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The radio and optical structure of 3C 66B

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Abstract. We report new, high-resolution radio observations of the jet in 3C 66B. The filaments in the optical jet seen in the HST image of Macchetto et al. are also visible in the radio image. The structure of the radio jet is complex and filamentary beyond the brightest knot. It is consistent with the HST image, which appears to consist of a central kinked tube containing oblique emission features, together with a surrounding shell of filaments. The radio-optical spectral index is remarkably constant along and across the jet.

Key words: galaxies: active – galaxies: jets – galaxies: individual: 3C 66B

1. Introduction

A few active galactic nuclei (AGN) contain optical jets extending from the core of the object and projecting into the intergalactic medium. Since the development of radio interferometry it has become clear that jets are also a common phenomenon in radio-loud AGN. However, the number of jets that we can study in both optical and radio wavebands remains small. The most famous of these jets are associated with the quasar 3C 273 (see e.g. Fraix-Burnet & Nieto 1989) and the radio galaxy M87. Further discoveries were made in the highly active galaxy PKS 0521–36 (Keel 1986; Sparks et al. 1990) and the galaxy 3C 66B (Butcher et al. 1980), the subject of this paper.

More recently the Hubble Space Telescope (HST) has offered us the prospect of examining the optical jets at resolutions similar to those obtained with radio interfero-

meters: such resolutions are impossible to achieve with ground-based optical telescopes. Macchetto et al. (1991a) give a review of the progress made with HST observations of three radio-optical jets: PKS 0521–36, M87 and 3C 66B. The agreement of the structure of the optical jet of M87 with the best radio map at comparable resolution (Owen et al. 1989) is impressive. It strongly supports the view that the optical jet is synchrotron radiation, and the detailed agreement of the two structures allows one to set limits, via the synchrotron loss timescale, of the time between the acceleration of the electrons and our seeing the synchrotron emission from them. The conclusion is either that local reacceleration is taking place, or that the electrons are conducted through a channel with very low synchrotron losses.

3C 66B is a radio galaxy at a redshift of 0.0215 (Matthews et al. 1964). (We assume a Hubble constant $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$ throughout this paper, for which $1'' = 400 \text{ pc}$). The jet in 3C 66B is smaller in angular size than that of M87 by a factor of 2. It was first seen by Butcher et al. (1980) and later investigated by Fraix-Burnet et al. (1989, 1991). The jet emission is almost certainly synchrotron radiation and shows no trace of line emission (Fraix-Burnet et al. 1989). An image taken with the Faint Object Camera (FOC) on the HST centred at $3100 \text{ \AA}$ and with a resolution of $0''.1$ after deconvolution was published by Macchetto et al. (1991b). Macchetto et al. found a double filament extending between $4''$ and $7''$ from the nucleus, kinked at about $6''$: at this distance from the core the two filaments are particularly noticeable. The best available comparison radio images were taken with the NRAO Very Large Array (VLA) at 5 GHz and a resolution of $0''.35$ (Leahy et al. 1986), which was not sufficient to show equivalent filamentary structure, although the smoothed HST image strongly resembled the VLA radio data. In order to make a more detailed comparison, we have therefore obtained new high-sensitivity VLA observations at 15 GHz (resolution $\approx 0''.2$).

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2. Observations

Observations of 3C 66B were made at two epochs. The higher-resolution data were taken using the VLA in A array on 1991 July 25. 10 hours of observations were obtained, although the loss of a significant number of antennas and calibration overheads reduced the effective integration time on 3C 66B to under 6 hours. Lower resolution B array data were taken on 1992 January 18. On this occasion 4 hours of observations were obtained.

The data were calibrated using the point source 0133+476 as primary calibrator and 3C 48 for flux bootstrapping (Baars et al. 1977). The flux scales of the two observations were tied together using the shortest (0–40 k λ) baselines of 3C 138, since no observation of 3C 48 was available for the A-array data and 3C 138 was observed on both occasions. Reduction followed standard VLA calibration procedure and was done using the NRAO AIPS package. Both observations were self-calibrated using a point source as an initial model, and several iterations of phase self-calibration and CLEANing were followed by an amplitude self-calibration step. A 35 mJy point source was subtracted from the A-array dataset to compensate for core variation between 1991 July and 1992 January. The A-array u–v data were then self-calibrated to the B-array map and the data sets were combined and CLEANed. After final CLEANing, there is a “negative bowl” around the source and positive artefacts 8" apart around it, corresponding to the missing u–v coverage at the centre of the u–v plane: attempts to remove this by specifying zerospacing fluxes were not successful. We hope to obtain shorter-baseline data to correct this, but it should not affect the results presented here.

The FOC/HST images that are available include the two 1500 s exposures using the F320W filter (λ 3100 Å), described by Macchetto et al. (1991b), a similar pair of exposures obtained at the same time using the F430W filter (λ 4100 Å) and a UV sequence of four 1200 s F220W (λ 2300 Å) exposures. The F430W and F220W images are of low signal-to-noise, but on each image the nucleus and jet are clearly visible.

3. Radio structure of 3C 66B

The final cleaned image is shown in Fig. 1. This is a naturally weighted image with a circular beam of 0".25, nearly equivalent to the fit to the centre of the dirty beam. Up to a factor of 2 higher resolution can be achieved with uniform weighting but the signal-to-noise suffers accordingly and much of the filamentary structure is resolved out. Although the resolution of the map in Fig. 1 is only a factor of 30% better than that of Leahy et al. (1986), it has a lower rms noise (35 μ Jy close to the source, or about 30% above the theoretical thermal noise). Also the map appears to

have a resolution just better than a critical level at which much interesting structure becomes visible.

The following features can be seen in the map:

- (a) 0"–2". There are two small knots close at distances of 1".3 and 1".8 from the core. These are also present in the Leahy et al. map.
- (b) 2"–4".5. A sudden broadening of the jet sets in at 2" from the core, along an almost conical opening. This coincides with the brightening seen on the HST images. A diversion of the flow appears to take place in the brightest knot, about 2".5 from the core. At this point the filamentary structure around the jet begins to appear. A little further on (3"–4") the main ridge of the jet breaks into blobs and filaments of radio emission. Note particularly the strong filament that breaks away to the northwest at 4".5 from the core.
- (c) 4".5–6".8. This region is the northernmost that is clearly visible on Macchetto et al.'s HST image. The shape of the central emission resembles a southeast-facing W, with bright blobs of emission at the three corners of the W. Extending from the top of the W we see the two strands that are also visible in the HST image. The emission structure is evidently complex but it is tempting to regard these strands, together with the arms of the W that lie parallel to them, as components of a tube of emission, and the perpendicular arms of the W as helices of emission climbing around the tube.
- (d) 6".8–9". In this region the extended filamentary structure extends over a region of at least 2".5 perpendicular to the jet and probably more, as the emission in our map fades into noise rather than coming to a definite end. Again we see that the jet resolves into blobs and filaments. A particularly intriguing structure is seen at 7"–8" from the core. Here the jet resolves into two emission blobs, connected by filaments which stretch away into the extended filamentary structure. A ring filament with a diameter of 0".6 stretches to the south of the main jet.
- (e) *Beyond 9"*. In the extended region of the jet we lose too much surface brightness sensitivity to say any more than that the filamentary nature of the jet continues.

Figure 2 shows the HST map of Macchetto et al. (1991b) together with the radio map: the two maps have been registered to the same plate scale and centre. The HST map has been smoothed so that a Gaussian fitted to the point in the northwest corner of the map has the same beam area as the resolution of the radio map. The edge of the map is not reliable in the HST image because of a combination of the edge of the field and the deconvolution process. We now discuss the similarities and differences in more detail.

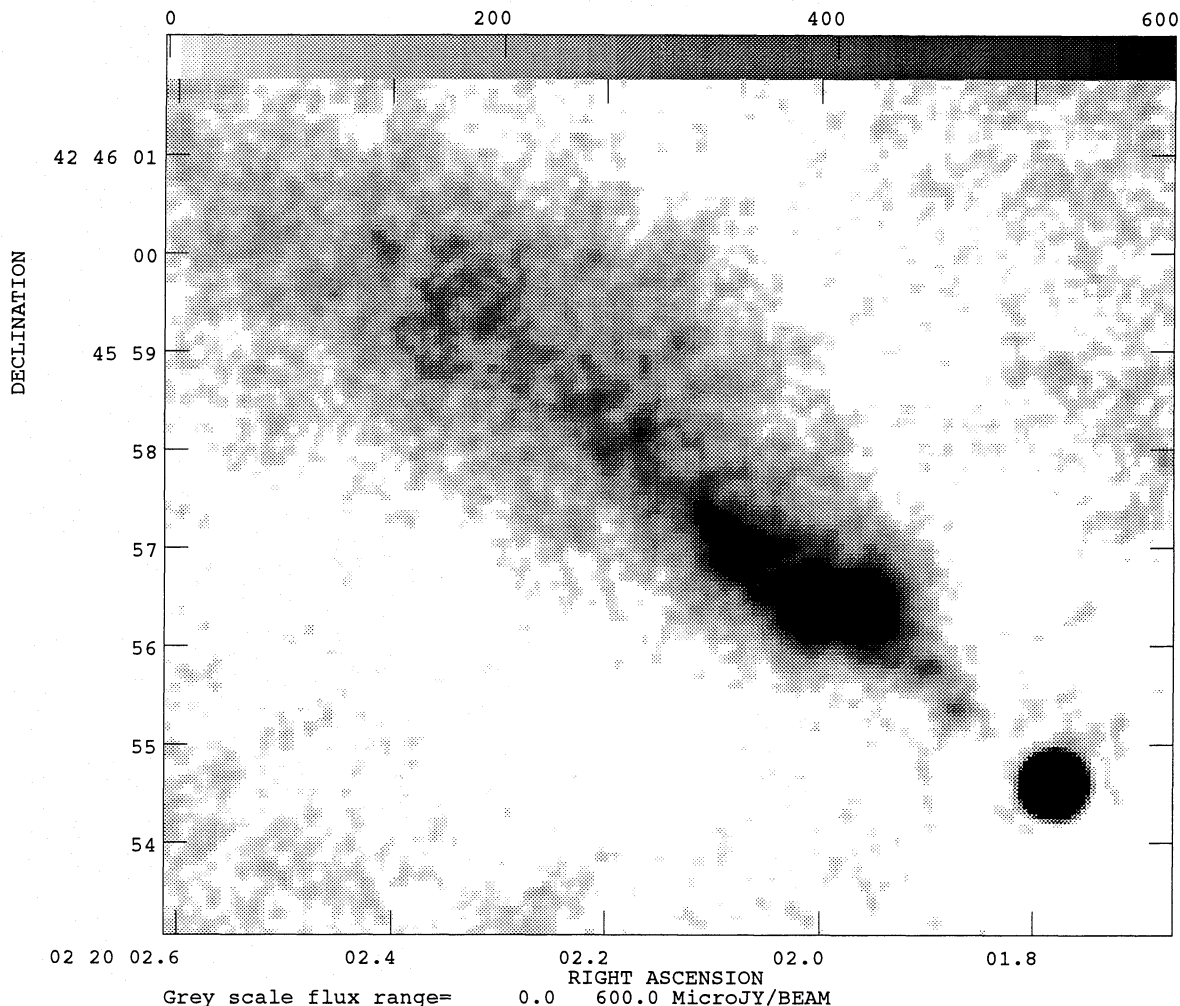


Fig. 1. Grey-scale of the radio image, plotted between 0 (white level) and 600 μJy (black level). The core flux is 172 mJy, in agreement with the values of Leahy et al. (1986) assuming a flat radio spectral index

4. Discussion

4.1. The radio structure and theoretical models

There are noticeable similarities in the optical and radio structures of the jet, as can be seen from Fig. 2. First, considerable filamentary structure is present in both maps, much of which runs perpendicular to the jet direction. Second, the double strands seen by Macchetto et al. (1991 b) are just visible in at least one part of the radio map (between $4''.5$ and $6''.8$ from the core). The fact that the same overall structure is seen in these two maps at different wavelengths produced using different deconvolution procedures suggests that both maps are basically reliable. In particular, features seen on both maps are likely to be real and not artefacts of the deconvolution process.

The major new emphasis we make, based on the comparison of the radio and optical data, is that as well as containing double structure extending along the jet, 3C 66B

also contains a considerable amount of structure perpendicular to the jet: this structure appears to us to consist of bars across the jet that are visible in both the radio and optical maps. These are consistent, for instance, with a two-dimensional projection of a helical jet structure. In their study of M 87, Owen et al. (1989) discussed a similar picture for the M 87 jet in which the emission was produced in helices winding up the jet and having pitch angles of 30° and upwards. In addition we see more lateral features further up the jet which fell outside the FOC field of view, together with more filamentary structure hinted at in the previous radio observations of Leahy et al. and suggested by the HST image. How can we use this extra structure to support or contradict theoretical models of the nature of the source?

In 1985 Königl & Choudhuri proposed a model in which the observed properties of jets were determined by a magnetic field configuration for which $\nabla \times \mathbf{B} = \mu \mathbf{B}$. They proposed that the magnetic field was made up of two

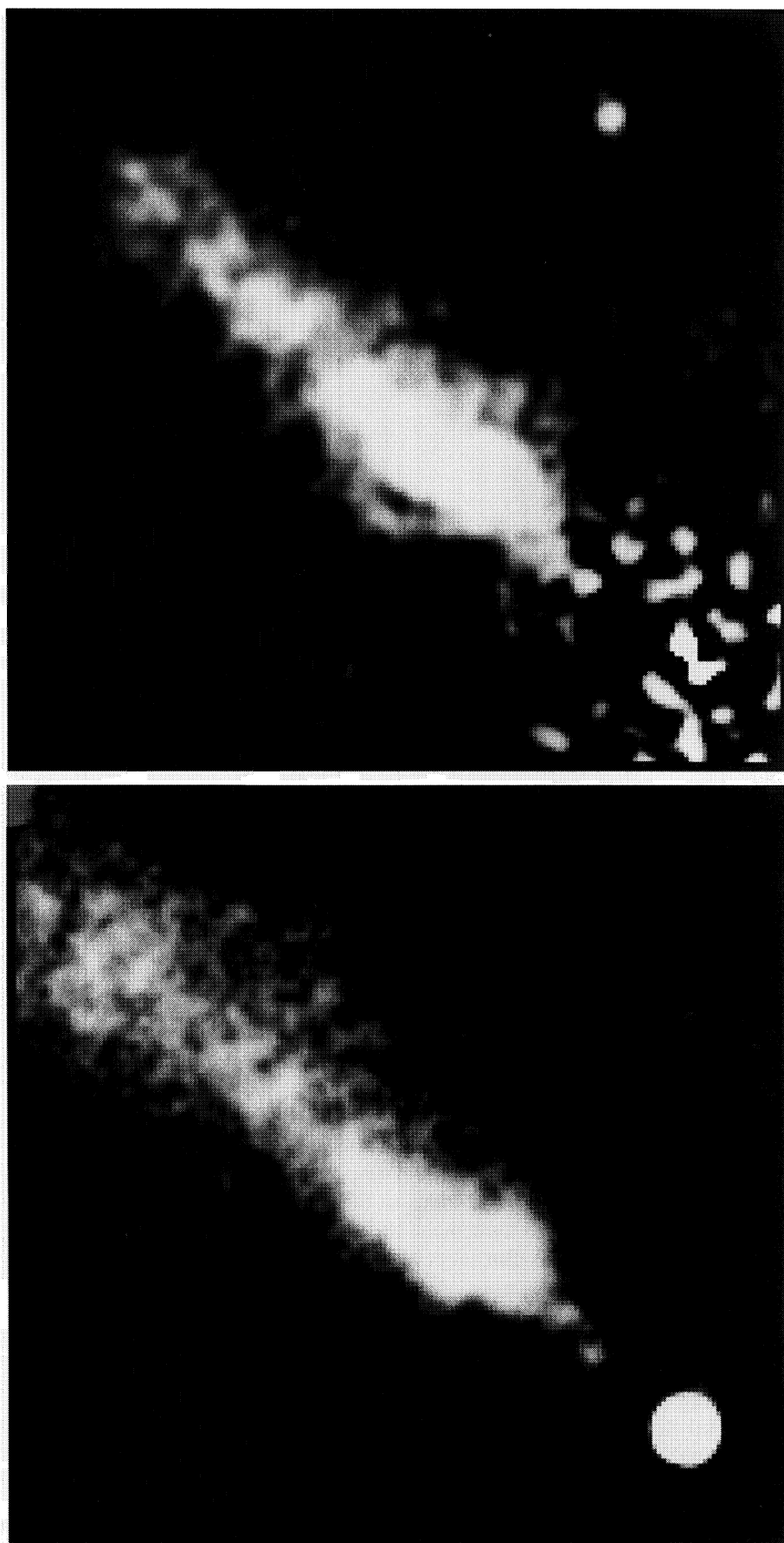


Fig. 2. The optical and radio maps of 3C 66B. On this grey-scale, points with a spectral index of -0.84 between 15 GHz and $3100\text{ \AA}$ would have equal brightness on the two images. The apparent dissimilarity towards the northwestern corner is probably due to the limited field of view of the FOC

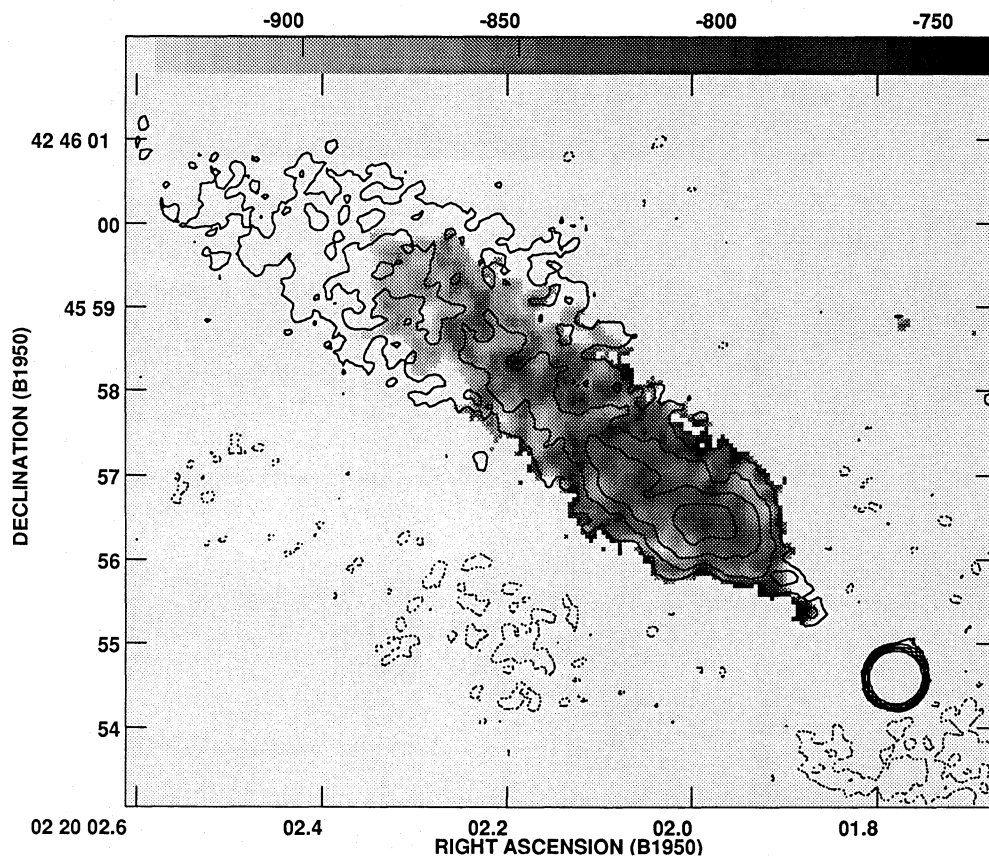


Fig. 3. The two-point spectral index between 15 GHz and 3000 Å, plotted as a grey-scale between spectral indices of -0.74 (black level) and -0.94 (white level). The bar gives the calibration of grey scale in units of spectral index $\times 1000$. Except towards the edge of the optical field of view, the index appears constant to within ± 0.05 everywhere in the jet. Contours are plotted at $150 \mu\text{Jy} \times (-1, 1, 2, 4, 8, 16)$

components: an axially symmetric component and a helical component. They used this to account for knots in the jet, and also to predict (and quantify the spatial wavelength of) wiggles in jets, with particular application to the jet in NGC 6251 (Perley et al. 1984). This model was invoked by Macchetto et al. as a possible explanation of the double-stranded optical structure. It has also been previously called upon to account for the structure and polarization of the bright radio jet in 0800 + 608 (Jackson et al. 1990). Our immediate impression is that the new results provide some support for this model. Particularly in the $4''.5$ – $6''.8$ section of the jet, there are some resemblances between the synchrotron emission and Königl & Choudhuri's twisted magnetic field configuration. Moreover, we can use the structure of the jet in this region to estimate the ratio of the helix pitch to the jet radius and find a value of approximately 2, in agreement with the model prediction.

4.2. Deductions from the spectral index map

The radio flux in the part of the jet that is also seen by the HST is about 47 mJy: the optical jet has a total flux of $6.25 \mu\text{Jy}$, giving a two-point spectral index of slightly less than -0.8 ($F_\nu \propto \gamma^\alpha$). The spectral index map (Fig. 3) shows a grey-scale of the spectral index between 15 GHz and 3200 Å, together with some contours of the radio emission.

The grey-scale has been blanked at 3σ in both the radio and optical maps. We find a spectral index of between -0.8 and -0.85 , in general agreement with the work of Fraix-Burnet et al. (1991), except that we do not find a significantly steeper spectral index just to the north of the brightest knot in the jet (Fraix-Burnet et al.'s knot C). In fact, apart from minor (and marginally significant) fluctuations, the spectral index is the same along and across the jet at this resolution of ≈ 100 pc. Figure 4 shows the flux distribution in the 15 GHz and 3200 Å maps over a slice along the ridge line of the jet.

Within the optical/UV region, we measure fluxes of $3.7 \mu\text{Jy}$, $6.2 \mu\text{Jy}$ and $8.0 \mu\text{Jy}$ ($\pm 25\%$ in each case) at 2300 Å, 3100 Å and 4100 Å respectively, leading to an estimate of the spectral index in the optical of about -1.4 . This is in rough agreement with the blue optical spectral indices of Fraix-Burnet et al. (1991).

4.3. Acceleration of the electrons

Macchetto et al. (1991b) pointed out that the synchrotron lifetime of the electrons was considerably shorter than the light travel time along the jet, assuming a standard equipartition magnetic field. This implies that either local reacceleration of particles is required or a low-magnetic field channel is necessary in order to transport electrons

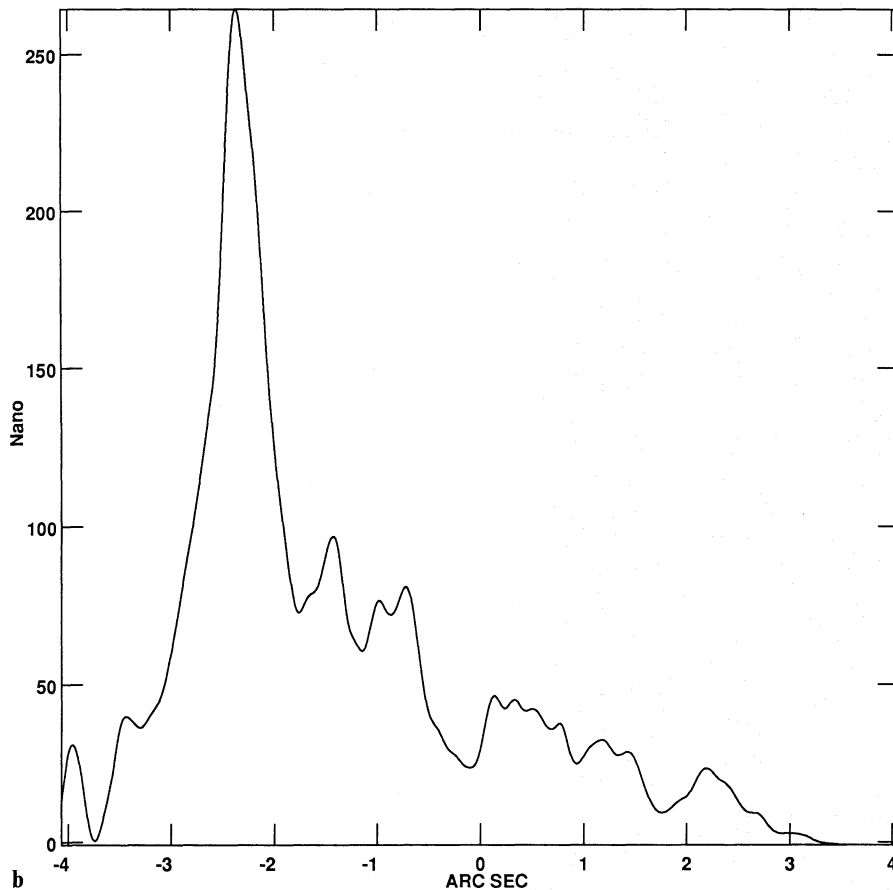
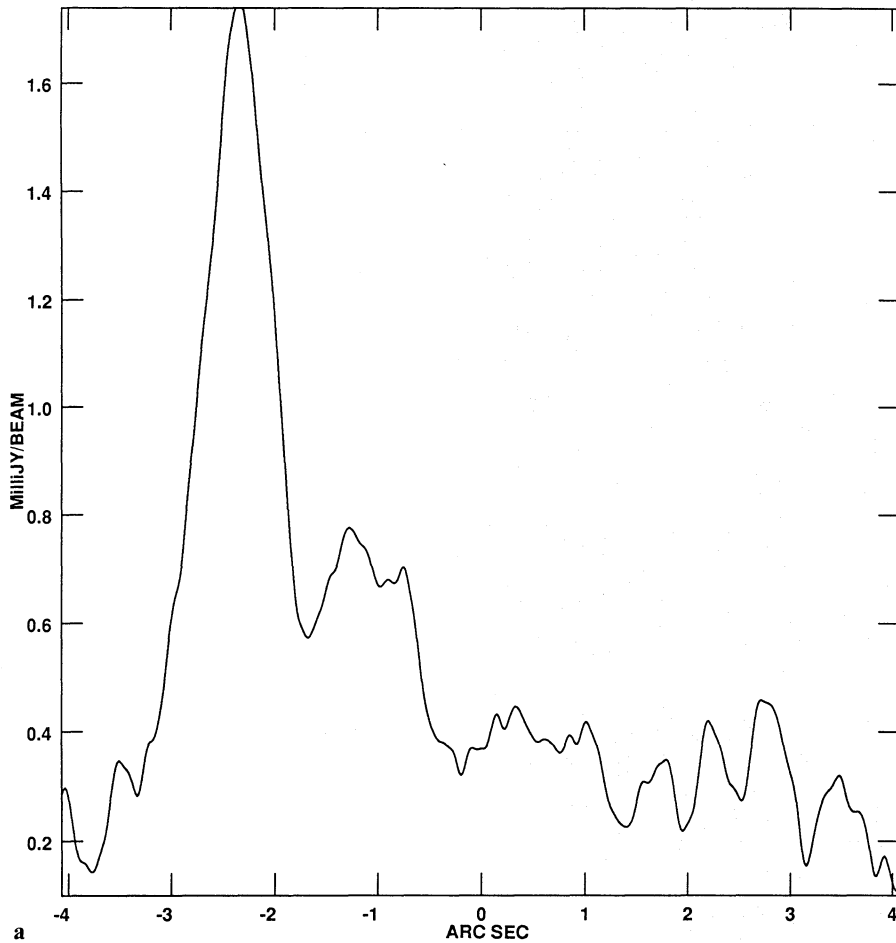


Fig. 4a and b. Two cuts representing the flux distribution along the jet, at **a** 15 GHz (units along the abscissa are mJy/beam) and **b** 3000 Å (units are nanoJy/beam). Note the marked similarity in the part of the jet closer to the core. The apparent discrepancy towards the end of the jet is again due to the limited HST/FOC field of view. Both cuts are taken at position angle $52^{\circ}9$ centred at right ascension $02^{\text{h}}21^{\text{m}}2^{\text{s}}.158$, declination $42^{\circ}45'57''.86$

without loss of too much energy. Similar conclusions were reached by Owen et al. (1989) for M87 and by Röser & Meisenheimer (1991) in the case of 3C 273. We note that synchrotron losses are likely to be the dominant loss mechanism rather than inverse Compton losses unless the magnetic field is very low ($< 20 \mu\text{G}$). For inverse Compton losses, using the formula of Owen et al. (1989), together with the critical frequency suggested by Fraix-Burnet et al. (1991) and a typical $100 \mu\text{G}$ equipartition field, we deduce an inverse Compton loss time of about 10^6 yr, compared to the light travel time up the jet of a few times 10^3 yr and a typical synchrotron lifetime of 10^3 yr in the optical (or a few hundred years in the UV).

Boksenberg et al. (1992) perform a similar analysis of the radio and optical structure of the jet in M87. They find that the radio and optical brightness distributions are similar over a scale of 10 pc, rather less than the light travel distances of 30 pc corresponding to the synchrotron loss times in this object. They argue that the in situ acceleration model is unlikely as the accelerators would have to be distributed smoothly over scales < 10 pc in order to prevent the optical flux distribution being significantly more lumpy than the radio flux distribution over very small scales. Their conclusion is therefore that the low-loss flux tube model is favoured over the in situ reacceleration model. It is important to attempt to evaluate these two models in the light of the new data on 3C 66B presented here.

The 3C 66B jet is more extended perpendicular to the jet direction than that of M87, and our spatial resolution is worse. The worse spatial resolution means that the constraint on the scale length of the smoothness of the accelerations is weaker by at least a factor of 5. The greater lateral extension means that the distance over which the electrons diffusing out of a central low-loss tube would have to travel to the edges of the jet is greater by a factor of 10, and corresponds to a light travel time of about 1000 years. Although we would not expect to see the central low-loss channel, we would expect to see a difference in radio-optical spectral index between the electrons close to the channel, which had been losing energy only for ≈ 100 yr, and those at the outer edges of the channel, which had been losing energy for at least a few thousand years even assuming relativistic diffusion speeds.

Thus the result we have reached here – that the radio and optical structures are very similar *across* the jet and *along* the jet between the knots, as well as along the jet in the knots as found by Fraix-Burnet et al. (1991) – suggests that local reacceleration of electrons really is taking place, and that we are not just seeing a loss-free channel in the centre (with high synchrotron cutoff energies) and a region outside the centre of the jet where synchrotron losses are more evident. The picture is complicated, however, by the fact that we would see the central regions of the jet through an outer shell of older electrons, and the exact constraint on the low-loss channel model must await detailed modelling.

5. Conclusion

We find a detailed agreement in the radio and optical fine-scale (100–300 pc) structure of the jet of 3C 66B. This structure resembles the Königl & Choudhuri model of a twisted helical magnetic field tube. We suggest that the optical strands discovered by Macchetto et al. are the boundaries of the tube, and the bars across it, seen with particular clarity in the radio map, are the helix twists.

We also find very little variation in spectral index along or across the jet, and use this to argue that local reacceleration is more likely than a low magnetic field channel along a central tube and a lossy region around it, unless the electron diffusion speed is very fast ($> 0.1 c$).

Further work is needed on this jet. The major priority is a higher signal-to-noise HST image. We are not yet able to confirm and investigate the ringed and looped structure further along the radio jet: this may indicate a region where the tubular structure is breaking down. An image with a larger field of view will also enable us to investigate the spectral index properties further along the jet.

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