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# X-RAY OBSERVATIONS OF SIX BL LACERTAE FIELDS

D. MACCAGNI[1]
Istituto di Fisica Cosmica, CNR, Milano, Italy
AND
M. TARENGHI[1,2]
European Southern Observatory, Genève, Switzerland
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## ABSTRACT

We have observed six fields containing BL Lacertae objects with the Imaging Proportional Counter (IPC) of the *Einstein* Observatory. Five out of six BL Lacertae objects (3C 66 A, PKS 0548 − 322, 1400 + 162, 4C 14.60, and OY 091) were found to be soft X-ray sources. 3C 66 A was observed to vary by 25% on a time scale of approximately 53 hours. Eight other X-ray sources were detected in these fields, one of which is extended.
*Subject headings:* BL Lacertae objects — X-rays: sources

## I. INTRODUCTION

BL Lacertae objects have been suspected to be X-ray sources since Ricketts, Cooke, and Pounds (1976) tentatively identified an X-ray transient source at high galactic latitude with Markarian 421. This object was then included in the *Ariel 5* catalog (Cooke *et al.* 1978) and Markarian 501 in the 4U catalog (Forman *et al.* 1978). More positive identifications for these two objects were obtained by Marshall and Jernigan (1978) and Schwartz *et al.* (1978), respectively. Later on Markarian 421 was also detected in the low-energy band (Hearn, Marshall, and Jernigan 1979). At present, 15 BL Lacertae objects are known to be X-ray sources (Schwartz *et al.* 1979; Ku 1979).

In this paper we present the analysis of a first set of data we obtained by observing six BL Lacertae fields with the IPC instrument of the *Einstein* Observatory (Giacconi *et al.* 1979). The six objects were chosen because among the BL Lacertae sample known in 1978, they seemed to be associated with clusters or groups of galaxies. BL Lacertae objects are known to occur in elliptical galaxies (Ulrich *et al.* 1975; Disney, Peterson, and Rodgers 1974; Thuan, Oke, and Gunn 1975) and have been found in the centers of large, regular clusters of galaxies (Butcher *et al.* 1976; Craine, Tapia, and Tarenghi 1975). Their high luminosity in the far-UV can modify the physical conditions of the intracluster gas, or, alternatively, their optical, IR, and X-ray emission could be enhanced if the mechanism at work is accretion from a denser medium (Pringle, Rees, and Pacholczyk 1973).

## II. DATA ANALYSIS

All observations were carried out by pointing the axis of the X-ray telescope at the best known optical positions of the BL Lacertae object. All objects but one have by now been observed twice, generally at about a month interval. The data have been reduced by making use of the standard programs made available to Guest Observers at the Center for Astrophysics: we restricted our consideration to sources detected above 3.5 sigma significance level in the total energy band. Fluxes were determined in the energy range ∼0.2–3.5 keV, taking into account differences in instrumental gain for the different observations and fitting to all a power-law photon spectrum with index 1.5 and negligible absorption. For 3C 66 A and PKS 0548 − 322 the statistical significance we have is large enough to obtain spectral information as soon as spatial gain variations are known with sufficient accuracy. Time variabilities were searched for with different time bins compatible with the source statistics; a further check was made when variability indications were present by checking the arrival time of each photon to avoid possible instrumental effects due to the passage through the South Atlantic Anomaly.

## III. THE OBSERVATIONS

In Table 1 we give, for each BL Lacertae object we have observed, the magnitude range in the visible, the redshift $z$ when known, the observation dates and lengths, the discrepancy in right ascension and declination between the optical and the X-ray position, the X-ray flux, and the X-ray luminosity of the object when the redshift is available. All X-ray positions coincide within about 0′.5 with the optical positions: this should be compared with the 1′ radius error circle positional accuracy of the Imaging Proportional Counter; X-ray fluxes span about two orders of magnitude.

In Table 2 we list the point sources we found in the six fields. For each source we give the observation dates, the 1950 coordinates of the X-ray position, the X-ray flux, the possible identification with the redshift $z$ when known and the corresponding X-ray luminosity, and, when no identification is evident, the plate where the optical field is reproduced.

[1] *Einstein* Guest Observer.
[2] On leave from Istituto di Fisica Cosmica, CNR, Milano, Italy.

TABLE 1

| Source Name | $m_V$[a] | $z$ | Observation Date(s) | Observation Length (s) | $\Delta\alpha$ | $\Delta\delta$ | $F_x$(ergs cm$^{-2}$ s$^{-1}$)[b] | $L_x$(ergs s$^{-1}$)[b] |
|---|---|---|---|---|---|---|---|---|
| 3C 66 A | 15.2–15.8 | 0.434[c] | 1979 Jul 29 | 1679 | ... | 23″ | $(1.50 \pm 0.05) \times 10^{-11}$ | $1.8 \times 10^{46}$ |
| | | | 1979 Aug 25/27 | 4581 | ... | 23″ | $(9.20 \pm 0.23) \times 10^{-12}$ | $1.1 \times 10^{46}$ |
| PKS 0548−322 | 15.5 | 0.069[d] | 1979 Feb 28 | 2417 | 1$^s$ | 30″ | $(5.52 \pm 0.09) \times 10^{-11}$ | $1.2 \times 10^{45}$ |
| | | | 1979 Mar 26 | 696 | ... | 26″ | $(5.59 \pm 0.17) \times 10^{-11}$ | $1.2 \times 10^{45}$ |
| 1400+162 | 17.4 | 0.244[e] | 1979 Jun 29 | 1252 | 2$^s$ | 22″ | $(9.89 \pm 2.00) \times 10^{-13}$ | $3.2 \times 10^{44}$ |
| | | | 1979 Jul 29 | 1638 | ... | 1″ | $(1.28 \pm 0.19) \times 10^{-12}$ | $4.1 \times 10^{44}$ |
| 4C 14.60 | 17.2–17.5 | | 1979 Feb 2 | 5652 | ... | 25″ | $(7.64 \pm 1.16) \times 10^{-13}$ | ... |
| | | | 1979 Aug 14/28 | 3787 | 1$^s$ | 25″ | $(1.11 \pm 0.12) \times 10^{-12}$ | ... |
| OY 091 | 16.4–16.7 | | 1979 May 24 | 1801 | ... | 34″ | $(6.51 \pm 0.93) \times 10^{-13}$ | ... |
| | | | 1979 Jun 21 | 1079 | 1$^s$ | 47″ | $(8.18 \pm 1.45) \times 10^{-13}$ | ... |
| PKS 2335+03 | 17.8–18.6 | | 1979 Jun 15 | 1675 | ... | ... | $<5.11 \times 10^{-13}$ | ... |

[a] Craine 1977.
[b] Between approximately 0.2 and 3.5 keV; $H_0 = 50$ km Mpc$^{-1}$ s$^{-1}$, $q_0 = 0$.
[c] Miller *et al.* 1978.
[d] Fosbury and Disney 1976.
[e] Baldwin *et al.* 1977.

## IV. THE SOURCES IN THE SIX FIELDS

### *a*) *The Field of 3C 66 A*

The radio source 3C 66 has two components: a compact one, 3C 66 A, identified with the BL Lacertae object (Wills and Wills 1974) surrounded by a storm of galaxies (Butcher *et al.* 1976; not visible on the Palomar Sky Survey Prints), and a wide-angle radio tail galaxy, 3C 66 B (Northover 1973).

This field shows a complex X-ray image, containing three point sources and one extended source. Figure 1 (Plate 2) shows the X-ray image of the whole field, and Figure 2 (Plate 3) the smoothed X-ray isocontours of the region of extended X-ray emission superposed on an ITT 140 mm image tube plate obtained with the 90 inch Steward telescope. The identification of the two point sources with the optical counterparts of 3C 66 A and 3C 66 B is evident.

The BL Lac object 3C 66 A has an optical polarization varying between 11 and 14% (Kinman 1976) and $V$ magnitudes ranging from 14.98 to 15.8 (Tapia, Craine, and Johnson 1976; Kinman 1976). Miller and McGimsey (1978) have reported a possible variation of 0.06 mag on a time scale of 3 minutes. We observed 3C 66 A on 1979 July 29 and on 1979 August 25 and 27. The July and August data are not directly comparable because the IPC gain was different, while the August observations were performed at constant gain. In all cases, 3C 66 A was at the center of the IPC field. The counting rate (see Fig. 3) was $0.39 \pm 0.02$ and $0.41 \pm 0.02$ on August 25 and decreased to $0.29 \pm 0.01$ 53 hours later on August 27, thus showing a 25% variation.

Of particular interest is the X-ray detection of 3C 66 B. We would like to note that this radio galaxy (possibly a cD galaxy) shows a bent optical jet (Butcher, van Bruegel, and Miley 1980) similar to that of M87. Furthermore the X-ray source identified with 3C 66 B is embedded in an extended source stretching southeast of 3C 66 A for about 10′ (see Fig. 2). This extended emission is most plausibly associated with a group of galaxies, themselves representing a subcondensation in the Abell cluster 347, the center of which is about 1° to the south and to which the radio galaxy 3C 66 B also belongs (Hintzen, Oegerle, and Scott 1978). Assuming a volume of $2 \times 10^{71}$ cm$^3$, the mass of the X-ray emitting gas (Ginzburg 1978) is $2.8 \times 10^{11} M_\odot$, the luminosity being $3 \times 10^{42}$ ergs s$^{-1}$. The gas density is sufficient to confine by ram pressure the components of 3C 66 B, assuming the energy densities given by Northover (1973) and the velocity dispersion measured by Hintzen, Oegerle, and Scott (1978).

When better calibrations of the IPC instrument and the new forthcoming observation of this field are available, we will be able to tell whether the X-ray spectrum of 3C 66 A is absorbed below about 1.5 keV by the gas present along the line of sight in this group of galaxies. The improved statistics will also allow us to verify an apparent asymmetry (see Figs. 1 and 2) of the X-ray source associated with 3C 66 B in the direction of the optical and radio jet.

There is no obvious identification for source no. 2 (Table 2). In spite of the low galactic latitude ($b = 16°$; $A_V = 1.3$), a large number of faint galaxies are visible in this field (Fig. 4 [Pl. 4, 5]), one of which falls inside the 1′ radius error circle of the X-ray position.

### *b*) *The Field of PKS 0548−322*

This object was first thought to belong to a small cluster of galaxies (Disney 1974), but the redshift derived from the absorption lines of a population of late-type stars in the halo surrounding it makes this possibility unlikely (Fosbury and Disney 1976). It was identified as an X-ray source by the scanning modulation collimator experiment on *HEAO 1* (Schwartz *et al.* 1979). The flux we measure is consistent with the spectral measurements of Riegier, Agrawal, and Mushotzky (1979) between 0.15 and 24 keV. Our observations, about 1 month apart, do not show any significant variation.

Source 3 (Table 2) has no conspicuous candidate for an identification. In this field (Fig. 4) an equal number of galaxies and stars are visible.

PLATE 2

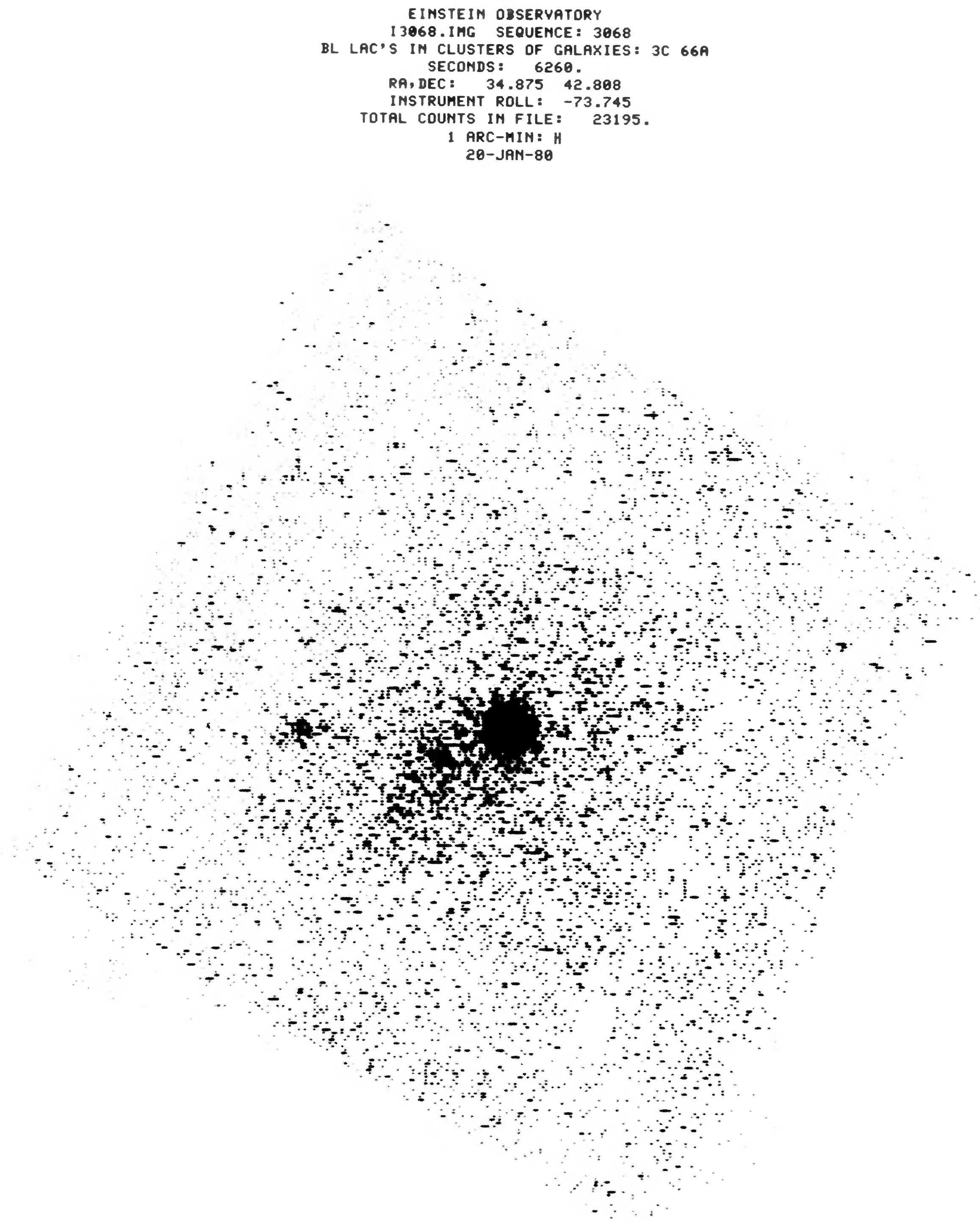


FIG. 1.—The X-ray image of the field surrounding 3C 66 A. The two observations of July 29 and August 25/27, 1979 have been added together. N is at the top and E to the left.

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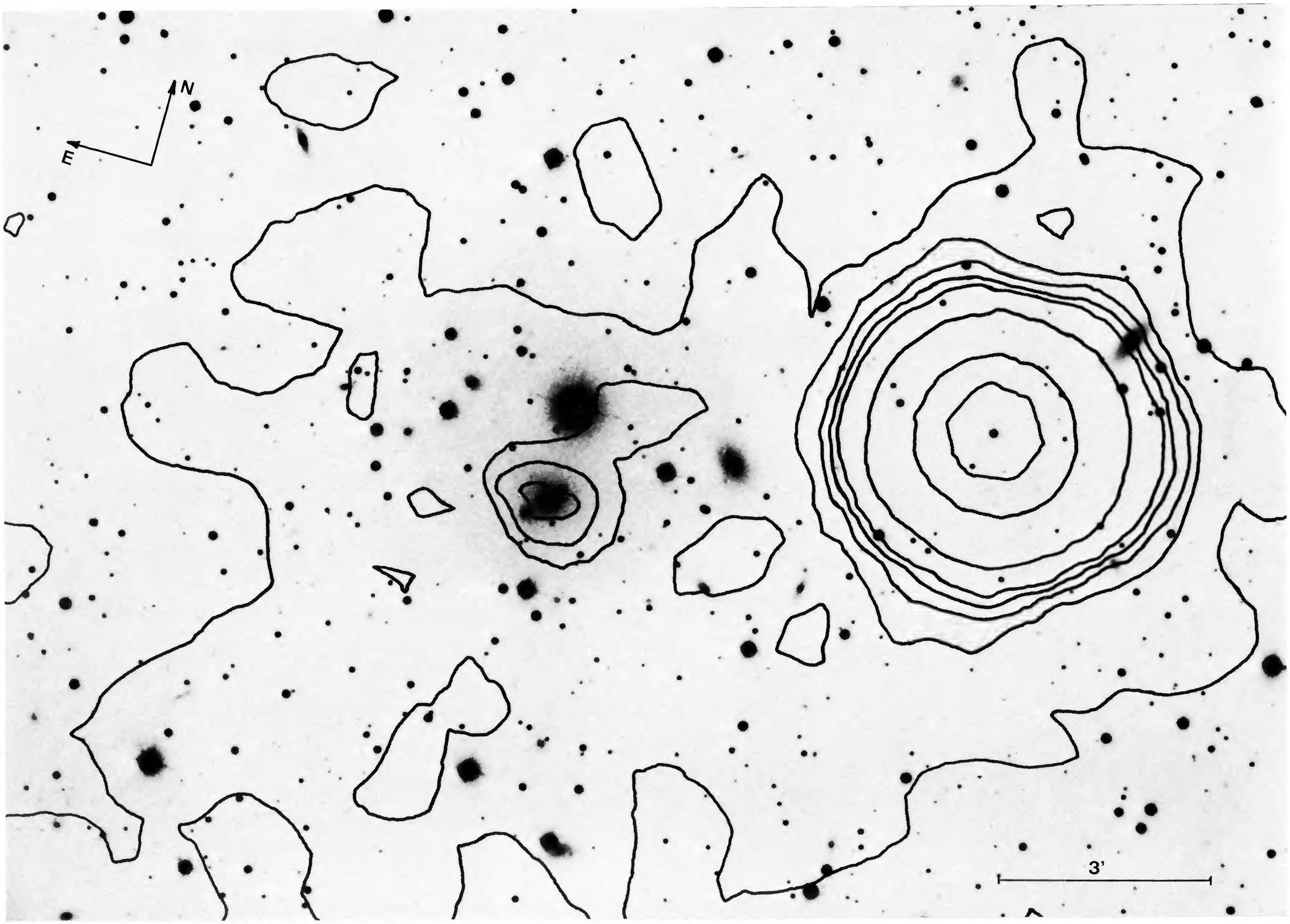


FIG. 2.—X-ray isocontours of part of the field of Plate 1, showing 3C 66 A (brightest source on the right) and 3C 66 B (fainter source in the middle) embedded in a region of extended emission, superposed on an ITT 140 mm image tube plate obtained with the 90 inch Steward telescope. The first contour level is 2 times the background and 50 times below the peak level.

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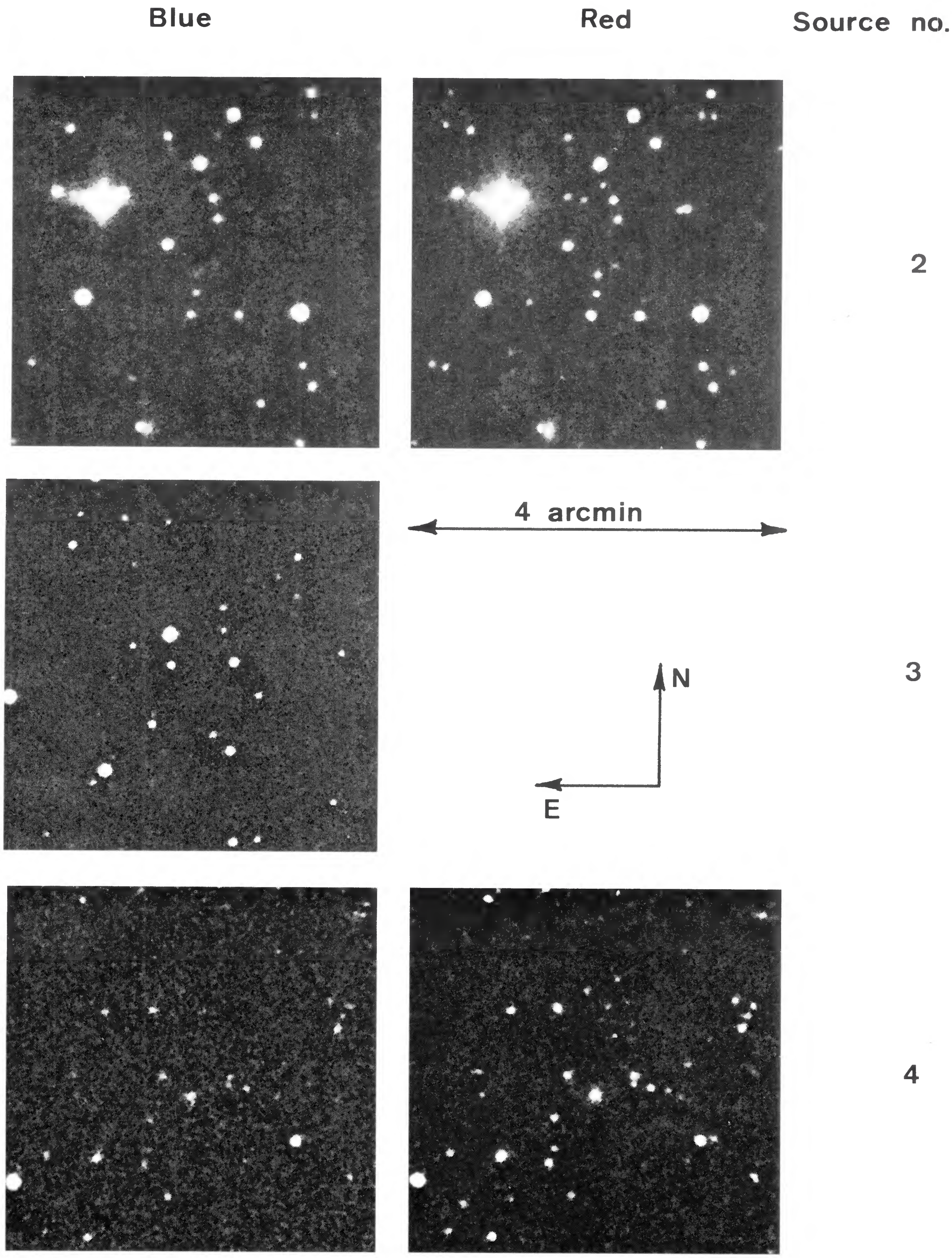


FIG. 4.—4′ × 4′ blue and red Palomar Sky Survey print (quick blue ESO survey plate for source 3) reproductions of the fields containing X-ray sources for which no straightforward identification is available. The best X-ray position coincides with the center of each field, and the error circle is 1′ radius. See Table 2 for cross-references.

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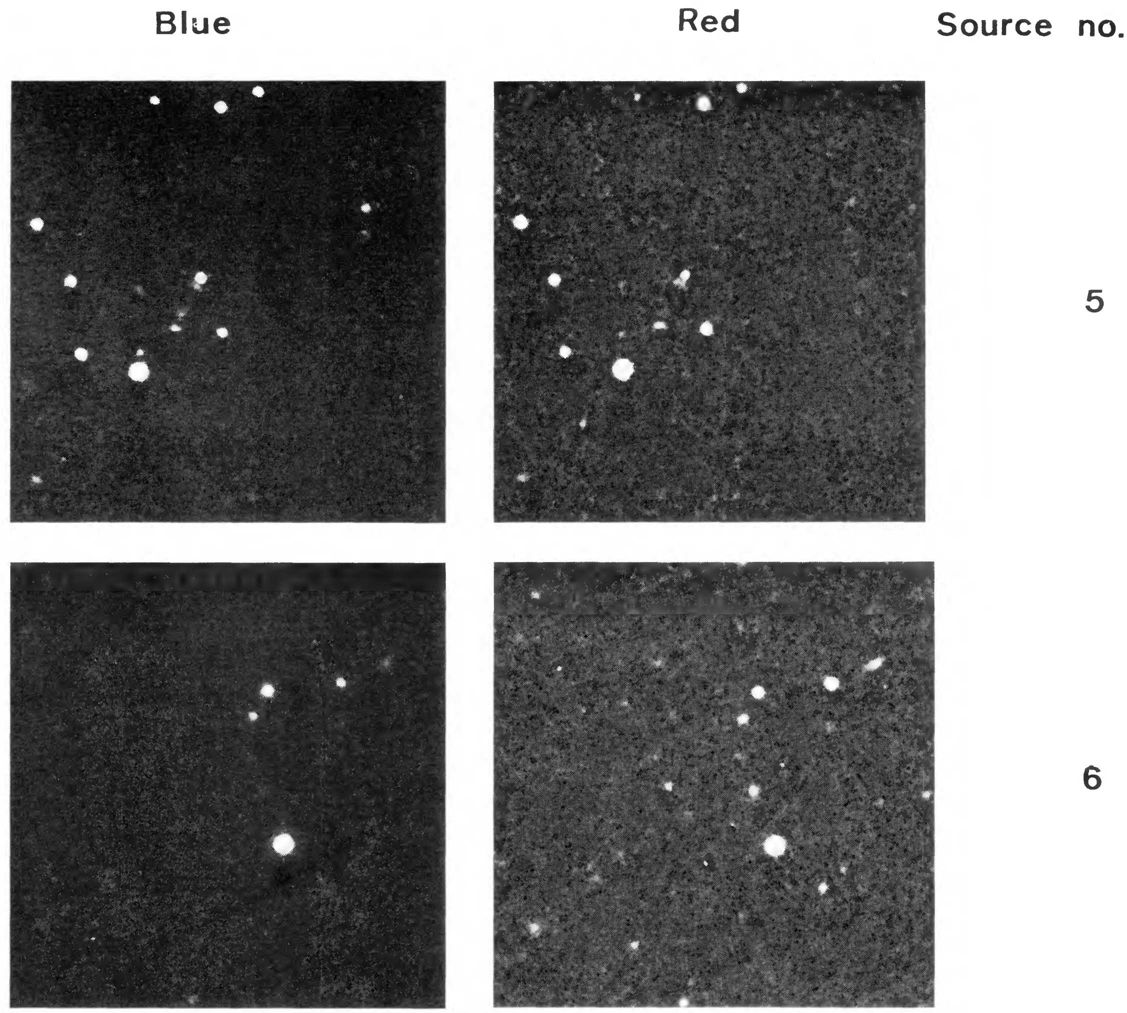


FIG. 4.—*Continued*

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TABLE 2

| Source Number | Observation Date(s) | 1950 Position $\alpha$ | 1950 Position $\delta$ | $F_x$(ergs cm$^{-2}$ s$^{-1}$)[a] | Identification | $z$ | $L_x$(ergs s$^{-1}$)[a] | Notes |
|---|---|---|---|---|---|---|---|---|
| 1 ........................ | 1979 Jul 29 | $02^h20^m03^s$ | 42°46′01″ | $(2.12 \pm 0.45) \times 10^{-13}$ | 3C 66 B | 0.0215[b] | $4.0 \times 10^{41}$ | Figs. 1, 2 |
| | 1979 Aug 25/27 | | | | | | | |
| 2 ........................ | 1979 Jul 29 | 02 21 06 | 42 48 00 | $(5.62 \pm 1.05) \times 10^{-13}$ | ... | ... | ... | Figs. 1, 4 |
| | 1979 Aug 25/27 | | | | | | | |
| 3 ........................ | 1979 Feb 28 | 05 49 29 | −32 07 09 | $(4.04 \pm 0.69) \times 10^{-13}$ | ... | ... | ... | Fig. 4 |
| | 1979 Mar 26 | | | | | | | |
| 4 ........................ | 1979 Jun 29 | 14 01 37 | 15 59 35 | $(1.15 \pm 0.36) \times 10^{-12}$ | Abell 1852 | 0.137[c] | $1.3 \times 10^{44}$ | Fig. 4 |
| | 1979 Jul 29 | 14 01 35 | 15 58 41 | $(1.83 \pm 0.37) \times 10^{-12}$ | | | | |
| 5 ........................ | 1979 Jun 29 | ... | ... | $<6.6 \times 10^{-13}$ | ... | ... | ... | Fig. 4 |
| | 1979 Jul 29 | 13 59 23 | 16 05 48 | $(9.10 \pm 2.46) \times 10^{-13}$ | ... | ... | ... | |
| 6 ........................ | 1979 May 24 | 22 54 12 | 07 11 53 | $(1.59 \pm 0.23) \times 10^{-12}$ | ... | ... | ... | Fig. 4 |
| | 1979 Jun 21 | ... | ... | $<8.0 \times 10^{-13}$ | ... | ... | ... | |
| 7 ........................ | 1979 Jun 15 | 23 35 15 | 03 05 13 | $(7.01 \pm 1.47) \times 10^{-13}$ | Star SAO 128293 | ... | ... | Spectral type F5 |

[a] Between approximately 0.2 and 3.5 keV; $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$; $q_0 = 0$.
[b] Hintzen *et al.* 1978.
[c] Leir and van den Bergh 1977.



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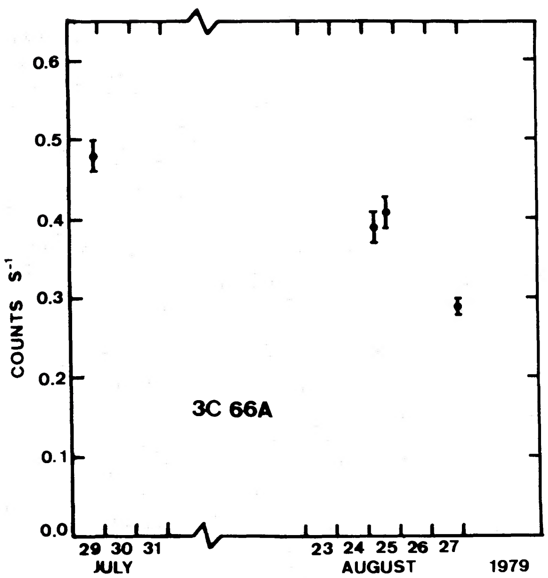


FIG. 3.—3C 66 A time history. The IPC gain was constant during the August observations but different from the July one.

### *c*) *The Field of 1400+162*

Baldwin *et al.* (1977) identified the extended radio source 1400+162 with a BL Lacertae object with a redshift in agreement with that of an adjacent group of galaxies. The infrared-visual continuum increased by about 50% between 1976 and 1977 (O'Dell *et al.* 1978). It is a weak X-ray source, and no variations above 50% were detected between 1979 June and July.

The X-ray source 4 (Table 2) can be identified with the cluster of galaxies Abell 1852, distance class 5 and richness class 1, Bautz-Morgan type III (Leir and van den Bergh 1977) (Fig. 4). The flux we measure is such that this cluster would have escaped detection by either *Uhuru* or *Ariel 5*.

We detected a third source in this field (No. 5 in Table 2) only during the 1979 July 29 observation; the upper limit we can derive for the observation of one month earlier is however only one sigma below the measured flux and therefore we cannot state that this source belongs to the class of variable X-ray sources. The X-ray position is close to a group of galaxies with magnitudes similar to the ones belonging to Abell 1852 (Fig. 4). Inspection of a larger area around the positions of these two X-ray sources suggests the existence of several condensations of galaxies, perhaps a supercluster.

### *d*) *The Field of 4C 14.60*

This BL Lacertae object was also studied by Kinman (1976). It appears stellar and superposed on a cluster of faint galaxies (Craine, Tapia, and Tarenghi 1975). It is definitely variable in optical by as much as about 3 mag (Pollock 1975; Wills and Wills 1976). We observed it twice, in 1979 February and August, but no variations in its X-ray flux were detected. No other sources were detected in this field.

### *e*) *The Field of OY 091*

Unlike 4C 14.60, this object has a nonstellar appearance (Craine, Tapia, and Tarenghi 1975), but it also is surrounded by a large number of galaxies. In X-rays, it is the faintest object detected; it did not show any flux variation between 1979 May 24 and June 21.

A definitely variable X-ray source (No. 6 in Table 2) is present in this field: the upper limit for June 21 is 3.5 sigma below the measured flux on May 24. Two galaxies (Fig. 4) are the closest objects to the center of the X-ray error circle. Both are extremely faint on the blue Palomar Sky Survey Print; the southern one shows, however, a very red color.

### *f*) *The Field of PKS 2335+03*

This object was observed by *Einstein* only once on 1979 June 25, and it was not detected. It is also the faintest optically and, like PKS 0548−322 and OY 091, has a nonstellar appearance; it is surrounded by several faint galaxies (Craine, Tapia, and Tarenghi 1975).

In this field we detected an X-ray source which we identify with the 8th mag F5 star, SAO 128293.

## V. CONCLUSIONS

These observations confirm that BL Lacertae objects are by now a class of observable X-ray sources. With the caution necessary when dealing with highly variable objects for which no simultaneous observations are yet available, we can say that a loose correlation exists between the 0.2–3.5 keV flux and the visual magnitude, the faintest objects in the visible being also the weakest X-ray sources.

Time variability is an important clue in understanding the nature of BL Lacertae objects, besides being one of their defining features. Unfortunately, at X-ray energies, only a few objects have been observed to be variable, probably because their time scales (e.g., days to months) are not easily monitored with the present day X-ray telescope schedules. In the case of 3C 66 A, the 53 hour variability we found determines a size of the emission region of $10^{15}$–$10^{16}$ cm. This is a few times the Schwarzschild radius of a black hole of $10^9$–$10^{10}$ $M_\odot$, accretion onto which can explain the X-ray luminosity observed (Strittmatter 1979).

The possibility that massive black holes could be the energy source of BL Lacertae objects adds to the similarity between these objects and QSOs and Seyfert galaxies, provided we meet two further requirements: little material around the central object to explain the absence of strong emission lines; a specific ordered geometry to provide for the optical polarization which, at least in certain cases, could arise from the same region as the X-rays in view of the similar time scale variations.

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DARIO MACCAGNI: Istituto di Fisica Cosmica, CNR, via Bassini 15, I-20133 Milano, Italy

MASSIMO TARENGHI: European Southern Observatory, c/o CERN, CH-1211 Genève 23, Switzerland