Pressure Balance between Thermal and Non-Thermal Plasmas in the 3C129 Cluster

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Abstract.
With new Chandra observations of the cluster containing the two radio galaxies 3C129 and 3C129.1, we have made a fit to the X-ray surface brightness to obtain thermal pressures. VLA data at 1.4 GHz have been obtained to complement previous maps at 0.33 GHz (Lane et al. 2002) and at 5 and 8 GHz (Taylor et al. 2001). From these radio data, we are able to derive the minimum non-thermal pressure of various emitting volumes along the tail of 3C129 and in the lobes of 3C129.1.

Under the assumption that the non-thermal plasma excludes significant thermal plasma, we may expect pressure balance for most features since ram pressure should be important only close to the cores of the galaxies. Since we find that the minimum non-thermal pressures are generally only a factor of a few below estimates of the ambient thermal pressure, we conclude that it is unlikely that relativistic protons contribute significantly to the total pressure. Reasonable contributions from low energy electrons and filling factors in the range 0.1 to 1 suffice to achieve pressure balance.

Although we do not find strong signatures for the exclusion of hot gas from the radio structures, we find soft features near the cores of both galaxies suggestive of cool gas stripping and hard features associated with radio jets and possibly a leading bow shock.

1. Goals

3C129 and 3C129.1 are two radio galaxies in a nearby cluster of galaxies (fig. 1) which lies close to the galactic plane. We proposed Chandra X-ray observations in order to find signatures of hydrodynamic interactions between the hot intracluster gas and the radio lobes and tails and to estimate the non-thermal pressures within the radio structures by determining the external gas pressure and assuming pressure balance. It seemed likely that given the long tail of 3C129 ($\approx 0.5$ Mpc projected length), that most of the source was close to the plane of the sky and that projection effects would thus be minimal. Since tailed radio
galaxies are found only in clusters of galaxies, it also seemed likely that the projected distance between the cluster center and 3C129 was not significantly less than the actual distance: 3C129 was already known to lie close to the edge of the detected gas distribution (Leahy & Yin, 2000). For these reasons, we believed 3C129 was a good target for detecting the sort of depression in X-ray surface brightness caused by cavities in the hot gas coinciding with radio lobes (e.g. Cygnus A, Carilli et al. 1994; and Hydra A, McNamara et al. 2000).

The reason we wanted to use pressure balance between thermal and non-thermal plasmas is that this procedure provides an estimate of the non-thermal pressure which can be compared to that obtained from the usual synchrotron formulae assuming equipartition between the energies in relativistic particles and the magnetic field. It is then possible to evaluate the likelihood for various values of the critical synchrotron parameters. To do this confidently, we require that unmeasurable ram pressures be negligible and that by defining various areas of the radio source, we can infer the emitting volumes.

We use the redshift of 3C129.1 (z=0.0208, Spinrad, 1975) as the distance indicator of the cluster, and with \( H_0 = 65 \text{ km s}^{-1} \text{ Mpc}^{-1} \), one arcsec corresponds to 450 pc.

2. Cluster Gas

The X-ray emission from the cluster gas is shown in fig. 1. It is relatively smooth unlike the clumpy distribution seen for the gas around the radio galaxies Hydra A (McNamara et al. 2000) and M84 (Finoguenov & Jones, 2001). We performed a spectral deprojection analysis (Krawczynski 2002) and \( \beta \) model fits to the radial distributions in two pie sections are shown in fig. 2. From these data we can obtain the thermal pressure as a function of distance from the cluster center which was judged to lie \( \approx \) 1’ SW of 3C129.1. It seems likely that the cluster has suffered a recent merger because the gas distribution is significantly elliptical (figs. 1 and 2); the cluster contains a radio galaxy with a long tail; and we find no evidence for a cooling flow (Krawczynski, 2002);

3. Non-thermal Pressures

The calculation of minimum non-thermal pressure involves 4 components: the assumption of equipartition between the relativistic particles and the magnetic field; the assumption that the filling factor is 1; the assumption that protons do not contribute significantly to the particle energy; and the assumption that most of the relativistic electrons have been ‘counted’ when the synchrotron luminosity is integrated over some frequency range. If any of these assumptions are violated, the total non-thermal pressure will be greater than the minimum value.

While the usual invocation of equipartition leads to the classical \( \frac{4}{3} \) power for the pressure’s dependence on the filling factor and the proton energy density, we should not forget that if we were to abandon equipartition and argue that we knew the average magnetic field strength from some other method (e.g. detection of inverse Compton emission from a known photon distribution), then the dependence is linear. Compare the basic equation for the total pressure with the expression for the minimum non-thermal pressure.
\[ P = nkT + \frac{1}{3} \frac{c_{12}(1+k)L}{\phi V B^2} + \frac{B^2}{8\pi} \]

For the field which minimizes the total pressure, \( B_{\text{min}P} \)

\[ P_{NT} = 0.265 \left[ \frac{c_{12}}{\phi V} \right] \frac{(1+k) L^4}{\pi} \]

where

\[ c_{12} = 1.06 \times 10^{12} \left[ \frac{\nu_1^{1-2\alpha}/2 - \nu_2^{1-2\alpha}/2}{\nu_1^{-\alpha} - \nu_2^{-\alpha}} \right] \]

\[ L = 4 \pi D_L^2 \left( 1 + z \right)^\alpha - 1 \int k_s \nu^{-\alpha} d\nu \]

\( \phi \) is the filling factor for the emitting volume, \( V \); \( k \) is the ratio of particle energy densities (protons to electrons), and \( k_s \) is the amplitude of the radiation power law: \( S_\nu = k_s \nu^{-\alpha} \).

It is also the case that various conditions can be chosen instead of the classical equipartition (particle energy density equals magnetic field energy density). We have chosen to use the magnetic field strength which minimizes the total pressure, \( B_{\text{min}P} \). Other choices which can change the value of the field by factors of up to 1.48 include assuming the field is smooth or tangled and equalizing pressures instead of minimizing the total pressure, or equalizing the energy densities instead of minimizing the total energy (see the appendix of Harris et al. 1995, for further details).

We have chosen regions in 3C129.1 and 3C129 on the basis of minimizing uncertainties in converting rectangular areas to cylindrical volumes and circular areas to spherical volumes (i.e. we chose regions for which the assumption that the depth dimension can be found from transverse dimensions is most likely valid). These regions are shown in fig. 3.

Flux densities for these regions were measured at 0.33, 1.4, 5, and 8 GHz. Spectral indices were determined for single or broken power laws from these flux densities as well as from spectral index maps produced by scaled arrays (5 and 8 GHz, Taylor et al. 2001) and from the similar uv coverage of our 0.33 and 1.4 GHz data. Details of this analysis can be found in Krawczynski et al. (2003).

The results are shown in fig. 4 and given in table 1 and it is immediately clear that the minimum non-thermal pressures are almost always less than the thermal pressures, and that the difference for most regions is a factor of order 0.5.

4. Implications of Pressure Balance

Given the uncertainties in calculating various pressures, we find it remarkable that the thermal and non-thermal pressures are so close to each other for most of the regions selected. Extending the integration of the synchrotron spectrum down to 1 MHz (and thereby including electrons with Lorentz factors in the range \( \gamma = 100 \) to 500) increases the minimum non-thermal pressures to values
Table 1. Non-thermal pressures

| Number | Region              | $P_{\text{min}}$ $10^{-12}$ CGS | $P_{\text{ther}}/P_{\text{NT}}$ $\nu_1 = 10^7$ Hz | $P_{\text{ther}}/P_{\text{NT}}$ $\nu_1 = 10^6$ Hz |
|--------|---------------------|---------------------------------|-----------------------------------------------|-----------------------------------------------|
| 1      | 129:1: N rectangle  | 6.0                             | 5.37                                          | 2.15                                          |
| 2      | 129:1: N inner      | 21.2                            | 1.60                                          | 1.20                                          |
| 3      | 129:1: S inner      | 24.3                            | 1.46                                          | 0.80                                          |
| 4      | 129: inner arm      | 3.70                            | 2.08                                          | 1.66                                          |
| 5      | 129: W eye          | 2.26                            | 3.31                                          | 2.36                                          |
| 6      | 129: E eye          | 2.30                            | 3.45                                          | 2.79                                          |
| 7      | 129: 4am            | 0.48                            | 18.0                                          | 13.5                                          |
| 8      | 129: 8.9am          | 0.74                            | 4.45                                          | 2.16                                          |
| 9      | 129: 10.5am         | 0.59                            | 5.25                                          | 2.08                                          |
| 10     | 129: 12.7am         | 0.92                            | 3.27                                          | 0.76                                          |

Notes to table

The thermal pressures at each location use the temperature from the spectral deprojection and the density from the deprojection (weight 2) and $\beta$ model fit (weight 1).

The non-thermal pressures were calculated by selecting the magnetic field strength which minimizes the total pressure, taking the filling factor, $\phi=1$, negligible energy density from protons ($k=0$); and integrating the synchrotron luminosity down to $\nu_1 = 10^7$ (columns 3 & 4) or $10^6$ Hz (column 5).

only a factor of two less than the thermal estimates for most regions. This factor of two is easy to obtain for example by invoking a value of the filling factor, $\phi = \frac{1}{3}$. Taken at face value, the small factors between the thermal and non-thermal pressures indicate that we cannot accommodate large values of $k$ (expected if relativistic protons are present); significant departures from equipartition (as hypothesized in a different context to facilitate explanations of excess euv emission as IC emission, Bowyer, this volume); anomalous numbers of low energy electrons (i.e. an excess over the extrapolation to low energies from the electron spectra inferred from the radio data); and/or values of the filling factor $< 0.1$.

5. Features and Conclusions

Although not all cavities will cause a depression in the X-ray surface brightness (Clarke et al. 1997), we interpret the absence of evidence for cavities associated with the radio structure of 3C129 to mean that the filling factor is likely to be something of order $1/3$ or $1/10$ (e.g. filaments of magnetic field and relativistic particles embedded within the ambient thermal plasma). For 3C129.1, the X-ray surface brightness is produced by a long integration of emissivities along the line of sight through the cluster center and the relatively small volume occupied by the radio structures would not be expected to produce an observable change in the X-ray surface brightness.

Whilst analyzing the morphology, we discovered X-ray emission coincident with the first few arcsec of the northern radio jet of 3C129 (Harris, Krawczynski,
and Taylor, 2002) and we find hard emission from the region next to the nucleus of 3C129.1, which might be associated with a radio jet in that source (fig. 5).

We have also constructed hardness ratio maps \( (H-S)/(H+S) \) with \( H = 2 \) to 5 keV and \( S = 1 \) to 2 keV. For both radio galaxies, there is a small region of significantly softer emission trailing off to the NW from the host galaxies (figs. 6 and 7), and in the case of 3C129, there is a harder region to the SE of the galaxy core (fig. 8). We will examine the statistical significance of these features in Krawczynski et al. (2003), but the obvious interpretation would be a stand-off bow shock heating the gas ahead of 3C129, and a short trail of cooler ISM being swept out of each galaxy. Although there is little debate about the direction of the relative velocity between 3C129 and the ambient gas because of the strong bending of both radio jets, previous evidence for relative motion for 3C129.1 has been marginal at best. The fact that both soft trails are in the same quadrant, is circumstantial evidence in favor of a large scale mass motion of the ICM instead of, or in addition to, the classical explanation for the long tail of 3C129 as being caused by a large velocity of the galaxy relative to a stationary cluster gas.

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Figure 1. The X-ray images for a 10ks ACIS-I observation of 3C129.1 (upper panel) and a 30ks observation of 3C129 with ACIS-S. Both observations have been divided into two bands: 1-2keV and 2-5keV. Each band map was divided by the appropriate exposure map and then the resulting band images were added together. The data were smoothed with a Gaussian of FWHM=30'' (3C 129.1) and FWHM=20'' (3C 129). For 3C129, the two back illuminated chips had a constant level subtracted to compensate for the additional background experienced from these chips. Contours from VLA data at 1400 MHz increase by factors of two and commence with 0.001mJy/beam. The restoring beam size is 18'' x 14'' in PA=-14°.

Figure 2. The modified King model fits to the data in two 90° pie sections; one to the north and the other to the West. The core radius is $\approx 9'$ and the value of $\beta$ is $\approx \frac{2}{3}$.

Figure 3. Selected regions in 3C129.1 and 3C129 for calculating non-thermal pressures.

Figure 4. The pressures from the spectral deprojection analysis (filled symbols), the beta model fit (solid curve), and the non-thermal pressures for $\nu_1 = 10^7$ Hz.

Figure 5. An X-ray map of 3C129.1 in the 2 to 5 keV band with radio contours overlayed. The X-ray data have been divided by the exposure map and smoothed with a Gaussian of FWHM=4''. The first brightness level visible is at 1.2 $\mu$photons cm$^{-2}$ s$^{-1}$ pixel$^{-1}$ and the peak brightness of the feature of interest to the SW of the radio core is at 2.2 $\mu$photons cm$^{-2}$ s$^{-1}$ pixel$^{-1}$. The radio map is at a frequency of 4.88 GHz (from Taylor et al. 2001) with contours increasing by factors of 2. The first contour level is 0.1 mJy/beam and the beam is 1.8''.

Figure 6. Hardness ratio map of 3C129. Darker grey corresponds to softer emission and the map has been smoothed with a Gaussian of FWHM=8''. The lowest greyscale visible has HR = -0.017 and the peak value is -0.032. On a map covering 16 times the area visible here, there are two features reaching -0.022. The radio contours are from a 4.7 GHz map (Taylor et al. 2001). The lowest contour is 0.4mJy/beam and successive contour levels increase by factors of 2. The clean beam size is 1.8'' FWHM.
Figure 7. Hardness ratio map of 3C129.1. The map has been smoothed with a Gaussian of FWHM=4″. The feature of interest (lying just to the NW of the radio core) has a peak value of -0.128. The faint greyscale patches have HR values close to -0.04 and the softest feature on a map which has 16 times the area shown here is -0.06. The radio contours are the same as those in fig. 5.

Figure 8. A 2 to 5 keV map of 3C129 divided by the exposure map and smoothed with a Gaussian of FWHM=8″. The first greyscale visible has a brightness of 0.92 $\mu$photons cm$^{-2}$ s$^{-1}$ pixel$^{-1}$ and the peak value just to the N of the radio nucleus (the last circular contour) is 2.14 $\mu$photons cm$^{-2}$ s$^{-1}$ pixel$^{-1}$. The pixel size is 0.492″. Radio contours are the same as in fig. 6. In addition to emission from the nucleus and the first segment of the northern jet, there is extended excess emission preceding the galaxy.
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