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Possible superluminal motion between two stationary components in the high-redshift quasar 1338+381

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Abstract. VLBI maps of the high-redshift quasar 1338+381 (z=3.1) have been made at five epochs between September 1992 and May 1994. They reveal structure with two well defined components separated by 3.6 milliarcseconds and suggest at one epoch a third weaker component in between. We have significant evidence that the two main components are stationary over the 1.7 year period of observations and might result from a bent jet structure, as in 4C 39.25. We propose a scenario in which the weaker third component moves between the two stationnary components at the high apparent velocity of $27{\pm}17$ h^{-1} c. We discuss briefly the location of this new compact F double sou rce in the $\mu - z$ diagram.

Key words: galaxies: jets – cosmology: observations – galaxies: distances and redshifts – quasars: individual: 1338+381

1. Introduction

Most of the compact extragalactic radio sources studied by very-long-baseline-interferometry (VLBI) consist of a bright, compact, flat-spectrum radio core and a weaker knotty jet extending to one side. This structure is explained in terms of a relativistic plasma flowing in a narrow angle cone with shock waves producing the moving knots (see, e.g., Readhead 1992). However, there is a fraction of enigmatic compact objects which does not exhibit this structure and possibly requires modifications to the basic model. We have identified such a source, the high-redshift quasar 1338+381, by means of VLBI observations and we show that its structure is reminiscent of the peculiar source 4C 39.25 (see, e.g., Marcaide et al. 1985).

The extragalactic radio source 1338+381 might have been discovered first in the Bologna B2.3 survey at 408 MHz (Colla et al. 1973). However, Machalski (1978) raises the possibility of a misidentification. Machalski & Condon (1979) determine a CD type (Compact Double) based on the radio spectra of 1338+381, suggesting the presence of two or more self-absorbed components in the source. Table 1 summarizes the history of the radio flux density measurements of 1338+381. The 4.85, 5.0 and 8.4 GHz observations indicate that this source is variable, as initially suggested by Condon et al. (1979).

The optical identification of 1338+381 was made by Condon et al. (1979) solely on the basis of accurate radio-optical position coincidence using the National Geographic-Palomar Observatory Sky Survey (POSS). 1338+381 was classified as a red, unresolved optical object of magnitude 18, suggesting it could be either a BL Lac object, a high-redshift QSO, or an object with unusually strong absorption spectra. The catalogue of extragalactic radio sources of Véron-Cetty & Véron (1983) indicates that 1338+381 is a quasar with redshift unknown. It is only recently that Hook et al. (1995) obtained its redshift: $z = 3.103 \pm 0.002$.

In this paper, we present results from the first VLBI observations of 1338+381, indicating that it is a compact radio source. VLBI maps at five epochs reveal an extended structure with two main components, as suggested by the spectrum of the source. These two main components appear to be stationary over the two-year span of our VLBI observations. In addition, there is a weaker component directly detected at the first epoch and, possibly, also at the fifth epoch. We make an attempt to classify this high-redshift quasar among the extragalactic radio sources.

2. Observations and data reduction

The extragalactic radio source 1338+381 was observed at 8.4 GHz at five epochs, between September 1992 and May 1994, using a variety of VLBI arrays and the Mark *III* VLBI data acquisition system (Rogers et al. 1983) with an integration bandwidth of 28 MHz. The data were correlated on the Mark *III* correlator at Haystack Observatory. Table 2 shows a summary of the observations and Table 3 includes the general characteristics of the antennas of the VLBI arrays. These observations were made under the auspices of the US VLBI Network, the European VLBI Network and the NASA/JPL Deep Space Network.

The calibration of the data was made by combining the system temperature and gain of each antenna according to standard procedures (see, e.g., Cohen et al. 1975). The antenna sensitivities of Table 3 were taken from the USA VLBI NETWORK Handbook (Backer & Mutel 1988) for stations L, G, and B; and VLBA Observational Status Summary (Wrobel 1994) for the VLBA stations (F, H, I, O, R) and Y. System temperatures

Table 1. Summary of radio observations of 1338+381

Epoch	Frequency (MHz)	Flux density (Jy)	Reference
1969	408	0.25±0.05	Colla et al. 1973 (Bologna)[1]
March 1975	1400	0.26±0.02	Machalski 1978 (Green Bank)
November 1975	5000	0.36±0.03	Machalski & Condon 1979 (NRAO)
April 1976	2695	0.41±0.02	Condon et al. 1979 (NRAO)
April 1976	8085	0.25±0.02	Condon et al. 1979 (NRAO)
October 1987	4850	0.305±0.038	Gregory & Condon 1991 (Green Bank)
February 1990	8400	0.154	Patnaik et al. 1992 (VLA)
September 1992	8400	0.116±0.002	this work (VLA)

[1] Possible misidentification: Machalski (1978) remarks that the B2 position of 1338+381 measured by Colla et al. (1973) at Bologna differed by $-8.6'$ in R.A. relative to his own position.

Table 2. Summary of VLBI Observations of 1338+381 at 8.4 GHz

Start Epoch	UT start-stop	Stations	Synthesized Beam (mas×mas)	Position Angle
11 sep 92	19h01-21h38	B,F,I,L,O,R,Y	1.8×0.6	−34.9
19 apr 93	01h39-10h29	D,F,I,R	2.1×1.8	73.5
08 jul 93	00h37-03h35	D,F,I,R	2.1×1.7	10.3
24 sep 93	13h56-21h11	H,I,O,R,Y	2.3×1.3	8.9
29 may 94	21h22-04h41	B,D,G,H,M,Y	1.3×0.5	-8.2

Table 3. Antennas used

Code	Name	Location	Diameter (m)	Zenith System Temperature (K)	Sensitivity (K/Jy)
B	Max-Planck-Institut	Effelsberg (Germany)	100	65	0.90
D	Deep Space Station 14	Goldstone (California)	70	20	0.85
F	VLBA-FD	Fort Davis (Texas)	26	32	0.11
G	NRAO-140	Green Bank (West Virginia)	43	48	0.20
H	VLBA-HN	Hancock (New Hampshire)	26	32	0.11
I	VLBA-NL	North Liberty (Iowa)	26	45	0.11
L	IRA-Bologna	Medicina (Italy)	32	40	0.13
M	Deep Space Station 63	Madrid (Spain)	70	20	0.85
O	VLBA-OV	Owens Valley (California)	26	50	0.11
R	VLBA-BR	Brewster (Washington State)	26	35	0.11
Y	VLA[1] in phase	Socorro (New Mexico)	130	28	2.16

[1] The Very Large Array is part of the National Radio Astronomy Observatory, a facility of the United States National Science Foundation operated by Associated Universities Inc. under a cooperative agreement.

were from measurements during the observations for the VLBA stations (F, H, I, O, R), Y, B, L and G. For the DSN antennas D and M, the system temperature and gain provided as a function of elevation by Bathker & Slobin (1989) were used. The numbers of u-v crossings used to check the antenna calibration are 3 points in September 1992, 5 points in April 1993, 6 points in September 1993 and 5 points in May 1994. No crossing points were available for July 1993 due to the limited u-v coverage. The initial antenna gains required modification by less than 30% to make the corresponding closure amplitudes unity within 15% for flux calibration sources close to point-like (DA193 and 0309+411) that were included in the observations. These calibration adjustments are typical for the pre-VLBA era. The total flux density of 1338+381 inferred from our VLBI calibration at epoch September 1992 is consistent within 5% with the total flux density measured at the VLA during the observation. Closure phases and calibrated amplitudes of VLBI visibilities were combined by the hybrid mapping algorithm (Cornwell & Wilkinson 1981) as implemented in the Caltech VLBI package. We used the CLEAN algorithm of the Caltech VLBI Package to produce maps with a dynamic range of about 100 to 1 for the best map and 25 to 1 for the worst.

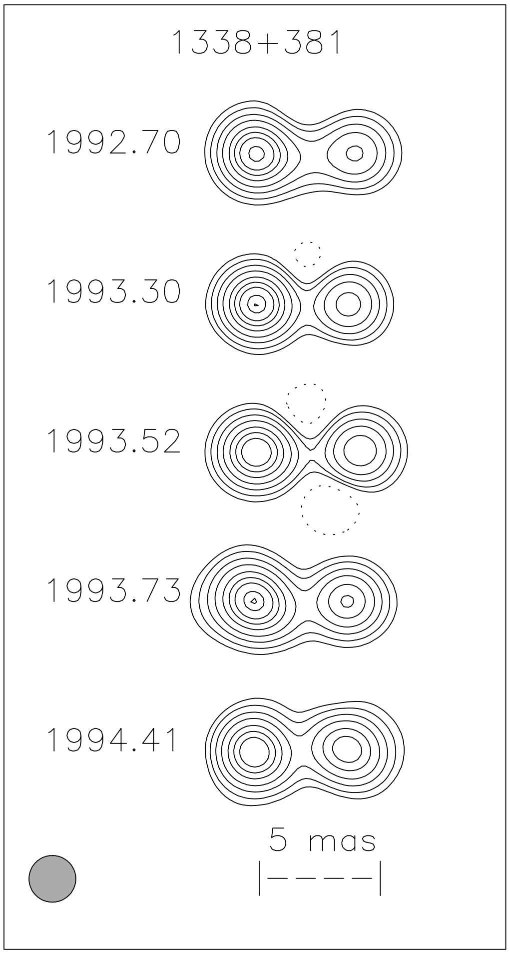

Fig. 1. VLBI maps of 1338+381 at five epochs (1992.70, 1993.30, 1993.52, 1993.73, 1994.41) with the same 1.87 mas restoring beam (dark area in the lower left of the figure). All maps have been rotated counter-clockwise by 73°. Contour levels represent −4,4,8,15,25,40,55,70,90, and 99% of the peak flux density of 74.7 mJy per beam.

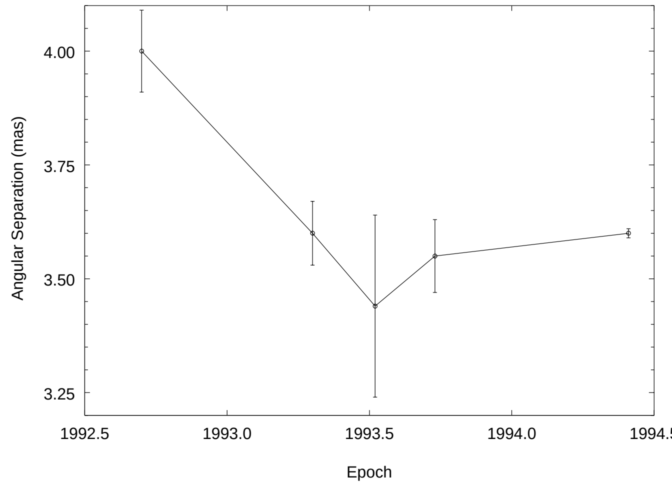

Fig. 2. Separation between components “a” and “b” of 1338+381.

3. Results and interpretation

The five 8.4 GHz VLBI hybrid maps of 1338+381 that we made are presented in Fig. 1 with the same synthesized beam and contour levels. We used a circular beam with a diameter equal to the mean of the major axes of the synthesized beams of the three poorest angular resolution epochs. This display of the maps is presented to make the comparison easier by visual inspection and to emphasize that the dominant structure of the source consists of two main components labelled “a” and “b”. However, we have not drawn quantitative information from these maps. Instead, we determined the component parameters listed in Table 4 by fitting directly the measured VLBI visibilities using MODELFIT of the Caltech VLBI Package, assuming that the source consists of two components each with a circular Gaussian brightness distribution. We determined the statistical standard errors in Table 4 using ERRFIT, assuming one degree of freedom per hour for each antenna as recommended by practitioners (Caltech VLBI Package). In the process of mapping, we increased the standard errors of the measured visibilities by adding in quadrature $3°$ to all the phase standard errors and adding in quadrature 10 mJy to all amplitude standard errors. These corrections are usual for calibration of VLBI data that include data from non VLBA antennas.

The separation of the two main components is plotted versus time in Fig. 2. The mean separation is 3.64 ± 0.09 milliarcseconds (mas) corresponding to a linear separation of $13.5 \pm 0.3\ h^{-1}$ pc ($H_o = 100\,h\,\mathrm{km\,s^{-1}}$ Mpc^{-1} and $q_o = 0.5$). There is a slight contraction of 0.4 ± 0.1 mas between September 1992 and September 1993, but the separation remains constant thereafter. This behavior is reminiscent of the contraction between the two main components of the quasar 4C 39.25 found by Shaffer (1984). Marcaide et al. (1985) interpreted the contraction of 4C 39.25 as the result of a moving component which emerges from, or blends into, one of the two stationary components and the angular resolution of the VLBI observations was not high enough to separate them.

The VLBI maps of 1338+381 for September 1992 and May 1994 are presented in Fig. 3a and b with their conventional synthesized beams and contour levels at the same fractions of each peak. The corresponding u-v coverages are presented in Fig. 4a and b for these 2 epochs. Fig. 3-a shows a third weak component ($12 \pm 2\%$ of the map peak), labelled “c” between “a” and “b” in September 1992, that is not present at the same location in May 1994. By comparing the 3 individual components of the map (a) of September 1992 to the restoring beam, we infer that these components are point-like. In contrast, each of the two components of Fig. 3b in May 1994 are clearly more complex than the restoring beam at this epoch. Unfortunately, the poorer angular resolution at the three intermediate epochs is not sufficient to monitor the evolution of component “c” between these two epochs.

We propose a scenario in which the weak component “c” detected in September 1992 (Fig. 3-a) has moved toward the main component “b” and merged into it in May 1994 (Fig. 3b), producing the extension of “b” to the left hand side. The exis-

Table 4. Two-component model-fitting results for 1338+381

Epoch	Component	S (mJy)	Separation (mas)	Position Angle (°)	Size (mas)
1992.70	a	81.1 ± 6.4	—	—	0.33 ± 0.07
	b	29.6 ± 5.9	4.00 ± 0.09	-162.4 ± 2.0	0.0
1993.30	a	90.8 ± 6.0	—	—	0.82 ± 0.21
	b	42.5 ± 3.6	3.60 ± 0.07	-163.3 ± 1.2	0.0
1993.52	a	89.3 ± 8.6	—	—	0.0
	b	44.8 ± 8.5	3.44 ± 0.20	-163.3 ± 2.4	0.0
1993.73	a	96.7 ± 4.5	—	—	0.84 ± 0.11
	b	45.0 ± 3.9	3.55 ± 0.08	-162.4 ± 0.8	0.0
1994.41	a	73.0 ± 8.3	—	—	0.52 ± 0.06
	b	69.1 ± 6.1	3.60 ± 0.01	-158.5 ± 0.1	0.49 ± 0.0 5

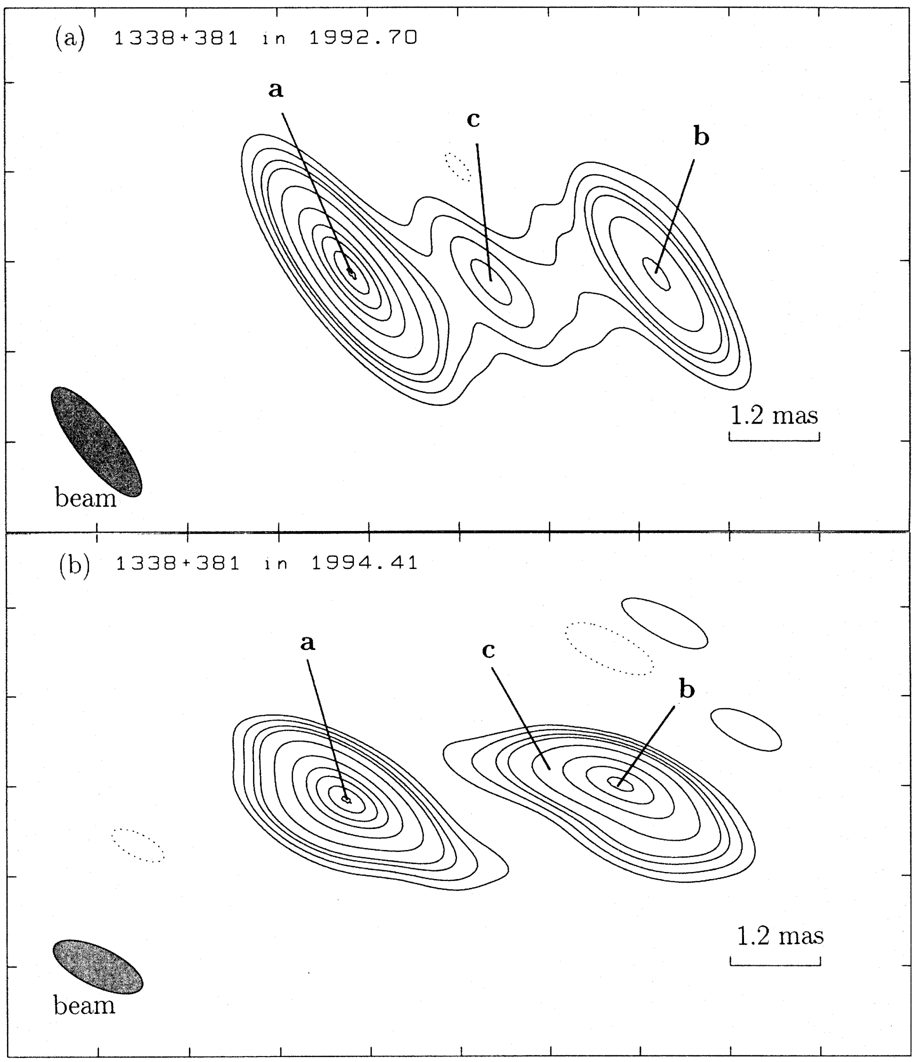

Fig. 3a and b VLBI maps of 1338+381 in September 1992 **a** and May 1994 **b** with their true restoring beams (dark areas in the lower left of the figures). Ticks are spaced at 1.2 mas interval. All maps have been rotated counter-clockwise by 73°. Contour levels represent −2,2,4,7,10,20,40,60,75,90, and 99% of the peak flux densities of 66.2 mJy per beam **a** and 47.1 mJy per beam **b**.

tence of the component "c" blended with "b" is also apparent in our superresolved May 1994 map. Note also that the extension of "a" in May 1994 might be due to a new moving component emerging from the main component "a".

If this scenario were correct, the resulting displacement of the component "c" could be determined from the parameters of the models determined with MODELFIT, in Table 5. In these fits, we assume that the source in September 1992 and May 1994 consists of three components, each with a circular Gaussian brightness distribution. We note that the agreement factor of the Caltech VLBI Package model-fitting, is ∼15% better than when only a two-component model is used. Such an improve-

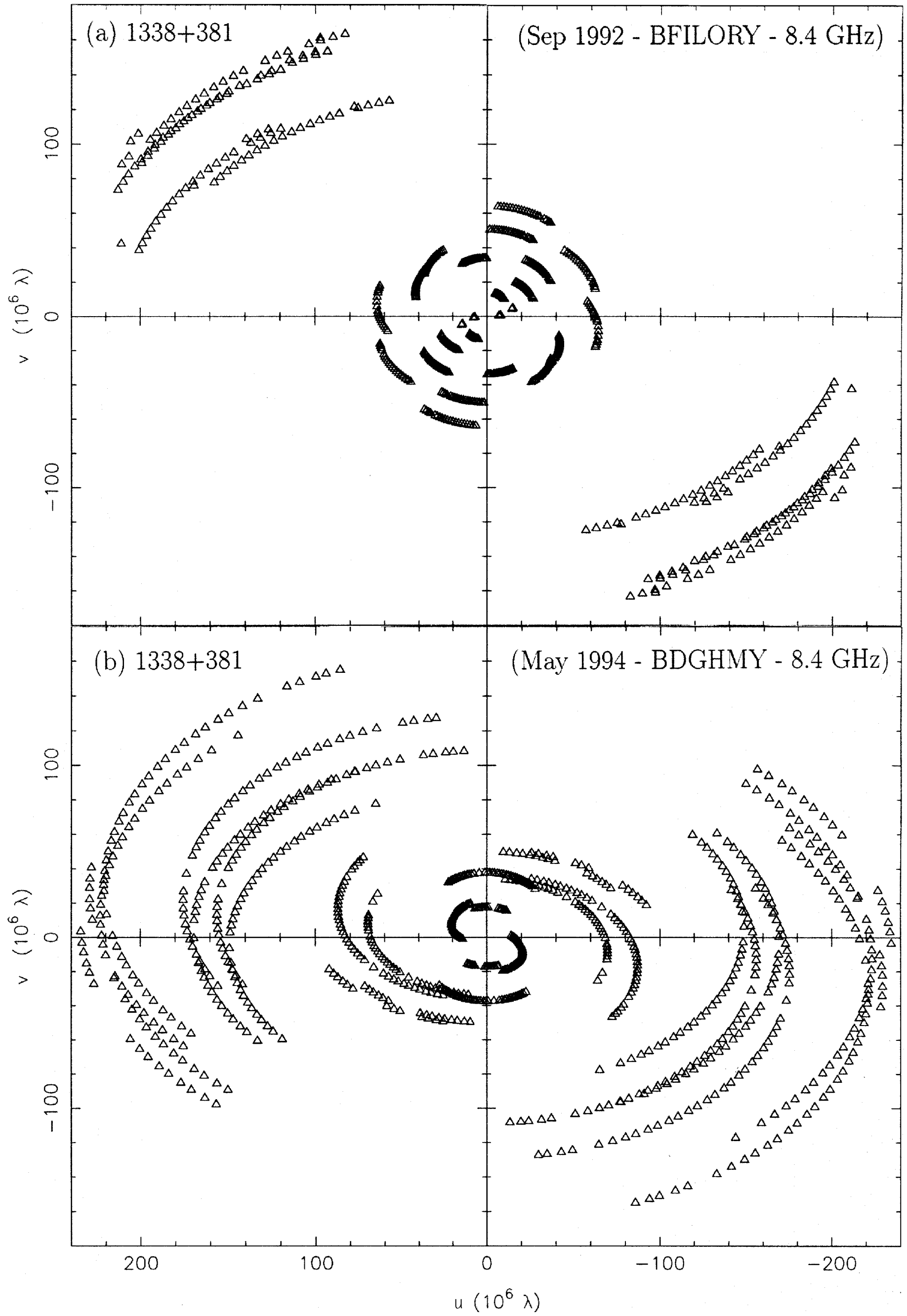

Fig. 4a and b u-v coverages for the VLBI observations of 1338+381 in September 1992 **a** and May 1994 **b**.

ment of the agreement factor in MODELFIT is interpreted as significant by practitioners of the Caltech VLBI package. The parameters of the three-component model are better constrained and their statistical standard errors become smaller (see Table 5). We attempted to determine the systematic standard errors of these parameters estimated by editing the data differently and by varying slightly the amplitude and phase calibration. The parameter values so determined differed from those in Table 5 by up to 2σ in flux density and size and up to 3σ in separation and position angle. It is also noticeable that between September 1992 and May 1994 component "c" in Fig. 3 has moved upward rather than along a straight line towards the centroid of component "b"; this curved motion is consistent with a bent or twisted jet. However, this upward motion is less than one standard error of position angle (Table 5) and we ignore it in our velocity estimate of "c" by taking the displacement of "c" to be 0.92 ± 0.60 mas over 1.71 yr. The standard error is taken to be $\sqrt{2}$ times the large statistical standard error for the separation between the 2 epochs. The resulting proper motion of component "c" is 0.54 ± 0.35 mas yr^{-1}, corresponding to a very high apparent linear velocity of 27 ± 17 h^{-1} c. This motion yields a maximum angle between the jet and the observer line of sight $\theta_{max} = 4.2°$ and a minimum value for the Lorentz factor $\gamma_{min} = 27$. The high luminosity of 1338+381 ($\sim 10^{35}$ erg.s^{-1}.Hz^{-1} at 5 GHz)

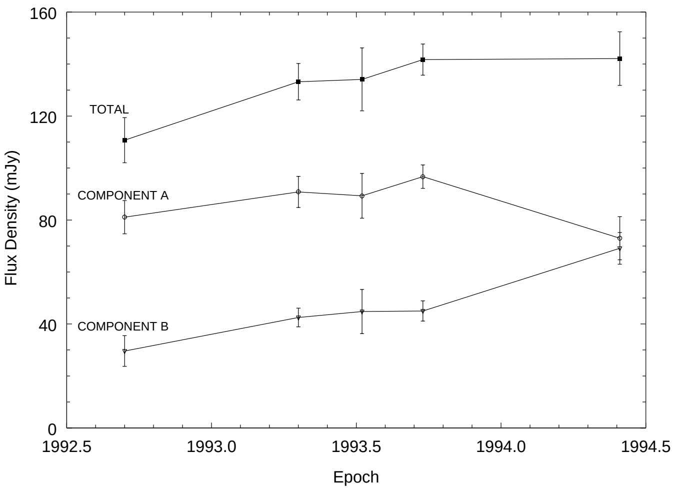

Fig. 5. Total and individual component flux densities of 1338+381.

and the high apparent linear velocity corroborate the correlation already noted by Vermeulen (1995) between β_{app} and luminosity.

In Fig. 5, we present the variation of the total and individual component flux densities at 8.4 GHz from September 1992 to May 1994. The component flux densities are from our two-component models in Table 4, and the total flux density of 1338+381 is their sum. During the time spanned by our observations, 1338+381 exhibited some variability of its 8.4 GHz total flux density. Between September 1992 and September 1993, the total flux density increased by $30 \pm 15\%$ but the flux density ratio remained constant at 0.4 ± 0.1. The total flux densities in September 1993 and May 1994 had the same value 0.14 ± 0.01 Jy, and are within 10% of the value measured at 8.4 GHz about four years earlier in February 1990 (Patnaik et al. 1992). Between September 1993 and May 1994, the flux density of "a" decreased by $25 \pm 12\%$ while that of "b" increased by $54 \pm 27\%$. The flux density ratio between the two components reached 0.95 ± 0.2 in May 94. According to our scenario, after September 1993, the flux density of "a" started to decrease because component "c" had moved far enough to separate from "a" and to merge with component "b" which steadily increased. This description is consistent with the motion of component "c" described above and the results of our three-component models.

If our scenario were correct, it would imply that 1338+381 resembles 4C 39.25, modelled as a bent jet (Alberdi et al. 1993) in which the bright stationary components are at the two positions where the jet bends towards the line of sight. The superluminal component moving between the two stationary components of 4C 39.25 was interpreted as a shock wave propagating down the bent relativistic jet. This model is supported by the recent observation of a fourth weak component west of the others that is probably the core of 4C 39.25 (Guirado et al. 1995). Note also that 4C 39.25 and 1338+381 have similar CD type spectra (Machalski & Condon, 1979).

Following the 4C 39.25 model and according to our scenario for 1338+381, we infer that component "b" must be at a location where the jet bends towards the line of sight. Component "a" could either be at another such location or it could be the core. Component "c" corresponds to a travelling shock and is moving towards "b". When component "c" approached component "b" in May 1994, its velocity vector was pointing closer to the line of sight than it was in September 1992, increasing the Doppler boosting and making it brighter.

In terms of classification, 1338+381 appears to be a "parsec-scale double", defined by Pearson & Readhead (1988) as a source with two or more well-separated components of comparable brightness. Pearson & Readhead (1988) divide these doubles into two physically distinct classes based on the steepness of their high-frequency spectra. The "compact S doubles" have a steep spectral index above the spectrum peak, whereas the "compact F doubles" have flatter spectra. Conway et al. (1994) describe this last class as sources associated with apparently one-sided radio jets with unusual properties. Such objects usually have subluminal velocities between the two major components. According to the model of compact F doubles, the bright stationary features in these objects would be generated by bent or twisted parsec-scale relativistic jets. In the Pearson-Readhead survey, the sources 0153+744, 0711+356, 2021+614 and 4C 39.25 are the only objects of this class. More recently, Akujor et al. (1996) associated 0646+600 with this class on the basis of a contraction apparent in angular separation between its two bright components. We suggest that the source 1338+381 is another compact F double.

Although other scenarios can be envisioned for 1338+381, they are less attractive. If we suppose that component "c" is moving toward "a" rather than "b", then we must invoke a separate explanation of the decrease of the flux density of "a". If we suppose, instead, that component "c" does not move but becomes less and less bright after September 1992 and disappears, we must still explain the increase of the flux density of component "b". Alternatively, if component "c" is the core of the source, so that 1338+381 is a compact symmetric double, then the disappearance of this component and the contraction measured between "a" and "b" are difficult to interpret.

Future VLBI observations should reveal new moving components between "a" and "b", if our scenario were correct. They sould also allow us to identify the core of 1338+381 be obtaining spectra of the two main components or by carrying out "absolute" VLBI astrometry.

4. Conclusions

The 8.4 GHz VLBI maps of 1338+381 at five epochs between September 1992 and May 1994 (Figs. 1 and 3), although modest in dynamic range, reveal interesting structure of this high-redshift quasar (z=3.1). The source 1338+381 consists of two main stationary components "a" and "b" separated on average by 3.64±0.09 mas with a weaker component "c" in between, directly detected only in September 1992. We propose a scenario where component "c" has moved towards component "b" over the two year period of the observations and eventually merged with "b" in May 1994. If this scenario were correct, the apparent angular velocity of component "c" would be 0.54±0.35

Table 5. Three-component model-fitting results for 1338+381

Epoch	Component	S (mJy)	Separation (mas)	Position Angle (°)	Size (mas)
1992.70	a	77.9 ± 5.0	—	—	0.27 ± 0.07
	b	30.7 ± 4.5	4.00 ± 0.08	-162.4 ± 1.6	0.0
	c	10.4 ± 3.6	2.04 ± 0.48	-166.9 ± 16.1	0.0
1994.41	a	80.9 ± 6.1	—	—	0.57 ± 0.03
	b	49.6 ± 5.3	3.75 ± 0.07	-159.3 ± 0.5	0.40 ± 0.03
	c	14.0 ± 3.8	2.96 ± 0.12	-155.9 ± 1.1	0.0

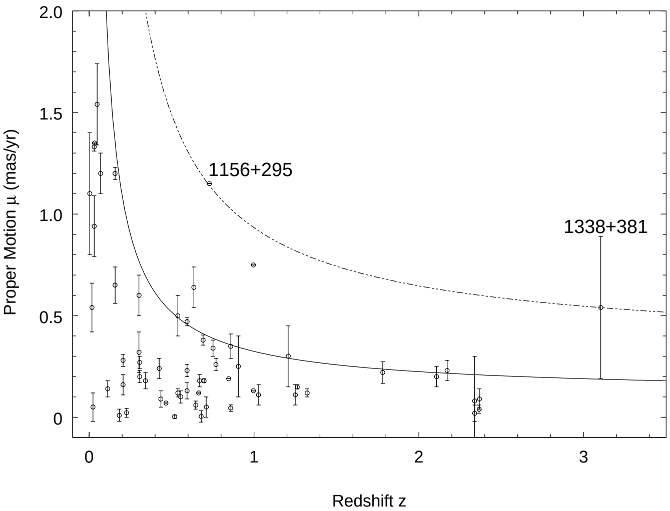

Fig. 6. Internal proper motion versus redshift for superluminal extragalactic radio sources adapted from Vermeulen & Cohen (1994). The solid and dashed lines show upper bounds in Friedmann cosmology for $\gamma H_o = 900$ and $\gamma H_o = 2590$ respectively.

mas yr^{-1}, corresponding to a high apparent linear velocity of 27±17 h^{-1} c. We stress that this proper motion has not been measured directly by tracking the component "c" over several years but is inferred from our scenario, which needs confirmation. Both the type of spectrum and this scenario lead us to classify 1338+381 as a compact F double similar to 4C 39.25, 0153+744, 0711+356 and 2021+614 (Conway et al. 1994) and maybe 0646+600 (Akujor et al. 1996). However, the redshift of 1338+381 (z=3.1) is much higher than 4C 39.25 (z=0.699). It is interesting to note that 1338+381 has a extreme position in the $\mu - z$ diagram (see Fig. 6) in which the observed internal proper motions μ of superluminal sources are plotted against the redshift z (Vermeulen & Cohen 1994). The large proper motion we propose for 1338+381, together with its high redshift, requires an upper envelop higher than the standard limit $\gamma H_o = 900\ km\ s^{-1}\ Mpc^{-1}$ in this diagram. Note, finally, that there is another source, 1156+295, that requires such a revision of the envelope in the diagram (McHardy et al. 1993).

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