A multiband study of Hercules A. II. Multifrequency VLA imaging

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ABSTRACT
We have mapped the powerful radio galaxy Hercules A at six frequencies spanning 1295 to 8440 MHz using the VLA in all four configurations. Here we discuss the structure revealed in total intensity, spectral index, polarization, and projected magnetic field.

Our observations clearly reveal the relation between the bright jets, prominent rings, bulbous outer lobes and faint bridge that make up the radio source. The jets and rings form a coherent structure with a dramatically flatter spectrum than the surrounding lobes and bridge, strongly suggesting that they represent a recently renewed outburst from the active nucleus. The spectrum of the lobes is also steeper than in typical radio sources, and steepens further towards the centre. The compact core is optically thin and also has a remarkably steep spectrum ($\alpha \simeq -1.2$). There is some evidence that the old lobe material has been swept up and compressed ahead of the new outburst. We interpret the dramatic asymmetry in the bright structure, and more subtle differences between diffuse lobe structures, in terms of relativistic beaming combined with front-to-back light-travel delays which mean that we view the two lobes at different stages of the outburst.

After correcting for Faraday rotation the projected magnetic field closely follows the edge of the lobes, the jets, and the rings; the field pattern in the two lobes is broadly similar. We confirm a strong asymmetry in depolarization and Faraday rotation, with the jet side the less depolarized and the flatter spectrum, consistent with general correlations between these asymmetries. The spectral index asymmetry is clearly present in the ‘old’ lobe material and so, at least in this case, is not due to beaming; but it can be understood in terms of the light-travel delay.

Key words: galaxies: active; galaxies: individual: Hercules A; galaxies: jets; radio continuum: galaxies; methods: data analysis; techniques: image processing.

1 INTRODUCTION
Hercules A, is the fourth brightest DRAGN1 in the sky at low frequencies. It is identified with the central cD galaxy of a cluster at $z = 0.154$, whose X-ray emission was studied by Gizani & Leahy (2002, hereafter Paper I). The angular size and width is $194 \times 70$ arcsec. For $H_0 = 65\,\text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1}$ and $q_0 = 0$, which we assume throughout, $1\,\text{arcsec}$ corresponds to $2.8\,\text{kpc}$, giving a linear size and width of 540 and $\simeq 200$ kpc. The total radio luminosity is $\sim 3.8 \times 10^{37}$ W in the band 10 MHz to 100 GHz.

The radio jets and the galaxy major axis are aligned very well, with position angles of 100° and $\sim 110°$ respectively. This alignment suggests that the galaxy is prolate in shape. West (1994) has cited this alignment as evidence for his model of the formation of cD galaxies and powerful radio sources through highly anisotropic mergers.

Optical observations with the HST (Baum et al. 1996) through a broad band red filter discovered kpc scale rings of obscuration, aligned near the radio axis with a slight offset from the galaxy nucleus. The rings are $\approx 2$ arcsec in diameter and the offset is $\simeq 1.5$ arcsec along the radio axis. The host cD galaxy has a fainter optical companion located $\simeq 4$ arcsec to the northwest. It is a typical faint elliptical; as such its central surface brightness is actually much higher than that of the cD.

The peculiar radio structure of Her A was first re-
revealed by Dreher & Feigelson (1984, hereafter DF84), using the VLA at up to 0.5 arcsec resolution. It is an exception to Fanaroff & Riley’s (1974) rule that DRAGNs with $P_{178\,\text{MHz}} > 1.5 \times 10^{28}\,\text{W Hz}^{-1}\,\text{sr}^{-1}$ show ‘classical double’ (FR II) structure. Her A has no compact hotspots, instead showing an unusual jet-dominated morphology, with two jets which are quite different in appearance. The western jet leads to a unique sequence of ‘rings’ which dominate the western lobe. The eastern jet is much brighter; indeed it has the highest flux density of any jet found so far, and contributes around 40 per cent of the total luminosity at 1.4 GHz. Even allowing for the dependence of the FR division on host galaxy magnitude, Her A remains an extreme outlier, lying 30 times above the best fit transition line in the radio/optical luminosity diagram of Leslie & Owen (1996).

In fact the radio structure of Her A is not typical of FR I DRAGNs either; in particular, its jets are well-collimated and knotty, more typical of the ‘strong-flavour’ jets in FR IIs than the ‘weak-flavour’ jets in FR Is (c.f. Bridle 1992). For these reasons, Her A is often classified as an intermediate case: FR I/II.

A wide variety of models, both kinematic (Mason, Morrison & Sadun 1988) and dynamic (Meier, Sadun & Lind 1991; Saxton, Bicknell & Sutherland 2002) have been proposed to explain the formation of the jets and rings of Her A. Some (e.g. Morrison & Sadun 1996; Sadun & Morrison 2002) are quite alien to the MHD-based twin-jet models normally applied to DRAGNs, and as yet there is no consensus picture.

S. T. Garrington and G. Holmes (unpublished) have found a strong depolarization asymmetry in Her A, using low-resolution VLA data. Because of its high flux density, Her A is a perfect target to study this effect at high resolution. Accordingly, in this paper we present new, deep, VLA images in the 8-, 5- and 1.4-GHz bands. The detailed structure revealed in total intensity, spectral index and projected magnetic field casts new light on the unusual morphology. Analysis of the Faraday rotation and depolarization is deferred to Gizani, Leahy & Garrington (in preparation; hereafter Paper III), where it will be assessed in the context of the thermal gas distribution studied in Paper I.

The rest of this paper is organized as follows. Sections 2 & 3 describe our observations, data reduction and analysis. Results are presented in Section 4 where we present a detailed nomenclature for the complex radio structure. Our discussion begins with an analysis of the global depolarization and spectral index asymmetries (Section 5.1), followed by a discussion of the geometric relation between radio-emitting and X-ray emitting plasma in the cluster core region (Section 5.2), and of the collimation of the jets (Section 5.3). Section 5.4 considers what light is shed on the speed of the jets by the (lack of) symmetry between the jets in the two lobes. In Section 5.5 we propose that the peculiar features of Her A can be understood if the jets have recently restarted. The implications of this idea for the interpretation of the bright eastern jet and the rings are discussed in Sections 5.6 & 5.7. We summarise our conclusions in Section 6.

2 OBSERVATIONS

We have used the NRAO VLA, in the continuum mode with full polarimetric imaging, to carry out our multi-band, multi-configuration observations in the 8- and 1.4-GHz bands. Table 1 gives the observational details. The pointing centre is about 5 arcsec south of the radio core, and was chosen to match earlier observations at 5 GHz which we retrieved from the VLA archive and have reprocessed. These include some data published by DF84, together with unpublished follow-up runs. In particular DF84 used an A-configuration run with 50 MHz bandwidth and a pointing centre at the peak of the eastern jet, which leads to appreciable bandwidth smearing at the core and in the western lobe. We use a later run with $2 \times 6.25$ MHz bandwidth which used our common pointing centre. This gives negligible smearing and allows a straightforward primary beam correction (see below), although it has only half the sensitivity of the earlier run. Calibrated 5-GHz D-configuration snapshot data was kindly provided by Dr. S. Garrington.

Our new observations in A and B configurations were full tracks, in order to obtain adequate $uv$-coverage to produce an accurate image of the complex structure of Her A and to provide enough sensitivity at full resolution. Approximately 70 per cent of the time was spent on the target source, the remainder on calibrators and on driving.

We used 3C 286 as the primary flux density and polarization angle calibrator, and B1648+015 as the phase calibrator. Because the source filled much of the primary beam at 8 GHz, in B, C, and D configurations we calibrated the antenna pointing each hour using B1648+015. We also pointed up on 3C 286 before each flux calibration scan.

For the 1.4-GHz band the time was split between two different pairs of frequencies across the range 1295 to 1665 MHz, giving just over 3 hours per IF setting in A configuration. The frequencies used are listed in Table 1.

Because of the large size of Her A and in order to avoid bandwidth depolarization and radio-frequency interference (RFI), we chose the narrow bandwidths of 6.25 and 12.5 MHz for the 1.4-GHz band. At 8 GHz we have made use of the full 50 MHz bandwidth and average the two IFs together as there is no compact structure there, this has little effect on the images. In any case our main goal was to match the somewhat lower resolution of the 1.4-GHz data.

In B configuration the time was split 6:3 between the 8- and 1.4-GHz bands respectively, because the 1.4-GHz observations were distributed to fill intermediate spacings. In C-configuration only about 10 min was spent at each 1.4-GHz IF setting.

The observations went almost as planned. Some of the 1.4-GHz data were affected by interference, and data were occasionally lost for other reasons including lightning strikes in the A configuration.

3 DATA REDUCTION AND ANALYSIS

Data sets from each configuration were separately edited, calibrated and imaged in the standard NRAO Astronomical Image Processing System (AIPS) software package.
3.1 Mapping

After initial external phase and amplitude calibration, the data were iteratively mapped and self-calibrated in the usual way (Pearson & Readhead 1984; Schwab 1984). Her A is a very strong source, so the self-calibration mechanism improved dramatically the dynamic range of most maps. At our highest resolution, at 8 and 5 GHz, little flux is detected on the longest baselines and to improve the signal to noise ratio in these cases we averaged right and left-hand polarizations, and used averaging times of up to 15 min for amplitude corrections.

In early cycles the $uv$-range was restricted so that spacings underestimating the observed visibilities were excluded. Two to four cycles of phase self-calibration were carried out and that initiated a new one with both amplitude and phase solutions (two to four loops again). Each loop of deconvolving and self-calibrating was carried out only if the noise was reduced significantly.

The structure of Her A, with bright compact (but resolved) features embedded in diffuse emission, is difficult to image accurately, as calibration errors and deconvolution artefacts associated with the bright features are superimposed on the genuine diffuse emission. Furthermore, its position near the equator means that the $uv$ tracks degenerate to nearly east-west strips, causing sidelobes to build up in the north-south direction. During cleaning, windows were used containing only emission from Her A as much as possible, restricting the area to be cleaned only to the immediate vicinity of the source. A straightforward Clark CLEAN algorithm (Clark 1980) proved adequate down to a level of $\sim 1$ mJy at 1.4 GHz, but after this point tended to develop strong CLEAN stripes. Some improvement was obtained by using a 'Prussian Hat' clean (Cornwell 1984), which encourages smoothness in the clean component model by adding a $\delta$-function to the centre of the beam.

Since CLEAN stripes result from gaps in the $uv$-coverage, for deeper imaging at 1.4 GHz we combined all the configurations and also the data at 1365 MHz and 1435 MHz. We chose these data (rather than those at 1665 and/or 1295 MHz because the combination gives excellent $uv$-coverage on the longer baselines, and also because the data suffered less from RFI and residual calibration errors. Further self-calibration gave an A+B+C 1365, 1435 MHz map with off-source noise $\sim 0.1$ mJy beam$^{-1}$, close to the theoretical noise level. This provided a set of clean components which were used to self-calibrate separately the 1.4-GHz data at each frequency.

To minimize striping in the final images the SDI method (Steer, Dewdney & Ito 1984) was used for the deconvolution. We chose a resolution of 1.4 arcsec for the final images. Because of the range in frequency in the 1.4-GHz band, this is smaller than the best-fit beam at 1295 MHz (by about 14 per cent), and is lower than the full resolution at 1665 MHz, allowing us to use robust weighting (Briggs, Schwab & Stansel 1999) at that frequency. The other 1.4-GHz band frequencies were uniformly weighted.

In the same way as for the total intensity Stokes $I$ map, $Q$ and $U$ `dirty’ maps were created and cleaned. Table 2 shows ‘cleaned’ integrated flux, as well as integrated polarized intensity $p$ and off-source r.m.s. values of the final maps. The $Q$ and $U$ maps are essentially noise-limited, while residual calibration errors increase the fluctuations on the $I$ maps by factors of less than 2. To maximize sensitivity in $I$, we also made a weighted average of the 4 single-frequency maps in the 1.4-GHz band, giving $\sigma = 0.095$ mJy beam$^{-1}$ at a nominal frequency of 1440 MHz.

The two IFs at 8465 and 8415 MHz were combined and their mean value (8440 MHz) is quoted in the table. Because the 8415-MHz data were affected by interference in D configuration, we initially self-calibrated the C+D configuration data at just 8465 MHz, and used the resulting model to self-calibrate the combined-frequency data. These were then combined with the B-configuration data to give uniformly-weighted maps at a full resolution of 0.74 arcsec. Initial maps from this process were used to self-calibrate the B-configuration data only (as B-configuration phase artefacts initially prevent the recovery of the faint, large-scale emission which dominates the shorter baselines). As the model improved the CD data were self-calibrated as well, initially with long time constants just to align positions and amplitudes between the datasets, after which all data was processed together. The fully self-calibrated data were remapped with robust weighting and a 150 k$\lambda$ taper to give maps at the standard 1.4-arcsec resolution.

In the archival 5-GHz data, different centre frequencies were used in each configuration (see Table 1), but all data were collected within a 100 MHz band. The observed Faraday rotation is too low to cause differential rotation across the band, so we averaged all the data, giving a weighted centre frequency of 5 GHz. The old data were affected by numerous phase glitches. Affected data were flagged, and the

### Table 1. VLA Observations of Her A.

| RA         | DEC         | Config | Frequency  | Bandwidth | Time  | Dates        |
|------------|-------------|--------|------------|-----------|-------|--------------|
| 16$^h$48$^m$40$^s$.000 | +05$^h$04$^m$30$^s$.0 | C      | 4885.1     | 50        | 7.5   | 1982-jan-10  |
| 16$^h$48$^m$40$^s$.000 | +05$^h$04$^m$30$^s$.0 | A      | 4883.2     | 50        | 7.5   | 1983-oct-24  |
| 16$^h$48$^m$40$^s$.000 | +05$^h$04$^m$30$^s$.0 | B      | 4872.6     | 25        | 7     | 1984-feb-19  |
| 16$^h$48$^m$40$^s$.010 | +05$^h$04$^m$28$^s$.0 | D      | 4885.1     | 50        | 0.16  | 1989-nov-16  |
| 16$^h$48$^m$40$^s$.000 | +05$^h$04$^m$30$^s$.0 | A      | L          | 50        | 9     | 1995-jul-22  |
| 16$^h$48$^m$40$^s$.000 | +05$^h$04$^m$30$^s$.0 | B      | X, L       | 50, 12.5  | 9     | 1995-nov-12  |
| 16$^h$48$^m$40$^s$.000 | +05$^h$04$^m$30$^s$.0 | C      | X, L       | 50, 12.5  | 4     | 1996-feb-23  |
| 16$^h$48$^m$40$^s$.000 | +05$^h$04$^m$30$^s$.0 | D      | X          | 50        | 1.5   | 1996-aug-14  |

Frequencies for the new observations: 8414.9/8464.9 MHz (X-band); 1664.9/1435.1 MHz and 1364.9/1295.0 MHz (L-band).
calibration/mapping cycle continued. As at 8440 MHz, we initially mapped the C+D data, then combined it with the B-configuration data. Super-uniform weighting (Briggs et al. 1991) was used to prevent the short-baseline data dominating the images; the combined BCD data then gave a best-fit resolution close to our standard 1.4 arcsec, and the final SDI clean image was restored with this beam.

Correlator offsets in B-configuration produced a −0.8 mJy artefact at the phase centre, just south of the core, and associated uncleannable ‘sidelobes’ to the north and south; fortunately these do not overlap any detectable emission at 5 GHz.

The large images needed for the full A-configuration resolution at 5 GHz made it more efficient to use the CLEAN+MEM method for imaging and self-calibration described by Leahy & Perley (1991). A particular problem for Her A is that the inner jets are compact, so best dealt with by CLEAN, but also very faint, so that to remove them one would have to clean out all the flux in the source, which is what we are trying to avoid by using MEM. Our (partially-effective) solution was to CLEAN a map from which the large-scale structure had been filtered out by excluding the shortest baselines; tight boxes were needed to avoid CLEAN-ing the resulting negative sidelobes. The resulting CLEAN components were then subtracted from the visibility data, which was then re-mapped using all baselines and deconvolved using VTESS.

The Maximum Entropy Method requires a ‘default image’, usually chosen to be a constant brightness at each pixel. This choice causes flux to spread into the off-source regions, giving large systematic errors on short baselines. These errors can be suppressed by using a more realistic default. We found it essential to do so to get a model that was usable for self-calibration. Specifically, we used an SDI-cleaned image made from the 5-GHz BCD data.

The signal-to-noise is low on the longest baselines, and so in A-configuration we only self-calibrated the amplitudes of the inner four antennas on each arm. The typical corrections found were < 2 per cent, and errors of this magnitude on the outer antennas will be negligible, as they only contribute to the longest baselines. A tapered 4-configuration image at 1.4 arcsec resolution was made but not used as it was slightly worse than the BCD image, probably because of residual amplitude errors in A-configuration.

Because they were processed separately, the 8- and 5-GHz images had to be accurately aligned with the 1.4-GHz A+B+C image, which was done using the compact core.

The final total intensity maps were also corrected for the primary beam attenuation of the VLA’s 25-metre antennas (Hjellming 1992), using the AIPS task pbcor. At 1.4 GHz these corrections are negligible and were omitted. At 8 and 5 GHz the corrections at the outer edge of the source were 27 and 6.5 per cent respectively.

Although all our observations were calibrated against 3C286, this was not strictly necessary as the integrated flux density of Her A is known from direct comparison to the absolute standards Cyg A and Cas A (Baars et al. 1977; Ott et al. 1994). We measured the total flux from our primary beam corrected images, within a rectangular box just enclosing the source. Our values agreed with the Ott et al. spectral model to better than 1 per cent, except at 1435 and 1665 MHz, where the VLA fluxes are 1.6 and 3.9 per cent high, respectively. We have rescaled the images at these frequencies to agree with the Ott et al. values.

### 3.2 Error Analysis

Until this point we have used the standard AIPS analysis to reduce our data. Specialized software, described by Johnson, Leahy & Garrington (1995) was applied to the images to estimate errors and propagate them into the final images of depolarization DP, rotation measurement RM, spectral index α, and intrinsic magnetic field position angles. For the error estimates we followed the prescription of Johnson et al. for VLA images with adequate sampling; that is, in quadrature with the off-source noise n we added a fractional error of 0.01S and an empirical term 0.15√nS where S is the signal, and a term proportional to the image gradient corresponding to r.m.s. misplacement of flux by 0.033 times the beamwidth.

### 3.3 Spectral index analysis

We adopt the AIPS sign convention for spectral index α, i.e. flux density $S_\nu \propto \nu^\alpha$.

We calculated the spectral index at each pixel at 1.4 arcsec resolution between 1.3 and 4.8 GHz, and between 4.8 and 8.4 GHz. In the former case we used a weighted least squares straight line fit in the log–log plane to the 5-frequency data.

| $\lambda$ (cm) | $\nu$ (MHz) | FWHM (arcsec) | Dynamic Range | $\sigma_I$ (mJy beam$^{-1}$) | $\sigma_{Q,U}$ (mJy beam$^{-1}$) | $\sum I$ (Jy) | $\sum Q$ (Jy) | $\sum U$ (Jy) | $\sum p$ (Jy) |
|---|---|---|---|---|---|---|---|---|---|
| 3.6 | 8440 | 1.4 | 3200:1 | 0.023 | 0.013 | 5.968 | 0.416 | 0.37 | 1.49 |
| 6 | 4848 | 1.4 | 4100:1 | 0.029 | 0.026 | 12.148 | 0.718 | 0.531 | 2.76 |
| 18 | 1665 | 1.4 | 2100:1 | 0.132 | 0.073 | 41.158 | −0.220 | 0.827 | 5.12 |
| 21 | 1435 | 1.4 | 2200:1 | 0.138 | 0.083 | 46.909 | −0.236 | 0.558 | 5.05 |
| 22 | 1365 | 1.4 | 2700:1 | 0.121 | 0.085 | 48.658 | −0.237 | 0.542 | 5.09 |
| 23 | 1295 | 1.4 | 2200:1 | 0.154 | 0.096 | 51.111 | 0.068 | 0.502 | 5.01 |

2 Of course, the default image must represent the same emission as the dirty map being deconvolved; therefore in the CLEAN+MEM process, the CLEAN components must be subtracted from the data before the default image is made.
We required a signal-to-noise ratio of $\geq 3:1$ at all frequencies to include data at a given pixel in the fit (in practice the limiting factor is the 4.8-GHz image).

Her A contains several regions where components with substantially different spectral indices are superimposed on the same line of sight, so directly-evaluated spectral indices give just a weighted average. To get estimates for each component we used the so-called 'spectral tomography' technique of Katz-Stone & Rudnick (1997) and Katz-Stone & Rudnick (1997). In this method, images at two frequencies are scaled and differenced so that material with a particular spectral index is cancelled. The process is repeated for a range of assumed $\alpha$ values. By comparing the sequence of images produced (e.g. as a 'movie' on a TV display), one can estimate the spectral index at which a particular feature vanishes, in the sense of having negligible contrast with surrounding material.

### 3.4 Polarization Analysis

In the presence of noise, the polarized intensity $p = \sqrt{Q^2 + U^2}$ suffers a slight positive Ricean bias on average. Therefore $p$ has been corrected for Ricean bias (Simmons & Stewart 1983; Leahy & Fernini 1989) by subtracting the error at each pixel in quadrature. $p$ was set to zero where the observed polarized intensity was less than the error. From the corrected $p$ images we calculated the fractional polarization $m = p/I$.

We have analysed the multi-wavelength data to derive the Faraday Rotation measure and projected magnetic field ($B$-field) direction, using the algorithm described by Johnson et al (1993). In this paper we only present the results for the $B$-field, and so defer full discussion to Paper III. However, we note that in the western lobe, depolarization is so strong that the $\chi^2$-law breaks down at 1.7 GHz, so the RM must be determined between 5 and 8 GHz only. This leads to ambiguities due to the unknown number of half-turns, $n_\pi$, between the two wavelengths. We have inserted these by hand, guided by continuity in the RM and $B$-field maps, together with the depolarization maps which reveal genuine abrupt changes in RM.

### 3.5 Measuring the collimation of the jets

We tracked the width of the jets by measuring $\theta_j$, the FWHM of 1-D Gaussian fits to slices oriented at PA 10°1, approximately perpendicular to the inner jets. The jets curve slightly, so our slices are not always perfectly perpendicular, but the misalignment is no more than 12°, giving a negligible over-estimate of the widths ($\lesssim 2$ per cent).

We used our full-resolution maps at both 5 and 8 GHz; in addition, as the signal-to-noise is low in the inner jets at 5 GHz, we smoothed the 5-GHz image to give an elliptical beam with FWHM $1.08 \times 0.36$ arcsec, with its major axis along the jet. Between 35 arcsec east of the core and 16 arcsec west, we fitted each profile with a single Gaussian and a linear baseline, using XGAUSS. Further from the core we had to model underlying diffuse emission with a second broad Gaussian, and this was done interactively using SLFIT. In all cases the FWHM beam width (perpendicular to the jet) was subtracted in quadrature, to give an estimate of the deconvolved jet width.

As the jet profile is generally not Gaussian, $\theta_j$ is just an empirical definition of 'width'. Note that the fitting behaves somewhat differently in the case where the jet is well resolved, when the fit is controlled by real residuals from Gaussian shape, and in the case where the jet is barely resolved, when the profile is nearly Gaussian and our fit effectively measures the second moment of the brightness distribution. Comparison of the results from the 5- and 8-GHz maps demonstrates this point: where the jet is well resolved or poorly resolved in both maps, agreement is excellent; but between 8 and 20 arcsec east of the core, the jet is well resolved at 5 GHz and not at 8 GHz, and the results are systematically different.

### 4 RESULTS

#### 4.1 Total Intensity

**4.1.1 Overview**

Fig. 1 presents contours of the total intensity of Her A at 1440 MHz. The source extends overall about 194 arcsec ($\simeq 540$ kpc), and its maximum width is $\simeq 70$ arcsec ($\simeq 200$ kpc). The inner jets, although prominent with logarithmic contouring, are actually quite faint (c.f. Fig. 2 below), but the eastern jet brightens dramatically in the outer lobe. The two lobes are almost symmetric in outline: the western extends about 97 arcsec (270 kpc) and the eastern $\simeq 96$ arcsec (267 kpc). The radio emission is generally bounded by a sharply-defined perimeter at which the intensity drops by an order of magnitude or more within one beamwidth. Exceptions to this are north and south of the bright parts of the eastern jet, at $10^4.48^m.44^s$ to $41^h.5$, and the very faint bridge emission just west of the core. The lack of definition in the former region may be due to residual sidelobes from the jet; the deepest published map, that of Kassim et al (1994) at 330 MHz, shows that we are missing little or no emission there; the western bridge is slightly wider in the 330 MHz image than in ours, with a full width of $\geq 40$ arcsec ($\simeq 110$ kpc), about the same as that east of the core.

Although not obvious from our contour map, the southwestern edge of the western lobe is edge-brightened, consisting of long thin filaments or possibly a single one. There are also signs of edge-brightening in the eastern lobe but this may be confused by residual artefacts parallel to the jet.

DF84 identified three distinct kinds of structure in Her A, all of which are visible in Fig. 1 and sketched in Fig. 2. The source is dominated by the high-brightness features, namely the jet on the eastern side, and on the west the narrow counter-jet, followed by the famous series of 'rings'. The surrounding lobe emission can be divided into two components: the relatively bright outer part, hereafter the 'bulb', and the much fainter 'bridges', which contain the long thin filaments noted earlier. Although the two bridges meet at the centre, there is a noticeable brightness minimum between them and the eastern bridge is several times brighter than the western, so they do seem to be two distinct structures.
4.1.2 The Bulbs

Fig. 3 shows a grey-scale of the full-resolution image at 8440 MHz, with the high-brightness features burnt out to reveal the structure of the bulbs. At this resolution and frequency the bridges are too faint to detect.

The two bulbs are notably different. The eastern is brighter and nearly circular, while the western is more oval. Both show arc-like filamentary structure but they differ in character. The filaments in the east are thicker and clumpier, those in the west are more wispy. As noted by DF84, the outer edge of the western lobe, though arc-like, is different in character from the bright rings; it seems to contain several overlapping filaments and is continuous with the diffuse lobe emission rather than the high-brightness features.

4.1.3 The jets and rings

The jets are first detectable \( \approx 2.9 \) and \( 3.8 \) arcsec east and west of the core respectively. The initial 4 arcsec of each jet, best seen in Fig. 3, is extremely faint. Fig. 4 shows the inner jets in the full resolution 4848 MHz image, while Figs 5 and 6 show the bright features in the eastern and western lobes respectively. We have labelled knots in the western and eastern jets as W1–W4 and E1–E13.

At our highest resolution the eastern jet is moderately to well resolved. The centre of the brightness profile is usually rather flat-topped although occasionally it can be quite sharply peaked; the implication is that in three dimensions,
Figure 3. Total intensity distribution of Her A at 8440 MHz. The beam size (0.74 arcsec) is shown in the lower left-hand corner. The grey-scale runs from -0.033 to 1 mJy.
Figure 4. The inner jets at 4848 MHz with 0.36 arcsec resolution. For ease of comparison the maps have been rotated by $-100^\circ1$ (East; top), and $-10^\circ1$ (West; bottom). Coordinates give distances from the core. Contours are at ($-1, 1, 2, 3, \ldots, 16, 24, \ldots$) $\times$ 0.13 mJy beam$^{-1}$.

Figure 5. The outer eastern jet at 4848 MHz with 0.36 arcsec resolution. The grey-scale runs from $-0.13$ to 10 mJy beam$^{-1}$. 
the emission is low along the jet axis and the jet has more
emission near the surface (c.f. Owen et al. [1989]). Beyond
knot E11 the jet contains (or may be composed of) a num-
ber of filaments running roughly parallel to the overall axis,
one of which curls around at the end of knot E13.

At first sight the edges of the jet look well defined, but
coloration between the jet brightness profiles and that of a
uniformly-filled cylinder convolved with a Gaussian beam
showed that the edges of the jets are less sharp, suggesting
that there is a boundary layer in which the intensity declines
slowly to zero.

Fig. 4 plots the FWHM $\theta J$ from Gaussian fits to slices
across the jet against $l$, the distance from the core. We
measure the western jet up to knot E8, after which it is too
disrupted to allow meaningful measurement of collimation.
Roughly, the full width may be $1.5\times2$ times $\theta J$. For com-
parison, Gaussian fits to a top-hat and filled cylinder of width
$w$ give $w = 1.14 \theta J$ and $1.75 \theta J$, respectively.

Structure at intermediate brightness is shown in Fig. 5
which gives details from the 8440 MHz image with lower
contrast than Fig. 4. The western jet is followed by the se-
quence of rim-brightened features which DF84 christened
‘rings’. We retain this word as a label for these features,
but the reader is requested to forget the literal meaning, as
it is probably quite misleading. In our usage, ‘ring’ means
the whole feature which in several cases contains significant
internal structure as well as a rim; in some cases the rim-
brightening is not very obvious.

We identify five of these ring features, which we have
labelled E through A, with their rough outer boundaries
sketched in Fig. 5. In most cases there is a bright ‘head’ to
the ring on the side more distant from the core, which we
label Ah, Ch, Dh, and Eh. Eh is itself a ‘mini-ring’, but we
consider this part of ring E because their outer boundaries
are continuous. Although several authors have claimed that
the ring features are genuinely circular or elliptical, in fact
ring C is the only one whose bright rim extends (nearly)
all the way round the structure. It is tempting to see ring B as
a rough elliptical arc (Ah). This is set back slightly from the
outer edge of A along the sections trailing towards the east,
giving an apparent double edge (see also Fig. 5).

Our terminology follows DF84: the reader should note
that the five rings described by Mason et al. [1988] and
Morrison & Sadun [1990] differ from ours: their first corre-
sponds to Eh rather than the whole of E, they do not identify
D, their third and fourth rings are fitted to the smoothly-
curved south-west and western segments of our B and A,
ignoring the rest of these features, and their fifth ring is the
outer edge of the lobe.

On the east side the centre-brightened jet co-exists with
counter-jet appears to vanish at W4, the main jet brightens
dramatically beyond E4 into the complex E5–E6 region, in
which the jet curves to the south by about $12^\circ$. Beyond E6
the jet narrows and fades until the highly-collimated part
terminates at knot E8 which is elongated perpendicular to
the jet. The faint ring J connects directly to E8. Beyond E8
the jet flares in width and no clear ridge-line can be followed
through the complex knots E9–E10. The structure of E8 and
ring J is repeated in E11 and ring I. The southern rim of
I joins the jet downstream of E11, so may not be part of a
coherent ‘ring’. Beyond E11 the jet is surrounded by ‘ring H’,
which is complex and may represent more than one ring-
type feature. In this segment the jet appears to re-collimate,
but this is most likely an illusion because somewhere in this
region it bifurcates into two strands which terminate in the
blunt knots E12 and E13 respectively. Ring G, surrounding
E13, seems to be embedded in the final section of the jet, the
broad fan of material F; in particular, the edge of F clearly
continues to the north of ring G in Fig. 5.

4.1.4 The core

The core is unresolved in all our images, with an upper
limit of 0.07 arcsec from Gaussian fitting to the full resolu-
tion 4848 MHz image. Its best-fit position, from the better-
calibrated 8440 MHz data, is $16^\mathrm{h}48^\mathrm{m}39.960, 05^\circ35.3718$. Fluxes at each frequency are given in Table 3.

| Frequency | Flux Density |
|-----------|-------------|
| 8440 MHz  | 4.52 mJy    |
| 4848 MHz  | 9.99 mJy    |
| 1665 MHz  | 32.7 mJy    |
| 1435 MHz  | 39.2 mJy    |
| 1365 MHz  | 41.5 mJy    |
| 1295 MHz  | 43.0 mJy    |

There is no sign of variability. In the four months be-
tween the A and B configuration observations at 4848 MHz,
the core flux changed by $<0.1$ mJy. Also in the three
months between the B and C configuration observations at
8440 MHz the core varied by less than 3%.

From the fact that it is optically thin down to 1295
MHz, we infer that the brightness temperature is less than
$10^{12}$ K. This gives a lower limit to the core diameter of 0.2
mas. Observationally, maximum brightness temperatures
are usually around $10^{11}$ K (Readhead [1994]), suggesting a
size $\lesssim0.7$ mas. In fact new EVN and MERLIN observations
of the core region (Gizani et al. [2002] and in preparation) re-
vealed emission elongated in the NW–SE direction on 10–20
mas scales, substantially misaligned with the kpc-scale jets.

4.2 Spectral Index

Fig. 4 shows the image of $\alpha_{4.8}$. The image at $\alpha_{4.8}$ is qualita-
tively similar, except that the bridge is too faint at 8 GHz
for its spectral index to be measured.

The spectral index image dramatically highlights the
distinction between the bright and diffuse structures that we
made in the previous section. The former have much flatter
spectra with a particularly sharp spectral boundary in the
western lobe. In the east the edge of the high-brightness

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3 This provides a reference model with a sharp outer boundary.

The crucial region near the edge of the jet is not affected by the
possible presence or absence of a dim region along the axis.
features is also a sharp edge in spectral index, except for the fan component (F) at the end of the jet, in which the spectrum appears to steepen smoothly into the lobe. There is also a rather abrupt separation between bulb and bridge on the eastern side (most of the western bridge is too faint to measure $\alpha$). In particular, patches with $\alpha \approx -2$ around the southern edge of the eastern lobe are part of the bridge, c.f. Fig. 6. For brevity we will speak of the flat, steep, and very steep spectrum components, as there is no truly flat spectrum structure in Her A.

Table 4 shows the average value of the spectral index in various regions of the source. As can be seen also from Fig. 6, the spectra of all parts of Her A are unusually steep. Even more interesting is that the core is not only optically thin, but has a steeper spectrum than the bright jet knots. The spectral index of the jets and rings is contaminated by the lobe material superposed along the line of sight, and so the apparent spectral index of the high-brightness features is steeper than the true value. The spectral tomography gives a better idea of the true values. The results for various features are listed in Table 5 in some cases (e.g. ring E) there is significant internal variation in $\alpha$, but for simplicity we just list typical values.

The tomography results show that the flattest-spectrum regions, with $\alpha_{1.4}^{4.8} \approx -0.6$ are the western jet and knot E4 in the eastern jet. The rest of the eastern jet has $\alpha_{1.4}^{4.8} \approx -0.75$, steepening to $-0.8$ beyond E8, only a little steeper than typical for bright jets ($\approx -0.6$), and close to typical values for hotspots, $\approx -0.75$. Rings A, C, D and I have similar spectral indices to the eastern jets, while rings B, E, F, and H are a little steeper at $\alpha_{1.4}^{4.8} \approx -0.85$. The bright western arc Ah has the steepest spectrum of any feature in the jet/ring system. It is situated on the boundary between the flat spectrum material in
A multiband study of Hercules A. II. Multifrequency VLA imaging

Figure 8. Close-ups of the high-brightness structure at 8440 MHz. Grey-scale runs from \(-0.033\) to \(4\) mJy beam\(^{-1}\) and contours are at 4, 5, 6, 8, 10, 12, 16, 20, 24 mJy beam\(^{-1}\). Top: eastern jet and rings. Bottom: western jet and rings. The angular scale is the same in the two plots. We have labelled the ring features and jet knots discussed in the text; for clearer identification of some of the eastern knots, see Fig. 5.

Fig. 10 shows the spectral tomography image for \(\alpha = -0.9\); that is, with the maps scaled so that emission with this spectral index is exactly subtracted out. Here essentially all the jet and ring components have been over-subtracted. Features in this image may represent a combination of intensity and spectral index structure. Comparison with Fig. 3 shows that most of the filamentary features in the lobes visible in Fig. 10 are intensity features, with the exception of the brightest. This is not the arc Ah, which is almost exactly subtracted here, but a filament of steep-spectrum emission just beyond it. With \(\alpha \approx -1.5\), its spectrum is significantly steeper than most of the emission in the western bulb. The emission remaining in Fig. 10 seems to be organised around the flat spectrum material. In the western lobe this takes the form of filaments arching around the ABC complex. In the eastern lobe the organisation is less coherent, but the brightest parts of the steep-spectrum emission are all close to the jet.

As expected for aged synchrotron emission, the spectra of all components (except the faint knot Dh) steepen at high frequency. The steepening is mild in the jets and the compact heads of the western rings, typically \(\Delta \alpha \approx 0.12\). All the rings show more steepening than the jets, typically \(\Delta \alpha \approx 0.23\). Steepening is clearest in the bulbs, where the
Figure 9. Grey-scale of the spectral index map between 1.3 and 4.8 GHz at 1.4 arcsec resolution. The grey-scale runs from $-2.3 \leq \alpha \leq -0.6$. The flattest value is $\alpha = -0.61$. Only a few pixels (with large errors) have $\alpha < -2.2$. Contours are of the stacked 1.4 GHz map, separated by factors of 3 starting at 0.5 mJy beam$^{-1}$. The mean error on displayed points is 0.07, with a full range from 0.01 to 0.3.

Table 5. Spectral indices measured from spectral tomography

| Component | $\alpha$(1.3, 4.8) | $\alpha$(4.8, 8.4) |
|-----------|-------------------|-------------------|
| W1−W2     | $-0.59 \pm 0.02$  | $-0.72 \pm 0.03$  |
| W4        | $-0.60 \pm 0.05$  | $-0.76 \pm 0.04$  |
| E         | $-0.85 \pm 0.03$  | $-1.04 \pm 0.05$  |
| Eh        | $-0.85 \pm 0.03$  | $-0.98 \pm 0.03$  |
| D         | $-0.75 \pm 0.05$  | $-0.98 \pm 0.03$  |
| Dh        | $-0.75 \pm 0.03$  | $-0.70 \pm 0.03$  |
| C         | $-0.77 \pm 0.03$  | $-1.06 \pm 0.04$  |
| Ch        | $-0.74 \pm 0.02$  | $-0.94 \pm 0.03$  |
| B         | $-0.82 \pm 0.03$  | $-1.04 \pm 0.03$  |
| A         | $-0.75 \pm 0.05$  | $-1.04 \pm 0.03$  |
| Ah (Arc)  | $-0.90 \pm 0.05$  | $-1.14 \pm 0.04$  |
| E1−E3     | $-0.76 \pm 0.02$  | $-0.90 \pm 0.03$  |
| E4        | $-0.61 \pm 0.02$  | $-0.76 \pm 0.03$  |
| E5−E6     | $-0.75 \pm 0.01$  | $-0.87 \pm 0.02$  |
| E7−E8     | $-0.80 \pm 0.03$  | $-0.90 \pm 0.03$  |
| E9        | $-0.79 \pm 0.02$  | $-0.87 \pm 0.03$  |
| E10−E11   | $-0.77 \pm 0.02$  | $-0.88 \pm 0.04$  |
| E12−E13   | $-0.80 \pm 0.03$  | $-0.92 \pm 0.03$  |
| F−H       | $-0.85 \pm 0.03$  | $-1.02 \pm 0.04$  |
| I         | $-0.76 \pm 0.02$  | $-1.04 \pm 0.06$  |

Figure 10. Tomography image (see Section 5.3) for $\alpha^{4.8} = -0.9$, i.e. any feature with a flatter spectrum (including essentially all of the jet and ring components) appears negative (light). The positive feature south of the core is the phase-centre artefact in the 5-GHz image.

4.3 Fractional Polarization

The fractional polarization maps at 8440, 4848 and 1665 MHz are presented in Figs 12, 13 and 14 respectively. These maps reveal strong asymmetrical Faraday depolarization with the eastern side, containing the stronger jet, being less affected. Therefore Her A exhibits a strong Laing-Garrington effect (Laing 1988, Garrington et al 1988).

On the western side, at 8 GHz the E-vectors are mainly
Figure 12. The fractional polarization map of Her A at 8440 MHz at 1.4 arcsec resolution. Line segment orientation gives the E-vector direction and the length is proportional to the fractional polarization. Contours are from the total intensity map and are separated by a factor of two. The bar labelled ‘100%’ gives the scale for the vectors, which are only plotted within the outer contour (0.07 mJy beam$^{-1}$), and when the signal-to-noise is greater than 2.

Figure 13. Fractional polarization map at 4848 MHz. Details as for Fig. 12 except that the outer contour is at 0.14 mJy beam$^{-1}$.

orthogonal to the edges of the ring-like features and the edges of the lobes, but at 4.8 GHz they begin to become disordered especially near the centre, and the degree of polarization begins to drop. At 1.7 GHz and lower frequencies, the fractional polarization is barely detectable over most of the lobe, except that some weak polarization remains at the extreme western end of the lobe.

On the eastern side, the vectors in the bulb remain ordered around the lobe edges, and the edges of the eastern jet, down to 4.8 GHz. In the faint eastern bridge emission, the 4.8-GHz polarization is noisy, but is at least roughly orthogonal to the edges of the lobe. At 1.7 MHz and below, the lobe polarization becomes disordered and generally depolarizes, although at some isolated points the degree of polarization at least temporarily increases.

Fig. 15 presents the distribution of the fractional polarization vectors in the inner jets at 8440 MHz at the higher resolution of 0.74 arcsec.

To quantify the dramatic changes in the polarization from one end of the source to the other, Fig. 16 plots ‘strip averages’ of the polarization across the source against position along the source axis. More precisely, we divided each
lobe into concentric ring segments centred on the radio core, of width 1 arcsec and radius up to 120 arcsec. In each ring we averaged the fractional polarization $m$ at 1295, 1665, 4848 and 8440 MHz from the maps. In the plots, negative distances denote the eastern side of the source (lobe and jet) and positive ones the western side. Note that near the centre the 1295 and 1665 MHz values reflect the faint inner bridge, but this is not detected at 4848 and 8440 MHz so the inner jets dominate at these wavelengths. Thus the curves cannot be directly compared in the inner $\approx 20$ arcsec.

This plot emphasises the dramatic Laing-Garrington effect in the source, which in Paper III we interpret as primarily due to external depolarization by the magnetic field in the cluster halo, with the western lobe on the far side of the cluster core and the eastern lobe in front. Some depolarization should be caused by the optical companion (its position is denoted by the ‘arrow’ symbol in Fig. 12) and by nearby galaxies. These points will be discussed in Paper III, where we present our rotation measure and depolarization maps.

4.4 Projected Magnetic Field

Our estimate of the $B$-field map is shown in Fig. 17. The faint inner bridge is only detected at 1.4 GHz, where Faraday rotation and depolarization are large; so that even when polarized flux is detected (usually at 1665 MHz), the Faraday correction to zero wavelength is very uncertain. For most of these pixels we therefore cannot determine a reliable $B$-field. As noted in Section 3.4, we had to resolve ambiguities in rotation by hand in the western lobe. In practice we have taken $n\pi = 0$ over the outer $\sim$ third of the lobe, which seems justified given the clear alignment of the uncorrected polarization pattern with the lobe boundary at both 8 and 5 GHz (Figs 12 & 13).

The projected magnetic field closely follows the edge
of the source, the jets, and the ring-like structures in the lobes; the field pattern in the two lobes is broadly similar. The overall trend for alignment of the magnetic field with edges in the emission is very typical for DRAGNs (e.g. Leahy, Pooley & Riley 1986), although the high quality of our data reveals this particularly well.

5 DISCUSSION

5.1 Spectral index asymmetry

The fact that in powerful DRAGNs the less depolarized lobe has a flatter spectrum has been observed by Liu & Pooley (1991), Garrington et al. (1991) and Garrington & Conway (1991). There has been a debate concerning the origin of depolarization and spectral asymmetries between the two lobes of DRAGNs, especially because Pedelty et al. (1989) found that depolarization was systematically stronger on the shorter side, which suggested an intrinsic effect rather than an orientation one as advocated by Garrington & Conway (1991). Explanations have been given either in terms of asymmetric environment (Fraix-Burnet 1992), or in terms of an intrinsic asymmetry in the DRAGN, perhaps in the kinetic power of the two jets, and/or the strength of the B-field in the lobes (Alexander 1993), or by projection effects alone, provided that the lobe magnetic flux decreases as the DRAGN evolves and that the DRAGN axis is no more than 20° from the plane of the sky (Blundell & Alexander 1994). A detailed study of ten quasars by Dennett-Thorpe et al. (1997) found that the high-brightness material obeyed the Liu-Pooley relation while fainter emission followed the Pedelty et al. result. In their interpretation, Doppler beaming boosted bright flat-spectrum emission in the approaching lobe, but at fainter levels intrinsic asymmetries dominate. Her A provides an interesting test of this model.

Fig. 18 shows strip averages of the spectral index, obtained in the same way described earlier. This is less useful than for depolarization because much of the structure in α is parallel to the DRAGN axis, so one can get a clearer and more detailed idea from the spectral index map (Fig. 9). From Figs 18 (cf. also Fig. 9) we can see that:

- At the ends of the source the eastern side has a steeper spectrum than the western one. Steep indices located towards the outer borders have been observed also in Centaurus A and in FR Is in general (e.g. Compi & Romero 1997).
- Moving from the eastern ends towards the core, the lobe (and partly the jet) spectra become flatter (from ≈ 90 to 60 arcsec east from the core) with α ≈ −1.25. The western lobe, which is more depolarized, shows a steeper spectrum than the eastern lobe. We derived the same result by comparing the depolarization maps (see Paper III) with the spectral index map (Fig. 9), and also the plots of the degree of polarization versus distance (Fig. 16) with the one for the spectral index (Fig. 18).
- At ≈ 40 arcsec east from the core the spectral index starts steepening towards the core. This is because the steep spectrum areas of extended emission, which contribute to the ‘strip averages’, are becoming apparent at 1.4 arcsec resolution (see Figs 9 and 14). This trend reverses close to
Figure 17. Projected $B$-field directions at 1.4 arcsec resolution. Vector length is proportional to $m(5)$ and the contours show total intensity at 5 GHz. Contours are plotted above 0.145 mJy beam$^{-1}$ (5σ), separated by a factor of two. The $B$-vectors are at 90° (roughly) to the fractional polarization vectors.
the core, especially on the western side, because the steep-spectrum material becomes too faint for us to determine spectral indices, leaving the flat spectrum jets to dominate again.

• Moving away from the core and into the western side the spectrum becomes steep again (due to the steep spectrum extended emission); \( \approx 25 \) arcsec west from the core \( \alpha \approx -1.7 \).

• There is a local maximum of the spectral index at 60 arcsec west from the core. This is because between 25 and 80 arcsec the 'strip average' have contributions from both the inner lobes (rings) and the old lobes. The rings get wider and wider until \( \approx 60 \) arcsec (rings C & B, see Fig. 8) and this makes the average spectral index flatter. From 60 to 80 arcsec the rings narrow to nothing and so the old lobes become more and more important, cancelling out the fact that in the old lobes themselves, the spectrum steadily flattens as you move away from the core. At \( \approx 80 \) arcsec west from the core the averaged spectrum steepens because the flat spectrum region around the rings comes to an end, giving a maximum \( \alpha \approx -1.45 \). Finally the most distant edges of the source appear flatter than the ends of the eastern side as mentioned before.

The sample which Liu & Pooley (1991) studied consisted of powerful radio sources, most of which show no jet, or a jet with flux a negligible fraction of the whole. For this reason they argued that the line-of-sight effects which can explain the Laing-Garrington effect cannot account for the depolarization-spectral index correlation. In the case of Her A (see Table 1) the flatter spectrum eastern jet dominates the flux of the surrounding steeper-spectrum lobe, so it is no surprise that the Liu-Pooley correlation holds when the spectral index is assessed for the entire lobe, including the jet. But the spectral index asymmetry is clearly present in the ‘old’ lobe material, and so, at least in this case, cannot be explained as an orientation effect. Our discussion in Section 5.5 explains the injection of new, flatter-spectrum material into the jet-side lobe in terms of the time delay across the source, but this explanation cannot work for most DRAGNs; only a small fraction of them will be observed shortly after the jets re-start. We note that Blundell & Alexander (1994) give a related explanation which can work in most cases.

In contrast, models which explain the asymmetry in terms of intrinsic differences between the lobes, reflecting either long-term asymmetries between the two jets, or some large-scale asymmetry in the environment, face a problem in Her A because of the almost-exactly equal size of the two lobes. Moreover, our X-ray images (Paper I) do not suggest a strongly asymmetric environment.

5.2 The bridges

The bridge emission in the centre of Her A poses a puzzle. These are the faintest parts of the source, which at first sight suggests the lowest emissivity and so the lowest internal pressure, and yet the bridges seem to occupy the cluster centre, where the thermal pressure in the environment is the highest. Similar faint bridges are found in many powerful DRAGNs (Leahy, Muxlow & Stephens 1981), but only in Her A and Cyg A can we compare the radio and X-ray structures (see Paper I). In Her A, the bridges are (in projection, at any rate) within the core of the thermal gas distribution of the cluster. Unlike the case of Cyg A, there is no hint of X-ray ‘holes’ indicating that the intra-cluster medium (ICM) has been displaced by the bridges. Thus if the source is roughly cylindrical, the radio-emitting region must be well mixed with the ICM. But in that case we would expect that after such mixing the concentration of relativistic plasma would decline smoothly with distance from the source axis (marked by the jets) whereas in fact the edges of the bridges are sharply-defined in Fig. 8 especially the eastern bridge which is actually edge-brightened. In addition, mixing should give turbulent eddies along the surface of the bridges and/or bulb edges in Her A, but there is no sign of such vortices.

In our spectral index map the bridges are the steepest-spectrum regions in Her A, and so at lower frequencies the brightness contrast between bridge and bulb will be less marked. One might be tempted to assume that, in an image at the lowest frequencies, the distinction between bulb and bridge will vanish altogether. This would allow roughly constant internal pressure, since the pressure is carried mainly by the electrons which radiate at the lowest frequencies. However, Kassim et al. (1993) show that the bridge region remains faint even at 74 MHz, and this is typical of other DRAGNs. As in other cases, the spectra cannot be extrapolated to low frequencies as power laws, because most of the spectral index structure reflects curvature of the spectrum in the GHz band.

A plausible model is that the bridges are only projected onto the cluster centre (and to some extent, onto each other). This makes it easier to understand how the clear division between the two bridges can be maintained. A narrow gap between the bridges is seen in some DRAGNs (Leahy & Perley 1991; Johnson et al. 1993), which from many viewing angles would be closed in projection. Thus in Her A, the bridge material consists of a skirt of emission displaced in front
of and behind the core. The thickness of the bridges along the line of sight could then be smaller than their width, so that their emissivity (and pressure) would be closer to those of the bulbs than the images initially suggest. This model also makes some sense of the edge-brightening of the eastern bridge.

On this interpretation of Her A, the inner jets are confined by the thermal gas in the cluster core, and it seems likely that the transitions in the jets near knots E4 and W4 mark the points of entry into the bulbs, as suggested by Meier et al. (1991). Our X-ray analysis (Paper I) gives a thermal pressure in the cluster core of 13 pPa, while the equipartition pressure in the eastern jet is ~2.3 pPa with the standard assumptions (including no protons). These values are certainly compatible with thermal confinement (c.f. Leahy & Gizani 2001).

### 5.3 Collimation

Fig. 4 shows that the inner jets have approximately constant width when they are bright enough to measure easily. The innermost parts of the jets (within ~8–10 arcsec of the core) are very faint, so width measurements become uncertain, but there is weak evidence that the jets narrow towards the core as expected. The broadening of the eastern jet at ~6 arcsec may be because the fits are affected by structure in the surrounding bridge. The initial FWHM opening angle (arctan \( d\theta / d\lambda \)) must be greater than 3°–4°. Rapid opening followed by near-constant width is typical of strong-flavour jets (Bridle, Perley & Henriksen 1986; Leahy & Perley 1995; Swain, Bridle & Baum 1998).

The western jet is obviously much narrower than the eastern. It is best to compare the western jet measured at 5 GHz with the eastern at 8 GHz, because the ratio of jet width to beam width is then similar; we find 0.40 (5 GHz with the eastern at 8 GHz, because the ratio of jet expansion; but this should be a relatively brief episode and our X-ray analysis (Paper I) gives a thermal pressure in the cluster core of 13 pPa, while the equipartition pressure in the eastern jet is ~2.3 pPa with the standard assumptions (including no protons). These values are certainly compatible with thermal confinement (c.f. Leahy & Gizani 2001).

### 5.4 Beaming and Symmetry

The flux ratio between the flat-spectrum features in the eastern and western lobe is ~1.9 at 1440 MHz, after correction for the underlying steep-spectrum emission. At first sight this suggests that the jets are not very asymmetric in flux, but very different features dominate this ratio: in the west the rings, in the east the narrow jet itself.

We cannot be absolutely sure that the western lobe contains a true jet beyond W4, but there are several features which suggest that one does exist, directly analogous to the eastern jet, but much fainter. Figs 8 and 9 (bottom) show that there are relatively compact features (which have flat spectra) within rings D and A, i.e. features which do not form part of the edge-brightened rims. At 8 GHz, these are at the level of ~0.2–0.5 mJy beam^−1, O(10) times fainter than the jet emission at corresponding distances in the eastern lobe. If we assume that these features belong to a western jet beyond W4, similar in its co-moving frame to the eastern jet, then, for \( \alpha = -0.75 \), this difference could be Doppler dimmed by a factor of ~20 with respect to the eastern, which is consistent with the values derived below for the outer jets.

This leaves unexplained the difference in width between the two jets. If our Doppler beaming estimate is correct, the western jet has an intrinsic emissivity ~30 times higher, and hence its equipartition pressure is ~7 times that in the eastern. Adiabatic expansion arguments give a similarly large pressure ratio (depending again on the assumed magnetic geometry). Since the jets have roughly constant width in this region, they must be confined and so a similar pressure difference must exist in the confining medium. It is not easy to see how this could be maintained statically within the cluster core, and our X-ray images in Paper I do not show a pronounced asymmetry (although a temperature difference might not be very obvious). In Section 5.5 we discuss a dynamic model.

The eastern jet starts to flare at 23 arcsec, just after E3 (see Fig. 4), with opening angle arctan(\( d\theta / d\lambda \)) \( \approx 7^\circ \). The narrow measured width at 26–28 arcsec reflects knots E4 and E5 rather than the underlying jet. It reaches a maximum width in the bright section between E5 and E6 before narrowing towards E8. Some way downstream of the disruption point at E8, the effective opening angle is around 6°. Meier et al. (1991) interpret the flaring of the jet as evidence that it becomes overpressured at around E3. In its simplest form this concept is not consistent with the narrowing between E6 and E8, but the jet is surely not in a steady state and so it is possible that the overpressure is recent and did not affect the part of the jet that has now reached E7–E8.

Could the broadening beyond E8 be due to the overpressure created by strong shocks at E8 and E11? The structure of these knots suggests shocks moving away from the core through the jet (c.f. Section 5.7), in which case material downstream would not yet have been affected. In this case these may be symptoms of the disruption downstream, which would create an obstacle to the incoming collimated flow. But this interpretation may be over-simplified; the shocks may be moving downstream more slowly than the underlying flow, allowing them to influence the downstream jet.
attributed to Doppler beaming with $\beta \cos i \approx 0.5$. In Paper III we find from the depolarization asymmetry that the inclination to the line of sight is $i \approx 50^\circ$. This value would give $\beta \approx 0.8$, consistent with the values inferred for FR II jets from beaming arguments (Wardle & Aaron 1997). We will use this combination of parameters as a fiducial ‘fast model’. With this value of $\beta \cos i$, a feature in the western jet corresponding to the brightest part of the eastern jet, at E5–E6, would have brightness $\sim 1$ mJy beam$^{-1}$. In fact at the same distance in the western lobe, the elliptical ring contains fairly compact flat spectrum features at about 0.6 mJy beam$^{-1}$, after correcting for underlying emission. Thus, while the difference between the Her A jets cannot be entirely due to Doppler beaming, the intrinsic differences could be much smaller than the images suggest, no greater than the observed irregular brightness variations along the eastern jet. This analysis implicitly assumes that the jets are in a steady state, so that the light-travel delay across the source does not prevent us from comparing like with like. In contrast, we argue below that overall the jet is highly variable. We excuse this contradiction on two grounds: first, in at least the case of knots E5–E6 vs. the features in ring E, it seems plausible that we are looking at structures associated with the entry of the jets into the bulbs, i.e. at quasi-stationary patterns, rather than moving ‘blobs’ in the jet. Secondly, relativistic beaming is a much more powerful source of asymmetry than fluid-dynamical fluctuations in the jet flow, so that a systematic, order-of-magnitude difference in jet brightness is likely to be predominantly due to beaming. Nevertheless, we will also consider a ‘slow model’ in which beaming is assumed to be negligible. A problem with a relativistic jet scenario is that the difference in width between the inner jets cannot reasonably be produced by beaming, but this is addressed in the follow section. We have seen that the the emissivity ratio of the inner jets, although at first sight in the wrong sense, is consistent with beaming combined with differential adiabatic expansion.

Previous authors starting with DF84 have claimed that the two lobes of Her A show several symmetries, including point-symmetric (S-type) distortion of the jets/rings and paired structures at similar distances on the two sides, from which they infer that nuclear outbursts rather than instabilities are responsible for the major ring and jet structures. On close inspection the situation is more complex. We have already noted (Section 4.1.2) that there are systematic differences between the fine-scale structure of the two bulbs (see also Fig. 10). As for the jets, Fig. 4 shows a very low amplitude S-distortion in the inner jets, with the knots in the eastern jet being brightest on the outside edges of the curves, as usual in jets. On the other hand, Fig. 5 shows a large-scale mirror (C-type) symmetry. Around this overall pattern, one can impose an S-type distortion by associating ring B with jet knot E12, both of which project out of the main envelope of the jet. Despite the wandering of the outer boundary of the rings, it is worth noting that knot W4 and the compact peaks Eh and Ch are almost perfectly aligned with the core.

As for pairing features on the two sides, beyond the striking coincidence of the bright region E5–E6 with the elliptical ring E on the western side, there are rather too many features available in the eastern jet to be sure of making the correct match. Table 6 gives distances from the core for the major features we have identified, showing a possible set of correspondences. By counting rings out from the centre, we find that E12 and ring B do not seem to correspond to each other, contrary to the association needed for S-symmetry.

The light travel time from the back to the front of the source means that we are seeing features in the nearer lobe at a later time in their development. From the depolarization data (Section 4.3) we know that the eastern side is approaching, so we would expect the ratio of east-to-west distances for corresponding components to be larger than one, as in the scheme proposed in Table 6. The distance (or separation) ratio should be given by $(1 + \beta \cos i)/(1 - \beta \cos i)$, so the observed ratios suggest that $\beta \cos i$ falls from about 0.16 near the core to $\sim 0.02$ near the ends of the lobes. With $i = 50^\circ$, we would have a modest $\beta = 0.25$ near the core, which we will refer to as our ‘slow’ model. In this case the jet brightness asymmetry could not be due to beaming, and so if these associations are real we must abandon the conventional interpretation of the Laing-Garrington effect, at least in Her A. Note that the arguments leading to the fast and slow models both constrain $\beta \cos i$; therefore any changes to the estimated inclination $i$ would affect both speeds in the same way, with the inconsistency between the two left unaltered.

If we retain $\beta \cos i \approx 0.5$ (fast model) as deduced from beaming, corresponding features will differ by a factor of 3 in their distance from the core, and the associations in Table 6 would be chance coincidences, or caused by symmetries in the environment (which of course would be unaffected by light travel effects). We have already noted one plausible example: the transitions in the jets at a projected radius of $\sim 20$ arcsec seem to be associated with their entry into the bulbs. In turn, the distance of the inner edges of the bulbs from the core may be controlled by the cluster core radius at 43 arcsec (see Paper I). In this case the similar spacing between the rings in the eastern and western lobes is puzzling, as the eastern ones should be spaced about three times further apart; in other words, the western rings would correspond to much more significant features in the jet than the rings we have identified on the eastern side. As we discuss in Section 5.6, this may be consistent with the more clearly-defined structure of the western rings.

### Table 6. Possible correspondence between features in the two lobes

| East feature | distance arcsec | West feature | distance arcsec | ratio |
|--------------|-----------------|--------------|-----------------|-------|
| E1           | 14.0            | W1           | 10.2            | 1.38  |
| E2           | 16.4            | W2           | 13.7            | 1.20  |
| E3           | 22.2            | W3           | 17.0            | 1.30  |
| E4           | 26.2            | W4           | 21.2            | 1.23  |
| J (E8)       | 42.5            | Eh           | 36.0            | 1.18  |
| I (E11)      | 50.9            | Dh           | 48.9            | 1.04  |
| H (E12)      | 64              | Ch           | 59.0            | 1.08  |
| G            | 74.4            | B rim        | 67              | 1.11  |
| F            | 85              | Ah           | 82.1            | 1.04  |
5.5 Restarting jets?

The spectral index map (Fig. 9) shows that the western jet and rings form a single coherent structure which is clearly distinct from the surrounding lobes; the geometry alone strongly suggests that these flat spectrum components represent a renewed outburst of central activity within an old lobe.

Numerical simulations of this scenario have been made by Wilson (1984) and Clarke & Burnn (1991). They found that the hotspots expand and fade on their internal sound-crossing time once the jet switches off. The lack of bright features at the outer edges of the western lobe of Her A implies that enough time has passed since the last major outburst for this to occur, leaving the lobe with a ‘relaxed’ structure. The simulations show that the restarted jet is over-dense because its ambient medium consists of a cocoon of rarefied and hot material from the original jet, which is under-dense relative to the quiescent intergalactic medium. This implies a higher advance speed for the restarted jet, but also a lower Mach number since the new ambient temperature is much greater. A further implication is that the bow shock excited by the new jet is weak. This neatly explains why there is no true hotspot at the end of the western jet (i.e. near the bright arc Ah), because the new jet has not yet encountered the lobe surface. Over-dense jets should be terminated by a weak shock, and only a small amount of jet material will be reprocessed to form an ‘inner lobe’ surrounding the end of the jet (c.f. Norman, Winkler & Smarr 1983). In the limit of a very low cocoon density, the advance speed will be equal to the jet flow speed, and we assume this for simplicity in the following. Meier et al. (1991) also concluded that the jets in Her A are heavy, but lacking the spectral index evidence they assume that the jet parameters must be extraordinary, whereas in our picture the jets are fairly typical except for effects associated with their recent re-birth.

On the eastern side, although the jet is distinct from the surrounding lobe over most of its length, there is a smooth change in spectral index at the end. Here the most striking spectral division is between the circular bulb, and the surrounding steep-spectrum bridge. This is consistent with the light-travel time delay across the source: the new outburst will have a flatter spectrum. An obvious problem with this scenario is the absence of the expected hotspot at the end of the eastern jet; this will be discussed in Section 5.6.

We can estimate the timescales for the renewed outburst quite simply. If $i \approx 50^\circ$ and the jet speed is 0.8$c$ (fast model), as suggested by beaming arguments, then we see Ah (taking it to mark the end of the western jet) about 1.2 Myr after the current outburst began. If $v \approx 0.25c$ (slow model), as suggested by the apparent symmetries in Table 8, this becomes 3.8 Myr. At the core, about 1.8 (4.5) Myr has passed for the fast (slow) model, because of the light-travel delay across the source, and at the end of the east lobe 2.5 (5) Myrs has passed. The individual flares which cause the major rings would be separated by $\approx 250$ (800) kyr.

If the lobes of Her A are purely relativistic plasma their sound speed is $c/\sqrt{3}$; relatively small amounts of mixing with the surrounding intra-cluster medium (ICM) could reduce this. We then need $\gtrsim 1$ Myr for any hotspots associated with the previous outburst to expand to equilibrium with the rest of the lobe. For comparison, the ‘spectral age’ at the end of the western bulb is $\gtrsim 13$ Myr, based on a minimum-energy magnetic field of $\sim 0.8$ nT and a fitted break frequency $\lesssim 24$ GHz, both assuming the integrated spectral index of $\alpha = -1.0$. Thus many flow-through times (or several, for the slow model) could have passed between the current outburst and the last time the lobes were actively powered.

The eastern bulb may be a zone of turbulent mixing between the old and new material; during this new outburst, the jet is unlikely to have delivered sufficient material to completely fill such a large region. In the ‘fast’ model, we see the end of the east lobe 2.5 Myr after the outburst starts, twice the time for material to flow all the way down the jet, so the contents of only one jet length have been delivered to the lobe (even less, for the slow model). Note that the western bulb has received no new material, except for the thin column containing the jets and rings, and yet its volume is about the same as the bulb on the eastern side. Thus the extra material delivered on the east should form only a small fraction of the lobe contents. This is consistent with overall lifetime arguments: we expect that Her A is $\gtrsim 11$ Myrs old (overall expansion speeds are $< 0.1c$ Scheuer 1967), and so in 1 or 2 Myrs the jet should deliver $\lesssim 10$ per cent of the matter that fills the lobes, whereas the bulb occupies more than half the volume on each side.

The time delay may also explain the difference in width between the two jets (c.f. Section 7), if the structure is changing, we will see it at different times in its development. The response of a jet to a sudden increase in power has been studied by Komissarov (1994). According to this study a significant increase of the kinetic luminosity of the central engine results in the jets becoming over-pressured and beginning to expand transversely. The expansion is confined by ram pressure of the external gas at a quasi-cylindrical shock around the jets, until the jets reach a sufficient diameter that adiabatic expansion of the jet material arriving from the AGN brings it into equilibrium with the ambient pressure. For a relativistic jet the time delay means that we would see the jet at its narrowest at its most distant point, corresponding to the initial low kinetic luminosity of the central source, and it should widen systematically from there back towards the core (except in the central $\lesssim 7$ arcsec (20 kpc), where the jet expands from the parsec scale to its quasi-equilibrium width), and continue to expand on the other side away from the core until equilibrium is reached. There is some evidence in Fig. 7 that the western jet narrows away from the core as this model predicts; evidently equilibrium is established beyond $\approx 10$ arcsec east of the core.

Spectral structure similar to Her A’s is found in two other DRAGNs. Roettiger et al. (1994) argued that 3C 388 shows two distinct epochs of jet activity on the basis of a sharp spectral index boundary between the bright inner lobes and surrounding ‘relic’ lobes. In this case the new outburst has reached a more mature stage, with a well-defined hotspot at the end of the brighter jet. In 3C 310, Leahy et al. (1986) found that the inner components B and
D of van Breugel & Fomalont (1984) had substantially flatter spectra than the surrounding lobes. Van Breugel & Fomalont already drew attention to the similarity between the edge-brightened feature B of 3C 310 and the western rings of Her A; the spectral index structure re-inforces this. 3C 310 also contains a prominent (and complete) ring in its southern lobe, but this is spectrally part of the ‘old’ lobes. In this case the young features extend only half-way to the edges of the lobes, so the new outburst is at an earlier stage than in Her A.

All three DRAGNs are in relatively X-ray bright galaxy groups or clusters (Paper I; Leahy & Gizani 2000; Hardcastle & Worrall 1999), so the old lobes can be considered as examples of ‘relaxed doubles’ which are common in cluster centres. Steep spectrum DRAGNs are believed to occur in clusters because the high pressure environment prevents lobe expansion and associated adiabatic losses, giving time for substantial spectral losses to occur. The observation of renewed jets/inner lobes as spectral index features in cluster DRAGNs may then be a selection effect: outside clusters, the old lobes could fade to invisibility before the next major outburst occurs. Other evidence for renewed outbursts in non-cluster DRAGNs is discussed by Leahy & Parma (1992) and Schoenmakers et al. (2000).

5.6 The disruption of the eastern jet

FR II DRAGNs are notable for the high collimation which allows them to form very compact hotspots at the lobe ends. However, we have seen that the Her A eastern jet seems to disrupt at knot E8; as a result it is rather broad by the time it ends. The detailed structure in the decollimation region gives several clues to the nature of the catastrophe. Knots in jets are often attributed to internal shocks induced by interaction with backflowing material in the ‘cocoon’ (Norman et al. 1982); but these conical shocks do not much resemble what is seen in Her A, and are at least partially artefacts of the assumed cylindrical symmetry. Instead, knots E8, E9 and E11 suggest the sort of internal ‘working surfaces’ expected from time dependent speed variations in an over-dense jet, which have been intensively studied in the context of jets from young stars (e.g. Stone & Norman 1996; Cerqueira & de Gouveia Dal Pino 2001). Such variations could be caused partially, at least, by the central engine but may be aided by local instabilities. Although the most detailed numerical modelling has assumed radiative, and hence nearly iso-thermal, flows, qualitatively similar structures occur in adiabatic, relativistic flows, as we expect in Her A (Kosmiarov & Falke 1997). The disrupted structure at knots E9–E10 resembles the combination of velocity and direction oscillations of the jet source, for jet beams surrounded by hot, low density ‘cocoon’ studied by Raga & Bird (1993), and also the complex structure of jets with well-developed Kelvin-Helmholtz instabilities (e.g. Rosen et al. 1999). Jet disruption is a characteristic feature of numerical simulations of DRAGNs (Hardee & Norman 1991; Clark 1996), unless artificially suppressed by enforced axial symmetry; to the point, in fact, where the stability of real jets seems rather mysterious.

An alternative mechanism for jet disruption is the passage of the jet through an interface such as a shock in the ambient medium (Norman, Burns & Sulkanen 1988), for instance caused by the impact of a galactic wind on the surrounding medium. A serious drawback with this picture is that high-resolution X-ray imaging has shown no sign of such shock fronts around galaxies. Our own ROSAT data is probably too noisy to rule out the idea in Her A itself, but no sign of such a shock is seen in a Chandra image kindly shown us by A. Wilson. A more obvious interface is the point of entry of the jets into the bulbs of the lobes, if, as argued in Section 5.5, the inner jets are directly confined by the cluster core. But this interface must be present in most FR II DRAGNs, yet their jets almost always survive to form hotspots.

In any case, if the unusual structure of Her A is caused by the recent restarting of its jets, this must explain all the abnormal features, including the jet disruption, because it is very unlikely that one object should be pathological in two independent ways. How, then, can we explain why a recently re-started jet should be disrupted? Possibly, the lobe material provides enough of an obstacle to trigger instability, until a channel to the lobe surface is fully established. But in our fast model, the eastern jet reached the end of its lobe about 1.2 Myr ago, long enough for a complete flow-through, so we would expect the channel to be as stable by now as at any later time (this explanation works better in our ‘slow’ model, in which only a third of a flow-through has happened). A more plausible scenario is that the AGN is far from a perfect jet engine: the renewed outburst is not a sudden return to a uniform flow, but instead fluctuates with a wide range of timescales. Such an irregular flow would disrupt at a distance from the engine set by the need for irregularities in the flow to form shocks and/or breaks in the jet (e.g. Raga & Bird 1994).

The idea of an irregular jet is supported by the structure on the western side. The bright features Eh and Ch, which are exactly aligned with the inner jets, seem to correspond to very strong internal shocks in the western jet – they are many times brighter than the assumed intervening sections (which are essentially invisible). The contrast is greater than for any knot in the eastern jet. In the fast jet picture, the western jet appears three times slower than the eastern, and so represents three times the time span. We would then expect to see more extreme internal events in the western jet if the amplitude of an event is inversely correlated with its probability of occurring; in other words, if irregularities in the flow occur on successively longer intervals with successively larger amplitudes. It seems that the output of the AGN splutters with a roughly 1/f power spectrum. It is worth emphasising that on this interpretation, the features in the western lobe corresponding to most of the eastern rings would appear as weak structure in the major western rings; of course shortened by a factor of three due to light-travel effects.

The disruption of the eastern jet does not fully explain the lack of a hotspot on that side. If the jet is over-pressured as suggested by Meier et al. (1991) then it should expand in a conical morphology at its Mach angle and although the collimation beyond E8 is poorer than for normal FR II jets, the implied Mach number would still be \( M \sim 10 \), so the jet should shock on contact with the external medium. This suggests that at least the last section of the jet, component F, is trans- or subsonic, and confined by the lobe pressure.
We argue below that in fact this is the only subsonic portion, that is, the flow up to knot E13 is supersonic.

In fact it might not be easy for the jet to decelerate while in the lobe. In the standard model for FR I\textsuperscript{a} (Bicknell 1984), jets decelerate by sharing their momentum with entrained ambient medium. But the lobe material should have a low density compared to the jet, which will make this mechanism rather ineffective. This leaves the impact on the lobe surface (that is, on the true intracluster medium) as the main deceleration mechanism. Nevertheless, if the jet material has been pre-heated and decollimated by internal shocks, this will not result in a compact hotspot.

5.7 The nature of the rings

As noted by Meier et al. (1991), the key to understanding the western rings in Her A is the observation that similar features exist in the eastern lobe. These eastern rings are closely associated with the eastern jet, surrounding it, but are clearly separated from the ridge-line marking the jet itself. We have already noted the evidence for faint compact structures within the western rings which may be part of a continuation of the counter-jet, so the apparent difference between the two sides is mostly just due to the fact that the counter-jet is much dimmer than the main jet; additional differences arise from the light-travel time delay, of course. The structure of the rings suggests two hypotheses: either the rings are a system of shocks induced by the jets in the surrounding lobe plasma, or the rings form an ‘inner lobe’ around the jets, consisting of material deposited by the new jets, and separated from the old lobes by a contact discontinuity. In either case, the material in the rings is not moving with the bulk velocity of the jets. This is particularly important in our ‘fast’ model as otherwise we would expect the same brightness asymmetry between the rings on the two sides as between the jets, whereas in fact the two sets of rings are similar in brightness. It will become apparent that these two models are not as distinct as first appears, and a combination of the two may be closer to the truth.

5.7.1 The rings as shocks

The best argument for the shock model is that the shape of the rings, especially around the eastern jet, strongly resembles the ‘side shocks’ known from stellar jet, that is, shocks propagating through the ambient material, caused by the passage of bumps on the jet surface (except ring G which seems to be a bow shock ahead of knot E13). There is a strong resemblance to the HH 47 stellar jet (Heathcote et al. 1994), where shocks in the surrounding neutral wind can be clearly identified by their Hα emission. Because of radiative cooling, HH 47 contains material with a wide range of densities but the side shocks are attached to dense clumps in the jet identifiable by strong [SⅡ] emission; thus like Her A it is effectively a dense jet. Jet surfaces can become irregular through variations in both the direction and speed of the jet, and also from the growth of instabilities (Heathcote et al. 1996). All of these are certainly present in HH 47, and we have seen that the same may be true in Her A.

The relatively flat spectrum of the rings is not easy to explain in this model. The low-frequency integrated spectrum of Her A is very close to $\alpha_{\text{low}} = -1.0$ (Kühr et al. 1983), and this is probably dominated by the bulbs. As we have seen (Table 1), the lobe spectra steepen at GHz frequencies. If the rings are shocks, adiabatic compression would shift the curved portion of the spectrum to higher frequencies, so that between a fixed pair of frequencies the spectral index would flatten, to limiting value set by $\alpha_{\text{low}}$. But the rings have a flatter spectrum than this, so we have to invoke particle acceleration, presumably by the shock–Fermi mechanism. This may not seem surprising, as shocks are believed to be the sites of particle acceleration in most radio sources. But it is then curious that the steepest-spectrum ring is Ah, which should mark the bow shock ahead of the Doppler-dimmed western jet, and therefore be the strongest shock of all (the internal bow shock ahead of the eastern jet having disappeared when it reached the end of the lobe). In fact, Ah is the only ring whose spectrum requires only adiabatic compression of the lobe material. Another problem for the shock model is the similarity between ring and jet spectra, which would have to be a coincidence. However, these are similar mainly in contrast to the extremely steep spectra in the undisturbed old lobes; there is a systematic spectral difference of about 0.1 and 0.2 between jet and rings in the eastern and western lobes respectively (Table 5), although it happens that $\alpha(1.5, 4.8)$ in the western rings is close to that of the eastern jet.

In fact the neat division into old lobe and new jet material is an oversimplification in at least one place. We argued in Section 5.6 that the material in the fan component F at the end of the eastern jet is at most trans-sonic. In contrast, the region up to at least E12, where side shocks are clearly seen, must (on this interpretation) be highly supersonic, because side shocks imply that the jet is supersonic with respect to the lobe, which should be hotter and therefore have a higher sound speed than the jet. We would therefore expect a shock in the fan material as the faster jet behind ploughs into it, and the ring G seems a plausible candidate for this. Some of the other rings may also be partly interactions with slower sections of the jet, rather than the undisturbed old lobe.

In side shocks, the angle of the shock front to the jet flow direction should tend to the Mach angle at large distances from the jet axis, providing that the bump on the jet which causes the side shock persists for long enough for the shock to reach this regime. In HH 47 the shocks become almost parallel to the jet, so the motion must be supersonic in the surrounding medium, and this is confirmed by measurement of the shock speed and ambient temperature. The structure in Her A is similar, although we note that if the jet is relativistic the apparent angle of the shocks will be affected by time-delay effects, giving an apparent Mach angle

$$\theta_{\text{app}} = \arcsin \left( \frac{\gamma \beta_\alpha (1 \pm \beta \cos i)}{\beta \sin i} \right),$$

where $\gamma \beta_\alpha$ refers to the sound speed, and the minus sign applies in the approaching jet. If the lobes are pure relativistic plasma we have $c_s = c/\sqrt{3}$ and hence $\gamma \beta_\alpha = 1/\sqrt{2}$. For our fast model ($\beta = 0.8$ and $i \approx 50^\circ$) we expect $\theta_{\text{app}} \approx 36^\circ$ in the approaching lobe, which is much larger than observed in rings I and J; while in the receding lobe we should not see a Mach cone at all. Similarly, in the slow model the jets would be subsonic if the lobe plasma was relativistic. Thus to make the shock model work we have to assume that enough gas...
from the ICM has been mixed into the lobes to reduce the sound speed. This need not be much: if the pressure is dominated by relativistic plasma, the sound speed is $\sqrt{\frac{4P}{3\rho}}$. If we take $P \approx 13$ pPa (pressure balance with the ICM), then to reduce the sound speed by an order of magnitude below the relativistic limit we would need a proton number density of $n \sim 16$ m$^{-3}$, still far below the density in the ICM.

If we do consider the ring opening angle to be related to the Mach angle, then there is some evidence for deceleration along the eastern jet: the apparent shocks in component H show a significantly larger opening angle than the ones in components I and J. Ring G, in contrast is tightly wrapped around knot E13. This is consistent with G being a shock in the jet as E13 runs into component F, because the jet material should be significantly denser than the lobe material and hence has a lower sound speed.

The argument for entrained material in the lobes would be circumvented if the jet knots causing the shocks were expanding transversely; in the limit that the knot expands rapidly, the shock will form an ellipse around the expansion. This seems an excellent candidate for lobe material swept up ahead of the new outburst, perhaps bounded by a weak shock. Because the shock is weak, we would not expect significant particle acceleration and only mild compression: the steep spectrum is then explicable, especially if this material has been carried out from the centre of the source, where the spectrum is very steep. Similarly, the apparent way that the faint intensity filaments in the western bulb arc around the ABC complex supports this hypothesis: on the shock model this part of the lobe should not yet be aware of jets.

The major drawback with the inner lobe interpretation is the strong rim-brightening of the rings: normal lobes do not usually show this feature (although in fact the western bulb of Her A is somewhat edge brightened, as shown in Fig. 3). At least in part this may be due to the narrowness of the inner lobe: the centre of the lobe is taken up by the jet, which is invisible due to Doppler anti-beaming, and so the lobe appears hollow. This is not the whole story, because we still see offset rings on the east side; but numerical models suggest that the jets should be bounded by an ultra-hot and low density sheath, which would be more apparent when the lobe is narrow.

6 CONCLUSIONS

Our observations of the powerful radio galaxy Her A have shown a strong Laing-Garrington effect: the jet side depolarizes less than the counter-jet side with increasing wavelength. The fact that depolarization is wavelength dependent is a characteristic of Faraday rotation (Burd 1964; Laing 1984), which will be discussed in more detail in Paper III.

We also find that the less depolarized lobe has a flatter spectrum, and that this is not simply due to the presence of the prominent (and possibly beamed) jet. This is in agreement with the trend discovered by Liu & Pooley (1991).

After correcting for Faraday rotation the projected magnetic field closely follows the edge of the source, the jets, and the ring-like structures in the lobes; the field pattern in the two lobes is broadly similar.

We have discovered a remarkable structure in spectral index, qualitatively similar on the two sides, which strongly suggests the recent ejection of high-brightness, relatively flat spectrum material into much steeper spectrum lobes.

We have argued that all the peculiar features of Her A can be understood if the outflow from the AGN effectively ceased for $\geq 1$ Myr, restarted some 2-5 Myr ago (depending on the speed of the jets), and has since fluctuated with a
roughly $1/f$ power spectrum. Of course, the overall fluctuations on timescales of several Myr might well be part of the same spectrum; the present episode may not be the first major re-start. At the other end of the fluctuation frequency spectrum, it may be significant that the compact ($\sim 10$-pc scale) core lacks bright sub-pc structure (since there is no flat-spectrum component). This suggests substantial variability on timescales of decades, with the outflow currently low or off.

Because re-starting jets propagate rapidly through the old lobes, Her A will only show its present peculiar structure for a small fraction of its life: rather than being a highly pathological AGN, we suspect that it is a fairly typical powerful DRAGN, caught at a very atypical phase in its development.

We have shown that a consistent model can be found in which the jets are fast ($v \approx 0.8c$) and the systematic asymmetries between the two jets are accounted for by relativistic beaming, together with other effects related to the light-travel delay across the source in the presence of fluctuating, but symmetric, outflow from the AGN. This model requires us to abandon some of the apparent morphological symmetries between the two lobes as merely accidental; but we have argued that these symmetries are not very impressive. This model is consistent with the conventional interpretation of the Laing-Garrington effect as strong evidence for relativistic flow in large-scale jets, and can also explain the Liu-Pooley asymmetry, at least for Her A.

We have also considered a model in which the apparent morphological symmetries reflect a series of pulses in ‘slow’ ($v \sim 0.25c$) jets. On this model, though, the main jet would be intrinsically brighter than the counter-jet and so the relativistic explanation of the Laing-Garrington effect would not apply, at least in this particular object. Both fast and slow models require fluctuating outflow from the AGN on timescales much shorter than the overall re-start. In general the slow model is less well constrained.

We considered two models for the famous ‘rings’ (which are found around both jets): that they represent a system of shocks in the old lobes excited by the renewed jets, or that the represent the surface of an ‘inner lobe’ surrounding the jets. When their consequences are followed through, both models imply that the rings are related to shock systems which at least partially involve interaction between components in the new outflow; thus a hybrid of these simple models may be the most plausible option. On any interpretation, the material in the old lobe must significantly obstruct the new jets; although for simplicity our kinematic models assumed no deceleration, this must be a rather rough approximation. Numerical simulations of re-starting relativistic jets could shed much light on the structures we have observed.

Our interpretation of Her A as showing restarting jets is entirely consistent with a simple interpretation of the spectral structure in terms of spectral ageing, which suggests that the jets and rings (on either interpretation) with their flatter and less curved spectra are significantly younger than the lobes (c.f. Leake, 1993). Of course, a detailed spectral ageing analysis should also take into account the effects of adiabatic expansion on the spectrum. We are planning such a study, incorporating new high resolution data at 330 and 74 MHz (Kassim et al., 1993, and in preparation) to better constrain the spectral fits.

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