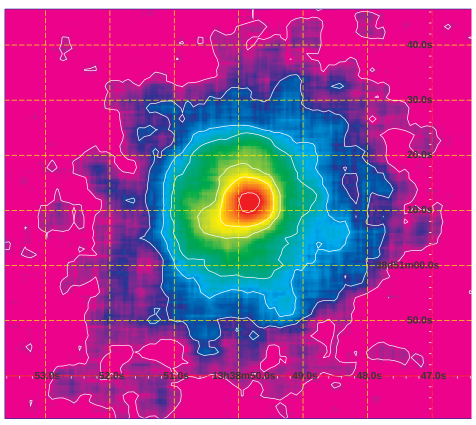
Chandra observation of 3C 288

Dharam Vir Lal[1]
R.P. Kraft[1], D.A. Evans[1,2], M.J. Hardcastle[3]
J.H. Croston[3], W.R. Forman[1], C. Jones[1], J.C. Lee[1]
[1] Harvard-Smithsonian CfA, USA; [2] MIT Kavli Institute for Astrophy & Space Research, USA; [3] Univ of Hertfordshire, UK.

ABSTRACT

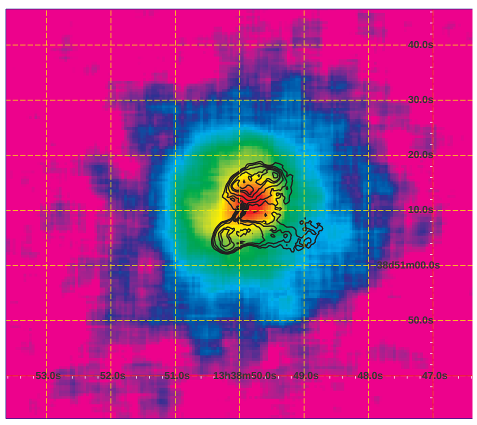
We present preliminary results from a 42 ks Chandra/ACIS-S observation of the hot X-ray emitting cluster gas associated with the transitional FR I/FR II radio galaxy 3C 288 at z = 0.246. We measure the total energy of the current outburst to be $\sim10^{60}$ ergs. We find multiple surface brightness discontinuities in the gas indicative of either supersonic heating by the inflation of the radio lobe or a recent merger event. The X-ray isophotes do not appear to be centered on the central galaxy, demonstrating the presence of non-hydrostatic gas motions on scales of kpcs. Additionally, we find a significant soft (<0.5 keV) excess X-ray emission above that predicted from the 3 keV cluster gas temperature.

Images



Left panel

Gaussian-smoothed ($radius$ = 2 arcsec) *Chandra*/ACIS-S image of 3C 288 in the 0.23–5.00 keV band with X-ray contours overlaid. We see diffuse thermal emission with a temperature of 3 keV extending to ~510 kpc (~104 arcsec).



Right panel

Same as left panel image with 5 GHz radio contours (0.6 arcsec resolution) overlaid. The contour levels are 0.4, 0.8, 1.6, ... mJy beam^{-1}. The radio galaxy lies well within the cluster gas core and the radio jet is not detected in the X-ray band.

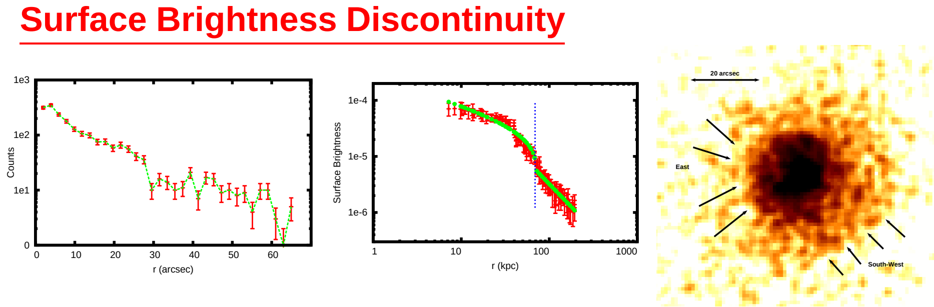
- The X-ray bright gas core is offset from the radio nucleus by 14.7 kpc (~3 arcsec);

  $\Rightarrow$ the presence of non-hydrostatic gas motions on scales of kpcs.
- Radio to X-ray spectral index:

  Nucleus $-\ \alpha^{\rm radio}_{\rm X-ray} \approx 0.93\ (S_\nu \propto \nu^{-\alpha})$,

  Jet $-\ \alpha^{\rm radio}_{\rm X-ray} > 0.97$.

Surface Brightness Discontinuity



Left panel

Surface brightness profile of the south-west projection.

Middle panel

Surface brightness profile of a 100 deg wedge (from P.A. 120 deg to 220 deg). The profiles inside the edge and outside the edge are modelled via $\rho = 1.89\left(\frac{r}{70.48}\right)^{-0.68}$ and $\rho = \left(\frac{r}{70.48}\right)^{-1.31}$, respectively. The model gives the best fit edge, blue vertical line, position as 70.5 kpc (= 14.4 arcsec) from the centre.

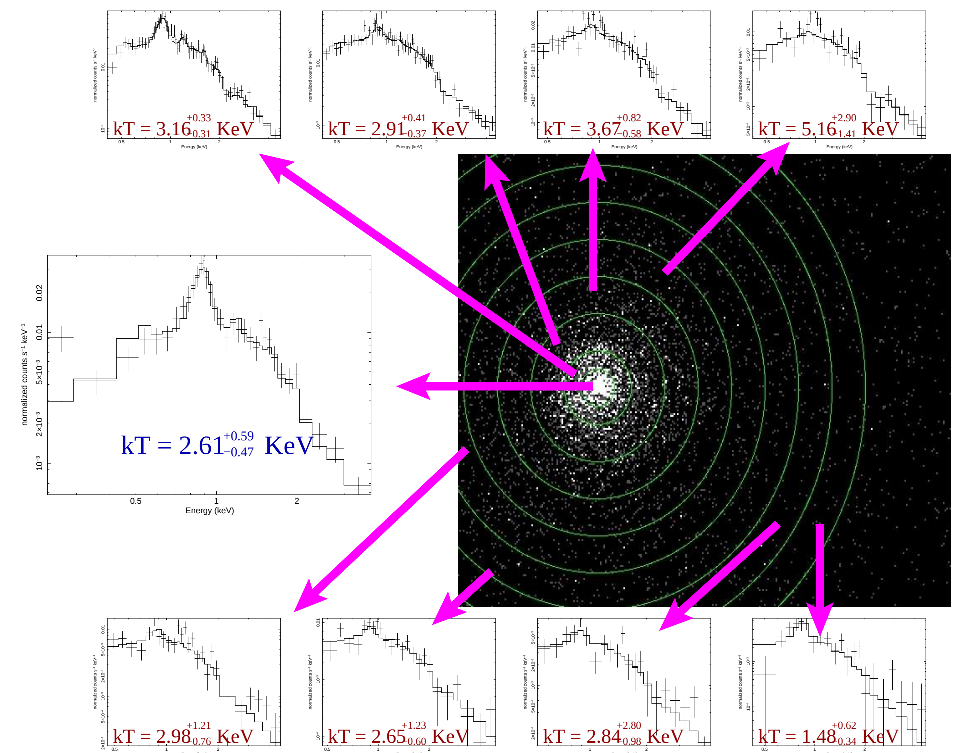
Right panel

Gaussian-smoothed ($radius$ = 2 arcsec) *Chandra*/ACIS-S image in the 0.23–2.50 keV band. The image has 2 arcsec bins. The black sets of arrows denote the positions of multiple surface brightness discontinuities.

Important References

1. Evans, D.A., et al., 2008, ApJ, 675, 1057
2. Fabian, A.C., et al., 2009, MNRAS, 395, L67
3. Hardcastle, M.J., 2008, ASP Conf. Ser., 386, 46
4. Hardcastle, M.J., 2007, Phil. Trans. R. Soc. A, 363, 2711
5. Hardcastle, M.J., & Worrall, D.M., 2000, MNRAS, 319, 562
6. Kraft, R.P., et al., 2005, ApJ, 622, 149
7. Kraft, R.P., et al., 2007, ApJ, 664, L83
8. Sarazin, C.L. & Lieu, R., 1998, ApJ, 494, L177
9. Young, A.J., et al. 2002, ApJ, 564, 176

Spectral Analysis



We fit spectra to several regions of the cluster gas. Single-temperature APEC models were fit with the elemental abundances frozen to half the solar value as well as a free parameter, the column density fixed to Galactic value (n_H = 9 × 10^{19} cm^{-2}), and the redshift frozen at the value measured for the host galaxy of 3C 288. The abundance is poorly constrained when allowed to vary freely. The uncertainties on the temperatures are at 90% confidence levels.

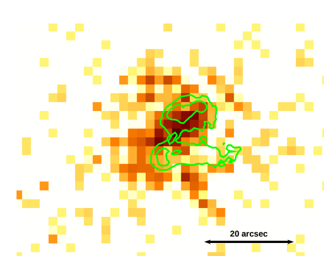
- Isothermal 3 keV cluster associated with the radio galaxy.
  - The best-fit temperature for the gas is 3 keV within 13 arcsec (= 63.7 kpc). The best-fit temperatures on larger spatial scales are consistent with this value, within large errors.
  - We use the gas density profile and the temperature along with the volume of the radio lobes to compute the enthalpy of the lobes;

    the enthalpy of the lobes ($4pV$) = 3.8 × 10^{60} ergs.
  - $P_{\rm lobe} = \frac{pV}{({\rm radio\ source\ size})/v_{\rm lobe}} \approx 2.8 \times 10^{44}$ erg s^{-1},

    assuming the lobe is buoyant, $v_{\rm lobe} = 0.5c_s$, $c_s = \left(\gamma\frac{kT}{\mu m_H}\right)^{0.5}$ and size (radius) of the radio galaxy being 46.6 kpc (9.5 arcsec).
  - X-ray luminosity within 147 kpc (30 arcsec);

    $L_{0.3-5.0\ {\rm keV}}$ = 4.3 × 10^{43} erg s^{-1}.

Soft X-ray Excess Below 0.5 keV



Chandra/ACIS-S image of 3C 288 in the 0.23–0.50 keV, soft X-ray band with 5 GHz radio contours (0.6 arcsec resolution) overlaid. The image has 2 arcsec bins.

- Presence of soft X-ray excess:

  modelling the soft excess with an electron energy spectrum and assuming
  - uniformly filled inverse-Compton source with a radius of 13 arcsec,
  - power law with energy index = 1,
  - Lorentz factor from 1 to 400 and
  - $\gamma_{\rm max}$ is chosen so as to have an exponential cutoff in the X-ray above 300 eV when scattering the CMB and that the radio flux is in the exponential cutoff regime above a few MHz.

  $\Rightarrow$ magnetic field strength = a few below the equipartition value,

  electron energy density = 8.9× 10^{-9} erg cm^{-3}, and

  total energy in electrons = 1.4 × 10^{62} ergs (~10^3 times energy$_{\rm min}$ in Cygnus A).

This soft X-ray excess is uniformly spread across the whole 42 ks observation and is clearly present in archival *ROSAT* observations of this cluster. The origin of this emission is unclear, it is not well described by either simple thermal or power-law models; but implies either massive cooling if thermal, or the presence of a population of ultra-relativistic electrons with a total energy far in excess of the energy of the current nuclear outburst. We are investigating the viability of thermal models.

Summary

- Isothermal 3 keV cluster.
- Non-detection of X-ray jet.
- Presence of multiple surface brightness discontinuities.
- Presence of soft (<0.5 keV) excess X-ray emission.