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Results from a decade-long VLBI astrometric monitoring of the pair of quasars 1038+528 A and B

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Abstract. We present results from three epochs, spanning nearly a decade, of VLBI monitoring of the angular separation between the quasars 1038+528 A and B. Our observations, made simultaneously at λ 3.6 cm and λ 13 cm, achieve submilliarcsecond (submas) precision in the measurement of the ∼33" separation between the two quasars. We detected changes in this angular separation of nearly 0.2 mas. These changes can be explained wholly, or mostly, by the motion of the reference feature used in quasar B which appears to be a component in the jet, separating from the core at a speed near *c*. We also conclude that any proper motion of quasar A is less than 10 μas yr^{-1}. There is an intriguing hint of a "jitter" in the position of the peak brightness of this quasar, but the signal-to-noise ratio is too low for us to draw a firm conclusion.

Key words: astrometry and celestial mechanics: instrumentation: interferometers – astrometry – galaxies: quasars – radio continuum: galaxies

1. Introduction

The application of Very-Long-Baseline Interferometry (VLBI) to the determination of positions of objects on the sky, and telescopes on the Earth (i.e., astrometry and geodesy) routinely provides precisions at the milli-arcsecond (mas) and centimeter levels, respectively. VLBI astrometry has allowed a celestial reference frame to be built on the stable positions of extragalactic radio sources determined with mas accuracy (Ma et al. 1990); this technique is now also accurate enough for geodetic determinations which are geophysically significant (see, for example, Herring et al. 1986; Robertson 1991; Haas et al. 1995). Its inherent resolution makes the VLBI technique ideal for the study of the kinematics of the inner parts of radio sources. The standard theory of extragalactic radio sources (relativistic jet theory; e.g., Blandford & Königl 1979) assumes that emission from quasars and active nuclei of galaxies comes from a central engine where energetic nuclear phenomena take place; this engine is believed to be stationary on the sky at the micro-arcsecond (μas) level.

VLBI position determinations are limited by errors in calibrating the contributions of the atmosphere and of source structure to propagation delays (Clark et al. 1989), and not by instrumental errors or the precision of the measurements. The interferometric quantities of astrometric interest are the phase delay, group delay, and phase delay rate (Shapiro 1976). The ratio of the statistical errors in the estimates of the group delay to those in the phase delay is about $10^1 - 10^2$ and is given approximately by the ratio of the central radio frequency (ν, a few GHz) observed to the *rms* spread of the totality of radio frequencies observed (some tens to hundreds of MHz) (see, for example, Thompson et al. 1986). Despite its high precision, the phase delay is not used routinely because of the difficulty in eliminating the "2π ambiguities". Its use requires knowledge of the changes between successive observations of the contributions to the delay from the propagation medium, the geometry, and the instrumentation, with an uncertainty well under $1/\nu$.

However, the difficulty is substantially reduced in difference astrometry. The difference between the phase delays for two sources close to one another on the sky is affected far less than the undifferenced delays by variations, for example, in the neutral atmosphere. The angular separation between the two sources is a crucial factor for the successful application of this technique. The radio sources 1038+528 A and B (Owen et al. 1978, 1980) are 33" apart and therefore lie within the primary beam of most radio telescopes at cm wavelengths. This pair is an excellent one for the application of differential astrometric techniques; the achievable accuracy in estimating the change in the angular separation between these sources at different epochs is limited primarily by the structure of the sources, i.e. by the uncertainty in locating stable reference features in the brightness distributions of the sources.

Simultaneous observations of the radio sources 1038+528 A and B at λ 3.6 cm and λ 13 cm have spanned nearly a decade;

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Table 1. Parameterized description of the brightness distributions of quasar B, in 1981.2, 1983.4 and 1990.5 at λ 3.6 cm. We derived these parameters by fitting models consisting of elliptical gaussian components to the calibrated visibility data using the program *modelfit*, from the Caltech package (*S:* fluxes; *R:* distance between components; θ: PA. The subscripts correspond to the labelling of the components in Fig. 2). Errors are standard errors, derived using the program *errfit*, also from the Caltech package.

1038+528 B

Epoch	S_{core} *(mJy)*	S_{ref} *(mJy)*	S_{core}/S_{ref}	$R_{core-ref}$ *(mas)*	$\theta_{core-ref}(^0)$
1981.2	29 ± 3	58 ± 6	0.5 ± 0.07	1.703 ± 0.020	-53.3 ± 0.4
1983.4	30 ± 3	53 ± 5	0.55 ± 0.07	1.739 ± 0.019	-53.4 ± 0.5
1990.5	32 ± 3	48 ± 5	0.7 ± 0.1	1.838 ± 0.035	-52.8 ± 0.8

their purpose has been to monitor the position of the core of one of them (1038+528 A, z=0.678) with respect to that of the other (1038+528 B, z=2.296). Observations at other wavelenghts have been reported by Marcaide et al. (1985) and Elósegui (1991). The observations of this pair made in March 1981 (1981.2) and May 1983 (1983.4) at λ 3.6 cm and λ 13 cm are described elsewhere (Marcaide & Shapiro 1983, 1984; Marcaide et al. 1985; Elósegui 1991; Marcaide et al. 1994, hereafter MES 1994). As a result of their analyses, a spectral dependence of the position of the observed core of 1038+528 A was discovered and later confirmed, and was explained in terms of opacity effects (Marcaide & Shapiro 1983, 1984). In addition, an unexpectedly large change in the angular separation between the A and B quasars from 1981.2 to 1983.4 was noted (MES 1994). To discriminate among several hypotheses proposed to explain this unexpected change, new observations were made in June 1990 (1990.5). We report here the analysis of the data from this third epoch, and propose a scenario which reproduces the astrometric results for all three epochs.

2. Observations

We observed these sources simultaneously at λ 3.6 cm and λ 13 cm for about 10 hours on 18-19 June 1990, using an intercontinental VLBI array of 9 radio telescopes (antenna diameters and locations from East to West in parentheses): Wettzell (20 m, Germany), Medicina (32 m, Italy), Effelsberg (100 m, Germany), DSS63 (70 m, Spain), Haystack (37 m, Massachusetts), Green Bank (43 m, W.Virginia), Pie Town (25 m, New Mexico), Owens Valley (40 m, California) and Fort Davis (26 m, Texas). Right hand circular polarization signals were recorded at each antenna using the MK III VLBI system (Rogers et al. 1983). Recording Mode A (28 MHz bandwidth at each wavelength) was used at all antennas except Pie Town, where the use of a VLBA recording terminal restricted the usable bandwidth to 16 and 12 MHz at λ 3.6 cm and λ 13 cm, respectively. The observing method in 1990.5 was similar to that used in the previous epochs and is described in detail elsewhere (Marcaide & Shapiro 1983).

Observations of the calibrator source 4C39.25 and the pair 1038+528 A and B were alternated in a repeated cycle throughout the experiment: 2 minutes pointing on the calibrator and 11 minutes on the midpoint between the sources of the pair. This scheme is a very convenient one for calibration of the array.

The data processing was carried out at the VLBI correlator center of the Max Planck Institute für Radioastronomie in Bonn (Germany). A two-pass correlation using different "a priori" geometric parameters was made, to determine separately the interferometric observables for each source. The correlated data were transferred into appropriate formats for further analysis using the Caltech mapping software (Pearson 1991) and the astrometric program VLBI3 (Robertson 1975).

3. Data analysis

In astrometric studies involving extended sources, we need to choose reference points within the source structures, from which to measure positions or angular separations. In long-term monitoring studies, the comparison of the angular separations between two radio sources measured at different epochs will be most meaningful if those reference points are identical from epoch to epoch.

For simplicity, we describe the data analysis in two parts: the first treats source structure and the second the astrometric analysis for point-like sources.

3.1. Milli-arcsecond scale structures of 1038+528 A and B

We made maps of 1038+528 A and B at λ 3.6 cm and λ 13 cm with the Caltech VLBI package, which uses hybrid mapping techniques and deconvolution algorithms like CLEAN. Calibration factors for converting the measured interferometric amplitudes and phases into the source complex visibility function were derived from the information provided by the participating observatories (system temperatures and gain curves), the contemporaneous observations of 4C39.25, and an iterative procedure of self-calibration (Cornwell & Wilkinson 1981). The maximum correlated flux densities on intercontinental baselines at λ 3.6 cm and λ 13 cm were, respectively, about 450 and 300 mJy for 1038+528 A, and about 90 and 130 mJy for 1038+528 B, with estimated standard errors of about 10% in each case. Fig. 1 shows the VLBI maps of 1038+528 A and B, at λ 3.6 cm and λ 13 cm, for June 1990 (Rioja 1993), and for previous epochs (Marcaide et al. 1985; Elósegui 1991). The pixel sizes of the maps at λ 3.6 cm and λ 13 cm are 170 and 550 μas, respectively. To parameterize the brightness distributions in Fig. 1, we used weighted least squares to fit models consisting of elliptical Gaussian components to the self-calibrated visibility data.

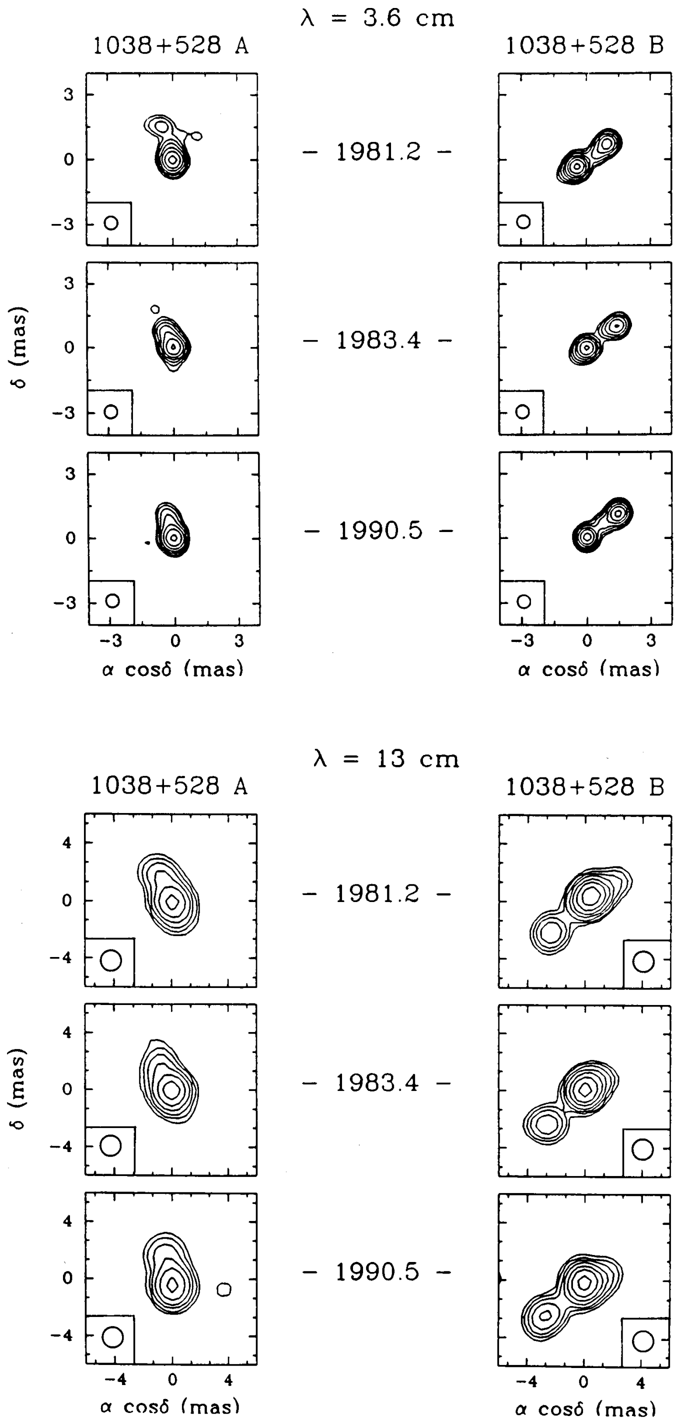

Fig. 1. (Top) Hybrid maps of the quasars 1038+528 A and B for epochs in March 1981, May 1983 and June 1990 at λ 3.6 cm. The contours are 1,2,5,10,20,40, and 80%, and 2,5,8,15,25,50, and 90% of the peak of brightness of each map for A and B, respectively. The restoring beam size (FWHM of a circular gaussian) is 0.6 mas. **(Bottom)** Corresponding hybrid maps at λ 13 cm. The contours are 2,5,10,20,40, and 80%, and 2,5,8,15,25,40, and 70% of the peak of brightness of each map for A and B, respectively. The restoring beam size (FWHM of a circular gaussian) is 1.5 mas. Nevertheless, note that the real interferometric beam size at λ 13 cm is nearly four times larger than at λ 3.6 cm.

Table 1 lists the resulting parameter values and their estimated standard errors at λ 3.6 cm for quasar B at the 3 epochs derived using the Caltech VLBI analysis programs MODELFIT and ERRFIT (Pearson 1991).

For long-term astrometric studies, the fiducial points in the brightness maps of the sources should be prominent features, whose positions can be precisely identified and measured from epoch to epoch. The reference points in the maps of 1038+528 A and B in June 1990 were chosen following the same criteria as for the analyses of the observations at the previous epochs. In particular, the choice of these locations was based on the most prominent delta function components used to construct the maps shown in Fig. 1. More specifically, each reference point corresponds to the centroid of the subset of delta functions which have flux densities exceeding 25% of the highest one and which lie within one beam area from it. Using these selection criteria, we expect the reference point in the map of 1038+528 A to coincide with the position of the core ($\alpha_{3.6-13cm}$ = 0.4, $S_\nu \propto \nu^\alpha$), whereas for 1038+528 B the reference point is the eastmost component in the maps at λ 3.6 cm ($\alpha_{3.6-13cm} = -0.4$). Fig. 2 shows the correspondence between the source components and the reference points used for the astrometric analysis, in both sources. The eastmost component for 1038+528 B at λ 13 cm is not detected at λ 3.6 cm; its spectral index must therefore satisfy $\alpha < -1.9$ (Marcaide et al. 1985).

The so-called *structure contribution* to the observed phase-delay can be estimated from the brightness distribution (Shapiro et al. 1979). We used the maps shown in Fig. 1 and the reference points (described above) to estimate the source structure contribution for each baseline for each observation. These contributions are as large as some tens of picoseconds (ps).

In Sect. 5 we consider other plausible criteria for choosing the reference points within the extended structures of both radio sources, along with the astrometric implications.

3.2. Astrometric analysis for point-like radio sources

VLBI observables are sensitive to the changing orientation of the telescope array with respect to the source as the Earth rotates. Essentially, the astrometric analysis consists of disentangling this geometric signature from other contributions to the observed interferometric quantities, and thereby estimating the position of a source or, for example, the angular separation between two sources.

At present, the *a priori* knowledge of baseline vectors, source position, clock behaviour, and propagation medium is not sufficiently accurate to allow the $2\pi n$ phase ambiguity in the measurements of phase delays to be eliminated. Hence, these quantities are ambiguous by an integral multiple of 120 and 450 ps at λ 3.6 cm and λ 13 cm, respectively. However, the differencing technique has been successfully used for pairs of radio sources up to several degrees apart, producing unambiguous differenced-phase-delay observables largely free from the main sources of error (Shapiro et al. 1979; Marcaide & Shapiro 1983; Bartel et al. 1986; Guirado et al. 1994, 1995; Lara et al. 1996).

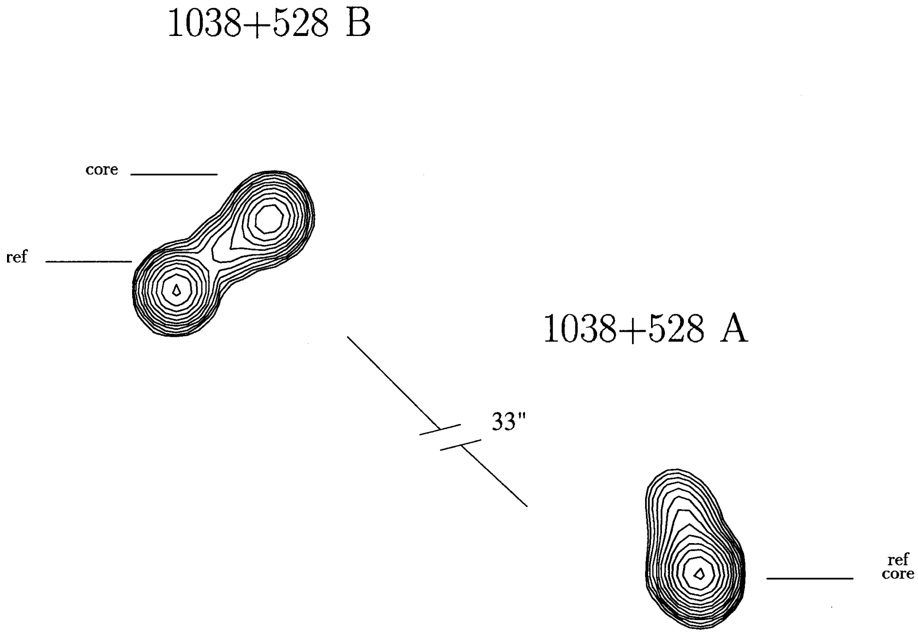

Fig. 2. Projection of quasars 1038+528 A and B on the sky. The components labelled as *ref* in both structures correspond to the reference points used in the astrometric analysis presented here. These are maps at λ 3.6 cm in June 1990.

The basic observable used in the astrometric analysis of the three epochs of observation of 1038+528 A and B is the differenced phase delay, formed by subtraction of the phase delay measured for one source from that measured for the second source observed simultaneously. The strategy followed in the data analysis was the same for all three epochs (see Marcaide & Shapiro 1983, for details). We used the differenced phase delays measured in June 1990 at λ 3.6 cm and λ 13 cm to estimate the angular separations between 1038+528 A and B at that epoch, in the barycentric celestial reference frame J2000.0, using a recent version of the astrometric program VLBI3 (Robertson 1975). The data analysis is carried out using theoretical models, plus weighted least squares, to estimate values for the relevant parameters. Values for the parameters which describe the Earth's orientation, the telescope locations, and the reference source coordinates, are taken from a global VLBI solution provided by Goddard Space Flight Center (GSFC) (Chopo Ma priv. comm.). VLBI3 uses time polynomials to model the atmospheric and instrumental contributions to the observables; alternative methods of astrometric analysis use stochastic models to account for these contributions (e.g., Kalman filters, used by OCCAM (Zarraoa 1993) and SOLVK (Herring 1990) softwares). The critical parameter determining the reliability of the ambiguity resolution is the relative separation of the two sources. In the case of 1038+528 A,B the effects of errors in the other parameters are scaled down by a factor of almost 10^{-4}, that is, the relative separation (33") expressed in radians (Shapiro et al. 1979). We had no problems in achieving a correct resolution of these phase-delay ambiguities by using the relative separation measured in 1983.4, which implies in turn that the separation changed by less than 1 mas during the interval spanned between 1983.4 and 1990.5. After removal of the ambiguities, the coordinates of quasar A with respect to those of quasar B were estimated from weighted-least-squares analysis of the differenced phase delays.

Finally, we re-analysed the observations from previous epochs (1981.2 and 1983.4) using a consistent set of values (global VLBI solution GLB831, provided by GSFC) for all three epochs for the parameters that describe the Earth's polar motion and rotation, the baseline vectors, and the reference source position in the sky.

4. Results

λ 3.6 cm

Fig. 1 shows that at λ 3.6 cm the inner part of the jet in 1038+528 A seems to curve more towards the NE in 1983.4 than in 1981.2. In the 1990.5 map this part of the jet appears oriented nearer to the North. The maps of 1038+528 B at epochs 1981.2 and 1983.4 do not reveal any significant changes in the structure of the source at the resolution of our maps. However, for 1990.5 both the map and the parameters listed in Table 1, show changes in the structure compared to those for the two previous epochs: the distance between the two components has increased by $135 \pm 50 \mu$as, whereas the flux density of the eastmost component has decreased by 17% since 1981.2.

The astrometric analysis of the 1981.2 and 1983.4 VLBI observations of this pair of radio sources is presented elsewhere (MES 1994). We present here the analysis of the June 1990 observations. Fig. 3 shows the evolution of the angular separation over a decade, expressed as the change in position of the reference point in quasar A with respect to that in B, and taking as the origin of coordinates the relative position in 1981.2. The position in 1983.4, with respect to that in 1981.2, corresponds to a vector of magnitude 66 ± 47 μas, in the NW direction (P.A. $-10^\circ \pm 45^\circ$), and the corresponding relative position in 1990.5 to a vector of magnitude 170 ± 50 μas in the NW direction (P.A. $-50^\circ \pm 27^\circ$). Table 2 lists the separations between A and B for

Table 2. Top: Relative separations between quasars A and B, in 1981.2, 1983.4, and 1990.5 at λ 3.6 cm derived from the astrometric analysis using VLBI3. The standard errors, σ, follow from the error analysis described in Sect. 5. **Bottom:** *fixed* J2000.0 source coordinates used for quasar A in the astrometric analysis (these coordinates correspond to GSFC global solution GLB831 (Chopo Ma, priv. comm.)).

Epoch	$\Delta\alpha_{B-A}$	$\sigma(\Delta\alpha_{B-A})$ (μas)	$\Delta\delta_{B-A}$	$\sigma(\Delta\delta_{B-A})$ (μas)
1981.2	$2^s.1160427$	25	$27''.376574$	36
1983.4	$2^s.1160439$	24	$27''.376510$	34
1990.5	$2^s.1160568$	28	$27''.376464$	36

	α_A	δ_A
1038+528 A	$10^h\ 41^m\ 46^s.781613$	52^0 33' 28".23373

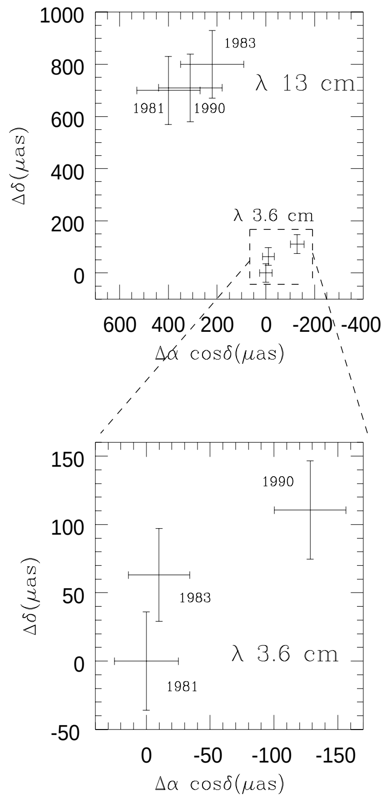

Fig. 3. Decadal evolution of the separation between quasars 1038+528 A and B at λ 3.6 cm and λ 13 cm. The lower figure is a "blow up" of the λ 3.6 cm part of the upper figure. This evolution is expressed as a change in the position of the reference point in quasar A with respect to that in B, starting from their relative positions in 1981.2. Error bars represent our estimated standard errors (see text). Opacity effects in the core of the quasars 1038+528 A are inferred to be responsible for the dependence of the relative position on the observing wavelength, as suggested by Marcaide and Shapiro (1983) (see text).

all three epochs. The error bars in Fig. 3 and Table 2 follow from the error analysis in Sect. 5.

λ 13 cm

Comparing the results from the λ 13 cm data for the three epochs we find no significant changes of the brightness distributions of the quasars A and B. We also find no evidence for any significant change in position of the reference point. However, there does exist a systematic difference between the angular separations measured at λ 3.6 cm and λ 13 cm; we find the difference in separation for 1981.2, 1983.4 and 1990.5 to be 797 $\pm$ 160, 827 $\pm$ 160 and 727 $\pm$ 160 μas, respectively, in the NE direction (P.A. 42° $\pm$ 13°, 15° $\pm$ 11° and 36° $\pm$ 13°, respectively). Thus, within our estimated standard errors, the magnitude of this difference remained constant.

5. Error analysis

An estimate of the standard error in the source-separation determination derived solely from the postfit residuals may well underestimate the true standard error. For example, slowly varying measurement errors may be absorbed in the astrometric analysis in such a way that they contribute to errors in the estimated values of the parameters, but do not leave traces in the residuals. Furthermore, errors in the parameters whose values are fixed instead of estimated may affect the solution significantly but have no perceptible effect on the residuals.

Elósegui et al. (1991) performed an error analysis to determine reliable standard errors for the estimates of the angular separations of 1038+528 A and B in 1981.2 and 1983.4 at λ 3.6 cm and λ 13 cm. Their analysis concerned the propagation of errors in the values assumed for the quantities used to model the geometric, atmospheric and instrumental contributions to the angular-separation determination (e.g., baseline vectors, position of reference source on the sky, tropospheric zenith delays, ionospheric delays, and amplitude calibration). We repeated this analysis for the third epoch of observation and reassessed the solar plasma contribution; Table 3 summarizes the results of this error analysis for 1990.5.

In this paper we readdress some types of errors which can affect the determination of the proper motion inferred from the direct comparison of the relative positions measured at different epochs. These types of error stem from: (1) the criteria used to choose the reference points within the brightness distributions; (2) the particular software used for the data analysis; (3) the set of values used for the Earth's pole position and orientation; and (4) the non-identical observing conditions for the three epochs. We summarize below the means we used to estimate these effects at λ 3.6 cm:

(1) We compared the positions of the reference points in the quasars A and B determined as indicated in Sect. 3, with positions derived using two other plausible procedures: (a) a two-dimensional interpolation with the method of "bicubic splines", and (b) different pixel sizes in the mapping with the same method of choosing the reference point. For 1038+528 A, the pairwise differences for the three methods are less than 6 μas in magnitude for all three epochs; for 1038+528 B, these differences are less than 29, 22 and 10 μas in 1981.2, 1983.4 and 1990.5, respectively.

Table 3. Compendium of effects considered in estimating the standard error in the relative position ($\Delta\theta$) of the quasars 1038+528 A and B in June 1990, at λ 3.6 cm and λ 13 cm.

	$\Delta\theta$	
Source of error	λ = 3.6cm	λ = 13cm
Beamwidth-SNR	$\sim 37\mu$as	$\sim 132\mu$as
Procedure to choose ref. points	$\sim 11\mu$as	
Solar plasma	$\sim 1\mu$as	$\sim 13\mu$as
Amplitude Calibration	$< 10\mu$as	
Astrometric software	$< 10\mu$as	
Ionosphere	$\sim 0.2\mu$as	$\sim 3\mu$as
Troposphere	$\sim 1\mu$as	$\sim 1\mu$as
EOP ($\star$)	$< 1\mu$as	$< 1\mu$as
Baseline Vector	$< 1\mu$as	$< 1\mu$as
Reference source position	$\sim 0.1\mu$as	$\sim 0.1\mu$as

($\star$) EOP = Earth Orientation Parameters

(2) We adapted two geodetic software packages, OCCAM (Zarraoa 1993) and CALC/SOLVK (see, for example, Herring 1990, and references therein), for differential astrometric analysis, and used them to analyze the observations of 1038+528 A and B from each of the three epochs. The pairwise differences in the determinations of the angular separation estimated using these two software packages and VLBI3 are at the μas level for each epoch.

(3) We re-analysed the data from the three epochs using four different sets of consistent values for the baseline vectors, the reference source coordinates, and the Earth orientation parameters provided by Goddard Space Flight Center (namely, GLB401, GLB622, GLB718 and GLB831) (Chopo Ma priv. comm.). The angular separations of A and B for each epoch were found to agree at the μas level.

(4) We studied the dependence of the angular separation determinations on the coverage of the (*uv*) plane. The (*uv*) coverages for the observations in 1981.2 and 1983.4 were quite similar, whereas that for 1990.5 was much less complete. We therefore selected a subset of the 1983.4 measurements which has a (*uv*) sampling similar to that in 1990.5. The difference in the angular separation determination for the 1983.4 data, estimated from this subset and from the total data set, was 11 μas in right ascension and 1 μas in declination.

Considering the above and looking at Table 3, we conclude that the largest source of uncertainty in the estimate of the angular separation of quasars A and B is the error in the identification of the reference points within the structures of each quasar, at λ 13 cm about 120μas, and at λ 3.6 cm, 37μas (Rioja 1993). This error is independent of the angular separation of the two sources; instead it is directly proportional to the interferometric beam size in each particular direction and inversely proportional to the signal-to-noise ratio in the maps (Thompson et al. 1986).

We take as reasonable estimates of the standard errors for the angular separations measured, at λ 3.6 cm and λ 13 cm, the root-sum-squares of the statistical standard deviations and the individual uncertainties listed in Table 3. These statistical standard deviations were derived from the postfit residuals and are between 7 and 10 times smaller than our above estimates of the standard errors at λ 3.6 cm for each of the three epochs.

6. Interpretation

The main goal of our program has been to monitor the time dependence of the location of the centre of mass of quasar A relative to an external reference. There is no guarantee that the fiducial points selected for the data analysis either coincide with, or are at fixed positions relative to, the centre of mass. Hence, the detection of a significant change in the position of these points does not necessarily imply motion of the centre of mass. We would expect any transverse motion of the centre of mass to be constant, while any "erratic" component could reasonably be interpreted as the relative proper motion of the reference points with respect to the centre of mass.

Here we interpret the changes in the separation observed at λ 3.6 cm (Fig. 3) as due to relative changes in reference-point locations in the two sources. A possible interpretation of the nature of these changes in each quasar is described below.

1038+528 B

We outline below some of the results from our independent imaging and astrometric analyses:

1. The vector which describes the angular separation between 1038+528 A and B in 1990.5 relative to their separation in 1981.2, as shown in Fig. 3, has modulus 170 $\pm$ 50 μas (P.A. 130° $\pm$ 27°) and is closely aligned with the direction of the jet in the λ 3.6 cm map of quasar 1038+528 B (Fig. 1 and Table 1).

2. The difference between the separation of the components in the model for 1038+528 B for 1990.5 and that for 1981.2, as shown in Table 1, is $\sim 135 \pm 50$ μas ; the relative orientation of the components is the same for both epochs, to within the estimated standard errors (P.A. $127^0 \pm 1^0$). These estimates measure the evolution of the relative separation between the two components in 1038+528 B, regardless whether the core component remains stationary or not.

3. The λ 3.6 cm maps of quasar A at epochs 1981.2 and 1990.5 do not show any significant differences from each other.

We conclude that the main contribution to the 170 $\pm$ 50 μas difference in the estimated angular separation between 1038+528 A and B in 1990.5 from that in 1981.2, is the displacement of the reference point in the quasar B. This displacement corresponds to an average near-luminal rate of change of the position of the peak of brightness of quasar B of 18 $\pm$ 5 μas yr^{-1} [v=(0.8 $\pm$ 0.2)h^{-1} c] between 1981.2 and 1990.5; in this model, the eastmost (steep spectrum) component in the λ 3.6 cm maps moves along the "jet" direction (i.e., towards the southeast, P.A. 130°) away from the northmost (inverted spectrum; $\alpha_{3.6-13cm}$ = 0.8) component. The reference point used in the astrometric analysis, as noted above, is defined by the centre of the eastmost (steep-spectrum) component. The change in the position of this reference point measured by astrometry is thus quite compatible with the changes measured in the maps of 1038+528 B.

The combination of the structural information in the maps (Fig. 1) with the astrometric results shown in Fig. 3 leads in a natural way to this interpretation for the change in the angular separation between 1981.2 and 1990.5.

1038+528 A

The changes in position of the chosen reference point in 1038+528 A can be deduced from the global astrometric results shown in Fig. 3 and the postulated evolution of the reference point in quasar B. The expansion of quasar B at a rate of 18 ± 5 μas yr^{-1} at P.A. 130° translates into a change of ca. 39 ± 11 μas in the angular separation between quasars A and B over the period from 1981.2 to 1983.4. On the other hand, between these epochs, Fig. 3 shows a measured change of the angular separation of 66 ± 47 μas towards the North (P.A. $-10^0 \pm 45^0$). According to our scenario, the difference between these changes must represent a change of the reference point location in quasar A from 1981.2 to 1983.4 of 43 ± 37 μas in P.A. $25^0 \pm 63^0$. Such a change is less than a tenth of a beamwidth at λ 3.6 cm and is in the direction of the jet in the maps of quasar A at λ 3.6 cm, as shown in Fig. 1. The uniform motion attributed to the reference point in quasar B also accounts for the angular separation between the two quasars measured in 1990.5 relative to that in 1981.2 (Fig. 3). Thus, the position of the reference point in quasar A in 1990.5 is the same, or nearly the same, as in 1981.2.

Fig. 4 shows the estimated angular separations of quasars A and B in 1990.5 and 1983.4 relative to that in 1981.2, first as observed and then after including the contribution attributed to the postulated motion of the reference point in B. The resulting random appearance of the motion of the reference point in A suggests that it is some kind of "jitter" of the observed core. It does not necessarily imply a physical displacement of a feature in the source; it might result from activity in the core region, and the early stage of ejecting new components as yet unresolved in the maps, or from changes in the physical conditions in the medium, or it might represent no motion at all, given that its magnitude is only of the order of its estimated standard error.

The results found at λ 13 cm in 1990.5, being essentially the same as those found earlier, support the explanation proposed by Marcaide and Shapiro (1983), namely that opacity effects in the core region of the quasar A are responsible for the wavelength-dependence of its observed position. The monitoring over a decade provides a firmer measure of the characteristic length for this kind of effect of the order of $4.6\,h^{-1}$pc ($\sim$ 700μas). The changes in angular separation inferred from the λ 3.6 cm data would not be detectable reliably at λ 13 cm because of the almost fourfold poorer resolution at λ 13 cm.

7. Conclusions

From three epochs of data, one each in 1981.2, 1983.4, and 1990.5, we have measured at λ 3.6 cm significant changes of up to 170 μas in the angular separation of the reference point chosen in quasar 1038+528 A from the one chosen in quasar 1038+528 B. We interpret this change as being due primarily to the motion [18 ± 5 μas yr^{-1}, v= $(0.8 \pm 0.2)h^{-1}$ c] of the reference point in quasar B relative to its core. For this interpretation, we conclude that there is no "bona fide" proper motion of the quasar A, the upper bound set on any such motion being about 10 μas yr^{-1} (v$\leq 0.2h^{-1}$ c).

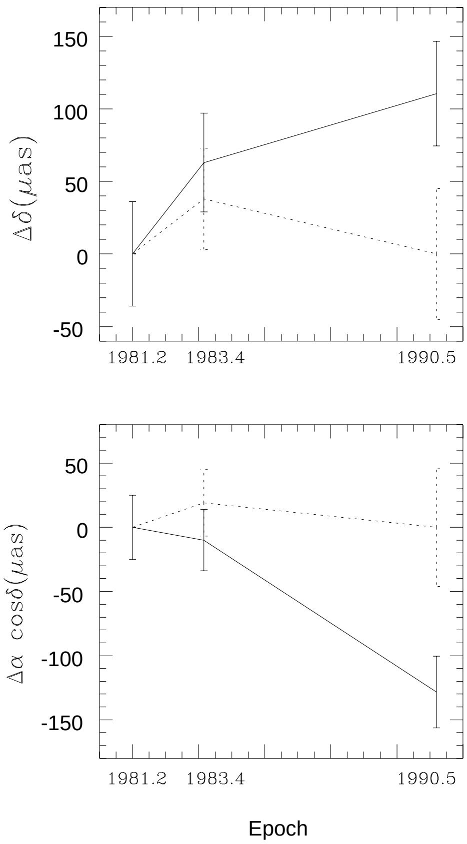

Fig. 4. The angular separation (**top:** relative declination; **bottom:** relative right ascension) between the reference points in quasars A and B at λ 3.6 cm in 1983.4 and 1990.5, with respect to their separation in 1981.2. The **continuous** line connects the values of the observationally estimated relative separations. The **dashed** line connects the values inferred for the positions of the reference point in quasar A, relative to those of a different reference point in quasar B (this reference point - see text - is obtained from the original one, by subtracting from the latter its average motion between 1981.2 and 1990.5 of $\sim 18 \pm 5$ μas yr^{-1} along PA 130°, as deduced from the proposed evolutionary model).

The null result on proper motion obtained from adding the λ 3.6 cm data from the third epoch of observations (1990.5) are consistent to within less than 1.5 standard deviations with the proper motion of 1038+528 A of 31 ± 22 μas yr^{-1} [corresponding to, v=$(0.7 \pm 0.5)h^{-1}$ c; H_0 = $100h$ km s^{-1} Mpc^{-1}; q_0 = 0.5] deduced from the 1981.2 and 1983.4 λ 3.6 cm observations (MES 1994).

We detected no change in the relative positions of the quasars from our observations at λ 13 cm, where the interferometric beam size is nearly four times larger (see Table 3 for contributions to the astrometric uncertainty). However, comparison of the observations at λ 3.6 cm and λ 13 cm shows that the position of the observed core in quasar A is frequency dependent (Marcaide & Shapiro 1983, 1984). Such an effect has since been reported for other sources, e.g. 3C345 (Biretta et al. 1986) and 3C395 (Lara et al. 1996).

At cosmological distances the standard theory for extragalactic radio sources predicts stable cores at the μas level. So far, astrometric studies have not reached this level of precision. Bartel et al. (1986) obtained bounds on the proper motion of 3C345 (with respect to NRAO150) equal to $\nu_\alpha \leq 20\mu$as yr^{-1} and $\nu_\delta \leq 50\mu$as yr^{-1}. The bound on the proper motion of quasar A presented here, $\nu \leq 10\mu$as yr^{-1}, is the lowest upper limit set to date, despite much lower flux densities in this source and in the reference source compared to the 3C345-NRAO150 pair, because of the formers' smaller angular separation. In our case, the accuracy of the angular separation estimate is limited by the signal-to-noise ratio for the maps and the interferometric resolution, both of which affect the determination of the location of reference features. This limitation is independent of the relative separation of the sources. For sources with larger angular separations between them, other effects usually limit the precision (Guirado et al. 1994).

The results from the third epoch of observations in 1990.5 allow us to reject the hypothesis of a possible "bona fide" proper motion of 31 ± 22 μas yr^{-1} for the core of quasar A, proposed (MES 1994) as one possible explanation for the change in position between 1981.2 and 1983.4, and favors the alternative model, proposed by those authors, based on opacity changes in the jet emission, where the displacements between 1981.2 and 1983.4 are related to core "jitter" effects in the quasar A, or the alternative of no motion.

The flat-spectrum quasar 1038+528 B displays expansion in the separation between its two main components at a rate near c. In the context of relativistic beaming models, such motions will be observed in sources with jets that move in directions not very close to perpendicular to the plane of the sky, and hence would be expected to display weak cores and jet-to-counter-jet flux ratios not greatly exceeding unity.

Based on its spectral index (Marcaide & Shapiro 1984), we assume that the centre of mass of quasar B is near the westmost component in the λ 3.6 cm maps. The astrometric analysis presented here used the eastmost component as the reference point, because it had the highest flux density. The selection of a weaker component as a reference point in the astrometric analysis would have had disadvantages: the uncertainty in the location of the reference point would have been larger; in addition, the core of quasar B might exhibit a "jitter" phenomenon, such as might be present in the core of quasar A.

Although our scenario successfully reproduces the kinematics of this quasar pair, we consider it important to continue to monitor these sources at the same frequencies and to start monitoring at new frequencies, with the highest feasible angular resolution. Such monitoring should allow further investigations, with unprecedented detail, of the physical conditions, and their variability, in a region very close to the central engine of a quasar.

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