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THE UNUSUAL X-RAY COLLISION MORPHOLOGY OF NGC 4782/4783 (3C 278)

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ABSTRACT

Deep *ROSAT* HRI (High-Resolution Imager) imaging of the X-ray–emitting gas associated with the colliding elliptical galaxy pair NGC 4782/4783 reveals for the first time the complexity of the hot gas distribution in a pair of close interacting galaxies.

The HRI image of NGC 4782/4783 shows hot gas around each galaxy, a high surface brightness X-ray *bridge* connecting the galaxy pair, tidal-like *tails* emerging from the two galaxies, and a *sheet* of gas at the interaction interface between the two galaxies. The hot gas distributions do not peak at the optical centers of the galaxies but are displaced in the same sense as the tidal distensions seen in the optical luminosity distributions. All of these remarkable features show the complexity of structure that develops in the hot gas distribution when both hydrodynamical and tidal forces come into play during collisions between ellipticals with hot gas components.

Models by Borne and Colina of the bent two-sided radio jet 3C 278 (associated with NGC 4782) indicated that there must be a strong interaction between the hot gas components of NGC 4782/4783 and that the deflection of the radio jets is likely caused by the ram pressure exerted on the jet plasma by the hot gas associated with the passing companion NGC 4783. These conclusions are qualitatively confirmed by the HRI image and substantiate the major role played by the hot interstellar medium, and its asymmetries, in the propagation and entrainment of radio jets in colliding radio host ellipticals.

Subject headings: galaxies: active — galaxies: interactions — galaxies: ISM

1. INTRODUCTION

In a CCD optical study of galaxies selected on the basis that they all contain well-defined radio jets, it was found that more than half of the sample consists of pairs of elliptical galaxies (Colina & Pérez-Fournon 1990a, b; de Juan, Colina, & Pérez-Fournon 1994; Colina & de Juan 1995). Many of these low-luminosity radio galaxies with companions (e.g., 3C 31, 3C 278, and 3C 449) show a well-defined distorted radio jet structure at the VLA scale with an S- or C-shaped morphology. Although massive nuclear dust/gas disks, such as those detected in some nearby radio galaxies (de Juan, Colina, & Golombek 1995, and references therein), could also play a role in the collimation and shaping of the radio jets, the large-scale disturbed jet morphologies have primarily been interpreted as being due either to the gravitational effect of the companion galaxy (Blandford & Icke 1978; Yokosawa & Inoue 1985) or to the motion of the radio galaxy through the intergalactic medium (O'Donoghue 1989). Since the discovery of hot gaseous halos around elliptical galaxies (see Fabbiano 1989 for a review), the effects of the hot interstellar medium on the bending of the jets have also been investigated (Jones & Owen 1979; Soker, O'Dea, & Sarazin 1988). Using this idea, we produced a simple numerical model of the specific two-sided jet morphology seen in the radio source 3C 278 associated with the elliptical galaxy NGC 4782 of the NGC 4782/4783 galaxy pair (Borne & Colina 1993, hereafter BC).

An estimate of the binary orbital parameters for the two galaxies NGC 4782/4783 was needed as input to our radio jet simulations. We used the orbital parameters that were determined from detailed optical imaging and the kinematic measurements of the pair by Borne, Balcells, & Hoessel (1988, hereafter BBH). In our radio jet models, the evolution of the jets was determined by their response to the time-dependent mechanical forces (i.e., gravity and ram pressure) that were acting on the constituent jet blobs. For 3C 278, we found that the structural evolution of the jet morphology was dominated by the ram pressure forces that were applied to the jet by the hot interstellar medium (ISM) of the passing NGC 4783 companion galaxy. A multicomponent representation of the ram pressure forces was invoked, which required an asymmetric ISM density distribution around the companion galaxy and zero ISM density in the jet galaxy. The latter result (zero density in the jet galaxy) is simply an indication that the jet has evacuated a channel through that galaxy's ISM and is now suffering relatively negligible ram pressure resistance from within the host galaxy. By comparison, no such "channeling" occurs within the companion galaxy's ISM because of its transverse relative velocity with respect to the jet: that galaxy's ISM is flowing past the jet, hitting it broadside, and hence inducing the observed jet deflection.

As a direct test of our model's prediction of the hot gas distribution in 3C 278, we obtained *ROSAT* HRI (High-Resolution Imager) observations for this system. Because of its relatively high positional accuracy and spatial resolution, the HRI is ideally suited to these types of investigations: (1) mapping the hot gas in the colliding galaxy pair (thereby revealing the effects of the tidal interaction on this particular galactic component), (2) identifying hot spots in the X-ray surface brightness distribution (perhaps identifying regions of intense jet-ISM interaction), and (3) correlating the hot gas distribution with the radio jet morphology (thus testing the ram pressure deflection model in detail). As a consequence of this work, it is possible to characterize the redistribution of gas in similar interacting systems and thus to elucidate the inter-

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TABLE 1

X-Ray Properties of the NGC 4782/4783 Pair of Galaxies

Region	Offsets	Radius	Counts (10^{-3} counts s^{-1})	F_X(0.1–2.4 keV) (10^{-13} ergs cm^{-2} s^{-1})	L_X(0.1–2.4 keV) (10^{41} ergs s^{-1})
NGC 4782	+0."0, +0."0	10."0	1.36 ± 0.30	0.64	0.23
NGC 4783	+3.2, +34.3	10.0	1.40 ± 0.30	0.66	0.24
Bridge.........	+0.2, +15.0	4.0	0.61 ± 0.23	0.28	0.10
Blob NW	−20.9, +38.0	6.0	0.35 ± 0.18	0.17	0.06
Blob NE	+17.1, +11.6	6.0	0.43 ± 0.19	0.20	0.07
System	+1.1, +17.0	40.0	7.95 ± 0.77	3.73	1.36
Star	−24.9, +23.0	8.0	0.49 ± 0.21	0.23	...

action-activity connection seen in other systems (e.g., low- and high-luminosity radio galaxies), perhaps even in ultraluminous infrared galaxies, high-redshift radio galaxies, and quasars.

For this Letter we assume a redshift of $z = 0.0138$ for the pair NGC 4782/4783 and a Hubble constant of $H_0 = 75$ km s^{-1} Mpc^{-1}. With these assumptions, the NGC 4782/4783 system is at a distance of 55.2 Mpc, where 1" corresponds to 268 pc.

2. OBSERVATIONS

The pair of colliding galaxies NGC 4782/4783 was observed with the *ROSAT* HRI from 1994 July 20 to July 25. The total integration time on source was 25,529.9 s, split into 15 separate OBIs. Each individual OBI was checked against possible shifts or pointing errors. All OBIs agreed in position to within an uncertainty of 2"–3" and were co-added. To improve the signal-to-noise ratio of the final HRI map, the original co-added HRI image has been sampled in bins of 2" and convolved with a Gaussian filter of 9."0 (FWHM). Subsequent analysis and net count measurements of the image were done in the original image using the PROS X-ray data analysis package installed at STScI. The errors and error propagation in the net counts were obtained assuming Poisson statistics and following the method given by Gehrels (1986), as explained in the PROS documentation. The background was measured in a region well beyond the main body of the NGC 4782/4783 system. The value was 1.1×10^{-6} counts s^{-1} arcsec^{-2}, in agreement with the average on-orbit background of 1.1×10^{-6} counts s^{-1} arcsec^{-2} (David et al. 1995).

The transformation factor from counts to X-ray flux in the HRI band (0.1–9.4 keV) was obtained following David et al. (1995) by assuming a column density of $N_H = 3.5 \times 10^{20}$ cm^{-2} (Fabbiano, Kim, & Trinchieri 1992) and by assuming that the emission corresponds to thermal bremsstrahlung characterized by a temperature of 1.25 keV, the average temperature of the hot X-ray–emitting gas measured in ellipticals (Fabbiano 1989).

3. RESULTS

3.1. *The Structure of the Hot X-Ray–emitting Gas in the Pair NGC 4782/4783*

The deep HRI image of the X-ray–emitting gas in the pair NGC 4782/4783 (Figs. 1*a* and 1*b* [Pls. L12–L13]) shows several remarkable features, observed for the first time in a pair of close colliding galaxies: (1) the detection of hot gas in the two galaxies NGC 4782 and NGC 4783 with their emission peaks displaced with respect to the stellar luminosity peaks, (2) a high surface brightness *bridge* along the line joining the two galaxy nuclei, (3) tidal-like *tails* emerging from the X-ray nuclei of the two galaxies, and (4) a *sheet* of gas at the interaction interface between the two galaxies.

The two elliptical components of the pair are similarly bright in X-rays with luminosities L_X(0.1–2.4 keV) = 2.3 and 2.4×10^{40} ergs s^{-1} for NGC 4782 (3C 278) and NGC 4783, respectively (see Table 1). Typical X-ray luminosities of ellipticals in the *Einstein* band (0.2–3.5 keV) vary from 10^{39} to 10^{42} ergs s^{-1} (Fabbiano 1989). The measured X-ray luminosities for NGC 4782 and NGC 4783 therefore place the two galaxies in the lower end of the X-ray luminosity function of ellipticals but consistent with the X-ray luminosity expected from the X-ray–blue luminosity correlation in ellipticals. The final HRI image (smoothed with a 9" FWHM Gaussian) did not allow us to obtain a profile of the X-ray surface brightness for each individual galaxy. Deeper HRI images are required to exploit the full resolution of *ROSAT* and therefore to attempt this kind of measurement.

The X-ray emission peaks associated with NGC 4782 and NGC 4783 are displaced with respect to the peaks of the stellar distribution by ~7" (1.9 kpc) and ~4" (1.1 kpc), respectively. Detailed orbital models of the NGC 4782/4783 motion (BBH) indicate that NGC 4782 is currently moving to the southwest, while NGC 4783 is moving to the northeast. The central displacements of the X-ray emission peaks are in the same direction as the tidal distensions seen in the optical isophotes of the two galaxies, which is in the direction opposite to the motion of the galaxies in the BBH models. These displacements are consistent with the idea that (1) both the X-ray–emitting gas and the stellar mass distribution are tidally distended by the gravitational interaction and that (2) the hot ISM in each galaxy is being "pushed back" by ram pressure from the incoming hot gas of the passing companion galaxy.

A high surface brightness *bridge* is seen in the *ROSAT* image, with a luminosity L_X(0.1–2.4 keV) = 1.0×10^{40} ergs s^{-1} (labeled as "Bridge" in Table 1). It is located at a distance of 15" (i.e., 4.0 kpc) north of NGC 4782 (Fig. 1*b*) and inside the effective radius of this galaxy ($r_e = 5.9$ kpc; Colina & de Juan 1995). This region of high surface brightness, located between the two colliding galaxies, is expected as a consequence of the compression of the hot interstellar media of the two galaxies in precisely this region in which the interaction of the two ISM is most intense (A. Suchkov, private communication).

Tidal-like *tails* are seen emerging from the X-ray nuclei of the two galaxies (Fig. 1*a*). The tail associated with NGC 4782 ends in a bright blob (labeled "Blob NE" in Table 1), with L_X(0.1–2.4 keV) = 7.4×10^{39} ergs s^{-1}, at a distance of 21" and position angle PA = 56°. The tail associated with NGC 4783 bends toward the northwest, away from the X-ray nucleus of this galaxy, and ends in a luminous blob (labeled "Blob NW"

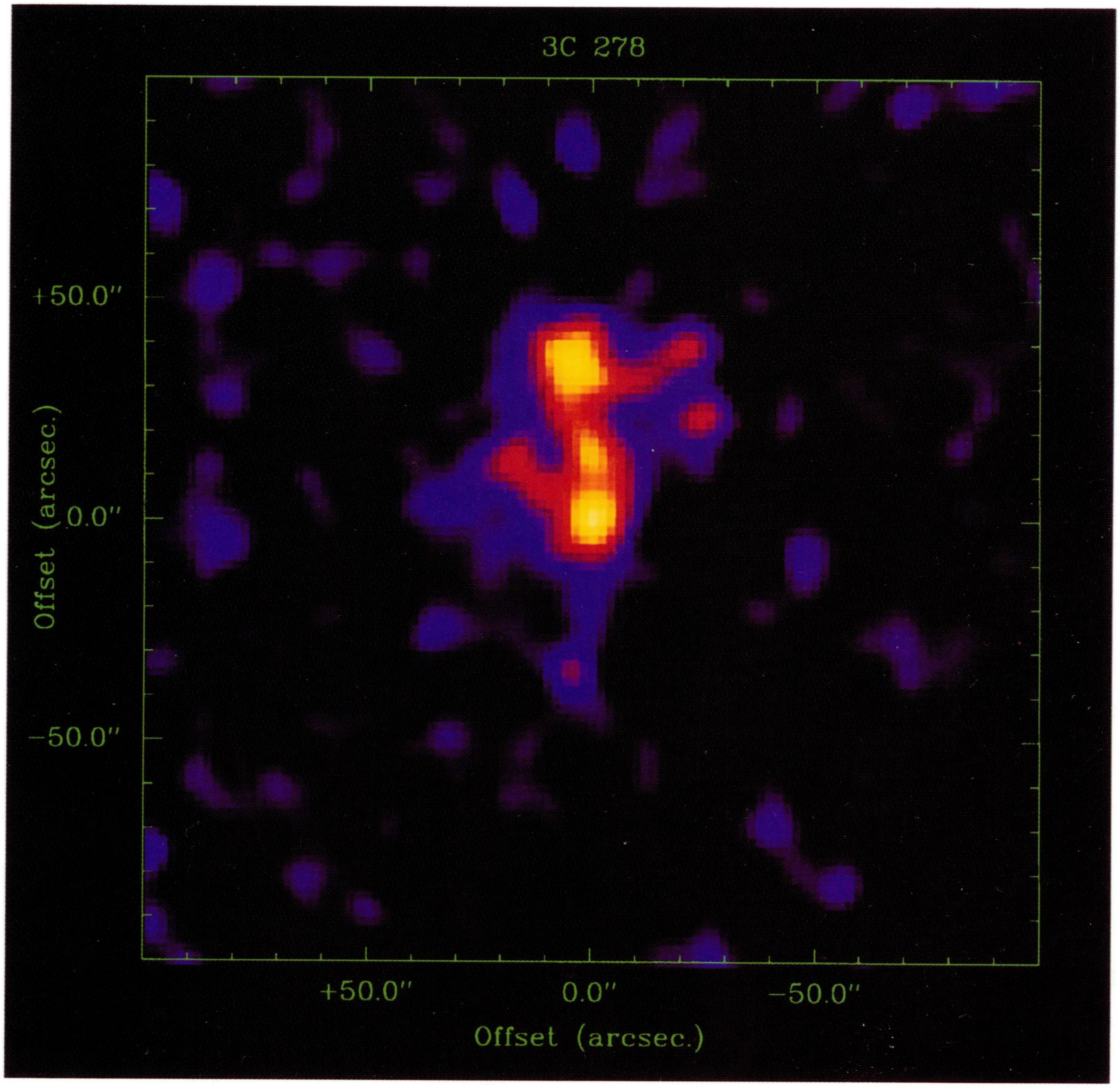

FIG. 1*a*

FIG. 1.—(*a*) False color-coded *ROSAT*/HRI image showing the distribution of the hot X-ray-emitting gas in the NGC 4782/4783 pair of galaxies. Clearly noted in the figure are the distinct X-ray features that are referred to in the text (see § 3.1 and § 3.2 for details). North is up, and east to the left. (*b*) False color-coded *ROSAT*/HRI image of the NGC 4782/4783 pair of galaxies overlaid with the *r*-band optical contours of the pair (de Juan et al. 1994). Galaxy NGC 4782 (the host for 3C 278) is the southern elliptical in the image. (*c*) False color-coded *ROSAT*/HRI image of the NGC 4782/4783 pair of galaxies overlaid with the 4.885 GHz VLA radio contours of the 3C 278 source (Baum et al. 1988). The radio source is centered on the peak of the stellar distribution.

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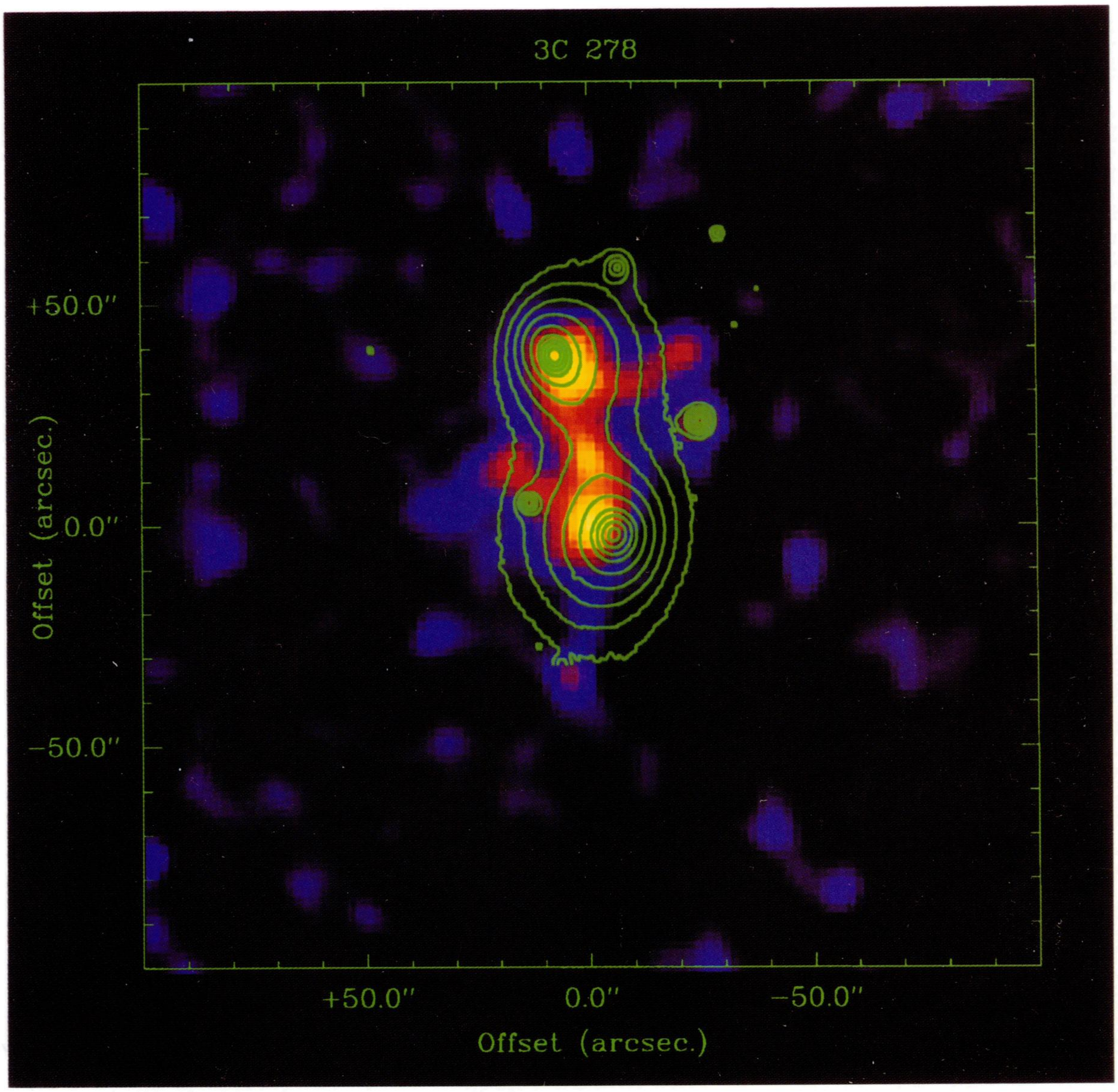

FIG. 1*b*

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in Table 1), with L_X(0.1–2.4 keV) = 6×10^{39} ergs s^{-1}. The linear length of each of these tail-like structures is ∼7.5 kpc.

A *sheet* of hot gas is seen, extending along PA = 125°, south of NGC 4783, with a total length of 72″ (19 kpc). The sheet includes part of the NGC 4783 tail structure and the NE blob of the NGC 4782 tail. However, it seems to extend to the southeast of the NE blob, although with a lower surface brightness (see Fig. 1*a*).

NGC 4782/4783 could be the dominant galaxy pair within a loose group of galaxies comprised mostly of ellipticals (de Souza & Quintana 1990). However, the NGC 4782/4783 system has a total X-ray luminosity (within a 40″ radius) of 1.4×10^{41} ergs s^{-1} (see Table 1) that is consistent with previous measurements obtained with the *Einstein* IPC (2.5×10^{41} ergs s^{-1} within a radius of 3′; Fabbiano et al. 1992). This value falls well below the X-ray luminosity of typical group- or cluster-dominant galaxies, which have X-ray luminosities in the *Einstein* band of the order of 10^{43} ergs s^{-1} (Fabbiano 1989).

3.2. *The Entrainment of the Radio Jets by the Hot X-ray Gas*

The elliptical galaxy NGC 4782 is the host of the Fanaroff-Riley type I (FR I) radio source 3C 278, which shows an east-west oriented two-sided jet with a C-shaped structure having very distinct bends in its morphology (see Fig. 1*c* [Pl. L14]). The jet shape can be explained as a consequence of its interaction with NGC 4783 (BC). According to BC, the observed deflections in the 3C 278 radio jets are primarily induced by the hot gas of the passing companion galaxy NGC 4783. The geometries of the BBH and BC models indicate that the west jet is ejected away from NGC 4783, always passing through a lower density hot ISM than does the east jet and therefore experiencing less deflection. The east jet has consequently been much more strongly affected by the hot ISM of NGC 4783. To explain the position and bend of the east jet, a core radius of 6 kpc (i.e., 22″) for the hot gas distribution in NGC 4783 was required in the BC model. This core radius is close to the effective radius (3.9 kpc) of the stellar component (Colina & de Juan 1995).

The best model capable of explaining the positions and angles of the bends in the 3C 278 radio jets predicts the presence of dense hot X-ray–emitting gas with three distinct properties: (1) it should be displaced with respect to the center of the 3C 278 radio source (i.e., away from the nucleus of NGC 4782), (2) it should be asymmetric with respect to the east and west jet, and (3) it should have a large extent with a slowly varying density (i.e., a large core radius).

The predictions of the model are in close qualitative agreement with what is observed in the *ROSAT*/HRI image. The bright hot ISM features are mostly located north and northeast of NGC 4782 (Fig. 1*c*), therefore implying an asymmetry in the gas distribution with respect to the east and west jets. The west jet is ejected in a region almost devoid of X-ray–emitting gas and suffers no deflection within the main optical body of the NGC 4782/4783 system. On the contrary, the east jet bends by almost 90° at a distance of about 15″ east of the stellar nucleus of NGC 4782. This is the region in which the hot ISM appears to be densest. As indicated in § 3.1, the peak of the X-ray emission associated with NGC 4782 is displaced by ∼7″ along position angle 70°, with a bright tail of X-ray–emitting gas that is continuous to a distance of 21″ at P.A. = 56° (Fig. 1*b*). Also, the east jet goes into a more diffuse expanding phase after traversing the sheet of hot X-ray gas, as if it were highly decelerated from its entrainment by the hot gas. This is also in agreement with the conclusions of the BC model: the east jet suffers a strong deceleration from its initial velocity of 10^4 km s^{-1} to its endpoint velocity of 900 km s^{-1}. For comparison, the model's west jet has an endpoint velocity of 3700 km s^{-1}.

It is remarkable to note that the stellar velocity dispersion of NGC 4782 increases from 310 km s^{-1} in the nucleus to over 400 km s^{-1} at distances of 8″–15″ at P.A. = 70° (Madejsky, Bender, & Möllenhof 1991; Madejsky 1992). This high velocity dispersion could most likely be the result of strong tidal heating in the stellar component of NGC 4782 produced during the collision. If the hot gas coexists in dynamical equilibrium with the stellar component, then the high stellar velocity dispersion in this region of the galaxy would be associated with an increase in the density and temperature of the hot ISM and therefore ultimately with a rapid disruption of the east jet by the hot dense ISM in that region, as is observed. Further deeper HRI *ROSAT* images with full spatial resolution are needed to study the structure of this X-ray–emitting gas east of NGC 4782 nucleus in greater detail.

4. SUMMARY

A deep high-resolution *ROSAT*/HRI image of the pair of interacting galaxies NGC 4782 (3C 278) and NGC 4783 has shown for the first time a remarkable variety of unexpected morphological features in the distribution of the hot X-ray–emitting gas in and around strongly interacting galaxies (Fig. 1*a* and 1*b*). These structures can be summarized in four distinct features: (1) the displacement by 1–2 kpc of the X-ray emission peaks associated with NGC 4782 and NGC 4783 with respect to the stellar centers of the galaxies; (2) the presence of a high surface brightness bridge of X-ray–emitting gas along the direction joining the two galaxies; (3) the presence of tidal-like tails (each ∼7.5 kpc in length) emerging from the X-ray–emitting peaks of the two galaxies; and (4) the presence of a sheet of X-ray–emitting gas elongated along the interaction interface between the two galaxies, with a total length of ∼19 kpc. All of these features are believed to be induced by the hydrodynamical and tidal forces acting in the strong close collision between NGC 4782 and NGC 4783 and are, most likely, believed to be a general characteristic of strongly interacting ellipticals.

The predictions of the model by BC that explained the two-sided radio jet morphology of 3C 278 are in good qualitative agreement with the HRI image. In particular, the prediction that the east jet should be encountering a more dense and asymmetric hot gas component than the west jet is beautifully shown in the VLA/HRI overlay image (Fig. 1*c*).

Detailed hydrodynamical simulations as well as deep *ROSAT*/HRI observations of NGC 4782/4783 and other similar galaxy pairs will be fundamental in understanding the effects of strong interactions on the hot X-ray–emitting component of ellipticals, as well as in elucidating in detail the primary role of the hot gas distribution asymmetries in the propagation and entrainment of radio jets in colliding FRI ellipticals.

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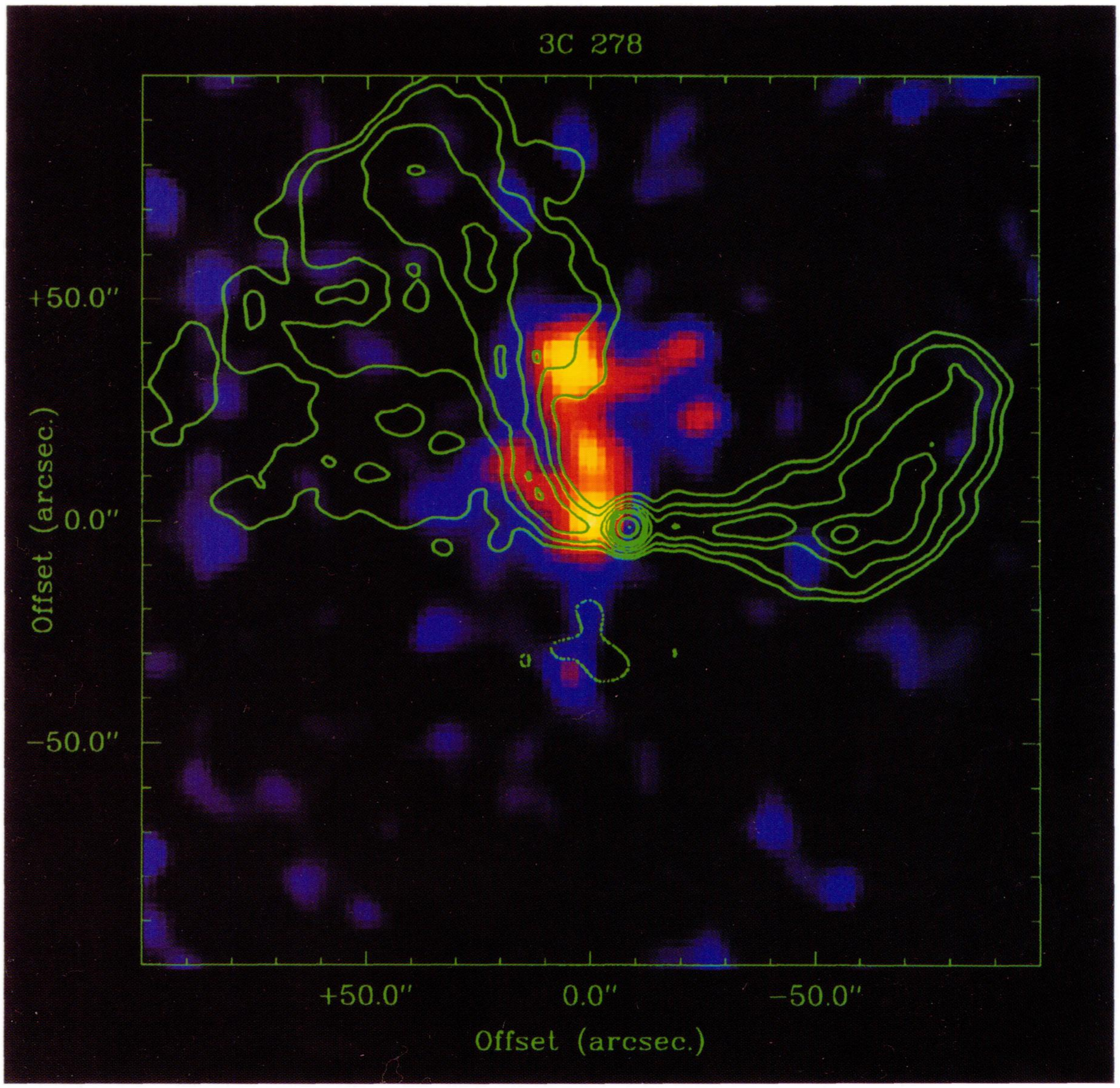

FIG. 1*c*

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