UNEXPECTED HIGH BRIGHTNESS TEMPERATURE 140 PC FROM THE CORE IN THE JET OF 3C 120

MAR ROCA-SORGOR1, JOSÉ L. GÓMEZ1, IVÁN AGUDO1, ALAN P. MARSCHER2, AND SVETLANA G. JORSTAD2
1 Instituto de Astrofísica de Andalucía, CSIC, Apartado 3004, 18080 Granada, Spain; mroca@iaa.es, jlgomez@iaa.es, iagudo@iaa.es
2 Institute for Astrophysical Research, Boston University, 725 Commonwealth Avenue, Boston, MA 02215, USA; marscher@bu.edu, jorstad@bu.edu

Received 2009 December 11; accepted 2010 February 26; published 2010 March 11

ABSTRACT
We present 1.7, 5, 15, 22 and 43 GHz polarimetric multi-epoch Very Long Baseline Array observations of the radio galaxy 3C 120. The higher frequency observations reveal a new component, not visible before 2007 April, located 80 mas from the core (which corresponds to a deprojected distance of 140 pc), with a brightness temperature about 600 times higher than expected at such distances. This component (hereafter C80) is observed to remain stationary and to undergo small changes in its brightness temperature during more than two years of observations. A helical shocked jet model—and perhaps some flow acceleration—may explain the unusually high $T_b$ of C80, but it seems unlikely that this corresponds to the usual shock that emerges from the core and travels downstream to the location of C80. It appears that some other intrinsic process in the jet, capable of providing a local burst in particle and/or magnetic field energy, may be responsible for the enhanced brightness temperature observed in C80, its sudden appearance in 2007 April, and apparent stationarity.

Key words: galaxies: active – galaxies: individual (3C 120) – galaxies: jets – polarization – radio continuum: galaxies

Online-only material: color figures

1. INTRODUCTION

3C 120 is an active and relatively nearby ($z = 0.033$) radio galaxy with a blazarlike one-sided superluminal radio jet that has proven to be an excellent laboratory for studying the physics of relativistic jets in active galactic nuclei (e.g., Walker et al. 1987, 2001; Gómez et al. 1998, 1999, 2000, 2001, 2008; Homan et al. 2001; Marscher et al. 2002, 2007; Jorstad et al. 2005, 2007; Chatterjee et al. 2009; Marshall et al. 2009). Previous observations using the Very Long Baseline Array (VLBA) at high frequencies (15, 22, and 43 GHz) have revealed a very rich inner jet structure, containing multiple superluminal components as well as evidence for stationary features suggestive of a helical pattern viewed in projection (Walker et al. 2001; Hardee et al. 2005).

2. OBSERVATIONS AND DATA REDUCTION

We present VLBA observations taken in 2007 November, as part of a multi-frequency program to map the rotation measure in 3C 120 at all accessible VLBA scales, and in 2001 February, when the VLBA was used as part of the ground array for HALCA observations of 3C 120 at 5 GHz.

The 2007 November VLBA observations were performed at 43, 22, 15, [4.6–5.1], and [1.35–1.75] GHz in dual polarization, with nine antennas of the VLBA (Saint Croix was down for maintenance). The highest frequency observations were performed with 32 MHz continuous bandwidth centered at the standard 43, 22, and 15 GHz frequencies. The 4 and 20 cm receivers were split into four 8 MHz bandwidths to maximize possible detection of low Faraday rotation measure.

Reduction of the data was performed with the AIPS software in the usual manner (e.g., Leppanen et al. 1995). The absolute phase offset between the right- and left-circularly polarized data, which determines the electric vector position angle (EVPA), was obtained by comparison of the integrated polarization of the VLBA images of several calibrators (0420–014, DA193, 3C 279, 3C 454.3, and 4C 39.25) with simultaneous Very Large Array (VLA) observations, as well as archival data from the UMRAO, MOJAVE, and NRAO long-term monitoring programs. Estimated errors in the orientation of the EVPAs lie in the range of 5°–10°. After the initial reduction, the data were edited, self-calibrated, and imaged both in total and polarized intensities with a combination of AIPS and DIFMAP (Pearson et al. 1994).

3. HIGH BRIGHTNESS TEMPERATURE IN 3C 120

Our high-frequency (15–43 GHz) VLBA observations during 2007 November (Figure 1) reveal a component (hereafter C80) located 80 mas from the core (deprojected to >140 pc for a viewing angle <20°; Gómez et al. 2000). This is an unusually large distance for detecting emission at these high frequencies—in fact, none of the previous VLBI observations of 3C 120 (starting in 1982) have ever reported emission at this distance at 5 GHz or higher frequencies. We have remapped our previous 15, 22, and 43 GHz VLBA data taken from 1996 to 2001 (Gómez et al. 1998, 1999, 2000, 2001, 2008), covering more than 30 epochs, to check whether we missed it in our previous analysis, but find no indication for emission at the region of C80. However, remapping of the 15 GHz data published in the MOJAVE database (also containing data from other programs3) revealed the first detection of C80 in 2007 April. After this epoch, C80 appears in all 15 GHz images, as shown in Figure 2.

This sequence of images shows no significant motions for C80 during the nearly two years covered by the observations. However, during 2007 the component is observed to increase in flux density and to remain quite compact. Later on, C80 becomes more extended, elongating in the south–west direction without significant changes in its flux.

Our lower frequency images at 1.7 and 5 GHz (see Figure 3) show that the region located around C80 corresponds to a double structure, with another component at ∼90 mas (hereafter C90)

3 http://www.physics.purdue.edu/MOJAVE
located at the southernmost side of the jet, after which the jet extends to the northwest direction. This contrasts to what is found in our previous 2001 image at 5 GHz (see Figure 3), which shows extended emission located at $\sim$85–95 mas and elongated in the northwest direction. We have used circular Gaussian brightness distributions to model-fit the different components in the jet for both epochs, from which we have estimated their observed (i.e., uncorrected by Doppler boosting) brightness temperatures, $T_b$ (see Figure 4). The $T_b$ along the jet is observed to decline with distance from the core following the $r^{-2.4}$ proportionality found by Walker et al. (1987). Component C80 has a brightness temperature of $5 \times 10^9$ K, which is about 600 times larger than the expected value of $\sim 8 \times 10^8$ K at such large distance from the core. $8 \times 10^8$ K is also the typical detection threshold for VLBA observations at 5 GHz. Hence, the fact that C80 has not been detected in any of the previous 5 GHz VLBA images implies an increase in its brightness temperature by at least a factor of 600. This unusually high $T_b$ explains why C80 has become visible even at the highest VLBA observing frequencies (see Figure 1).

Figures 1–3 show the EVPA to be aligned with the local direction of the jet in C80 for observations after 2007, in contrast to what is found for the remainder of the jet (see also Walker et al. 2001), and to that shown in the 5 GHz image taken in 2001 (see Figure 3). Maps of the rotation measure at different frequency intervals during 2007 November (J. L. Gómez et al. 2010, in preparation) show values of the order of 10 rad m$^{-2}$ for C80, small enough to marginally rotate only the EVPAs at 1.7 GHz. Hence, we can conclude that the observed magnetic field in C80 is perpendicular to the local intensity structure for observations after 2007. The degree of polarization of C80 is $\sim$20% and the spectral index of the region is $\alpha \sim -1$ ($S_v \propto \nu^\alpha$), which is similar to the values found for the rest of the optically thin jet.

4. DISCUSSION

3C 120 has been extensively observed at 1.7 GHz by Walker et al. (2001), showing a variety of moving knots and a side-to-side structure suggestive of a helical pattern seen in projection (see also Hardee et al. 2005), in which the helical twisted flow along the southern side of the jet is more closely aligned with the line of sight. Walker et al. (2001) identified a component located at 81 mas from the core that appeared to be stationary (between 1982 and 1997) and could correspond to one of the southernmost components produced by the enhanced differential Doppler boosting. We are therefore tempted to identify this with component C80. However, our low-frequency observations show that at the location of the C80 component the emission structure changed significantly between 2001 and 2007, and that the southernmost emission in 2007 corresponds to C90, instead of C80 (see Figure 3). Hence, C90 would be associated with a jet region flowing at a smaller viewing angle, and it is therefore very unlikely that C80 would correspond to another bend in the jet, given the estimated helical wavelengths (Hardee et al. 2005). Furthermore, a bend in the jet would lead to an increase in $T_b$ by a factor of $(\delta_{\text{new}}/\delta_{\text{old}})^3$, where $\delta$ is the Doppler factor and $n = 2 - \alpha$ for the case of continuous jet or $3 - \alpha$ for a moving inhomogeneity (Readhead 1994). In our case of a bend in the jet and an estimated spectral index of $\alpha = -1$, we have $n = 3$; therefore, to account for the 600 increase in $T_b$ it is required an increase in $\delta$ by a factor of $\sim 8.4$ with respect to the estimated mean Doppler factor $\delta_{\text{old}} = 2.4$ (corresponding to a Lorentz factor $\gamma_{\text{old}} = 5.3$ and viewing angle $\theta_{\text{old}} = 20^\circ$; Jorstad et al. 2005). This involves an unlikely acceleration of the jet from a Lorentz factor of 5.3 to $\sim 10.1$, even for the most favorable case of a jet pointing directly toward the observer.

Could C80 instead correspond to a moving shock whose motion through a bend toward the observer has resulted in an apparently stationary feature? The effect of a shock is determined by the compression factor, $\eta$, so that the magnetic field is scaled up as $B \rightarrow B/\eta$ and the electron energy density as $N_0 \rightarrow N_0\eta^{-\gamma+2)/3}$, where $\gamma$ is the electron energy spectral index (e.g., Hughes et al. 1989; Gómez et al. 1993). This yields an increase in the optically thin specific intensity of synchrotron radiation by a factor of $\eta^{-(5\gamma+7)/6}$, or equivalently $\eta^{(5\alpha-5)/2}$. The most likely scenario would then involve a shocked helical jet, in which the effects of the shock wave compression and the differential Doppler boosting would add to produce an increase in the brightness temperature by a factor of $(\delta_{\text{new}}/\delta_{\text{old}})^3 = n\eta^{5\alpha-6)/3}$. Note that for a moving shock we use $n = 3 - \alpha$, on the assumption that the radiating fluid is moving close enough to the shock speed. It is possible to obtain an upper limit to $\eta$ by maximizing the contribution from the Doppler boosting considering that in
C80 the jet points directly toward the observer, but maintains
the same Lorentz factor of 5.3. The factor of 600 increase in
$T_b$ for C80 would then require a relatively weak shock with
$\eta \leq 0.87$. This is in fact a too conservative value, since as
mentioned previously C90 is at a smaller viewing angle than is
C80, so that the jet cannot point directly toward the observer at
C80. If the jet instead bends to a viewing angle of $5^\circ$ ($10^\circ$) then
$\eta \approx 0.71$ ($\eta = 0.45$). For comparison, the component located at
$\sim 12$ mas (C12; see Figure 1), which is one of the most intense
ever observed in 3C 120, has $\eta \sim 0.35$. The unusually high $T_b$
of C80 could therefore be explained by a combination of jet
bending and a moving shock—and perhaps also some jet flow
acceleration and/or unusually large particle acceleration—but
it seems very unlikely that it corresponds to the usual shock that
appears near the core and moves downstream to the location of

C80: as simulated by Gómez et al. (1994), a component moving
through a helical jet would progressively increase in flux as it
approaches the bend, accompanied by a rotation of its EVPA.
An increase in the flux density of C80 is indeed observed during
2007, but not later. Some motion of C80 would also be expected
as it approaches the most favorably oriented jet region corre-
sponding to C90, which contrasts with the quasi-stationarity of
C80 shown in Figure 5. Therefore, a shock moving through a
helical jet cannot account entirely for the observed properties of
C80.
It appears that a strong, stationary shock generated in situ, at the location of C80, is needed. This can be a standing shock, produced perhaps by a steep decrease in the external pressure. As has been proposed to explain the flaring HST-1 knot in the M87 jet by Stawarz et al. (2006), the brightening of C80 in 2007 April may mark the arrival of excess particles and photons produced by the active nucleus in the past. For a jet flow Lorentz factor similar to that measured for the components in 3C 120 has not been previously observed (Walker et al. 1987, 2001; Gómez et al. 2001; Homan et al. 2001, 2009; Jorstad et al. 2005).

Component C80 could also result from a strong interaction with the external medium, similar to that proposed for the inner jet regions (Gómez et al. 2000). However, the low values of the rotation measure (RM \~ \sim 10 \text{ rad m}^{-2}) found for the C80–C90 region suggest that such an interaction with the external medium is probably not taking place.

The observations made by Walker et al. (2001), covering 1982–1997, and those presented in this work (2001 and 2007) show evidence that, although the region located at \~ \sim 80–90 mas changes with time, it appears to correspond to a common bent region, where the jet is oriented more toward the observer. In this case, the region located at 81 mas in 1997, identified by Walker et al. (2001) as a stationary component, could in fact correspond to the southernmost region located at \~ \sim 86 mas in 2001, and this in turn to the C90 component seen in 2007. This motion of the bent jet region can be explained in the framework of a slowly moving helical pattern, as simulated by Hardee et al. (2005). The estimated upper limit of \~ \sim 0.55 \text{ mas yr}^{-1} (\~ \sim 1.1 c; Walker et al. 2001) for the pattern speed of the helix is consistent with the observations between 2001 and 2009.

Although the helical jet model can explain the observed properties of C90, none of the proposed models provide a complete explanation for the unusually high $T_b$ of C80, its sudden appearance in 2007 April, and its apparent stationarity. It appears that some other intrinsic process in the jet, capable of providing a local burst in particle and/or magnetic field energy, may be responsible for the enhanced brightness temperature observed in C80. Further mid-frequency VLBI observations, currently under way, should provide the kinematical and flux evolution information necessary to obtain a better understanding of the nature of C80.

This research has been supported in part by the Spanish Ministerio de Ciencia e Innovación grant AYA2007-67627-C03-03, the regional government of Andalucía grant P09-FQM-4784, and by the U.S. National Science Foundation grant AST-0907893. I.A. acknowledges support by a I3P contract by the Spanish Consejo Superior de Investigaciones Científicas. We thank the anonymous referee for helpful comments that improved significantly our manuscript. The VLBA is an instrument of the National Radio Astronomy Observatory, a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc. This research has made use of data from the MOJAVE database that is maintained.
This research has made use of data from the University of Michigan Radio Astronomy Observatory which has been supported by the University of Michigan and by a series of grants from the National Science Foundation, most recently AST-0607523.

Facilities: VLBA, VLA

REFERENCES

Agudo, I., Gómez, J. L., Martí, J. M., Ibáñez, J. M., Marscher, A. P., Alberdi, A., Aloy, M. A., & Hardee, P. E. 2001, ApJ, 549, L183
Chatterjee, R., et al. 2009, ApJ, 704, 1689
Gómez, J. L., Alberdi, A., & Marcaide, J. M. 1993, A&A, 274, 55
Gómez, J. L., Alberdi, A., & Marcaide, J. M. 1994, A&A, 284, 51
Gómez, J. L., Marscher, A. P., & Alberdi, A. 1999, ApJ, 521, L29
Gómez, J. L., Marscher, A. P., Alberdi, A., Jorstad, S. G., & Agudo, I. 2001, ApJ, 561, L161
Gómez, J. L., Marscher, A. P., Alberdi, A., Jorstad, S. G., & García-Miró, C. 2000, Science, 289, 2317
Gómez, J. L., Marscher, A. P., Alberdi, A., Martí, J. M., & Ibáñez, J. M. 1998, ApJ, 499, 221
Gómez, J. L., Marscher, A. P., Jorstad, S. G., Agudo, I., & Roca-Sogorb, M. 2008, ApJ, 681, L69
Gómez, J. L., Martí, J. M., Marscher, A. P., Ibáñez, J. M., & Alberdi, A. 1997, ApJ, 482, L33
Hardee, P. E., Walker, R. C., & Gómez, J. L. 2005, ApJ, 620, 646
Homan, D. C., Kadler, M., Kellerman, K. I., Kovalev, Y. Y., Lister, M. L., Ros, E., Savolainen, T., & Zensus, J. A. 2009, ApJ, 706, 1253
Homan, D. C., Ojha, R., Wardle, J. F. C., Roberts, D. H., Aller, M. F., Aller, H. D., & Hughes, P. A. 2001, ApJ, 549, 840
Hughes, P. A., Aller, H. D., & Aller, M. F. 1989, ApJ, 341, 54
Jorstad, S. G., et al. 2005, AJ, 130, 1418
Jorstad, S. G., et al. 2007, AJ, 134, 799
Leppanen, K. I., Zensus, J. A., & Diamond, P. J. 1995, AJ, 110, 2479
Lister, M. L., et al. 2009, AJ, 137, 3718
Marscher, A. P., Jorstad, S. G., Gómez, J., Aller, M. F., Teräsranta, H., Lister, M. L., & Stirling, A. M. 2002, Nature, 417, 625
Marscher, A. P., Jorstad, S. G., Gómez, J. L., McHardy, I. M., Krichbaum, T. P., & Agudo, I. 2007, ApJ, 665, 232
Marshall, K., Ryle, W. T., Miller, H. R., Marscher, A. P., Jorstad, S. G., Chicka, B., & McHardy, I. M. 2009, ApJ, 696, 601
Pearson, T. J., Shepherd, M. C., Taylor, G. B., & Myers, S. T. 1994, BAAS, 26, 1318
Readhead, A. C. S. 1994, ApJ, 426, 51
Stawarz, Ł., Aharonian, F., Kataoka, J., Ostrowski, M., Siemiginowska, A., & Sikora, M. 2006, MNRAS, 370, 981
Walker, R. C., Benson, J. M., & Unwin, S. C. 1987, ApJ, 316, 546
Walker, R. C., Benson, J. M., Unwin, S. C., Lystrup, M. B., Hunter, T. R., Pilbratt, G., & Hardee, P. E. 2001, ApJ, 556, 756