X-RAY SYNCHROTRON RADIATION AND PARTICLE ACCELERATION

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Abstract

I discuss X-ray synchrotron emission as a probe of particle acceleration, concentrating mainly on low-power (FRI) jets but also touching on the hotspots in FRII sources. Combining X-ray and radio data has allowed us to locate the sites of high-energy particle acceleration, and hence jet kinetic energy dissipation, in a number of objects. Recent data solve some old problems but present some new ones.

1 Introduction

In studies of extragalactic radio sources it is important to locate the sites where jet energy is dissipated; these are the regions where the bulk kinetic energy of the jet is transferred into the randomly directed kinetic energy of thermal and non-thermal particles. It has been clear for many years that one key jet dissipation process is the acceleration of the high-energy particles that give rise to the observed synchrotron emission (see Kirk, these proceedings). But locating the exact sites of particle acceleration is difficult: particles move away from their acceleration sites, and can continue to radiate for a long time after the initial acceleration. X-ray synchrotron radiation is a key probe of the location of particle acceleration, because the loss timescale ($\tau = E/(\mathrm{d}E/\mathrm{d}t)$) is only a few tens of years for a plausible magnetic field strength and an electron energy great enough to produce synchrotron radiation. Consequently, an electron of this energy can travel only a few parsecs from the site of its acceleration[1] before it ceases to be energetic enough to radiate in the X-ray; observations of X-ray synchrotron radiation thus locate the sites of particle acceleration with accuracy impossible to obtain in any other way. Here I discuss two sites in which X-ray synchrotron radiation and particle acceleration are associated: the jets of low-power (FRI) radio galaxies and the hotspots of powerful (FRII) sources.

2 FRI jets

2.1 Introduction

It is now generally accepted that the jets in FRI sources are initially relativistic and decelerate on scales of a few to a few tens of kpc to mildly relativistic or sub-relativistic speeds (Laing, these proceedings). The jet deceleration, as well as accounting for the fact that these jets are one-sided at the base but symmetrical further out, is necessary to explain the fact that the brightness profile of the jets is often found to be sub-adiabatic (Burch 1979); that is, the jets decline in surface brightness less rapidly than would be expected if a fluid of electrons and magnetic field simply expanded down the jet. Deceleration allows some of the bulk kinetic energy of the jet to be put into the acceleration of new relativistic particles, counteracting the effects of adiabatic losses.

FRI X-ray jets were known before the launch of *Chandra* (in Cen A, M87, and NGC6251) but *Chandra* observations have shown them to be relatively common (Worrall, Birkinshaw & Hardcastle 2001). At the time of writing 16 FRI sources (including two BL Lac objects) have known X-ray jets (see http://hea-www.harvard.edu/XJET/ for an up-to-date list and bib-

[1] Highly relativistic bulk motions of the particles can help them to evade this constraint, but they also make other loss processes important, such as inverse-Compton losses against the microwave background radiation, which appears boosted in the jet frame. In specific cases it has been shown that highly relativistic motions do not remove the necessity for local particle acceleration. In this paper I shall concentrate on the case where the motions are at best mildly relativistic

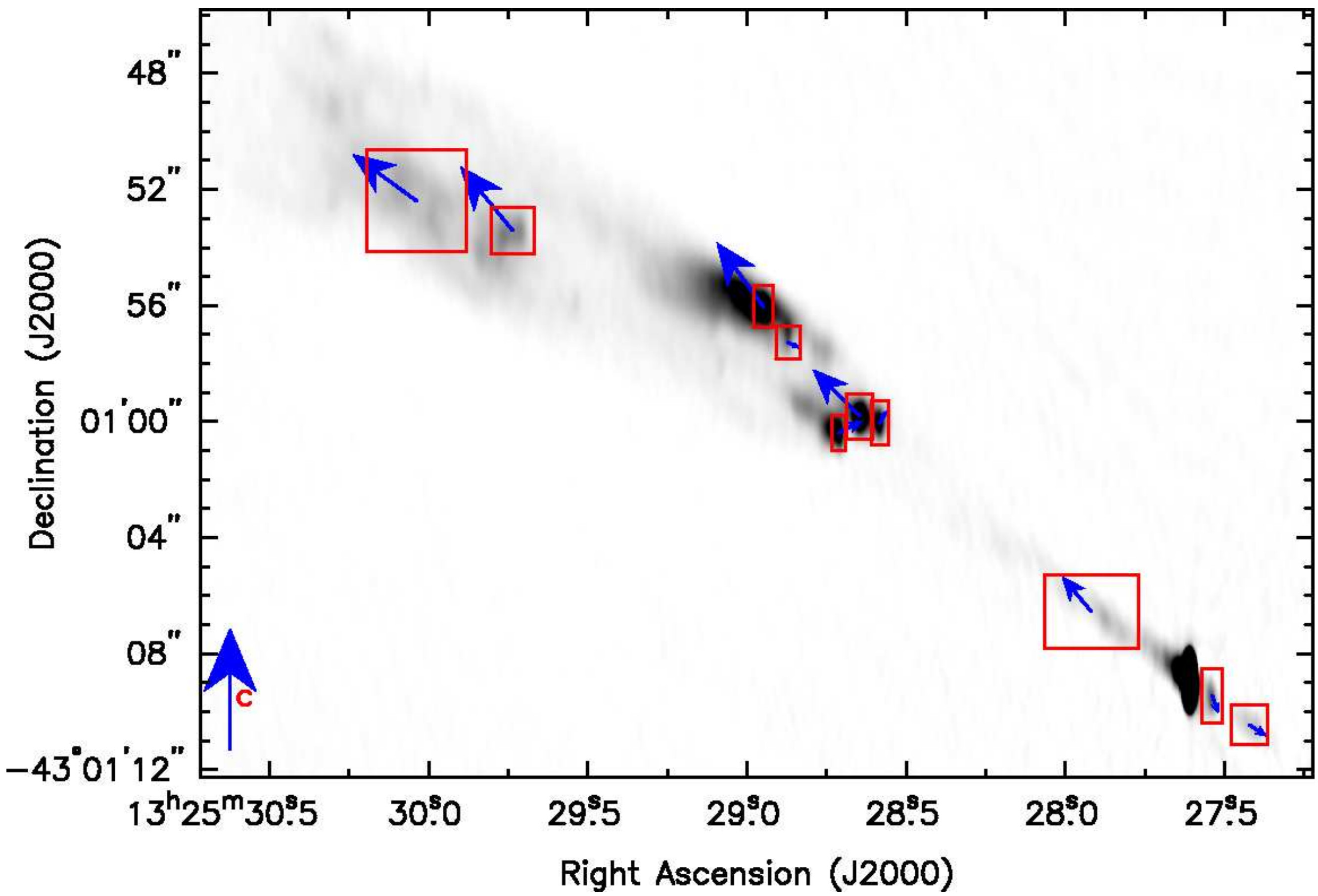

Figure 1: Motions in the Cen A jet between 2002 and 1991. The greyscale shows the 2002 A-configuration image, convolved to a resolution of $0.77 \times 0.20''$. Boxes indicate regions within which this image was compared with the 1991 image, convolved to the same resolution. Vectors show the best-fitting offsets between the two maps for each sub-image, exaggerated by a factor 20 for visibility. The vector in the bottom left-hand corner shows the offset that would be observed for a feature with an apparent speed of c. Note that only the four largest apparent motions are significantly detected.

liography). In almost all well-studied cases the X-ray emission has been taken to be synchrotron radiation, based on the observed steep X-ray spectra and, in the best-studied cases, the good agreement between the observed radio, optical and X-ray flux densities and the predictions of a simple, broken power-law synchrotron model (e.g., Hardcastle, Birkinshaw & Worrall 2001).

The association between particle acceleration and jet bulk deceleration is qualitatively quite convincing. Almost all FRI X-ray jets extend only a few kpc, in projection, from the nucleus, which is exactly the region where sidedness studies suggest that the jets are strongly decelerating. [The exception is NGC6251 (Sambruna et al. 2004; Evans et al., in prep.) where X-ray emission is detected not only in the inner few kpc but also on hundred-kpc scales; but here the jet remains very one-sided on those scales.] More quantitatively, in the case of 3C31, Laing & Bridle (2004) have shown that adiabatic models for the radio structure of the jet of 3C31 break down exactly where the X-ray emission from the jet is observed, while the kinetic power of the jet (e.g., Laing & Bridle 2002) is ample to provide the observed X-ray luminosity.

However, some important questions are not answered in this picture:

- What is the acceleration process responsible for the apparently diffuse X-ray emission from FRI jets, which in many cases is not associated with radio knots?
- What gives rise to the observed point-to-point differences in radio/X-ray flux ratio? (e.g., Hardcastle et al. 2001; Wilson & Yang 2002)

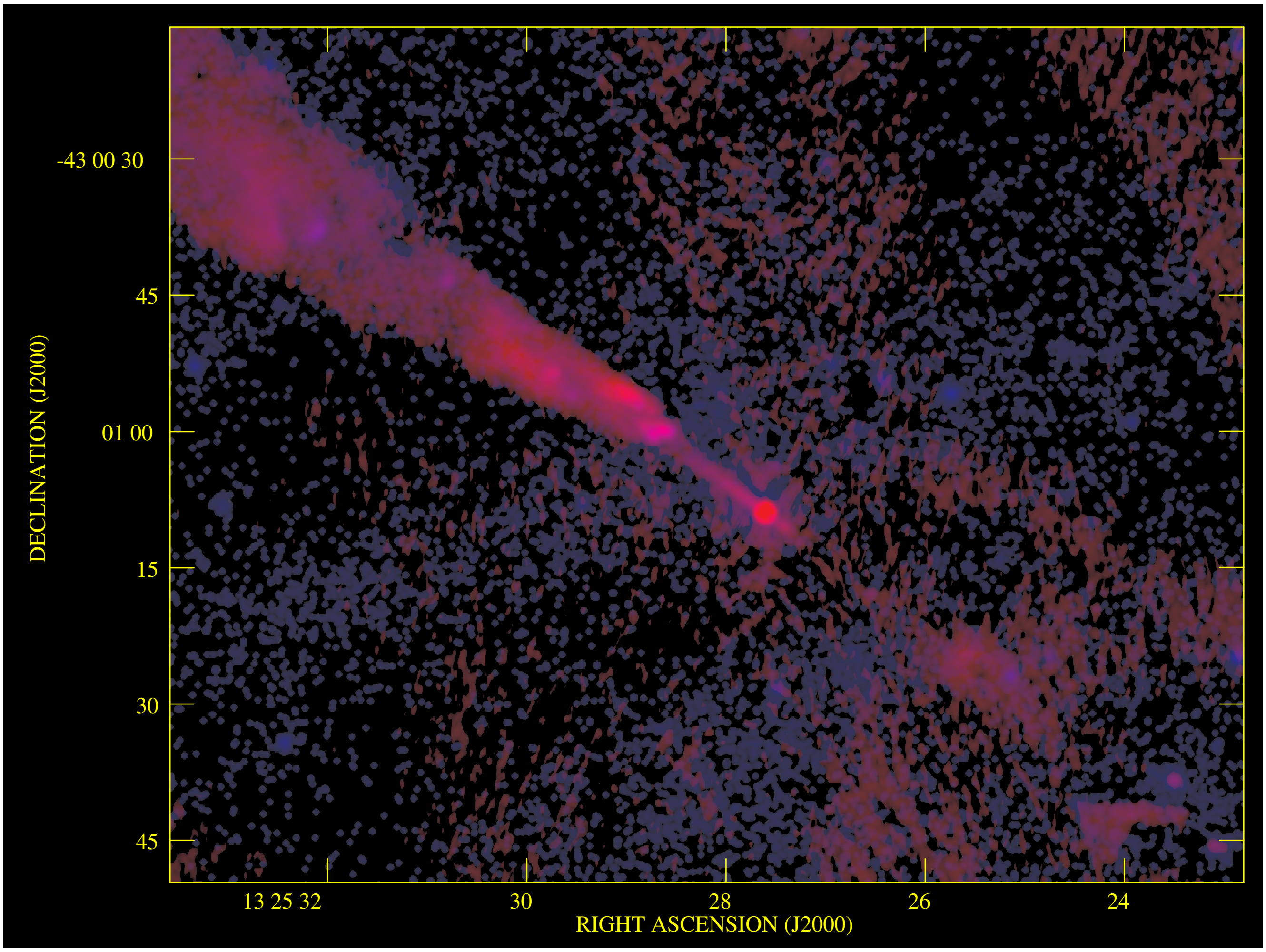

Figure 2: The X-ray and radio structure of the Cen A jet. The X-ray image, made from events with energies between 0.4 and 2.5 keV, is in blue and the radio image, at 8.4 GHz, is in red. The X-ray data have been smoothed with a Gaussian and the restoring beam of the radio map has been chosen so that both radio and X-ray data have a resolution (FWHM) around $0.85''$. The transfer function is non-linear to allow low-surface-brightness structure to be seen.

- Why are there apparent offsets between the peak positions of knots in the radio and X-ray, in the sense that the X-ray peaks closer to the nucleus? (e.g., Hardcastle et al. 2001; Wilson & Yang 2002; Hardcastle et al. 2002a).

- Why do the overall spectra of jets have a spectral break > 0.5, contrary to the predictions of continuous-injection models (Heavens & Meisenheimer 1987)?

In general the distance to the known FRI jet sources is ~ 100 Mpc, so that *Chandra*'s resolution is hundreds of pc, and each resolution element averages over many electron energy loss distances. Answering these questions requires a spatial resolution comparable to the electron energy loss scale, which is available in only one object, Centaurus A.

2.2 Cen A

Cen A's distance of 3.4 Mpc (Israel 1998) means that *Chandra*'s $0.65''$ resolution corresponds to around 10 pc. As Cen A is not only the closest radio galaxy but also the closest AGN and the closest large elliptical galaxy, it has been extensively studied at all wavebands, and the jet, discovered with *EINSTEIN* (Schreier et al. 1979) has been observed a number of times with *Chandra* (e.g., Kraft et al. 2000, 2002). Here we discuss mainly the results of AO3 observations taken on 2002 Sep 03 and reported previously by Hardcastle et al. (2003). The new approach in this paper was to combine *Chandra* ACIS-S observations

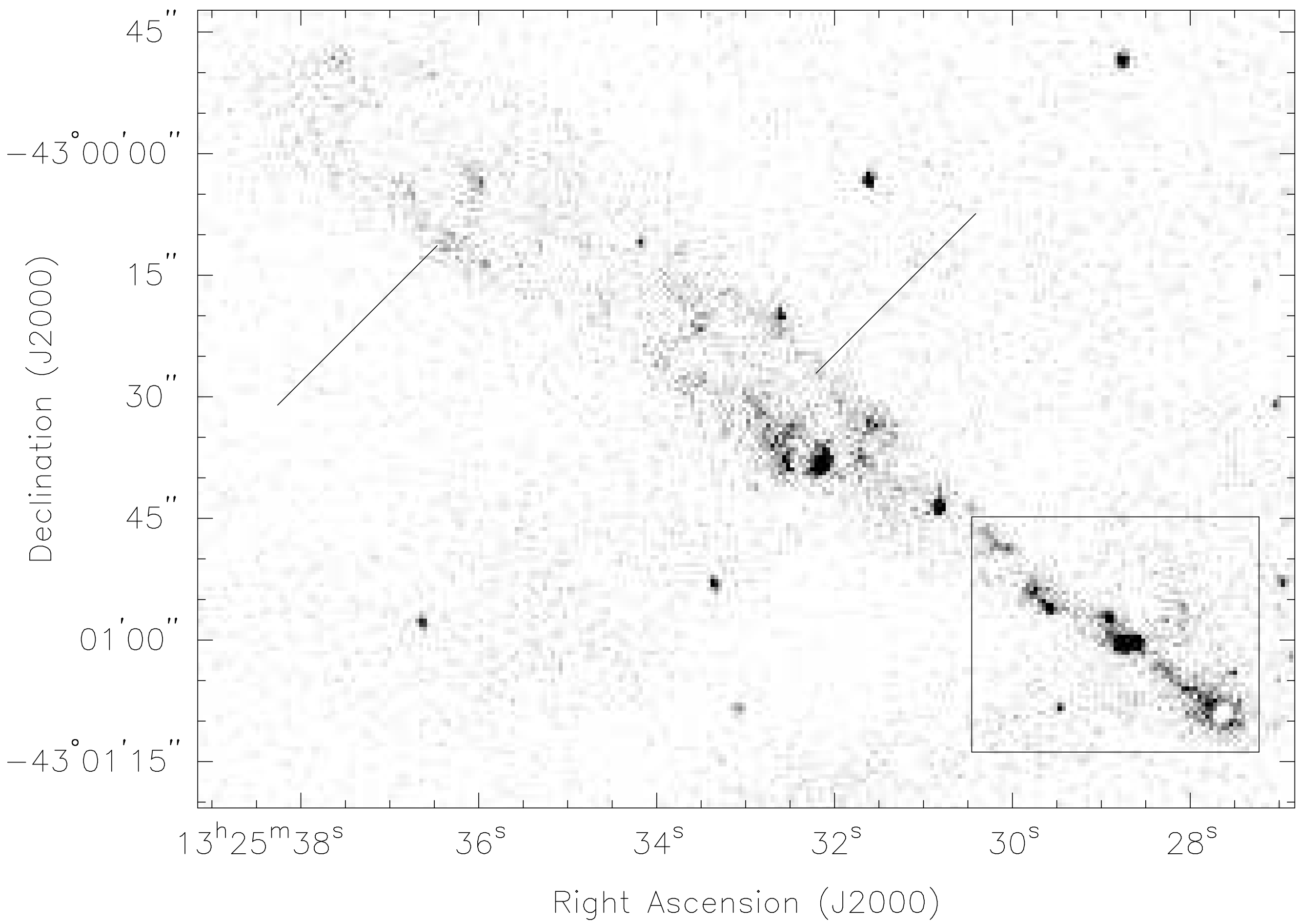

Figure 3: The X-ray structure of the large-scale Cen A jet. The greyscale shows the raw counts in the 0.4–2.5 keV band; the pixels are 0.492″ on a side and black is 12 counts per pixel. The lines indicate two regions where the X-ray jet appears significantly edge-brightened (see the text). The box, shown for orientation purposes only, shows the region of Fig. 1.

(with good soft X-ray sensitivity and high spatial resolution) with new and previously reduced Very Large Array (VLA) data in the A and B configurations.

By using two epochs of VLA data separated by 11 years, and by using specialized calibration techniques to achieve high dynamic range in the radio, we were able to detect radio proper motions in the kpc-scale jet of Cen A for the first time (Fig. 1). The motions, which correspond to a projected speed around 0.5c, are interesting in their own right; not only are they faster than the observed motions on pc scales (Tingay et al. 1998) but they show for the first time in any source large-scale coherent motion of extended regions of the jet, while some knots, nearer to the nucleus, remain stationary or have undetectably small motions. A program of observations monitoring the Cen A jet with the VLA (including the Pie Town antenna) is now under way.

However, the greatest interest in the radio observations comes from combining them with the X-ray data. This combination shows strong radio to X-ray flux ratio variation throughout the jet (Fig. 2). Previously a number of compact X-ray knots had been seen in the jet (Kraft et al. 2002); the new radio data detects radio counterparts to almost all of these and allows them to be identified as true jet features (rather than chance superpositions with background sources). These weak radio knots with bright X-ray counterparts were clearly stationary or slow-moving compared with the radio features that exhibited significant proper motion. The knots that did exhibit proper motion had radio-to-X-ray flux ratios comparable to that of the jet as a whole; it is important to note that a significant fraction of the X-ray flux from the jet appears to be diffuse (Fig. 3) and is not associated with any compact radio features.

The radio-to-X-ray spectra of the radio-faint, X-ray-bright, stationary or slow-moving knots, compared with the spectrum of the extended emission, rule out the possibility that they are simply compressions in the fluid flow, and we can also reject models in which they are related to jet-triggered supernovae. Instead, they must be privileged sites for particle acceleration in the jet. It is therefore very tempting to relate their particle acceleration to their static nature, and suggest that they represent shocks in the fluid flow. The radio-bright, static knots at the base of the jet may well be related to a reconfinement shock associated with the transition to trans-sonic flow. However, the fainter knots embedded in the jet flow further out seem more likely to be related to shocks caused by the interaction of the jet with obstacles that are stationary (in practice, $v < 0.1c$) in the frame of the host galaxy (cf. Blandford & Königl 1979). The obstacles are most likely to be clumps of cold gas.

In the case of Cen A *Chandra* has certainly allowed us to make some progress in understanding the acceleration process; some of the acceleration can be associated with small-scale shocks. Whether this can account for all the X-ray emission is debatable. A population of smaller obstacles, each with its own small shock, can in principle provide the diffuse emission; but the edge-brightened regions in the outer jet (Fig. 3) seem to point more toward some process related to shear or turbulence (e.g., Stawarz & Ostrowski 2002). The apparent offsets seen in more distant jets, and perhaps also their unusual spectra, can be explained in terms of averaging over a number of knots and their downstream regions, but there is still more to be understood in this area (Hardcastle et al. 2003).

3 FRII hotspots

If our conclusions about Cen A are correct, shocks in the jets of FRI radio galaxies can accelerate particles to X-ray emitting energies. The terminal hotspots of FRII sources are well modeled as strong shocks at the ends of jets (Meisenheimer et al. 2001) and a number of them are known to have optical synchrotron emission, implying the possibility of high-energy particle acceleration. Can these sources also produce X-ray synchrotron emission?

The X-ray hotspots that have been most widely discussed have been those in which the X-ray flux levels are in good agreement with the predictions of a synchrotron self-Compton (SSC) model, with the hotspot magnetic field strength close to the equipartition value (e.g., Harris, Carilli & Perley 1994; Harris et al. 2000; Hardcastle et al. 2001, 2002b). In many of these cases there are optical upper limits or detections that imply that a simple one-zone synchrotron model with a single electron energy spectrum (like the one used for the FRI jets) cannot fit the broad-band data. However, there are also some well-studied hotspots (e.g., 3C390.3, Harris, Leighly & Leahy 1998; Pictor A, Röser & Meisenheimer 1987) where an SSC model is not viable unless the hotspot magnetic field strength is orders of magnitude below the equipartition value; these sources also exhibit a spectrum that is too steep to be inverse-Compton emission. Recently, even more extreme X-ray hotspots have been discovered (e.g., 3C403: Kraft et al., in prep.). In some, but not all, of these cases, a simple one-zone synchrotron spectrum *is* a good fit to the radio, optical and X-ray data points. In addition, there are several sources (the best example being 3C351: Hardcastle et al. 2002b) where the X-ray structure is clearly different from that seen in the radio maps, which is impossible in a simple SSC model with a homogeneous magnetic field and electron distribution. In a synchrotron model for some or all of the X-rays, differences in the spatial structure are to be expected because of the very different loss timescales for radio- and X-ray-emitting electrons.

We have tried to address the question of *why* there are apparently two origins for the X-ray emission from hotspots by collating data from the *Chandra* archive for all currently observed FRII 3C sources and analyzing them in a systematic way (this work is described in more detail by Hardcastle et al. 2004). Taking radio images from the VLA archive, we used the code of Hardcastle, Birkinshaw & Worrall (1998) to predict the flux level expected for inverse-Compton emission at equipartition (taking into account both synchrotron self-Compton emission and inverse-Compton scattering of microwave background photons). We then calculated the value of R, the ratio between the observed and predicted X-ray flux density. Where no compact X-ray hotspot was detected, we determined an upper limit on R. The final sample we used contained 37 sources with 65 hotspot flux densities or upper limits. The distribution of R values is plotted in Fig. 4. Two interesting points are immediately obvious: firstly, there are no sources with an R value clearly much lower than 1 (which would imply a flux level *below* the SSC prediction, requiring a magnetically dom-

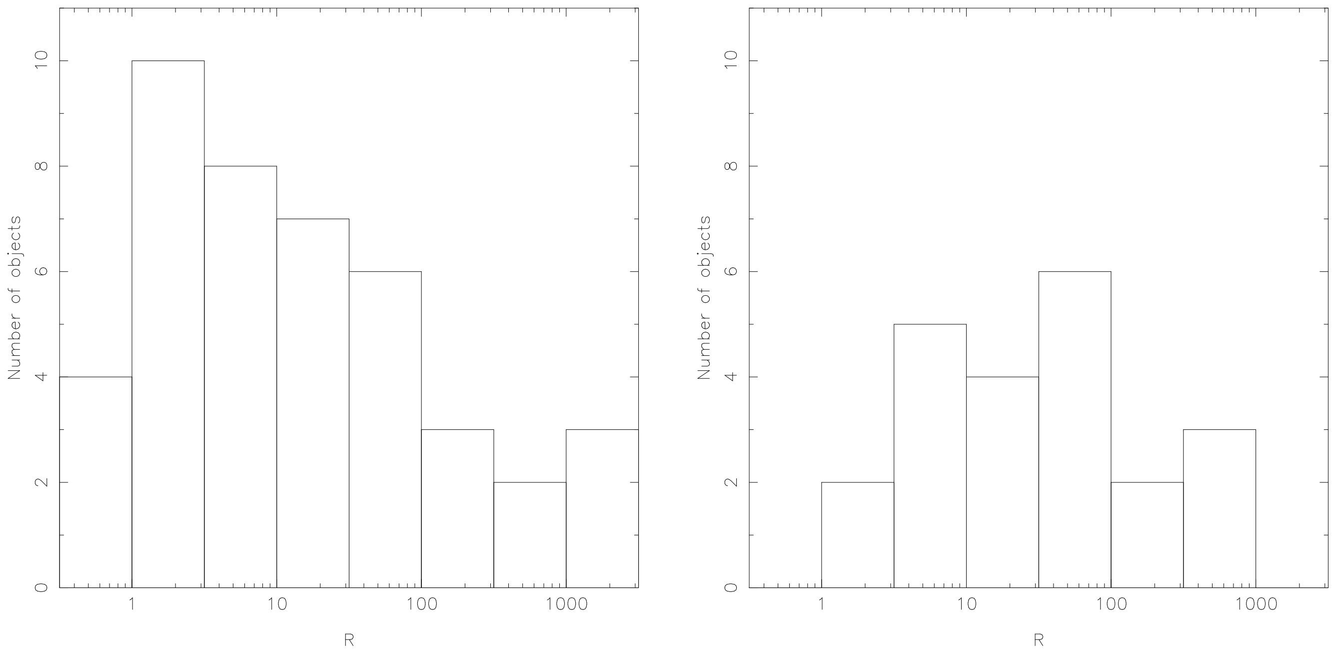

Figure 4: Distribution of the ratio R of observed X-ray flux to inverse-Compton prediction for the *Chandra* sample. Left: distribution for X-ray detected hotspots. Right: distribution for compact hotspots with no detection (sources can move to the left).

inated hotspot); and secondly, there is a wide distribution of R values, with some sources being brighter than the equipartition prediction by three orders of magnitude, and with no obvious bi-modality in the population.

What determines the value of R for a particular hotspot? The dominant effect appears to be the hotspot's radio luminosity (Fig. 5). We cannot populate the bottom left-hand corner of this figure, because *Chandra* is not sensitive enough to detect the predicted SSC emission from the least luminous hotspots. But we certainly could have detected any hotspots that lay in the top right-hand corner of the plot; *there are no high-luminosity hotspots with high* R *values*. Low-luminosity hotspots appear to be able to have high R values, though we cannot say with certainty that all of them do. In the past it had been proposed that beaming effects could explain the fact that many of the then-observed high-R sources were broad-line radio galaxies or quasars (Hardcastle et al. 2002, Georganopoulos & Kazanas 2003) but we find that any beaming effect is weak compared to the luminosity dependence (Fig. 6) and in fact may purely have been due to selection effects in the small samples available until recently. There are now known narrow-line radio galaxies (which should not have strong beaming effects) that

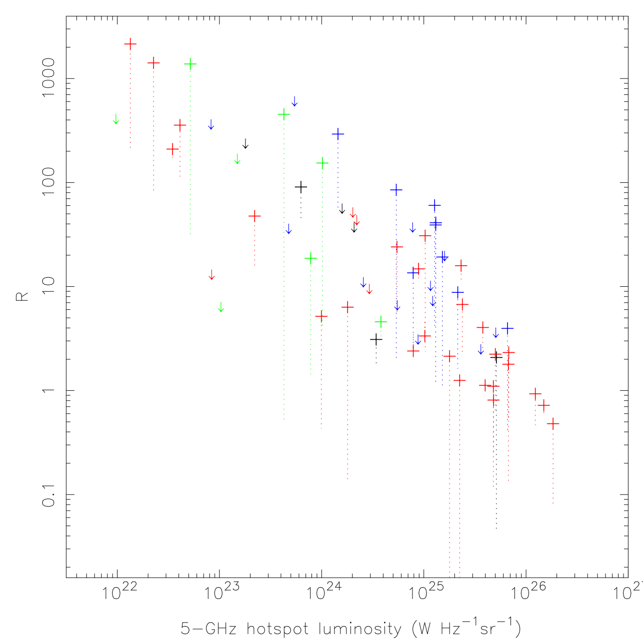

Figure 5: The relationship between the rest-frame 5-GHz luminosity of the *Chandra* hotspots and R. The dotted lines extending down from the data points show the approximate lowest value of R that could have been detected with the data, assuming a nominal *Chandra* sensitivity of 0.1 nJy at 1 keV. Arrows indicate upper limits on R. Black data points indicate low-excitation radio galaxies, red narrow-line objects, green broad-line radio galaxies and blue quasars.

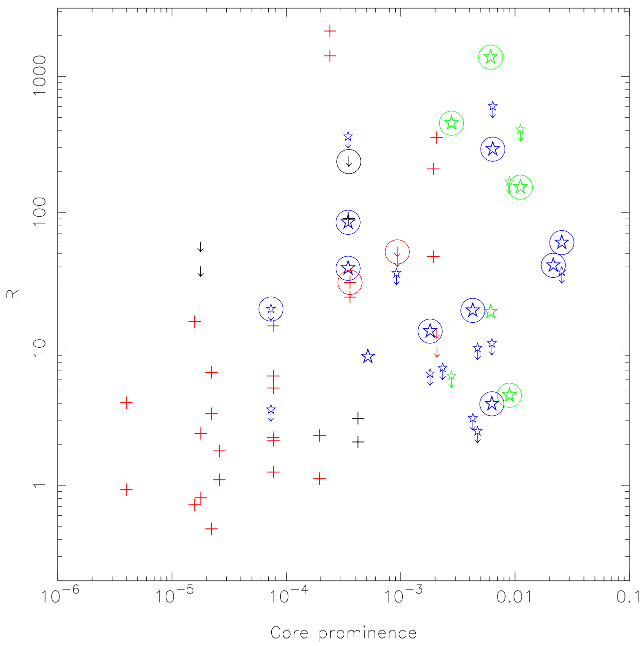

Figure 6: The relationship between 5-GHz core prominence (the ratio of the core flux density to the 178-MHz extended flux density, an indicator of beaming) and R. Colors as in Fig. 5. Circles indicate a hotspot on the same side of the source as a known one-sided radio jet. Although some of the high-R sources are certainly in highly beamed objects, the correlation is weak.

have high R values, which reduces the motivation for such models.

Our interpretation of the data is therefore as follows:

- In the radio-luminous hotspots, the good agreement between the SSC prediction and observation continues to suggest that the X-ray emission mechanism is inverse-Compton and that magnetic fields in hotspots are close to their equipartition values.
- In lower-luminosity hotspots, some or all of the X-ray emission is plausibly synchrotron radiation. It has already been suggested that there is a relationship between the synchrotron break energy and the luminosity of hotspots, based on optical observations (Brunetti et al. 2003); the new X-ray observations suggest that the synchrotron high-energy *cutoff* is also luminosity-dependent.

4 Conclusions

I have tried to argue in the work presented here that X-ray synchrotron emission is an important process in several areas. In FRI jets, where its existence is best established, it allows us to locate sites of particle acceleration and, in the case of Cen A, to relate it to the small-scale dynamics of the jet. The unexpectedly strong X-ray emission from a number of low-luminosity FRII hotspots strongly suggests that high-energy particle acceleration is possible there as well, and this will have consequences for the location of hotspot acceleration sites and processes that can be explored in future work.

Acknowledgments

The work described here has been carried out in collaboration with a large number of people, too many to list here; the input of Dan Harris, Diana Worrall, Mark Birkinshaw, Ralph Kraft and Robert Laing has been particularly important. I thank the Royal Society for a Research Fellowship.

References

Blandford, R. D., Königl, A. 1979, ApL 20 15

Brunetti, G., Mack, K. H., Prieto, M. A., Varano, S. 2003, MNRAS, 345, L40

Burch, S. F. 1979, MNRAS, 187, 187

Georganopoulos, M., Kazanas, D. 2003, ApJ, 589, L5

Hardcastle, M. J., Birkinshaw, M., Worrall, D. M. 1998, MNRAS, 294, 615

Hardcastle, M. J., Birkinshaw, M., Worrall, D. M. 2001a, MNRAS, 323, L17

Hardcastle, M. J., Birkinshaw, M., Worrall, D. M. 2001b, MNRAS, 326, 1499

Hardcastle, M. J., Birkinshaw, M., Cameron, R., Harris, D. E., Looney, L. W., Worrall, D. M. 2002, ApJ, 581, 948

Hardcastle, M. J., Harris, D. E., Worrall, D. M., Birkinshaw, M. 2004, ApJ, submitted

Hardcastle, M. J., Worrall, D. M., Birkinshaw, M., Laing, R. A., Bridle, A. H. 2002, MNRAS, 334, 182

Hardcastle, M. J., Worrall, D. M., Kraft, R. P., Forman, W. R., Jones, C., Murray, S. S. 2003, ApJ, 593, 169

Harris, D. E., Carilli, C. L., Perley, R. A. 1994, Nature, 367, 713

Harris, D. E., Leighly, K. M., Leahy, J. P. 1998, ApJ, 499, L149

Harris, D. E., et al. 2000, ApJ, 530, L81

Heavens, A. F., Meisenheimer, K. 1987, MNRAS, 225, 335

Israel, F. P. 1998, ARA&A, 8, 237

Kraft, R. P., et al. 2000, ApJ, 531, L9

Kraft, R. P., Forman, W. R., Jones, C., Murray, S. S., Hardcastle, M. J., Worrall, D. M. 2002, ApJ, 569, 54
Laing, R. A., Bridle, A. H. 2002, MNRAS, 336, 1161
Laing, R. A., Bridle, A. H. 2004, MNRAS, 348, 1459
Röser, H.-J., Meisenheimer, K. 1987, ApJ, 314, 70
Sambruna, R. M., Gliozzi, M., Donato, D., Tavecchio, F., Cheung, C. C., Mushotzky, R. F. 2004, A&A, 414, 885
Schreier, E. J., Feigelson, E., Delvaille, J., Giacconi, R., Grindlay, J., Schwartz, D. A., Fabian, A. C. 1979, ApJ, 234, L39
Stawarz, L., Ostrowski, M. 2002, ApJ, 578, 763
Tingay, S. J., et al. 1998, AJ, 115, 960
Wilson, A. S., Yang, Y. 2002, ApJ, 568, 133
Worrall, D. M., Birkinshaw, M., Hardcastle, M. J. 2001, MNRAS, 326, L7