A CHANDRA STUDY OF PARTICLE ACCELERATION IN THE MULTIPLE HOT SPOTS OF NEARBY RADIO GALAXIES

M. J. HARDCASTLE AND J. H. CROSTON
School of Physics, Astronomy and Mathematics, University of Hertfordshire, College Lane, Hatfield AL10 9AB, UK

AND

R. P. KRAFT
Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138

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ABSTRACT

We present Chandra observations of a small sample of nearby classical double radio galaxies that have more than one radio hot spot in at least one of their lobes. The X-ray emission from the hot spots of these comparatively low-power objects is expected to be synchrotron in origin, and therefore to provide information about the locations of high-energy particle acceleration. In some models of the relationship between the jet and hot spot, the hot spots that are not the current jet termination points should be detached from the energy supply from the active nucleus, and therefore not capable of accelerating particles to high energies. We find that in fact some secondary hot spots are X-ray sources, and thus probably locations for high-energy particle acceleration after the initial jet termination shock. In detail, however, we show that the spatial structures seen in X-rays are not consistent with naive expectations from a simple shock model: the current locations of the acceleration of the highest energy observable particles in powerful radio galaxies need not be coincident with the peaks of radio or even optical emission.

Subject headings: galaxies: active — X-rays: galaxies

1. INTRODUCTION

In the standard model for powerful extragalactic double radio sources (also known as classical double or FRII sources; Fanaroff & Riley 1974), hot spots, the bright compact regions at the ends of the source, are the visible manifestation of a strong shock as the relativistic beam of energetic particles is suddenly decelerated by interaction with the slow-moving or stationary plasma within the radio lobes (e.g., Blandford & Rees 1974). The particle acceleration at these shocks determines the energy distribution of the electrons (and possibly protons) that go on to form the large-scale lobes and expand into the external medium, and so an understanding of how and where it happens is essential to an understanding of the dynamics and environmental impact of radio sources; in addition, the strong shocks in FRIIs are often invoked as a possible region of acceleration for the high-energy cosmic ray population, so that it is important to understand where (and if) high-energy particles are accelerated in these systems.

The best evidence for this shock model comes from the radio through optical spectra of hot spots, which have been shown (e.g., Meisenheimer et al. 1989) to be commonly consistent with the predictions of a simple model for shock particle acceleration and downstream losses (Heavens & Meisenheimer 1987). However, the idea that the hot spots always trace the shock at the jet termination is challenged by the observation that the lobes of radio galaxies and quasars very frequently have more than one compact bright radio feature that meets whatever definition of a hot spot is in use (e.g., Leahy et al. 1997). Where these appear in the jet, or embedded deep in the lobe, they are usually interpreted as “jet knots”; the assumption encoded in this terminology is that they are telling us about internal dissipation in the jet rather than disruption, and that they are not relevant to the particle acceleration history of the source. But in many systems there are multiple hot spots at the far end of the lobe, and in these the configuration of the hot spots relative to the jet flow often suggests that more than one is associated with the beam termination. Models to explain this observation include those in which the beam end-point moves about from place to place in the lobe (the “dentist’s drill” model of Scheuer 1982), or in which material flows out from the initial impact point of the beam to impact elsewhere on the lobe edge (the “splatter-spot” model of Williams & Gull 1985, or the jet-deflection model of Lonsdale & Barthel 1986). All these models predict that one of the hot spots, the one associated with the first or current termination of the jet, should be more compact than the other or others; it is in fact observed in the radio that where jets are explicitly seen to terminate, they always do so in the most compact, “primary” hot spot (e.g., Leahy et al. 1997; Hardcastle et al. 1997). But it is very difficult to distinguish between different models of multiple hotspot formation using radio data alone. The secondary (less compact) hot spots exhibit a wide variety of structures and relationships to the primary hot spots, and, while in some cases radio structure seems to favor one model rather than another, the nature of the secondaries is never unambiguously constrained by single-frequency radio data. One area in which different models do make different predictions is that of the high-energy particle acceleration in the secondary (less compact) hot spots. If these are relics left behind by the motion of the jet, as in the “dentist’s drill” model, then in general we expect shock-driven particle acceleration to have ceased (although the secondary hot spot may continue to be fed for some time if the jet is disconnected some way upstream; Cox et al. 1991). Synchrotron losses will then deplete the high-energy electrons in the secondary hot spot. If secondary hot spots continue to be fed by outflow from the primary hot spot, then there is still an energy supply and particle acceleration will continue to operate.

High-resolution X-ray observations of synchrotron radiation with Chandra have provided key insights into the particle
acceleration in the jets of low-power, FRI-type radio galaxies, allowing us to locate the sites of particle acceleration and relate them to the dynamics of individual jets (e.g., Hardcastle et al. 2003). X-ray observations are vital in these cases, because the synchrotron loss timescale for X-ray–emitting electrons is tens of years, assuming field strengths close to the equipartition values: thus, unlike radio and even optical observations of synchrotron radiation, X-ray synchrotron detections tell us where particle acceleration is happening now, rather than where it has happened in the past. To date, however, it has been difficult to use X-ray observations to study particle acceleration in the hot spots of the more powerful FRII radio sources because of the importance of hot spots of a second emission process, inverse-Compton emission. This process, particularly important in bright, compact hot spots, traces the low-energy electrons rather than the high-energy ones, and has been the subject of much work with Chandra because of its potential to measure physical conditions (magnetic field strengths and energy densities) in hot spots (see, e.g., Harris et al. 2000; Hardcastle et al. 2001; Brunetti et al. 2001). Some hot spots have been known since the ROSAT epoch to be best described by a synchrotron rather than inverse-Compton model (e.g., Harris et al. 1998), but until recently it has not been clear what controls the relative dominance of the two processes. Based on new and archival observations of a large sample of FRIs, we recently showed (Hardcastle et al. 2004) that the controlling parameter is related to the overall luminosity of the hot spot: high-luminosity hot spots never show X-ray synchrotron emission, while low-luminosity hot spots often do. We argued that this is due to the higher magnetic field strengths and photon energy densities found in the more luminous hot spots: these increase the energy loss rate for high-energy electrons and prevent efficient particle acceleration to the energies needed for X-ray synchrotron radiation. In contrast, low-luminosity hot spots can readily accelerate particles to X-ray emitting energies, and the expected inverse-Compton emission is negligible, so that synchrotron radiation is dominant in these systems. It is important to note that this picture, while qualitatively plausible, relies on details of the microphysics, such as the magnetic field configuration and electron diffusion coefficient in the acceleration region (see, e.g., Brunetti et al. 2003), and so it cannot yet be shown quantitatively to be correct.

If this model is accepted, however, X-ray synchrotron emission can be used to probe high-energy particle acceleration in low-luminosity FRII radio galaxies. An example of this is provided by observations of the low-power FRII 3C 403 (Kraft et al. 2005). These observations were important for two reasons. First, as 3C 403 is a narrow-line radio galaxy, any relativistic beaming effects (of the kind thought to be important in some core-dominated quasars) must be minimal if unified models are correct, as 3C 403 should lie close to the plane of the sky: thus, models for anomalous X-ray emission involving beaming, like those of Georganopoulos & Kazanas (2003) need not be considered. Second, 3C 403’s east lobe is a multiple-hot spot system, and the observations show a clear difference between features of the jet and the primary hot spot, on the one hand, and the secondary hot spot (much brighter in the radio), on the other: we found that the upper limit on the X-ray emission from the secondary was an order of magnitude below what would have been detected if its X-ray to radio ratio had been the same as that in the primary. This strongly suggests that, in this source at least, the secondary hot spot is unable to accelerate particles to the highest observable energies.

The results of our work on 3C 403 motivated us to carry out further observations of nearby sources with multiple hot spots, and to examine data available in the Chandra archive, with the aim of seeing whether, and in what circumstances, the different hot spot components can give rise to high-energy particle acceleration, and so constrain the nature of multiple hot spots. In this paper we report on our results.

Throughout the paper we use a cosmology with $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.3$, and $\Omega_{\Lambda} = 0.7$. The spectral index $\alpha$ is defined in the sense that flux density $\propto \nu^{-\alpha}$; the relationship between the spectral index $\alpha$ and the photon index $\Gamma$ is thus $\Gamma = \alpha + 1$.

### 2. OBSERVATIONS

#### 2.1. Sample

We selected our targets from the sample of Leahy et al. (1997, hereafter L97). This sample consists of FRII radio galaxies with $z < 0.15$ taken from the 3CR sample (Spinrad et al. 1985, see L97 for details of the selection). We chose this parent sample because of its low redshift (and therefore, in general, low luminosity, implying negligible X-ray inverse-Compton radiation from the hot spots in the picture of Hardcastle et al. 2004) and because of the availability of excellent radio data, with resolution matching or exceeding that of Chandra, for almost all members of the sample. From the L97 sample, we selected the sources with clear, well separated, bright multiple hot spots as seen in the radio maps. Two of these, 3C 390.3 and 3C 403, had already been observed with Chandra (as discussed in Hardcastle & Croston 2005; and Kraft et al. 2005, respectively). We were awarded time for two more, 3C 227 and 3C 327, giving us two broad-line and two narrow-line radio galaxies in total. Basic properties of the sample objects are given in Table 1. We discuss the radio and X-ray data for these objects in §§ 2.2 and 2.3.

#### 2.2. Chandra Observations

Details of the Chandra observations of our targets are given in Table 2. All Chandra observations were taken with the ACIS-S array with the aimpoint, as standard, on the S3 chip. For 3C 403 and 3C 390.3 the nucleus was positioned near the aimpoint. However, for 3C 227 and 3C 327, our new targets, the (brighter) double

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### Table 1

| Name       | $z$   | Emission-Line Type | $L_{170}$ (W Hz$^{-1}$ sr$^{-1}$) | Angular Scale (kpc arcsec$^{-1}$) | Largest Hot Spot Separation (kpc) | $N_{HI}$ (cm$^{-3}$) |
|------------|------|--------------------|----------------------------------|-----------------------------------|----------------------------------|------------------|
| 3C 227     | 0.0861 | BLRG               | 4.7 x 10$^5$                     | 1.61                              | 17                               | 2.08 x 10$^{20}$ |
| 3C 327     | 0.1039 | NLRG               | 8.1 x 10$^5$                     | 1.91                              | 5                                | 6.49 x 10$^{20}$ |
| 3C 390.3   | 0.0561 | BLRG               | 3.1 x 10$^5$                     | 1.09                              | 28                               | 3.68 x 10$^{20}$ |
| 3C 403     | 0.059  | NLRG               | 1.9 x 10$^5$                     | 1.14                              | 4                                | 1.54 x 10$^{21}$ |

References—References for Galactic column densities used are as follows: 3C 227, Jahoda et al. (1985); 3C 327, interpolated from results of Stark et al. (1992); 3C 390.3, Murphy et al. (1996); 3C 403, from Kraft et al. (2005).
hot spots were placed near the aimpoint. This had the effect that the sources spanned multiple Chandra chips. 3C 227 and 3C 327 were also observed in very faint (VF) mode to reduce the background levels, while 3C 390.3 and 3C 403 were observed in faint (F) mode. The observations of 3C 227 were split into two segments for scheduling reasons.

We did not reanalyze the data for 3C 403, as all the relevant measurements had already been made (Kraft et al. 2005). For the other three sources we reprocessed the Chandra data with the latest versions of CIAO and CALDB at the time of writing (versions 3.3 and 3.2.3, respectively), following the standard CIAO procedures. We removed the 0.5-pixel event position randomization (since high spatial resolution is important to us) and applied VF mode cleaning to the data for 3C 227 and 3C 327 to improve the background. Intervals of high background levels, while 3C 390.3 and 3C 403 were observed in very faint (VF) mode to reduce the background. The sources spanned multiple hot spots were placed near the aimpoint. This had the effect that the high-resolution maps available to us were subimages that did not show the core. Details of the radio data we used are given in Table 3. All of the radio data were reduced in AIPS in the standard manner: individual data sets were first self-calibrated and then cross calibrated and merged with appropriate weights to give a final multi-source data set that was used for imaging. Where maps at more than one resolution were required, we applied appropriate tapering to the uv plane in the imaging process. Except where otherwise stated, maps used in the figures were made for this paper.

As detailed comparison between the radio and X-ray spatial structures of the hot spots is important to us, we aligned the radio and X-ray frames for all the sources by shifting the X-ray nuclear position to match the best available radio position. Where there were significant offsets between the radio core positions at different frequencies, we shifted the low-frequency positions to match the high-frequency ones. We expect the relative astrometry of the radio and X-ray frames to be limited by the accuracy of X-ray centroiding, but in all cases it should be better than ~0.1". 3C 390.3 is a special case, as extreme pileup has removed all counts from the center of the nuclear X-ray emission: we still believe that we have been able to determine the X-ray position to the required level of accuracy, and in this case the default astrometry of the Chandra data appears to be correct.

For radio data, resolutions are quoted as the major × minor axis (FWHM) of the elliptical restoring Gaussian: where only one dimension is quoted the restoring beam used was constrained to be circular.

### 3. RESULTS

#### 3.1. Non-Hot Spot X-Rays in 3C 227 and 3C 327

In this subsection we briefly comment on the features of the new Chandra observations of 3C 227 and 3C 327 unrelated to the hot spots. The Chandra observations of the other sample sources have been discussed elsewhere (see Kraft et al. 2005;
Hardcastle et al. 2004; Hardcastle & Croston 2005; Evans et al. 2006). Images showing the large-scale X-ray emission from the two objects are shown in Figures 1 and 2.

3.1.1. Cores

The raw Chandra count rate from the core of the BLRG 3C 227 is roughly 0.14 s$^{-1}$; with a frame time of 3.1 s, this means that we might expect it to be affected by pileup at a significant level. Fitting to the total spectrum of the nucleus within 15 Chandra pixels ($7''$), using a concentric adjacent background annulus, we found a good fit ($\chi^2 = 228$ for 213 dof) to a model consisting of two power laws, one with Galactic absorption only and one with additional intrinsic absorption at the redshift of the source. The power-law component without intrinsic absorption had a very flat photon index ($\Gamma = 3.4^{+0.6}_{-0.2}$), while the absorbed component, with $N_{\text{H,int}} = (1.4 \pm 0.1) \times 10^{22}$ cm$^{-2}$, had a very flat photon index, $\Gamma = 0.73 \pm 0.06$. The data are almost equally well fitted ($\chi^2 = 231/214$) with an ionized absorber model (ABSORI), but this has clear residuals at soft energies, suggesting that in any event some of the soft X-ray emission must come from a second nuclear X-ray component, or from soft thermal X-ray emission close to the nucleus. This is unsurprising as we know that in general radio-loud AGN have a soft X-ray component, which is probably related to the jet (e.g., Hardcastle et al. 2006). The significant intrinsic absorption seen here, although unusual for a broad-line object, is consistent with what is seen in some other BLRG or quasars (e.g., 3C 109, Allen et al. 1997, Hardcastle et al. 2006a; 3C 351, Nicastro et al. 1999, Hardcastle et al. 2002). From optical spectropolarimetry Cohen et al. (1999) estimate that the optical broad lines and continuum may be obscured by 1–2 mag in the V band. Although our column density would imply substantially higher extinction, $A_V \sim 6$ for Galactic gas/dust ratios, the optical results, including the detection of polarized broad emission lines, give us some additional reason for believing that there might be intrinsic X-ray absorption in this source.

The very flat photon index of the absorbed component is likely to be partly the result of pileup, and to investigate this we also extracted a spectrum for an annular region between 2 and 15 Chandra pixels with the same background region. This excludes the region where pileup is likely to be significant. We applied energy-dependent corrections to the ARF using the algorithm of the ARFCORR software$^2$ implemented using the funtool package. Fitting the same double power-law spectrum, we find similar parameters—the slightly larger intrinsic absorbing column (1.7$^{+0.3}_{-0.0}$ $10^{22}$ cm$^{-2}$) is consistent within the errors—and only a slightly steeper photon index for the absorbed component, 0.91 $\pm$ 0.18. However, the 99% confidence upper limit on the photon index in this extraction region (which obviously contains only a small fraction of the total counts) is 2.4, so more typical photon indices are certainly not excluded by the non-piled-up data. Crawford & Fabian (1995), who discuss observations of 3C 227 with the ROSAT PSPC, found that the nuclear spectrum was well fitted by a power-law model with $\Gamma \sim 1.5$. With the limited S/N of their ROSAT data and the restricted energy range of the PSPC, it is not clear that they could have identified the absorption features seen in our spectrum.

For 3C 327, which has a much fainter X-ray nucleus, we extracted a spectrum from a source circle of radius 4 Chandra pixels ($2''$) with an adjacent concentric background annulus. The best-fitting spectrum ($\chi^2 = 35$ for 21 dof) again requires multiple components: at soft energies the source is dominated by an unabsorbed power law with $\Gamma = 3.07 \pm 0.15$, while the residuals at high energy require an additional heavily absorbed power law, with the poorly constrained $\Gamma$ fixed at 1.7 (following Hardcastle et al. 2006a) and $N_{\text{H,int}} = (6.5^{+2.3}_{-1.2}) \times 10^{22}$ cm$^{-2}$, together with a strong line-like feature modeled as a Gaussian with $E = 6.42 \pm 0.05$ keV and $\sigma = 0.19 \pm 0.08$ keV. Except for the steep power-law index for the unabsorbed component, this is a typical spectrum for a narrow-line radio galaxy; iron features around 6.4 keV are often found in these objects (Sambruna et al. 1999; Evans et al. 2006; Hardcastle et al. 2006a).

3.1.2. Lobes

The lobes of 3C 227 are both clearly detected in the Chandra observations (Fig. 1). Extended X-ray emission from lobes of radio sources is generally attributed to inverse-Compton scattering from the cosmic microwave background radiation (CMB; Hardcastle et al. 2002; Kataoka & Stawarz 2005; Croston et al. 2005). We extracted a spectrum for the west lobe, as the east lobe spans a chip boundary, using a polygonal extraction region defined by the radio emission, but excluding the central part of the lobe where the nucleus and central extended X-ray emission might contribute, as well as compact sources, including the hot spots. The spectrum was well fitted ($\chi^2 = 10.6$ for 10 dof) with a power-law model with $\Gamma = 1.77 \pm 0.26$ and 1 keV unabsorbed flux density.

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1 See http://cxc.harvard.edu/proposer/POG/html/ACIS.html.

2 See http://agyo.rikkyo.ac.jp/~tsujimoto/arfcorr.html.
of 4.8 ± 0.5 nJy. We used the code of Hardcastle et al. (1998) to calculate the predicted inverse-Compton emission from the whole lobe, modeling the lobe crudely as a uniform cylinder with length 98′ and radius 26′, assuming equipartition and using the same electron spectral assumptions as Croston et al. (2005) with a low-energy electron energy index (“injection index”), $p$, of 2. The equipartition magnetic field strength is 0.58 nT; the predicted emission corresponds to a 1 keV flux density of 1.4 nJy, i.e., about a factor 3.5 below what is observed. Reducing the field strength to 0.29 nT is required to produce all the observed X-ray emission by the inverse-Compton process.

For 3C 327 there is a clear detection of the east lobe and a weaker but still significant detection of the west lobe. Again, we extracted a spectrum for the lobe that does not span a chip boundary, in this case the east lobe, excluding point sources and the components near the hot spots. This was well fitted ($\chi^2 = 6.9$ for 6 dof) with a power-law model with $\Gamma = 1.55 \pm 0.30$ and unabsorbed 1 keV flux density of 6.4 ± 1.1 nJy. The inverse-Compton prediction here on the same assumptions (modeling the lobe as a cylinder with length 90′ and radius 27′) is 1.5 nJy, so again the observations exceed the equipartition prediction by a factor ~4. The equipartition field here is 0.73 nT, and the field required to produce the observed X-rays by inverse-Compton processes is 0.34 nT.

Both objects are thus consistent with the trend seen in many other sources for the observed inverse-Compton emission to lie somewhat above the equipartition, $p = 2$ prediction (Croston et al. 2005). We know that 3C 227′s lobes are likely to make a relatively small angle to the line of sight, but this makes only a small difference to the inverse-Compton prediction for $\theta = 45°$.

### 4. HOT SPOT OBSERVATIONS

In this section we discuss the X-ray, radio and (where possible) optical properties of the hot spots in our target systems.

**Table 4:** Properties of the Hot Spot Components Discussed in the Paper

| Source Name | Lobe (2) | X-Ray Name | Radio Name | Offset (arcsec) | Counts (0.5–5.0 keV) | Photon Index | 1 keV Flux Density (nJy) | Optical? | Type (9) | Morphology |
|-------------|---------|------------|------------|----------------|---------------------|--------------|------------------------|----------|---------|------------|
| 3C 227      | W       | P1/2       | 0.8 ± 0.1  | 84 ± 9        | 1.63 ± 0.22         | 1.5 ± 0.2    | Y                      | Primary  | Resolved, flattened |
| 3C 327      | E       | S1'        | 2.3 ± 0.2  | 19 ± 5        | 1.63 ± 0.2          | 0.3 ± 0.1    | Y                      | Secondary| Resolved          |
| 3C 390.3    | N       | SX1        | 0.5 ± 0.5  | 10 ± 3        | 1.63 ± 0.4          | 0.3 ± 0.1    | Y                      | Primary  | Compact + diffuse  |
| 3C 403      | E       | S2'        | 2.4 ± 0.1  | 12 ± 3        | 1.7 ± 0.27          | 0.3 ± 0.07   | Y                      | Secondary| Compact          |
|              | S       | SX1        | 0.8 ± 0.2  | 12 ± 3        | 1.7 ± 0.27          | 0.3 ± 0.07   | ?                      | Secondary| Compact          |
|              | S       | NX1        | 0.4 ± 0.1  | 164 ± 13      | 1.95 ± 0.15         | 4.2 ± 0.3    | ?                      | Secondary| Compact          |
|              | S       | NX2        | 72 ± 9     | 2.13 ± 0.24   | 1.9 ± 0.2           | 0.2 ± 0     | ?                      | Pointlike| Compact          |
|              | S       | G', E, D?  | 1.0 ± 0.2  | 14 ± 4        | 1.4 ± 0.4           | 0.4 ± 0.1    | N?                     | Primary?| Compact          |
|              | S       | Diffuse    | 96 ± 11    | 1.4 ± 0.2     | 2.7 ± 0.3           | 2.8 ± 0.2    | Y?                     | Secondary| Diffuse          |
| 3C 403      | E       | F1         | 34 ± 6     | 1.75 ± 0.4    | 0.9 ± 0.2           | 2.0 ± 0.5    | N                      | Jet knot| Compact          |
|              | F1b     | 15 ± 4     | 2.0 ± 0.5   | 0.1 ± 0.2     | 0.2 ± 0.1           | 0.3 ± 0.1    | S                     | No X-ray detection| Compact          |
|              | F2      | <4         | 2.0 ± 0.5   | <0.13         |                     |              | S                     | No X-ray detection| Compact          |
|              | F6      | 83 ± 9     | 1.70 ± 0.2 | 2.3 ± 0.2     | 0.2 ± 0             | 0.1 ± 0.2    | Y                      | Jet knot| Elongated        |

**Notes.—** Col. (3) gives the name we have associated with the X-ray feature. Where none is given, no specific name has been assigned in the text. Col. (5) gives the offset between the peak of the radio counterpart named in col. (4) and the centroid of the X-ray emission; it is blank if no radio counterpart is known. The photon index in col. (7) is derived from the data if an error is quoted and is the value assumed in the text otherwise. Col. (8) is the 1 keV flux density, determined from the spectral fit if possible, and otherwise from the count rate using the spectral assumption specified in col. (7). Col. (9) indicates whether there is an optical counterpart to the hot spot: Y = yes, N = no, ? = not known. Col. (10) this describes the nature of the radio hot spot, if known. Col. (11) describes the X-ray structure: “compact” here indicates a weak source that is consistent with being <0.5′ in extent, and may be pointlike. Measured parameters for 3C 403 are taken from Kraft et al. (2005); as no significant offsets are described in that paper no values are tabulated here.
definite offset. In contrast, the centroid of the emission from F1 and its surroundings is consistent with the position of the radio peak within the large errors.

The X-ray counterpart of P1/2 contained enough counts ($84 \pm 9$ in the 0.5–5.0 keV energy range) for us to extract a spectrum, which we took from a circular region with radius 6 Chandra pixels ($3''$) with a background from a concentric annular region. We find a good fit ($\chi^2 = 0.5$ for 3 dof) with a power-law model with $\Gamma = 1.63 \pm 0.22$ and 1 keV unabsorbed flux density $1.5 \pm 0.2$ nJy. The fainter hot spots P3 and P4 contain $19 \pm 5$ and $22 \pm 5$ net 0.5–5.0 keV counts, respectively, which for the same spectrum would correspond to flux densities of $0.3 \pm 0.1$ and $0.4 \pm 0.1$ nJy. The counterpart of the F1 hot spot, which lies on the S1 chip, contains $10 \pm 3$ counts in a similarly sized extraction region, which corresponds to $0.3 \pm 0.1$ nJy if again we assume the same spectrum as seen in P1/2.

K.-H. Mack kindly provided us with electronic versions of ground-based near-infrared (NIR) images (Mack et al. 2003, and 2008, in preparation). When shifted to our radio-based coordinate system by alignment at the peak of the optical emission from the galaxy these show that the optical emission from the P1/2 region extends over both the radio and X-ray peaks. In detail, however, the brightest regions of NIR emission are not coincident with either radio or X-ray peaks. The NIR emission disappears in between the peak of the X-ray and the peak of the radio emission at P2. Similarly, the peak of the NIR emission coincident with P3 agrees neither with the radio nor the X-ray peak positions, although it is roughly coincident with the X-ray centroid. There is no NIR counterpart of the radio/X-ray knot P4.

4.2. 3C 327

3C 327 is the only object in our sample to have no optical hot spot detection: as pointed out by Mack et al. (2003), a nearby bright disk galaxy makes it hard to detect potentially faint counterparts to the bright double eastern radio hot spots. In the new Chandra data, although there is nearby X-ray emission (Fig. 2), there is no detection of a compact component corresponding to the west hot spot. There is, however, a clear detection of compact components near the double east hot spots (Fig. 6). Neither of the two X-ray components detected bears a very obvious relation to the radio structure. The component (denoted SX1) closest to the primary hot spot (S1) is separated from it by $2.4'' \pm 0.1''$ (4.5 kpc) along the line connecting S1 and the core, while the other X-ray component (SX2) is at $0.8'' \pm 0.1''$ (1.5 kpc) from the nearest peak of the radio emission in the S2 region, and considerably farther from its center, in the sense of being farther away from the primary hot spot than the peak of the radio emission. In DSS2 and 2MASS images SX2 is close to the nearby disk galaxy, but not at its nucleus. We cannot rule out the possibility that SX2 is associated with this galaxy rather than with the 3C 327 hot spot system. SX1 is farther away from the galaxy than SX2.

The two compact X-ray components each contain $12 \pm 3$ net 0.5–5.0 keV counts, so that spectral fitting is not possible. If we...
assume a power-law spectrum with $\Gamma = 1.7$, the observed net counts correspond to flux densities of $0.27 \pm 0.07$ mJy in each component. We estimated the hardness ratios of the two components (defining the soft band as 0.5−2.0 keV and the hard band as 2.0−5.0 keV) and compared them to the hardness ratio expected for a $\Gamma = 1.5$ power law with Galactic absorption (this model was chosen because the spectral index is unlikely to be flatter than $\Gamma = 1.5$). We found that SX2 is significantly harder (at the 99% confidence level on a binomial test) than would be expected for such a model, while SX1 is not inconsistent with it. This suggests either that SX2 is not related to the hot spot (e.g., that it is a background type 2 AGN), or that there is some additional source of absorption, conceivably in the disk galaxy, that affects SX2 but not SX1. We cannot distinguish between these models with the available data.

4.3 3C 390.3

The northern compact hot spot of 3C 390 is a well-known X-ray source (Saslaw et al. 1978; Prieto 1997; Harris et al. 1998; Hardcastle et al. 2004). Diffuse X-ray emission from the large hot spot region of the south lobe was discussed by Hardcastle & Croston (2005). A detailed examination of the Chandra data shows that several components of the north hot spot complex are X-ray sources (Fig. 7). The radio jet, which is detectable throughout the northern lobe (Leahy & Perley 1995) brightens strongly in the area shown by our image, and there is faint but clear X-ray emission associated with this section of the jet. The strongest X-ray “source” is the known X-ray counterpart of the primary hot spot (Leahy & Perley 1995), knot B, here denoted NX1. The centroid of this region is only slightly (0.4″ ± 0.1″, 0.4 kpc) offset to the south of the peak of the radio emission, but the resolution of Chandra shows that the X-ray feature is actually resolved into two components, separated by 1.5″ (1.6 kpc) and placed symmetrically on either side of the radio peak. This is a much smaller distance than that of the nearby galaxy, possibly interacting with the jet, described by Harris et al. (1998), which is 5.8″ to the northeast. At higher radio resolutions (e.g., in Fig. 5 of Leahy & Perley 1995) knot B is resolved into a linear structure that lies between the two X-ray peaks; there is no sign of any double structure in the radio. Nor is there any evidence in the optical image of Prieto & Kotilainen (1997) or in the archival Spitzer data for resolution of the hot spot in the east-west direction: Prieto & Kotilainen show that the optical hot spot is in fact extended in the same direction as the radio. Another bright X-ray source in the hot spot region is the object we denote NX2. This has no radio counterpart and is well separated from any compact structure in the radio, so it seems most likely to be a chance superposition with a background object, although it is detected in the optical and infrared, and its properties at these wavelengths are consistent with it being similar to knot B (its infrared colors mean that it is certainly not a background normal galaxy). Radial profile analysis shows that it is consistent with being a point source. Finally, the secondary hot spot (knots F and A) shows no significant X-ray emission, even though in 3C 390.3 there is clear evidence (in the form of the continued collimated outflow from knot B, features N1−4 in Fig. 7) that this hot spot is connected to the jet. The radio/X-ray ratio in the secondary hot spot region is a factor ≥50 greater than in knot B. There is no optical detection of the secondary (Prieto & Kotilainen 1997), nor is it detected in the archival Spitzer data. We extracted spectra for the jet, for the counterpart to knot B (NX1) as a whole, for its two subcomponents (denoted NX1E and NX1W) and for the possibly unrelated source NX2, taking background from a nearby blank-sky region. The overall spectrum of NX1 is not particularly well fitted with a single power-law model ($\chi^2 = 15.9/8$, $\Gamma = 1.95 \pm 0.15$). The east component of the X-ray source is well fitted with a power-law model ($\chi^2 = 18.9/7$, $\Gamma = 2.23 \pm 0.23$), but the west component is not ($\chi^2 = 10.5/3$, $\Gamma = 1.7 \pm 0.2$), the poor fit being the result of one high bin at soft energies. Neither component is acceptably fitted with a thermal model. Within the limited statistics, it seems likely that the two components of knot B have
that could be responsible for producing the observed X-rays from the sources themselves. As the available X-ray data suggest power-law spectra and thus nonthermal emission, we focus on inverse-Compton and synchrotron processes.

As discussed by Hardcastle et al. (2002) in the context of the more distant double hot spot source 3C 351 (where inverse-Compton emission almost certainly plays some role in the complex X-ray structures seen), synchrotron self-Compton emission (SSC) or inverse-Compton scattering of the CMB (CMBIC) cannot produce offsets between the radio and X-ray, unless there is very strong spatial variation in the positions of the low-energy electrons and/or important beaming effects. We first consider a model in which there are strong point-to-point variations in the number density of low-energy electrons. To produce offset X-ray emission via inverse-Compton processes, we require a large population of low-energy (\( \gamma \lesssim 10^3 \)) electrons at the location of the X-ray emission, while either the electron spectrum or the magnetic field strength must be tuned so as to avoid significant emission from this population of electrons at radio frequencies. We used the code of Hardcastle et al. (2002) to calculate the expected inverse-Compton emission from components matching P1, P2, and the X-ray source in 3C 227, using an upper limit on the radio flux density of the X-ray component of 2 mJy to normalize the radio spectrum and using the observed sizes in the radio and X-ray to choose component sizes. We modeled the three components for simplicity as uniformly filled ellipsoids.
in the plane of the sky. We found that for standard broken power-
law spectra for the three components we require the X-ray source
to have a departure from equipartition of a factor ∼ 60 in mag-
netic field strength, and an electron energy density that is ∼ 10^3
times greater than that in P2, in order to produce the observed
X-rays by inverse-Compton processes (where the upper limits
come from the fact that we have no unambiguous detection of a
radio counterpart of the X-ray source). In this situation we find
that the dominant photon field is the CMB, and so the conclu-
sions are robust against uncertainties in the geometry, which af-
flect only the number density of synchrotron photons from P1/2.
Such an electron distribution seems highly unlikely simply on
energetic grounds, since it requires essentially all the energy
scattered of the CMB that has been proposed to explain the
X-ray emission should have no particular relationship to the
properties) are less extreme, and the range of plausible angles
to the line of sight can be greater. In the beamed CMB models
respect, taken from or derived as in Table 4. Col. (8) gives the 1 keV inverse-Compton prediction (SSC+CMBIC). Col. (9) gives
the ratio of the X-ray and radio flux densities, corrected to 8.35 GHz assuming α = 0.5. Col. (10) gives any comments on the relationship between the X-ray flux quoted and the radio hot spot for which the inverse-Compton calculation was made. Data for 3C 403 are taken from Kraft et al. (2005).

The GK03 model might be applied to the offset between the primary hot spot of 3C 227, P1/2, and its X-ray counterpart. 3C 227 is a broad-line object, so that the lobes make a relatively small angle to the line of sight (≤ 45°), and if we take P4 to be a jet knot, the only evidence that we have suggests that the west lobe is likely to contain the jet pointing toward us, although the comparatively weak radio core, the nondetection of any other components of the jet, and the presence of intrinsic absorption in the X-ray spectrum (§ 3.1.1) suggest that it is not at a very small angle to the line of sight (compared to, say, 3C 390.3, with its bright radio core, unabsorbed nuclear X-ray emission and well-detected kpc-scale jet). The flat X-ray spectrum of the X-ray counterpart of P1/2 is consistent with an inverse-Compton model. If we suppose that the jet decelerates on kiloparsec scales and that
X-ray emission from the fast-moving component can be pro-
duced by inverse-Compton scattering of the synchrotron pho-
ton from the slower, downstream component. This external
inverse-Compton process is strongly directional and can only be
seen if the jet is aligned close to the line of sight (and, of
course, is approaching rather than receding). The GK03 model
should not be confused with the process of inverse-Compton
scattering of the CMB that has been proposed to explain the
X-ray jets in core-dominated quasars (e.g., Tavecchio et al.
2000): in the GK03 model the photon energy density is domi-
nated by synchrotron photons from the upstream hot spot, and
as a consequence the beaming factors required (for given jet
properties) are less extreme, and the range of plausible angles
to the line of sight can be greater. In the beamed CMB models
the X-ray emission should have no particular relationship to the
radio hot spot, and the angle to the line of sight of the jet is re-
quired to be small; we therefore do not consider these models
further.

Georganopoulos & Kazanas (2003, hereafter GK03) proposed to
explain the X-ray properties of hot spots in objects aligned
close to the line of sight using a model involving emission from
the decelerating relativistic jet. At the time they were writing,
there was an apparent correlation between observations of hot
spots with X-ray emission too bright to be SSC in origin and the
jet side of broad-line objects, such as broad-line radio galaxies
and radio-loud quasars, that are expected to lie at small angles
to the line of sight in unified models. Since then, further observ-
ations have established that these non-SSC hot spots can occur
in objects in all orientations (Hardcastle et al. 2004). However,
the GK03 model is still interesting, because it predicts spatial off-
ssets between the peak of the X-ray and that of the radio. They
proposed that the jet decelerates on kiloparsec scales and that
X-ray emission from the fast-moving component can be pro-
duced by inverse-Compton scattering of the synchrotron pho-
ton from the slower, downstream component. This external
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lobe is likely to contain the jet pointing toward us, although the
comparatively weak radio core, the nondetection of any other
components of the jet, and the presence of intrinsic absorption in
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angle to the line of sight (compared to, say, 3C 390.3, with its
bright radio core, unabsorbed nuclear X-ray emission and well-
detected kpc-scale jet). The flat X-ray spectrum of the X-ray
counterpart of P1/2 is consistent with an inverse-Compton model.
If we suppose that the jet decelerates on scales of a few kpc (set
by the observed projected size of the offset between radio and
X-ray) from relativistic to subrelativistic speeds, it is possible

TABLE 5

| Source      | Lobe | Radio Name | Size (arcsec) | Radio Frequency (GHz) | Radio Flux (mJy) | 1 keV Flux (mJy) | Predicted IC Flux (nJy) | X-Ray/Radio Ratio (×10^-6) | Notes |
|-------------|------|------------|---------------|-----------------------|-----------------|-----------------|------------------------|----------------------------|-------|
| 3C 227 ...... | W    | P1         | 1.5 × 0.5     | 8.35                  | 16              | 1.5 ± 0.2       | 0.0010                 | 0.09                       | Offset X-ray               |
|             |      | P2         | 3.5 × 0.5     | 8.35                  | 25              | 1.5 ± 0.2       | 0.0019                 | 0.06                       | Offset X-ray               |
|             |      | P3         | 3.7 × 0.6     | 8.35                  | 13              | 0.3 ± 0.1       | 0.0014                 | 0.02                       | Offset X-ray               |
|             |      | P4         | 1.4 × 0.25    | 8.35                  | 1.2             | 0.4 ± 0.1       | 1.0 × 10^-4            | 0.3                        | Jet knot?                   |
| 3C 327 ...... | E    | F1         | 1.2 × 0.25    | 8.35                  | 3.5             | 0.3 ± 0.1       | 2.7 × 10^-4            | 0.06                       | Offset X-ray               |
| 3C 390.3 .... | N    | B          | 1.3 × 0.5     | 8.35                  | 3.2             | 0.27 ± 0.07     | 1.2 × 10^-4            | 0.09                       | Offset X-ray               |
|             |      | F           | 3.7           | 4.99                  | 190             | <0.2            | 0.009                  | <0.001                     | Upper limit                |
|             |      | S           | 0.5           | 4.99                  | 20              | <0.4 ± 0.1      | 6 × 10^-4              | 0.02                       | Offset X-ray               |
|             |      | G           | 0.5           | 4.99                  | 36              | <0.1            | 0.0013                 | <0.004                     | Upper limit                |
|             |      | E           | 0.7           | 4.99                  | 106             | <0.1            | 0.0056                 | <0.001                     | Upper limit                |
|             |      | D           | 1.2           | 4.99                  | 206             | <0.2            | 0.011                  | <0.001                     | Upper limit                |
| 3C 403 ...... | E    | F1b         | 0.275         | 8.35                  | 15              | 0.27 ± 0.07     | 1.2 × 10^-4            | 0.09                       | 2 sub-components           |
|             |      | F2          | 1.8 × 0.25    | 8.35                  | 27              | <0.13           | 0.0011                 | <0.004                     | Upper limit                |
|             |      | F6          | 0.272         | 8.35                  | 27              | 2.3 ± 0.2       | 0.0014                 | 0.06                       | Jet knot                   |

Notes.—Cols. (1), (2), and (3) are as in Table 4. Col. (4) gives the size used in modeling, derived from fits to the high-resolution radio data. The angular sizes used are the radii of homogenous sphere models fitted to the data, as described by Hardcastle et al. (2004) except where two numbers are quoted, in which case they are the length and radius of a cylinder. Cols. (5) and (6) give the frequency and flux of the radio data used to normalize the inverse-Compton models. Col. (7) is the 1 keV X-ray flux of the radio hot spot for which the inverse-Compton calculation was made. Data for 3C 403 are taken from Kraft et al. (2005).
that the GK03 model could explain the observed offset in 3C 227? In principle the answer is “yes,” since the GK03 model can explain any observation with a suitable choice of the (observationally unconstrained) parameters of the position-dependent bulk flow speed and electron energy spectrum of the jet. The jet would have to be quite wide at the position of P4/2 to produce the observed X-ray morphology, but not impossibly so: the distribution of emitting particles and jet velocities would also require some fine tuning in order to produce an offset X-ray peak rather than some more jetlike X-ray structure. However, we consider an explanation in terms of the GK03 model to be hard to sustain when all the observations of our sample are considered together. The secondary hot spot of 3C 227 shows a similar offset, yet the bulk flow clearly cannot decelerate to subrelativistic speeds twice, and the direction of any flow between the primary and secondary is not the same as the direction between P4 and P1/2. A series of coincidences is therefore required to explain the similarity between the primary and secondary hot spots in 3C 227. The model clearly cannot explain the offsets between radio and X-ray peaks in 3C 390.3 (not in the direction of the jet) or the offsets and variations in radio/X-ray ratio seen in 3C 327 and 403 (too large an angle to the line of sight). We conclude that the GK03 model, while not ruled out by the data for the primary hot spot of 3C 227, is of little use in providing a general explanation of the problems posed by our observations.

Since inverse-Compton explanations seem difficult to accept, we next consider synchrotron emission. Synchrotron explanations also require point-to-point electron spectrum (or possibly magnetic field strength) variations to account for offsets between the radio and X-ray emission. However, the magnitude of the variation is comparatively very small: the high-energy tail of the electron population responsible for the X-ray emission is energetically, and a fortiori numerically, a negligible fraction of the total, whereas for the inverse-Compton process a doubling of the emissivity by adjusting the electron spectrum requires a doubling of the number density of low-energy electrons, and so effectively a doubling of the energy density of the system. Energetically, therefore, it is not difficult to produce what we see via synchrotron radiation. Since the electron energy-loss timescale is likely to be very short (for field strengths close to the equipartition value), what is required to produce the observed X-ray structures is some process that can accelerate particles wherever we observe X-ray emission. As we discussed in §1, there is strong evidence from radio and optical data that hot spots are sites of particle acceleration, and their spectra are consistent with models involving a single shock followed by downstream losses. In some cases the X-ray emission from hot spots lies on an extrapolation of these models (Kraft et al. 2005). But observations of diffuse X-ray emission, often poorly matched to the observed radio structures (e.g., in Pictor A, Hardcastle & Croston 2005; 3C 33, Kraft et al. 2007; 3C 390.3 S, this paper) make it hard to sustain a model in which the particle acceleration at the hot spots is only occurring at jet termination shocks. Similar conclusions have been reached by other authors based on optical data (e.g., Röser & Meisenheimer 1987; Prieto et al. 2002).

Observations of compact but offset X-ray emission, as in 3C 227, present a different problem. Here it seems possible that there is a discrete acceleration region that is related to the jet termination shock, but, if so, the shock is not where we would have inferred it to be from radio observations. For 3C 227 we could imagine a picture in which the X-ray emission in both primary and secondary hot spots tells us where the shock is now, while the radio traces material that has passed through this shock region, expanded and decelerated. This would imply that the X-ray emission should have a radio/optical counterpart, but for a flat synchrotron spectrum ($\alpha \sim 0.5$) extending between radio and X-ray the emission at other wave bands could be undetectably faint, at the 10 $\mu$Jy level in the radio (i.e., substantially below the upper limit of $\sim 2$ mJy on the flux density of this component from radio maps. Such a flat synchrotron spectrum extending all the way to the X-ray has never been observed (precisely because of the difficulty of detecting the radio counterparts) but might be expected in models of shock acceleration. The bulk of the optical emission in 3C 227 P1/2 seems to lie in between the X-ray and radio peaks, which is qualitatively consistent with this picture. The questions to be asked are then why other hot spots seen with similar spatial resolution, such as those in 3C 403, do not show the same radio/X-ray offsets; why the offsets in 3C 327, if they have the same origin, are so much larger; and what the origin is of the compact structure transverse to the jet direction in the hot spot of 3C 390.3.

Recent numerical simulations suggest that the picture of particle acceleration in the lobes of FRII sources may be less simple than in the traditional model of acceleration at strong shocks in one or more hot spots. Tregillis et al. (2001) carried out three-dimensional MHD simulations that modeled the transport of relativistic electrons and of particle acceleration at shocks. They found that the interaction of the jet and the back-flowing plasma at the head of the jet produced what they called a “shock-web complex,” “a region of shocks of varying strengths and sizes spread throughout the source.” Even when there was a single terminal shock, not all the jet material necessarily passed through it, and the terminal shock was not always the strongest shock in the system. While it is not clear that their simulations are perfectly matched to real radio sources, they are capable of producing simulated synchrotron images that show apparent clear discrete multiple hot spots (Tregillis et al. 2002), and in these cases the particle acceleration is not necessarily well matched to the locations of the hot spots: hot spot locations in their model can have more to do with magnetic field amplification than with particle acceleration. The notion of a “shock-web complex” at the head of the jet could help to explain the diffuse X-ray emission now seen in the radio-bright but noncompact source head regions of a number of objects, as discussed above, while the idea that the particle acceleration region may not always be co-spatial with the observed radio hot spot might help to explain observed offsets. It should be possible to carry out numerical simulations that allow synthetic maps of the location of high-energy synchrotron-emitting particles to be generated for qualitative comparison with the range of structures seen in X-ray observations.

We can also compare the X-ray observations of hot spots with observations of systems in which the X-ray emission is almost certain to be synchrotron in origin, the FRI jets (§1). In the nearest FRI jet, Centaurus A (Hardcastle et al. 2003), there is direct dynamical evidence for shock-acceleration of particles, as we believe is going on in FRI hot spots. There are also offsets, albeit on scales of only tens of parsecs rather than kiloparsecs, between the peak of the X-ray emission and the brightest radio emission, in the sense that the radio emission peaks downstream of the X-ray. And there is diffuse X-ray emission, not associated with any compact radio source or dynamical feature of the jet, which in some cases has a diffuse optical counterpart (Hardcastle et al. 2006b). Other FRI jets show similar features. At present we do not understand the nature of the radio/X-ray peak offsets in FRI jets or the distributed particle acceleration process responsible for the diffuse X-ray emission, but the qualitative similarity between the Cen A jet and a jet termination region like 3C 390.3 S...
or 3C 33 S means that we might hope to gain some insight into one problem by studying the other. In both cases the observational requirement is sensitive, multifrequency observations that allow us to construct a detailed map of the synchrotron SED as a function of position.

5.2. The Nature of Multiple Hot Spots

Our two new targets, 3C 227 and 3C 327, provide at least one clear example (3C 227 W), and possibly two, of an object where the primary and secondary hot spot are both detected in the X-ray, setting aside the problem of offsets between the components. 3C 33 N (Kraft et al. 2007) is another example of a source with multiple X-ray hot spots. 3C 390.3 N, on the other hand, behaves more similarly to 3C 403 E: the bright secondary hot spot is not an X-ray (or optical) synchrotron source even though there is an apparently clear connection between the primary and secondary hot spot indicative of continuing energy supply (but cf. the discussion of this point in Leahy & Perley 1995). Taking SX1 and its radio counterpart G to be the primary hot spot of the southern hot spot complex, a similar statement can be made for this system too. In both these cases, the upper limit on the X-ray to radio flux ratio in the nondetected hot spots, which are generally brighter in the radio, is 1–2 orders of magnitude below the measured value for the primary hot spots (Table 5). If we assume, as discussed in § 5.1, that the X-ray emission mechanism is synchrotron, then this tells us that secondary hot spots can be different: some, at least, are able to accelerate particles to the highest observable energies, but others are at least an order of magnitude less efficient than the primaries in producing X-ray emission for a given radio emissivity. This conclusion would be stronger if the nature of the X-ray emission in the secondary hot spots were more obvious.

If some secondary hot spots can accelerate particles to high energies and some do not, what is the difference between them? Relic hot spots left behind by a jet that has moved (“dentist’s drill” model) would certainly not be expected to have high-energy particle acceleration. But in our observations one secondary that apparently is connected to the jet (3C 390.3 N) does not have high-energy particle acceleration, while one that has no apparent connection in sensitive radio observations (3C 227 W) does. Radio morphology is therefore not a good guide to a hot spot’s ability to accelerate particles, or to its relationship to the energy supply, nor is the radio brightness of the hot spot.

One trend that is apparent in the data is that a hot spot is more likely to be an X-ray emitter (and therefore a privileged site for high-energy particle acceleration?) if it is compact. The secondary hot spots in 3C 227 and 3C 327 are similar in size to the primaries. Those in 3C 390.3 and 3C 403 are several times larger. “Compact” here appears to mean less than a few kiloparsec in size. However, although this may be a necessary condition, it is not a sufficient one, as the nondetection of relatively compact hot spots in, e.g., 3C 390.3 S shows. Secondary hot spot compactness could thus be an indicator of relatively well-collimated continued outflow from the primary hot spot to the secondary (or, in the case of the Cox et al. [1991] model, of a well-collimated disconnected jet); this makes sense, since (for a given luminosity) a more compact hot spot is more overpressured with respect to the lobe material and will have a shorter timescale for disappearance via adiabatic expansion in the absence of the energy supply. But the lack of a one-to-one correlation reinforces what we already know from observations of single hot spots: the ability of even low-luminosity, low-B-field hot spots, even when clearly connected to the energy supply, to produce X-ray emission is very variable and must depend on details of the microphysics that are not yet accessible to us.

6. CONCLUSIONS

We have looked with very high spatial resolution at the hot spot X-ray emission from a small sample of radio galaxies that show multiple radio hot spots. As in earlier work, we argue that the X-ray emission from the hot spots comes predominantly from the synchrotron process, and so traces high-energy particle acceleration. To our knowledge this paper represents the first attempt to use synchrotron emission to probe the particle acceleration properties in a sample of FRII sources, although several individual objects have previously been studied in detail.

Our principal results can be summarized as follows:

1. The cores and lobes of the two new sources in our sample have X-ray properties that are entirely consistent with expectations and with the sources’ places in unified models. There is evidence for intrinsic absorption in the spectrum of the BLRG 3C 227.

2. All the target sources exhibit structure in the X-ray images of their hot spots that would not have been predicted in a simple model in which particle acceleration occurs only at the jet termination as traced by the bright radio hot spot. This structure ranges from small-scale offsets in the radio and X-ray peaks (e.g., in 3C 227 W or 3C 390.3 N) through diffuse X-ray emission that is not well correlated with compact radio structure (e.g., 3C 390.3 S; see also 3C 33 S, Kraft et al. 2007; Pictor A E, Hardecastle & Croston 2005) to pointlike sources in the jet termination region that bear little obvious relationship to the current radio hot spots (3C 327 E). If most or all of these structures can be taken to indicate the location of particle acceleration in these sources, then our observations support models in which the particle acceleration history in FRIIs can be complicated, nonlocal, and not well traced by radio observations.

3. Our observations were obtained to investigate the nature of multiple hot spots, and we have found some evidence that some secondary hot spots are indeed associated with acceleration of particles to the highest observable energies, while others (as we had found previously) are not. This implies that at least some secondary hot spots have ongoing access to a supply of energy. All X-ray–synchrotron emitting hot spots appear to be compact, but not all compact hot spots are detected in X-rays. We cannot at present say whether this is because some of these compact hot spots are true relics, disconnected from the energy supply, or whether they are X-ray faint for some other reason related to the microphysics of their particle acceleration. Sensitive multiwavelength observations in radio and optical will be required to make further progress.

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