

ON THE RELATIVE PROPER MOTION OF QUASARS 1038+528 A,B

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ABSTRACT

We observed the pair of quasars 1038+528 A ($z=0.678$) and 1038+528 B ($z=2.296$), separated on the sky by $33''$, using very long baseline interferometry in 1981 and 1983, simultaneously at $\lambda=3.6$ and 13 cm. From hybrid maps of the compact structures of the two quasars made from these observations, we were able to identify reference points in each. By comparing the relative positions of the points in the two quasars, we obtained an estimate of their relative proper motion at $\lambda=3.6$ cm: 31 ± 22 microarcsec/yr. This value, being only about 1.5 standard deviations, cannot be considered a detection of proper motion. We propose a smooth jet model consistent with this result. The proper-motion prediction from this model differs from that of "bona fide" proper motion and could likely be distinguished from it with measurements spanning a decade or more, were the maximum instantaneous proper motion to be of the order of 30 microarcsec/yr.

1. INTRODUCTION

When studied with the technique of very long baseline interferometry (VLBI), a large fraction of radio sources shows compact structures at scales of milliarcseconds (mas). The fraction is particularly large for quasars and BL Lac type sources with flat or inverted spectra (Pearson *et al.* 1987). The most common morphology is that of a core-jet where the jet often contains distinct components that move superluminally relative to the core. The existence of many superluminal sources among the brightest compact radio objects, and the properties of these, have been explained by what is known as the standard relativistic jet model (Blandford & Konigl 1979). Such a model consists of (i) a nozzle where relativistic plasma flows outward; (ii) a magnetic field which has a large random component and a small ordered component along the jet; and (iii) shock waves which travel along the jet. Superluminal components can be modeled by choosing an appropriate set of physical parameters for the plasma flow speed, the shock wave speed, the magnetic field strength, and the orientation of the nozzle to the observer (Gómez *et al.* 1993a, b). Components with different apparent superluminal speeds can be interpreted as emission from shock waves of different speeds. Finally, stationary components can be successfully modeled as bends in the jet. In such bends, changes of Doppler boosting factors for the relativistic plasma, due solely to geometry, could cause components to appear stationary (Gómez *et al.* 1993a).

In the standard jet model the plasma flows relativistically away from a central engine whose nature is not known. Near the central engine, the radiation is optically thick. The core detected by VLBI corresponds to the region where the optically thick part of the jet turns thin. The central engine can thus be observed only at infinitely high frequency and, hence, in practice cannot be observed. In the standard cos-

mology and for the standard jet model, in the absence of variable opacity effects (see below), the core should appear stationary. How can we test this prediction?

On the one hand, the hybrid mapping technique employed in VLBI can make use of fringe phase only in closure conditions (Rogers *et al.* 1974; Thompson *et al.* 1986) with the result of a loss of information on the "absolute" position of the mapped radio source. The use of group-delay and fringe-rate observables to determine the source position usually does not allow the maps made from observations at different wavelengths to be properly "registered" with respect to one another since the errors in the position determinations are most often substantially larger than the map resolutions. On the other hand, to check usefully on the stationarity of the core, we need a precision in determining its position even finer than the map resolution. The phase-delay observable has the needed precision. However, the phase-delay observable, by itself, is ambiguous by multiples of the delay corresponding to 2π in phase, a direct consequence of the 2π ambiguity of phase. A solution to this problem that is sometimes feasible is to observe pairs of radio sources such that changes with time in the ambiguity in phase can be eliminated from the difference of the phase delays observed for the two members of the pair. Thus, given, say, some ambiguity in the differenced phase delay from observations of two sources at the initial epoch, no change in this ambiguity will be introduced into successive measurements of the differenced phase delay if these differenced observations can be properly "phase connected." If the pair of sources can be observed simultaneously, because their separation is substantially smaller than the diameter of the main beam of each of the telescopes used in the VLBI array, then the phase connection is much simpler and the attainable precision in determining the relative sky position of the two sources is much higher. The pair 1038+528A,B, with a separation of

33", is such an ideal pair for which both sources can be observed simultaneously. Furthermore, the Mark III VLBI equipment (Rogers *et al.* 1983), allows the observations of the two quasars to be made simultaneously at two wavelengths, $\lambda=3.6$ and 13 cm.

2. THE QUASARS 1038+528 A AND B

The redshifts of the quasars 1038+528 A and B have been determined as $z=0.678$ and 2.296, respectively (Owen *et al.* 1980). VLA maps at $\lambda=6$ cm show diffuse radio emission surrounding the 1038+528 A quasar (Owen *et al.* 1980) whose relation to the quasar is unknown. The quasar 1038+528 A is a member of a small cluster of galaxies (Marcaide 1982; Pérez-Fournon 1993). Past VLBI observations (Marcaide *et al.* 1985) have shown that both 1038+528 A and B have compact structures and flat spectra. Typical total flux densities of the compact structures of 1038+528 A and B are 400 and 100 mJy, respectively. For both sources these compact structures are of the core-jet type (Marcaide *et al.* 1985).

3. VLBI OBSERVATIONS

On 1981 March 17, simultaneous VLBI observations, at $\lambda=3.6$ and 13 cm, were made with an array of seven radio-telescopes, three in Europe and four in the United States, utilizing Mark III instrumentation. The details of these observations and the results obtained from them have already been published (Marcaide *et al.* 1985). On 1983 May 10, a second set of simultaneous VLBI observations at $\lambda=3.6$ and 13 cm were made in a very similar manner and will therefore not be further described.

4. SOURCE MAPS AND ASTROMETRIC ANALYSIS

The hybrid maps obtained for the sources 1038+528 A and B from the 1983 May observations are presented in Fig. 1. The detailed analyses of these figures and their comparison with those from 1981 March will be published elsewhere (Elósegui *et al.* 1995). Here the main aspect to be noticed is that the maps of 1038+528 B from 1983 are nearly identical to those from 1981, as shown in Fig. 2. The maps at $\lambda=3.6$ cm obtained from the 1983 data fit the 1981 data as well as do the maps obtained from data from 1981, and vice versa.

The source 1038+528 A, on the other hand, has undergone small, but clearly detectable changes between 1981 and 1983, in agreement with its previously reported mild superluminal character (Marcaide *et al.* 1985). It appears at $\lambda=3.6$ cm that a component, which was in 1981 about 1.7 milliarcseconds (mas) from the core at a position angle (PA) of 23° , has faded while a new component not visible in 1981 was discernible in 1983 because it had emerged from the core. This result appears to be consistent with the notion that adiabatic losses from a shock wave traveling in a relativistic plasma are rather large: the jet components visible at $\lambda=3.6$ cm fade away rapidly, while at $\lambda=13$ cm they can be seen, albeit at a very low contrast level, out to about 100 mas (Marcaide *et al.* 1985).

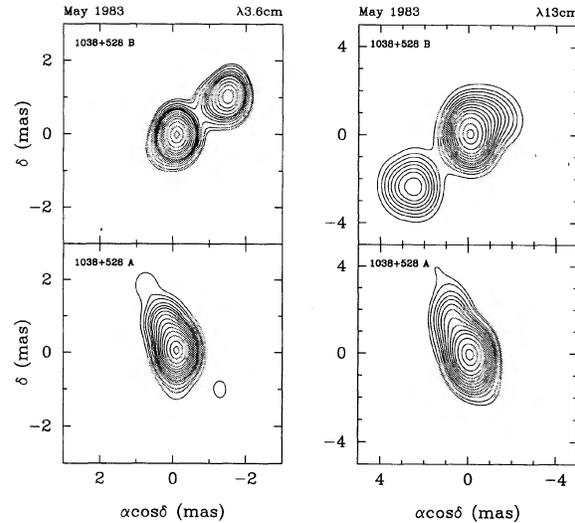


FIG. 1. Hybrid maps of the quasars 1038+528 A (bottom) and B (top) at $\lambda=3.6$ (left) and 13 cm (right) from the 1983 May observations. Note the difference in scale between the maps at the two wavelengths.

Our main goal in this paper is to determine or set a limit on any change in the position of the core of the quasar 1038+528 A relative to a reference point on the brightness map of 1038+528 B. According to theoretical models that do not consider variable opacity effects, the core of a quasar such as 1038+528 A should be stationary to a level well below one microarcsecond/year ($\mu\text{as/yr}$). To investigate any possible change in the position of the core of A, we determined with high precision the position of this core relative to the reference point in 1038+528 B for the 1981 and 1983 observations separately. We were able to use approximately the same reference point—the brightness peak of the map of 1038+528 B—for both epochs because the maps obtained at $\lambda=3.6$ cm for these two epochs are virtually indistinguishable. Nonetheless, the uncertainty in the identification of the reference points as being the same physical point at both epochs provides the largest single contribution to our result (see below).

Since our maps are gridded, the location of the core

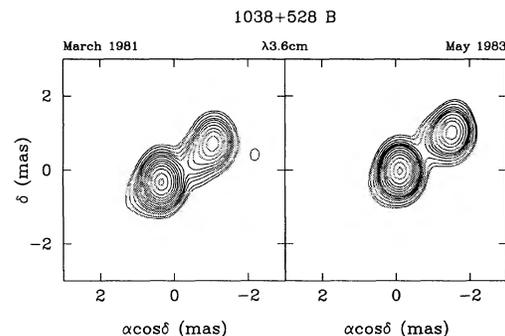


FIG. 2. Hybrid maps of the quasar 1038+528 B at $\lambda=3.6$ cm from the 1981 March (left) and 1983 May (right) observations.

TABLE 1. Estimated position of the core of 1038+528 A relative to the reference position on 1038+528 B, relative to the position estimated at epoch 1981.2 at $\lambda=3.6$ cm.*

| Epoch | λ (cm) | $\Delta\alpha \cos \delta$ (μas) | $\Delta\delta$ (μas) |
|--------|-------------------|--|--------------------------------------|
| 1981.2 | 3.6 | 0.0 ± 1.5 | 0.0 ± 2.6 |
| 1983.4 | 3.6 | -10.9 ± 1.4 | 65.0 ± 2.3 |
| 1981.2 | 13.0 | 408.0 ± 4.8 | 721.1 ± 8.1 |
| 1983.4 | 13.0 | 219.3 ± 7.1 | 797.1 ± 11.1 |

*All errors shown are statistical standard errors. Systematic errors may be as much as tenfold larger (see text).

would, in general, be affected by any blending of the core with other nearby structure. Fortunately, for 1038+528 A, the core is well isolated. We chose as the reference point for this core the center of brightness of the emission with spatial brightness densities within 25% of that of the peak. We conducted numerous tests (Elósegui 1991; Elósegui *et al.* 1991) with different grids and different brightness density cutoffs which show that this choice is robust and does not introduce errors at $\lambda=3.6$ cm larger than about $5 \mu\text{as}$ in the determination of the relative position of the two quasars.

Using these reference locations, we subtracted the phase contributions due to the source structures, from the differenced phase delays obtained from each scan, and brought the differenced phase delays for all scans within the same phase-delay ambiguity by following a procedure described previously (Marcaide & Shapiro 1983). We then estimated the angular separation of the two reference points using weighted least squares. For this purpose, we used our latest version of the astrometric program VLBI-3 (Robertson 1975), with 1980 IAU conventions and the J2000.0 epoch. The details of this astrometric analysis will be presented elsewhere (Elósegui *et al.* 1995); the results are presented in Table 1 and discussed below.

5. ASTROMETRIC RESULTS AND DISCUSSION

From Table 1, and the corresponding Figs. 3 and 4, we immediately notice: (1) the separation between the quasars is wavelength dependent, and (2) the separation has changed over two years corresponding to a constant rate of $31 \pm 2 \mu\text{as/yr}$ (statistical standard error) at $\lambda=3.6$ cm. Notice, too, that the source-structure contributions to the phase delays are huge in comparison to the rms of the postfit residuals. One might therefore suspect that the map gridding or the identification of the map features that are used as reference points might have substantial effects on the results. One might also suspect that the contributions of the propagation medium, and even the contributions of imperfections in the instrumentation, affect the differenced phase-delay observables at a level higher than the purely statistical standard deviations shown in the table. Indeed, the identification and quantification of the sources of systematic error are of prime importance in setting a realistic error on this result for proper motion.

We performed extensive and detailed tests with the $\lambda=3.6$ cm data to investigate systematic errors (Elósegui 1991). Be-

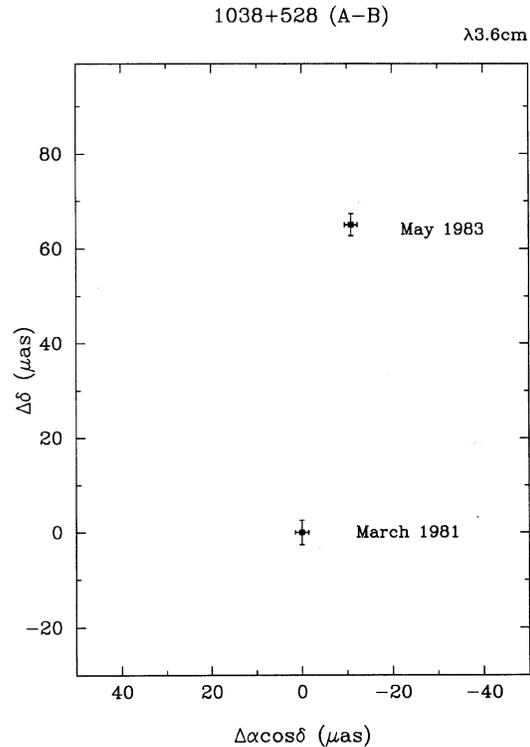


FIG. 3. Estimated position at $\lambda=3.6$ cm of the core of the quasar 1038+528 A relative to the reference point on the quasar 1038+528 B. The origin of the figure corresponds to the relative position estimated from the 1981 March observations. The error bars shown correspond to statistical standard errors.

cause of the technical content of those tests and their general interest for astrometry, we will present a detailed account elsewhere (Elósegui *et al.* 1995); a concise discussion has already been presented (Elósegui *et al.* 1991). Those tests show that a given determination of relative position at $\lambda=3.6$ cm is reproducible to within four statistical standard deviations, except for the effect of misidentification of the reference point. This reproducibility was obtained even with considerable degradation of the visibility function for each source, with substantial change of the grid in map making, and with use of disjoint subsets of data from each epoch of observation (created by separating the original data by epoch, by baselines, or by both). Figure 5 shows representative results of these tests. As an example, we comment here on one of them: the possible change, between the two epochs, of the reference position of 1038+528 B along its major axis. There might have been a shift in the peak brightness between the two epochs, which is imperceptible in the maps. However, the axis of symmetry in the map of the B quasar is along $\text{PA}=135^\circ$, whereas our inferred position shift is along $\text{PA}=-10^\circ$. Because of this geometry, if something changed imperceptibly, say by less than a twentieth of a beam, along $\text{PA}=135^\circ$, the corresponding effect on the change along $\text{PA}=-10^\circ$ would be limited to a maximum of $15 \mu\text{as}$, only about a fourth of the $66 \mu\text{as}$ deduced from the observations. However, theoretical considerations indicate (Thompson

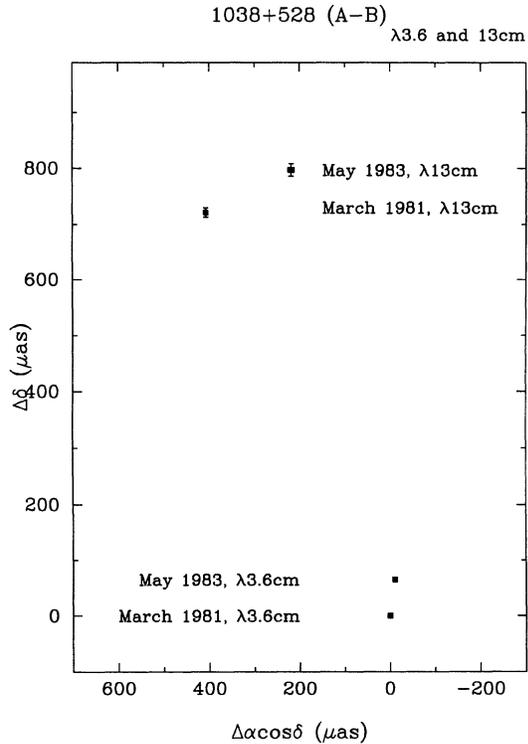


FIG. 4. Estimated positions at $\lambda=3.6$ and 13 cm of the core of the quasar 1038+528 A relative to the reference point on the quasar 1038+528 B. The origin of the figure corresponds to the relative position at $\lambda=3.6$ cm estimated from the 1981 March observations. The error bars shown correspond to statistical standard errors.

et al. 1986; Rioja 1993) that our ability to locate a specific feature in a map is limited by the signal-to-noise ratio of that feature. For the reference features chosen on 1038+528 A and B, these location errors amount to a combined $20 \mu\text{as}$ error, principally caused by the weak source 1038+528 B. This error being about tenfold higher than our estimated statistical standard error dominates all other sources of error which combined yield a standard error fourfold higher than the statistical standard error.

Thus, an increase by a factor of ten in the purely statistical standard deviation should include the systematic errors at a confidence level of nearly 70%; the estimate of proper motion remains unchanged, but its “true” standard error is increased, yielding $31 \pm 22 \mu\text{as/yr}$.

Let us now consider the first point mentioned in this section, namely the wavelength dependence of the results for the separation of the two quasars. This dependence was initially based on data obtained simultaneously at $\lambda=3.6$ and 13 cm at a single epoch, and explained as being due to wavelength-dependent opacity effects in 1038+528 A, which made the peak of brightness of this quasar’s core appear at different sky positions for observations at different wavelengths (Marcaide & Shapiro 1984). Using a computer code developed recently to investigate the emission from compact relativistic extragalactic jets (Gómez *et al.* 1993a), we investigated the wavelength-dependent displacement of

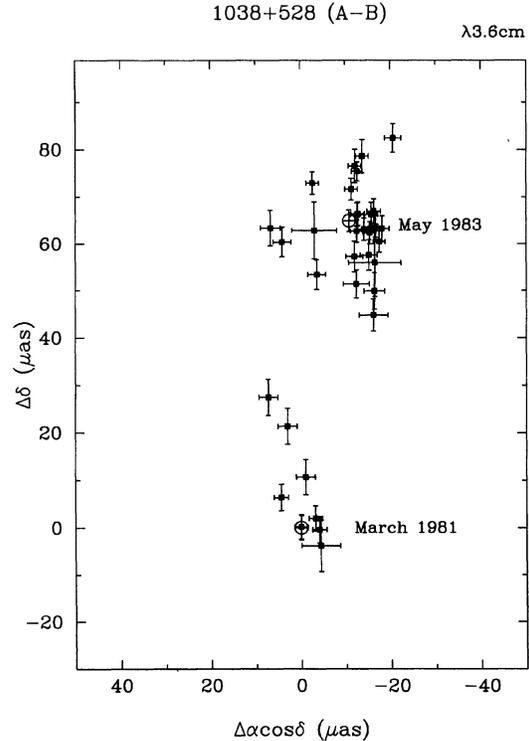


FIG. 5. Scatter in a representative sample of the determinations at $\lambda=3.6$ cm of the position of the core of the quasar 1038+528 A relative to the position of the reference point on the quasar 1038+528 B, obtained from numerical simulations of various effects performed with the 1981 March and 1983 May data. The “best” solution for each of the two epochs is circled. The error bars shown correspond to statistical standard errors.

the peak of brightness of the core. Figure 6 shows the expected spatial distribution of emission for the wavelengths of 3.6 and 13 cm for a particular choice of magnetic field and plasma electron density in a straight jet. Decreasing the angle between the jet and the observer’s line of sight means increasing the Doppler effect on the emission by some factor that is slightly different at the two wavelengths. Hence, not knowing the actual orientation of the direction of jet motion with respect to the observer’s line of sight, we cannot determine a unique set of physical parameters in the jet, even for this model. The main point, however, is that this simple model can reproduce the observed wavelength dependence of the sky position of the peak of brightness.

Let us move to the second point: at a given wavelength of observation, does the position of the peak of brightness of the core of 1038+528 A remain fixed? For $\lambda=3.6$ cm, we concluded above that this peak had shifted by $66 \pm 47 \mu\text{as}$ over a span of about two years. Would such a change, if significant, be due to an (internally caused) change in the brightness distribution of the quasar’s core, to a relative motion of the centers of mass of the two quasars, or to some combination?

Since the jet emanating from the core of 1038+528 A appears to be mildly superluminal, this core must be active. This activity, whatever its underlying cause, could lead to shock waves traveling along the jet and/or to injections of

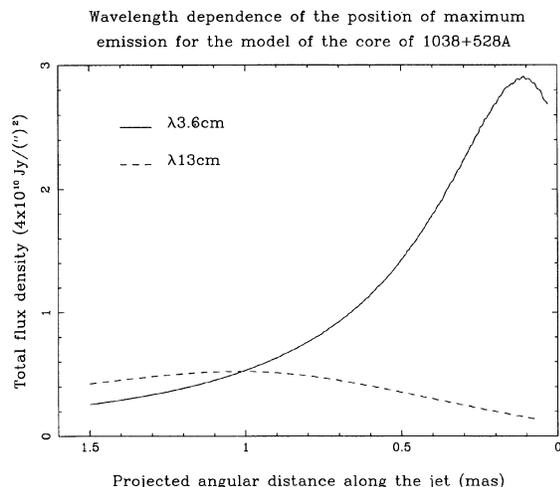


FIG. 6. The astrometric results of Fig. 4 for the 1981 observations can be replicated if, for the proposed model (Gómez *et al.* 1993a) (see text), the following jet parameters are chosen: jet opening half-angle: $\phi=5.0^\circ$; jet axis angle with respect to observer: 20° ; electron density in the jet at position 0.5 pc from jet apex: $n_e=0.0042e^{-3}\text{ cm}^{-3}\text{ erg}^{-1}$; total magnetic field in the jet at position 0.5 pc from jet apex: $B=0.021\text{ G}$; plasma flow speed: $\Gamma=9$; electron energy spectrum spectral index: $\gamma=2.21$. A parameter selection within about 10% of the given one reproduces acceptably the wavelength dependence of the position of maximum emission.

plasma in the jet having larger than average densities. When such a traveling disturbance reaches the region where, for a given wavelength, the transition from optically thick to optically thin emission takes place, the disturbance may alter the position where the transition takes place, thus also altering the location of the brightness peak. For example, we find that with all other relevant physical parameters kept constant at appropriate values, a 20% change in electron density and in magnetic field strength will shift the position of the peak of emission by about $70\ \mu\text{as}$ as displayed in Fig. 7. Further, a traveling shock, just after going through such a jet position, will also cause a shift of the position of the apparent peak of emission, due to a blending of the emission from the shock itself with that from the region of the thick-thin transition. These two effects may be indistinguishable observationally since the shock need not be very strong nor visible later as an independent VLBI component. The slightly curved jet model shown in Fig. 8 (Marcaide *et al.* 1990) is consistent with the maps of 1038+528 A and with the astrometric results at $\lambda=3.6$ and 13 cm.

What about the possibility of “bona fide” proper motion? At the proper-motion distance $D=2.3h^{-1}\text{ Gpc}$ of 1038+528 A ($H_0=100h\text{ km s}^{-1}\text{ Mpc}^{-1}$; $q_0=0.5$), the estimated proper motion corresponds to the enormous transverse speed of $0.7h^{-1}c$, where c is the speed of light. This transverse speed is about twice larger than the radial velocity of 1038+528 A due to the expansion of the Universe. Such a result would be difficult to accommodate within the standard cosmological model. It would, of course, be easier to accommodate in some nonstandard interpretations of the distance of quasars (Arp 1987). Fortunately, the predictions from these two types of explanation are distinguishable, given sufficient time. For

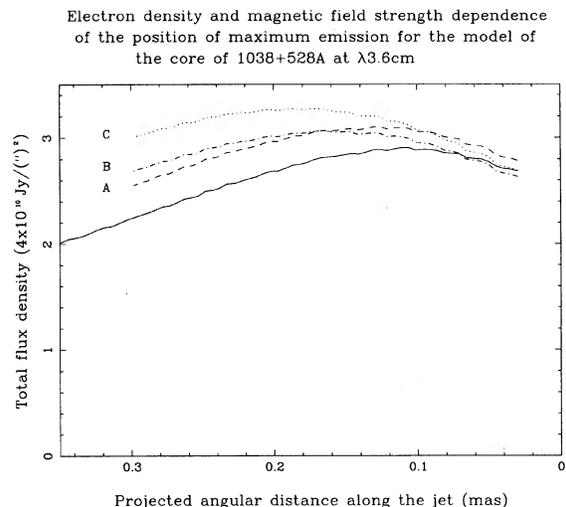


FIG. 7. An increase of 20% in electron density (line A), or an increase of 20% in magnetic field strength (line B), or an increase of 20% in electron density and magnetic field strength (line C) for the model given in the caption for Fig. 6 (continuous line) produces a shift in the position of maximum emission at $\lambda=3.6\text{ cm}$ which replicates the astrometric results of Fig. 3.

the optical-depth type, one would expect the position of the peak of brightness to remain within some characteristic arclength related to the magnitude of the disturbances mentioned above; for the “bona fide” proper motion one would

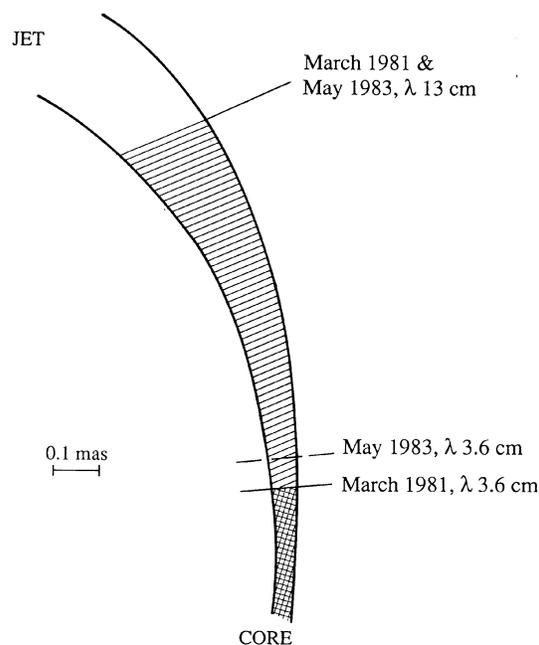


FIG. 8. Model for the core of the quasar 1038+528 A. Doubly hatched area is optically thick to radiation at $\lambda=3.6\text{ cm}$ and singly hatched area to radiation at 13 cm. The continuous and dashed lines indicate the jet positions where the optically thick region turns optically thin to 3.6 cm radiation for the epochs 1981 March and 1983 May, respectively. The jet emission is maximum at these jet positions. See also related Figs. 5 and 6.

expect, of course, displacements linearly increasing with time. Altering the electron density and magnetic field strength of the model by a factor of two around the best estimate (square root of two larger versus square root of two smaller), we can obtain a measure of such a characteristic arc length; we find a value of about 200 μas at $\lambda=3.6$ cm.

6. CONCLUSIONS

From two sets of VLBI observations at $\lambda=3.6$ cm, made in 1981 and 1983, we estimated a proper motion of 31 ± 22 $\mu\text{as/yr}$ for the core of the quasar 1038+528 A, relative to a reference point in 1038+528 B. The standard error quoted includes estimates of the effects of systematic errors and is thereby about tenfold larger than the statistical standard error. Simultaneous VLBI observations made at $\lambda=13$ cm at the same two epochs were not as sensitive, for two reasons: firstly because, intrinsically, at $\lambda=13$ cm the location of the reference point is about fourfold less precise, and secondly because at $\lambda=13$ cm the effects of plasma make an important contribution to the systematic errors, causing them to be considerably larger than at shorter wavelengths (Elósegui 1991). However, these simultaneous $\lambda=13$ cm observations do show that the position of the core is wavelength dependent as previously reported (Marcaide & Shapiro 1983, 1984).

It is as yet unclear whether our estimate of proper motion is significantly different from zero; but, if so, it is also unclear whether an opacity effect, "bona fide" proper motion, or a combination is the cause. If the proper motion were "bona fide," then it would correspond, at the cosmological distance of the quasar, to a transverse velocity of about $0.7h^{-1}c$. This velocity would be very difficult to accommodate in conventional cosmologies. If, on the other hand, the cause of the apparent proper motion lies within the core, then

we would be studying with unprecedented detail the physical conditions, and their variability, at a region very close to the central engine of the quasar.

The present astrometric results at $\lambda=3.6$ and 13 cm can be reproduced with a model based on a slightly curved jet, with values of electron densities and magnetic fields not unusual for models of other VLBI sources. In this model, the apparent proper motion could be explained by changes in the two main parameters, electron density and magnetic field strength, which influence the opacity of the jet emission and shift the maximum of the core emission to match the measured change in position of the peak brightness.

Whether the estimated nonzero proper motion turns out to be significant and, if so, whether the jet model is the correct one, as opposed, say, to the interpretation of the corresponding proper motion as "bona fide" remains to be seen. Predictions of the future behavior of the jet model are quite distinct from the corresponding predictions for a "bona fide" proper motion. In the first case, future measurements should show that the separation of the two quasars remain bounded by a certain model-dependent characteristic length. In the second case, the separation should continue to increase linearly with time. The discrimination between these alternatives will be possible through continued monitoring with VLBI which will disclose whether the proper motion is significant and, if so, will allow discrimination among some of the alternative explanations.

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