

THE CORE AND HALO STRUCTURE OF THE QUASAR 4C 18.68

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ABSTRACT

We present new VLA observations of this complex low-redshift quasar, which was previously modeled as a precessing twin-jet source. A 2 cm A configuration map fails to reveal the curvature of the jet near the nucleus predicted by this model. B and C configuration maps have been obtained to study the halo of the source, which is compact and shows no edge-brightened outer lobes. These results suggest that the radio source is not very old, and that it appears to have undergone two major changes of orientation in its $< 10^7$ yr history.

I. INTRODUCTION

We have previously published VLA* A configuration maps of this $z = 0.3$ quasar (Gower and Hutchings 1982) and fitted them with a model of a precessing relativistic radio jet (Gower *et al.* 1982). Features of this model are that the opening angle of the precession cone has increased with time, and the prediction of curvature of the jet close to the core, previously unresolved. The model also should be compatible with the halo of the source, if it applies through the history of the source. We report here new VLA observations at 2 cm to study the core, and also at 6 and 20 cm in lower-resolution configurations (C and B) to study the outer parts of the source.

Optical imaging has revealed the orientation of the underlying galaxy of the quasar (at $\sim 60^\circ$ to the inner radio axis), a very close companion galaxy, a tight group of nearby galaxies, and complex structure in the light of [O III], including a curved (tidal?) tail (Hutchings *et al.* 1984; Green and Yee 1984; Shara, Moffat, and Albrecht 1985).

We examine here the interrelation of these different morphological studies, with particular attention to the precessing jet model.

II. 2 cm MAP

The source was observed at 2 cm with the VLA in the A configuration on 17 June 1982 for a total of 6 hr. The data were self-calibrated, and the resulting map appears in Fig. 1. The beam size is 0.15 arcsec and the rms noise level on the map is ~ 0.3 mJy.

The inner jet is seen to be well resolved and appears very straight. It also shows no structure to the south of the core. Comparison with the model of Gower *et al.* (1982) thus shows that it is now incompatible with the data. The high degree of linearity of the jet to the first hotspot suggests that no significant bending or change in direction has occurred in the recent past, so that a different class of model is required. VLBI data were also obtained at 21 cm on the European network. While the signal was too weak to derive a map, preliminary analysis is compatible with the straight jet seen in Fig. 1. A precession model is still possible if the line of sight is such that the inner jet lies along the edge of the projected precession cone, and the cone angle has stopped in-

creasing. However, in addition to being very improbable, this model also fits the outer jet data considerably less well than the published model. We therefore are unable to support such a specific simple model for this source any longer. General properties of the model involving the one-sidedness and changes of direction of the jet, however, still seem to be strongly indicated, and as we show below, related to the outermost halo structure.

III. HALO OBSERVATIONS

The halo was observed at 20 cm in the B configuration on 21 September 1982 and at 6 cm in the C configuration on 19 February 1983, with approximately the same UV coverage to give similar synthesized beams at the two wavelengths. 6 cm B configuration data were also obtained on 21 September 1982 to match the 20 cm A configuration data taken on 25 April 1981 (Gower and Hutchings 1982). In Fig. 2, we show the lower-resolution maps and the polarization vectors. In Figs. 3 (a) and (b), we show them combined with the high-resolution images to show both outer and inner structure. At both wavelengths, we see that the halo has a different long axis from the inner structure. This also is inconsistent with the simple precession model, whose axis does not change. We also note that the source is not edge-brightened, except in a small area on the west side. The outer (earlier) axis is approximately aligned with the *short* axis of the optical galaxy (see, for example, Hutchings *et al.* 1984). The appearance of the halo is consistent with the idea that there have been three major directions of a jet, which has always been stronger on the same (originally SW) side. While the inner jet shows no sign of curvature, the outer halo and previously modeled (intermediate) structure both suggest minor changes of direction ($\sim 10^\circ$) over time scales longer than the lifetime of the present inner jet.

Our matched map pairs allow a study of the spectral index of the halo (Fig. 4). The central source has a flat spectrum, but the index of the extended structure is surprisingly uniform, and is not very steep anywhere. In general, the spectral index steepens with distance from the core, to ~ -1 , with only the SW extreme of the halo any steeper. Azimuthally averaged, outside the core, α steepens by 0.1 per ~ 2.3 arcsec (6.7 kpc) of radius, fairly smoothly. This suggests synchrotron aging effects rather than a contained region of thermal particles, which would have a flatter spectrum. If it is synchrotron, then the whole source is relatively young, or at

* The VLA is a facility of the NRAO, operated by Associated Universities, Inc., under contract with the NSF.

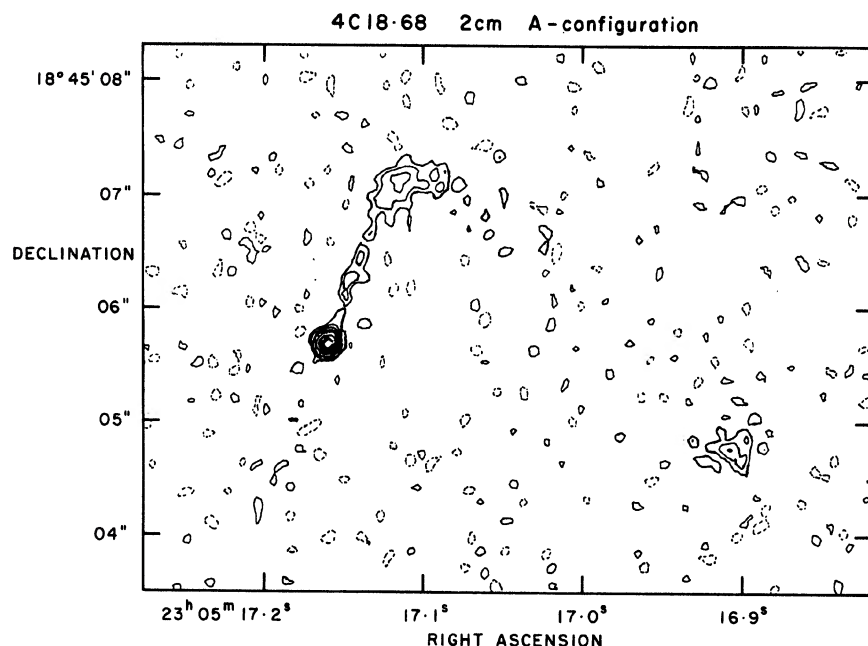


FIG. 1. VLA A configuration 2 cm map of 4C 18.68. Contours at -1% , 1% , 2% , 4% , 8% , 16% , 25% , 37% , 50% , 70% , 90% , of peak 0.070 Jy/beam. Beam width is 0.15 arcsec. Note that inner jet appears completely one-sided, and straight.

least replenished over a time scale of 10^7 yr. There appears to be no region of reacceleration in the outer halo. The equipartition field is $\sim 10^{-4}$ Gauss, which implies synchrotron loss time scales of several million years for the steepest spectral index observed.

In Figs. 3(c) and (d) we show the contours of fractional polarization in the halo. There is a very different distribution of polarized radiation from the total intensity. These data reveal the outer long axis of the halo to a greater extent than the total intensity maps, by having troughs of low fractional polarization along it. The fractional polarization appears to be greatest at the edges, as expected for a uniformly filled space with random fields. The low central polarization fractions suggest a depolarization has occurred (by the halo material?), being greatest in the center and greater at 20 cm.

The polarization angle is different between the two wavelengths (probably due to Faraday rotation) [see Fig. 3(f)]. This difference is remarkably uniform over the whole source, indicating a uniform rotating medium in the line of

sight: this steady component of the rotation may well be due to foreground material in our galaxy. It is unlikely to be due to the halo itself since its depth presumably varies considerably from edge to center. The regions where the rotation is not uniform are of interest. Firstly, the region defining the outer (SW) jet, which is also suggested in the change of fractional polarization, and lies slightly N of the main axis at this point; secondly, a small area just outside the place where the innermost jet first turns to the SW; finally, two lines which intersect at right angles to the SE of the core. In this area, the intensity contours outline this structure too.

The overall structure of the source has no classical lobes and the structure is subtle. However, there are a few consistent features seen in flux, spectral index, and polarization maps, as pointed out above.

IV. OPTICAL MORPHOLOGY AND DISCUSSION

The optical pictures are highly suggestive of some sort of interaction, but the interpretation is not clear (see Shara *et*

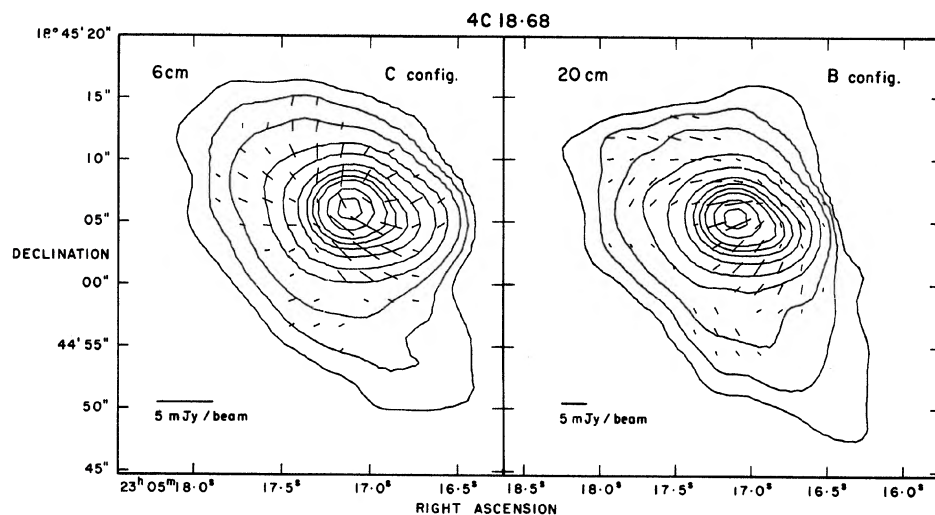


FIG. 2. VLA C configuration 6 cm and B configuration 20 cm maps of 4C 18.68 halo, with polarization vectors. Vector scales indicated in each box. Intensity contours at -0.5% , 0.5% , 1% , 2% , 5% , 10% , 20% , 30% , 40% , 50% , 70% , 90% , of peak (0.171 Jy/beam at 6 cm and 0.335 Jy/beam at 20 cm). Beam width is 4 arcsec. Note extended structure to SW and area of edge-brightening to W.

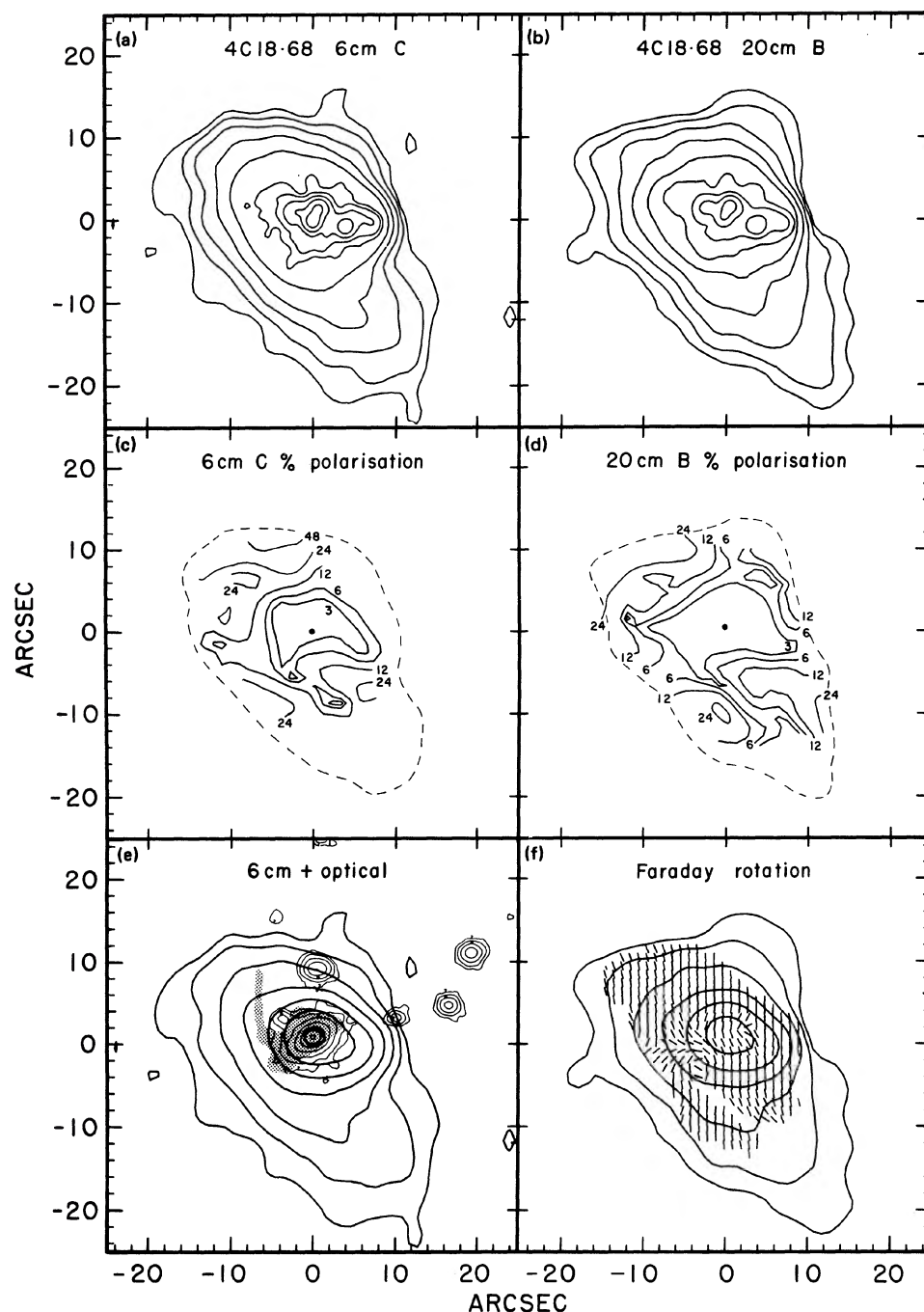


FIG. 3. (a and b) superposed halo and inner region maps. (a) contour levels 0.2, 0.4, 0.8, 1.6, 3.2 mJy/4 arcsec beam, and 1.8, 3.6, 7.2, 20, 40 mJy/1.4 arcsec beam. (b) contour levels 0.8, 1.6, 3.2, 6.4, 12.8 mJy/4 arcsec beam, and 3, 9, 27, 81 mJy/1.4 arcsec beam. (c and d) percentage polarization maps as marked. Central dot locates the core. Note the depolarization of the central region and the trough along the SW axis. (e) optical contours and [O III] emitting halo and tail (shaded) overlaid on 6 cm map. Note lack of correspondence between radio and optical morphology. (f) Faraday-rotation vectors overlaid on 20 cm halo map. Vectors show the difference in polarization angle between 20 and 6 cm, and are plotted at 1 arcsec intervals (4 arcsec beam) for clarity. Vectors are only plotted if the estimated errors are $\pm 10^\circ$ or less. Note general uniformity of rotation. Deviations occur (i) near the first bend of the inner jet, (ii) where the optical tail emerges, and possibly (iii) along the outer SW axis. Polarized intensity is weaker in the SW.

et al. 1985). The radio structures show little detailed relationship with the optical (see Fig. 3). We have noted that the optical short axis appears to line up with the halo axis, consistent with an initial radio ejection normal to the plane of a disk galaxy. The tidal tail and an area of [O III] emission to the SE lie close to the region of differing Faraday rotation. The steep drop of radio emission intensity to the W occurs near to a companion galaxy in this direction. However, the halo appears unaffected by the presence of another galaxy to the N. The very close companion galaxy to the NE lies near to the inner radio axis. None of these is very suggestive, and it appears that there is no detected optical luminosity associated with radio features.

The possibility of an encounter between galaxies (or series of passes between a bound pair of galaxies), however, raises the possibility of causing changes in the orientation of the radio axis. If such events caused the gross changes in the radio ejection *direction* as suggested above, then they appear to have occurred with increasing frequency (a damped elliptical orbit?). The relative sizes of features may be a clue to the history of this object. The tidal tail extends for some 30 kpc. At typical velocities of $\sim 1000 \text{ km s}^{-1}$ (e.g., Hickson and Hutchings 1986), this would take 3×10^7 yr to form. The halo extends some three times further, but velocities in radio jets are typically much faster (the precession model, which matched the one-sidedness by relativistic beaming,

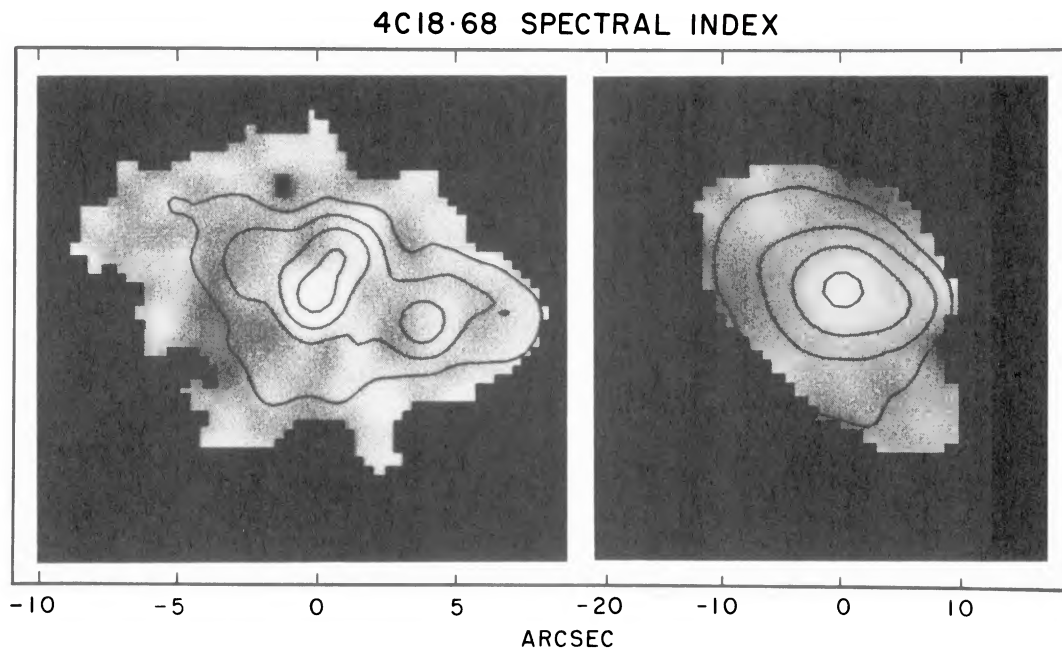


FIG. 4. Spectral index maps of inner region and halo, from AB and BC configuration matched map pairs. Inner region grey scale runs from -0.1 to 1.0 , and halo from 0.3 to 1.3 . Azimuthal averages show that steepness increases monotonically with distance from the core.

had velocity of $0.7c$). Even at $0.1c$, the age is of order 3×10^6 yr, and the age of the innermost straight jet is of order 10^5 yr. Thus, the events that have changed the direction of the jet are probably much more recent than those that relate to the optical morphology. While the simple precession model does not seem to apply, the host galaxy may still have a double nucleus that is optically unresolved, which has an impulsive interaction at intervals of order 10^5 or 10^6 yr. This situation in turn may have resulted from an encounter which formed the tidal tail. Note that this idea does not appear to involve the presence of the very close optical companion.

An alternative scenario involves the radio structure arising from *proper motion* of the source, with constant direction. Such models have been proposed by Blandford and Icke (1978) for 3C 31, and Perley, Willis, and Scott (1979) for 3C 449. In this case, the inner structure *might* fit such a model involving a bound orbit with a companion galaxy (possibly the resolved very close one). At 1000 km s^{-1} , the $\sim 5 \text{ kpc}$ amplitude of the inner jet structure would have a period of $\sim 10^7$ yr. The relatively compact radio structure would then require the radio jet velocity to be comparable with the proposed orbital velocity, or a line of sight very close to the jet. The former of these possibilities introduces severe problems with the one-sidedness of the radio structure and the synchrotron aging arguments above. In any case, this type of scenario would not explain the radio halo and its SW axis, or the lack of wiggles in the optical tail, so that at best it is only part of the explanation.

The rounded shape of the halo (cocoon) is unusual. However, there are a few other examples (e.g., $1400 + 162$, $1150 + 497$). The halo is also unusual in its strength, and its

general lack of structure. It resembles the Crab Nebula in these respects. It may be that it represents material present in the potential well of the galaxy (or group), and energized by the quasar. Alternatively, it may represent a diffusion of relativistic electrons from the jet. Thirdly, it may be an end-on view of a normal large double-lobed source. If this last idea is correct, it must be consistent with any model for the inner structure as well.

There is an x-ray image of the field by the *Einstein* observatory IPC. This shows the quasar to be detected with a (relatively high) luminosity ($0.4\text{--}3.5 \text{ keV}$) of $10^{45.7} \text{ erg s}^{-1}$. It is marginally resolved in soft x rays and extended SE-NW, or orthogonal to the radio halo. This *may* be evidence for a hot confining medium for the radio halo, but the IPC resolution of $\sim 3 \text{ arcmin}$ is not good enough to be certain.

Overall, our data seem to point to the existence of earlier different jet directions, and we seem to have an object connected with an optical interaction, with a one-sided radio jet whose direction changes in time scales of $\sim 10^5$ yr. Further work is needed in optical imaging (with HST resolution), and spectroscopy of the galaxies and line-emitting gas, before this complex system can be understood.

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