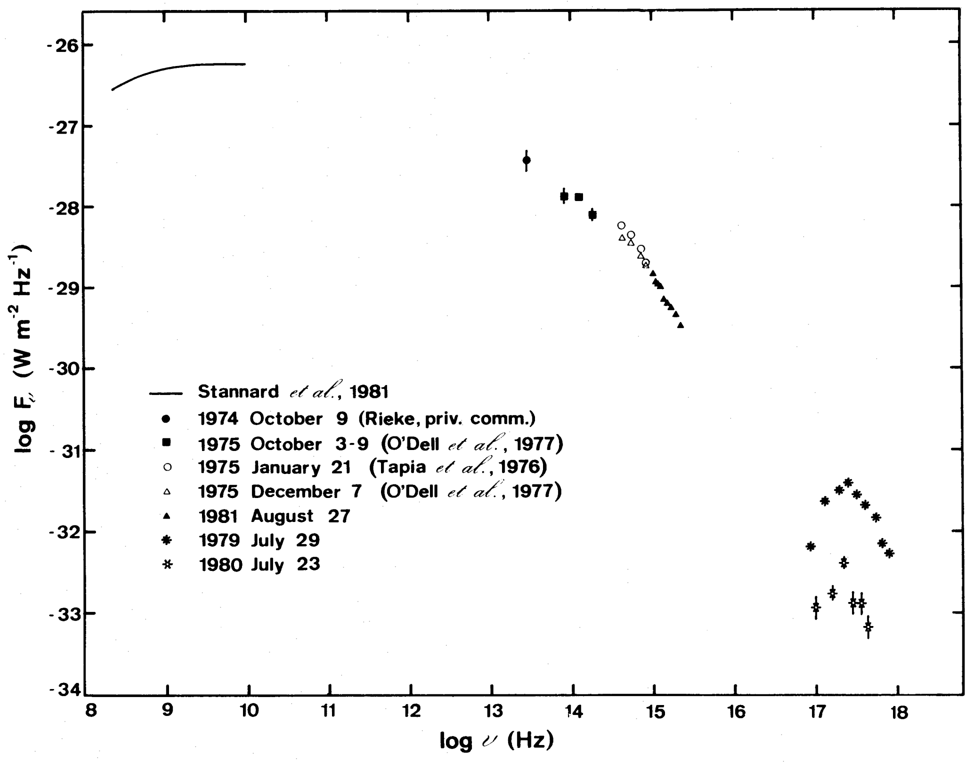

FIG. 4.—The composite nonsimultaneous frequency spectrum of 3C 66A

frequencies is due to the same emitting region, the size of which could be inferred from the X-ray variability ($R \sim 10^{17}$ cm), with a self-absorption frequency $\nu_{\rm sa}$ of 10^9 Hz, the predicted Compton X-ray flux is many orders of magnitudes larger than observed unless one invokes relativistic beaming of the emission in the observer's direction (Urry and Mushotzky 1982).

On the other hand, if the overall spectrum is assumed to consist of the superposed contribution of different components, as seems likely in view of the different variability properties at different frequencies, for instance a radio emitting region with dimensions deduced from the VLBI measurements ($R \sim 10^{19}$ cm) and $\nu_{\rm sa} \sim 10^9$ Hz plus a region emitting the infrared to X-ray radiation with $R \sim 10^{17}$ cm but $\nu_{\rm sa} \sim 10^{12}$ Hz, the predicted Compton X-ray flux can satisfy the observational constraints without any additional assumption.

Another problem is posed by the presence of a spectral break, which the observations suggest to occur in the optical–UV range. Its most straightforward interpretation is in terms of the radiative lifetime of the particles, $t_{\rm rad}$, becoming comparable to some critical time (see, e.g., Tucker 1975). Assuming that the magnetic energy density equals the photon energy density $W_{\rm ph}$ (Blandford and Rees 1978), the radiative lifetime is given by:

$$t_{\rm rad} = 4 \times 10^{-4} L_{46}{}^{-3/4} t_{\rm var}{}^{3/2} (\nu_B/10^{15})^{-1/2}\ {\rm yr}\ , \quad (1)$$

where L_{46} is the luminosity in units of 10^{46} ergs s^{-1} and $t_{\rm var}$ the observed variability time scale in years. For $t_{\rm var} \sim 10^{-1}$ yr and $\nu_B \sim 10^{15}$ Hz, $t_{\rm rad} \sim 10^{-5}$ yr, much shorter than the variability time scale itself and than any plausible crossing time of the emission region. One should therefore invoke an acceleration process with time scale 10^{-5} yr operating in the whole emission region of size $R \sim ct_{\rm var} \sim 10^{17}$ cm. This may not be considered as a serious difficulty since the necessity of particle reacceleration has been pointed out on different grounds (e.g., Blandford and Rees 1978; Cavaliere and Morrison 1980). The possible relativistic bulk motion of the plasma toward the observer, which has been proposed to explain the BL Lac type objects (Blandford and Rees 1978), reduces the discrepancy discussed above introducing in equation (1) a factor $\delta^{7/2}$, where δ is the Doppler factor (see Königl 1981). A high value of δ is required ($\delta \sim 40$) in order to have the crossing time of the emission region, $t_{\rm cross} = \delta t_{\rm var}$, equal to the radiative lifetime.

An entirely different explanation for the spectral break is given in the jet model of Marscher (1980), where the difference in spectral shape below and above ν_B is due to the radiation coming from physically different regions (the accelerating and the free region) of the jet. In the steep part of the spectrum, higher frequencies originate at smaller distances from the nozzle which is the origin of the jet: therefore, time scales are expected to decrease with increasing frequencies, and lower frequencies are expected to be delayed with respect to higher frequencies. This model therefore accounts at least qualitatively not only for the overall spectrum but also for the different optical and X-ray variabilities (see Fig. 2). In this picture the optical brightening observed to occur about 3 months after the X-ray event could indeed be associated with it.

V. CONCLUSION

The violent X-ray activity exhibited by 3C 66A indicates that also in the X-ray band the amplitude of variations might distinguish BL Lac objects from quasars which typically fluctuate by 30%–40% over time scales of 6 months (Zamorani 1982).

Although the overall energy distribution resembles that predicted by synchro-Compton models, the probable lack of simultaneity between the X-ray and optical variations suggests that the apparent simplicity of the observed spectrum may hide superposed contributions from different emission regions, as schematized, for instance, in the jet model of Marscher (1980). Extensive campaigns for simultaneous observations over a wide frequency range are clearly essential for a progress in our understanding of BL Lac objects.

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