Physical conditions in hotspots — what the new data are telling us

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Abstract

I review the current constraints on the nature of the hotspots of FRII radio sources, and the physical conditions that obtain in them. New *Chandra* observations suggest that the majority of X-ray detections of hotspots are due to inverse-Compton processes, with magnetic field strengths close to the standard equipartition/minimum-energy values. However, a few broad-line objects have X-ray emission much brighter than the expected inverse-Compton level. These may be due to synchrotron emission from a second population of electrons. I discuss the advantages and disadvantages of models for the anomalous objects involving relativistic bulk motions in the hotspots.

Key words:

1 Radio observational constraints

From a very early stage in the study of radio sources the bright radio features at the extreme ends of classical double objects have been identified with the terminations of the 'beams' supplying energy from the active nucleus to the lobes (e.g. Scheuer 1974). Many of us still identify 'the hotspot' with 'the terminal shock' in a radio source.

For some time (Laing 1982) it has been clear that the observational situation is more complicated than this simple picture would suggest: half of the nearby 3CR sources that have been studied at high resolution with the VLA (Leahy et al. 1997, Hardcastle et al. 1997) show more than one bright compact feature at the end of the lobe. Since we believe that the jet terminates only in one place, this implies that the physics of one hotspot is different from that of the others. Conventionally the most compact feature is called the 'primary' hotspot, while the others are known as 'secondary' hotspots. The primary hotspot is always the one which the jet is observed to enter, if a jet is present,

The controversy over the generation of multiple hotspots (Scheuer 1982, Williams & Gull 1985, Lonsdale & Barthel 1986, Cox, Gull & Scheuer

1991) is of mainly historical interest today, since numerical simulations suggest that all the proposed mechanisms can operate. It remains of interest to ask whether a particular secondary hotspot continues to be supplied with energy by the beam, a point I'll return to in section 4.

At radio frequencies, hotspots are often well fitted with models based on power-law or broken power-law electron energy spectra (Meisenheimer et al. 1989). A high-energy cutoff in the electron spectrum is often required to reproduce the IR and optical data. *Low-energy* cutoffs appear to be required in the spectra of some hotspots (Carilli et al. 1991, Hardcastle 2001), with typical values of the cutoff Lorentz factor being ~ 500 – 1000 (corresponding to observed frequencies in the 100-MHz range). These observations appear to hold good for both primary and secondary hotspots. They are consistent with a picture in which the hotspots are the sites of particle acceleration. The low-energy cutoff may be telling us something about the energies of the electrons transported up the beam, while the high-energy cutoff in the conventional picture arises from the balance between energy input and radiative losses.

2 Simulation

Numerical simulations are beginning to have the power needed to trace the complex electron spatial and energy distributions that we know must be present in real sources (e.g. Tregillis et al. 2001). From an observational standpoint, it is still a concern that such simulations do not always produce observable hotspots, since we know that powerful double sources without compact hotspots in the lobes are rare. However, if the simulations are working in anything like the right area of parameter space, it seems clear that hotspots are transient features on timescales much shorter than the lifetime of the source. It is important to bear this in mind in what follows.

3 Beaming

Before we can start to infer physical conditions from observations of hotspots, we need a good reason for believing that we are not being misled by the effects of relativistic beaming. There are several distinct types of constraint on the amount of beaming that can be present:

(1) Lobe advance speeds. Work on lobe length asymmetries (e.g. Scheuer 1995) shows that the lobes cannot be expanding relativistically ($v/c < 0.1$). The *bulk* advance speed of the hotspots should not exceed the lobe head advance speed. However, this does not place very strong constraints on the fluid flow *through* the hotspot, particularly if the terminal shock is not planar.

(2) Jet/hotspot correlations. There is an observed tendency for the brighter or only kpc-scale jet to point to the more compact or brighter hotspot (e.g. Bridle et

al. 1994) which is more obvious in samples of quasars than of sources unbiased with respect to orientation (Hardcastle et al. 1998) and so is likely to be related to beaming.

(3) In quasars, a correlation between jet side and lobe spectral index (Dennett-Thorpe et al. 1997) turns out to affect the hotspots and their environments more than the low surface brightness regions of the lobes — suggestive of a beaming effect.

The last two constraints require only moderate amounts of relativistic beaming in the hotspot regions (say $v/c \sim 0.3$). There is no direct evidence for extremely large bulk Lorentz factors, but Doppler suppression effects mean that we would expect to see the effects of these only in a few rare, extreme sources.

4 X-ray observations

Chandra has detected a reasonably large number of X-ray hotspots in FRIIs. Table 1 lists detections that are published or in press as at December 2002. Of these ten sources, Cygnus A, 3C 295, 3C 123, 3C 207, 3C 263 and 3C 330 have X-ray emission that is consistent with being inverse-Compton (synchrotron self-Compton, SSC) emission from a population of electrons with magnetic fields close to (within a factor ~ 2 of) the equipartition/minimum energy values, assuming no proton content and a filling factor of unity.

Table 1
X-ray hotspots in FRII radio sources

Source	z	Optical?	Reference
Pictor A	0.035	Y	1,2
Cygnus A	0.056	N	3,4
3C 390.3	0.057	Y	5,6
3C 303	0.141	Y	7,8
3C 295	0.4614	Y	9
3C 123	0.2177	N	10
3C 351	0.371	Y	11, 12
3C 207	0.684	N	13
3C 263	0.6563	Y	12
3C 330	0.5490	N	12

1: Röser & Meisenheimer 1987; 2: Wilson et al. 2001; 3: Harris et al. 1994; 4: Wilson et al. 2000; 5: Prieto 1997; 6: Harris et al. 1998; 7: Hardcastle & Worrall 1999; 8: Kataoka et al. 2003; 9: Harris et al. 2000; 10: Hardcastle et al. 2001; 11: Brunetti et al. 2001; 12: Hardcastle et al. 2002; 13: Brunetti et al. 2002

However, 3C 390.3, Pictor A, 3C 303 and 3C 351 have significantly more X-ray emission than would be expected from an inverse-Compton model without large departures from equipartition. It is noteworthy that these four are broad-line (and so aligned) objects with optical hotspots (Table 1).

The SSC/IC calculations are usually carried out assuming that the hotspots are homogeneous spheres uniformly filled with a single simple electron population (e.g. broken power law). Radio observations show that these are not very accurate assumptions! For a few of the sources in Hardcastle et al. (2002) we used more complicated spectral and spatial models to reproduce the observed spatial and spectral structure of the hotspots. We found that this does not make a significant difference to the eventual results, so we can conclude with reasonable confidence that the magnetic fields in hotspots are close to their equipartition values.

The sources where IC models don't appear to work fail for a variety of reasons. All the anomalous sources are *too bright* in X-rays to be SSC from a plasma near equipartition. (There are as yet no known sources where the X-ray emission is too faint for an SSC model.) Pic A and 3C 390.3 have steep X-ray hotspot spectra, which are inconsistent with an inverse-Compton model. 3C 351 and 3C 303 have flat spectra, but 3C 351 shows offsets between the radio and X-ray peaks (in the resolved secondary hotspot) that are not expected in a simple inverse-Compton picture. A simple synchrotron model describes 3C 390.3 well, but fails in the case of 3C 351 because of the flat X-ray spectrum. However, we should bear in mind that we don't expect to see detailed agreement between synchrotron emission in the X-ray (where the electron loss timescales are tens of years) and radio (where the loss timescales are $\sim 10^5$ years). We certainly would expect to see variations in the electron spectrum as a function of position in resolved, kpc-scale hotspots, a fact that ties in with what we know about the unambiguously synchrotron X-ray jets in FRI sources. So a synchrotron model with a complex distribution of emitting electrons cannot be ruled out in the case of these anomalous hotspots. For it to operate in the widely separated double hotspot of 3C 351, we require ongoing particle acceleration (and thus energy supply) in the secondary hotspot. The similarity of the two hotspots in 3C 351 is intriguing in view of the belief that hotspots are transient structures.

5 Consequences

If protons were present in energetically *dominant* quantities in the hotspots, the good agreement between the measured magnetic field strengths and the minimum-energy/equipartition values would have to be a coincidence. It seems more likely that protons are not energetically dominant. We cannot rule out a population of protons with an energy density similar to that of the magnetic field or the electrons.

A synchrotron model (with spatial and/or temporal variations in the distribution of high-energy electrons) can in principle explain all the anomalously bright X-ray hotspots. However, it is not at all clear what is special about these hotspots that allows them to accelerate electrons to the required very high energies (though we know they are optical synchrotron sources), and it's certainly a concern that they all appear to be in broad-line objects.

Is beaming important? We know (Wardle & Aaron 1997, Hardcastle et al. 1999) that FRII jets are at least mildly relativistic ($v/c \sim 0.5$) on large scales: it is possible (e.g. Tavecchio et al. 2000) that they contain highly relativistic ($\Gamma \sim 20$) spines: while the work on hotspots discussed above gives us observational reasons to believe in post-shock relativistic flow. A beaming model in hotspots would require velocity structure in the emitting regions of the hotspot, otherwise the radio galaxies close to the plane of the sky (like Cygnus A) would not give the observed good agreement between SSC/equipartition predictions and observation. However, velocity structure in hotspots is not impossible: in fact, in some sense it's required by the fact that the flow must decelerate from at least mildly relativistic to sub-relativistic speeds. What is less clear is whether there is much velocity structure in the *emitting regions* of the hotspot.

We find that a simple boosted-CMB beaming model of the type proposed for the PKS 0637−752 jet by Tavecchio et al. (2000) requires extreme conditions (bulk Lorentz factor > 5 and very small angles to the line of sight) to give rise to the observed X-rays in 3C 351. These values are not plausible for a lobe-dominated quasar, and there are probably already too many anomalous hotspot sources in the 3CR catalogue for the statistical predictions of such a model to be viable in general. More plausible is the idea (Georganopoulos & Kazanas, these proceedings) that there are velocity inhomogeneities in the hotspots and that X-rays come from a moderately beamed synchrotron population, while radio emission is largely unbeamed. However, there are still some observational problems with this picture:

- The 3C 263 hotspot (Hardcastle et al. 2002) works with an SSC model, suggesting that the radio and optical emission here is not strongly beamed, although 3C 263 is a quasar.
- There is X-ray emission from both the N and S hotspots of 3C 390.3, although it is a broad-line object with a jet clearly pointing N.
- The double hotspot in 3C 351 almost certainly involves a difference between the magnitudes and directions of the velocity vectors of the flows into the primary and secondary components. The similarity of the radio/X-ray ratios in the two hotspots would have to be coincidental in a beaming model.

Clearly our understanding of the properties of these objects remains incomplete.

6 Summary

- The majority of X-ray detected hotspots are likely to be due to the SSC process, and imply hotspot magnetic field strengths close to the equipartition values.
- A few are much brighter than would be expected from SSC. Synchrotron emission could explain their X-ray emission, but would in some cases require a second electron population and/or some beaming effects.

References

Bridle, A.H., Hough, D.H., Lonsdale, C.J., Burns, J.O., Laing, R.A., 1994, AJ, 108, 766

Brunetti, G., Bondi, M., Comastri, A., Pedani, M., Varano, S., Setti,

G., Hardcastle, M.J., 2001, ApJ, 561, L157
Brunetti, G., Bondi, M., Comastri, A., Setti, G., 2002, A&A, 381, 795
Carilli, C.L., Perley, R.A., Dreher, J.W., Leahy, J.P., 1991, ApJ, 383, 554
Cox, C.I., Gull, S.F., Scheuer, P.A.G., 1991, MNRAS, 252, 588
Dennett-Thorpe, J., Bridle, A.H., Laing, R.A., Scheuer, P.A.G., Leahy, J.P., 1997, MNRAS, 289, 753
Hardcastle, M.J., 2001, A&A, 373, 881
Hardcastle, M.J., Alexander, P., Pooley, G.G., Riley, J.M., 1997, MNRAS, 288, 859
Hardcastle, M.J., Alexander, P., Pooley, G.G., Riley, J.M., 1998, MNRAS, 296, 445
Hardcastle, M.J., Alexander, P., Pooley, G.G., Riley, J.M., 1999, MNRAS, 304, 135
Hardcastle, M.J., Birkinshaw, M., Worrall, D.M., 2001, MNRAS, 323, L17
Hardcastle, M.J., Birkinshaw, M., Cameron, R., Harris, D.E., Looney, L.W., Worrall, D.M., 2002, ApJ, 581, 948
Hardcastle, M.J., Worrall, D.M., 1999, MNRAS, 309, 969
Harris, D.E., Carilli, C.L., Perley, R.A., 1994, Nat, 367, 713
Harris, D.E., Leighly, K.M., Leahy, J.P., 1998, ApJ, 499, L149
Harris, D.E., et al., 2000, ApJ, 530, L81
Kataoka, J., Edwards, P., Georganopoulos, M., Takahara, F., Wagner, S., 2003, A&A, 399, 91
Laing, R.A., 1982, in Heeschen, D.S., Wade C.M., eds, Extragalactic Radio Sources, IAU Symposium 97, Reidel, Dordrecht, p. 161
Leahy, J.P., Black, A.R.S., Dennett-Thorpe, J., Hardcastle, M.J., Komissarov, S., Perley, R.A., Riley, J.M., Scheuer, P.A.G., 1997, MNRAS, 291, 20
Lonsdale, C.J., Barthel, P.D., 1986, AJ, 92, 12
Meisenheimer, K., Röser, H.-J., Hiltner, P.R., Yates, M.G., Longair, M.S., Chini, R., Perley, R.A., 1989, A&A, 219, 63
Prieto, M.A., 1997, MNRAS, 284, 627
Röser, H.-J., Meisenheimer, K., 1987, ApJ, 314, 70
Scheuer, P.A.G., 1974, MNRAS, 166, 513
Scheuer, P.A.G., 1982, in Heeschen, D.S., Wade C.M., eds, Extragalactic Radio Sources, IAU Symposium 97, Reidel, Dordrecht, p. 163
Scheuer, P.A.G., 1995, MNRAS, 277, 331
Tavecchio, F., Maraschi, L., Sambruna, R.M., Urry, C.M., 2000, ApJ, 544, L23
Tregillis, I.L., Jones, T.W., Ryu, D., 2001, ApJ, 557, 475
Wardle, J.F.C., Aaron, S.E., 1997, MNRAS, 286, 425
Williams, A.G., Gull, S.F., 1985, Nat, 313, 34
Wilson, A.S., Young, A.J., Shopbell, P.L., 2000, ApJ, 544, L27
Wilson, A.S., Young, A.J., Shopbell, P.L., 2001, ApJ, 547, 740