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18 GHz SZ Measurements of the Bullet Cluster

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Abstract. We present 18 GHz observations of the Bullet cluster using the Austalia Telescope Compact Array (ATCA), which show structure in the Sunyaev–Zeldovich effect; in particular, a deep, compact feature which does not correspond to any bright feature in X-ray, optical or lensing maps. In general, the relatively deeper SZE features appear to avoid the regions with the most intense X-ray emission. SZE displaced from X-ray centres implies that modeling cluster dynamics is non-trivial. The SZE distribution in the western parts of the cluster are co-spatial with the radio halo indicative of a common origin for the hot and relativistic electrons in the turbulent wake of the Bullet.

Key words. Galaxies: clusters: individual (1E 0657-56, RX J0658-5557)—radio continuum: general—techniques: interferometric.

1. Introduction

1E0657-56, known as the ‘Bullet cluster’, is one of the hottest known clusters. It is a cluster collision/merger event at $z \sim 0.296$, with the larger, westward cluster being ∼10 times the mass of the smaller ‘bullet’. It is known to have a strong radio halo (Liang *et al.* 2000), and the Sunyaev–Zel’dovich effect (Andreani *et al.* 1999; Halverson *et al.* 2009), and is X-ray bright (Markevitch *et al.* 2002), though it is known most notably for providing the most direct proof of the existence of dark matter (Clowe *et al.* 2006).

We present 18 GHz SZE observations of the Bullet cluster, after subtracting a model of the radio halo, which is also observed at 18 GHz. Details about observations, source-subtraction and imaging are described in Malu *et al.* (2010).

2. Subtraction of the radio halo

Previous observations of the radio halo in the Bullet cluster (Liang *et al.* 2000) provide spectral index and intensity distribution with sufficient angular resolution, and we model the radio halo contribution in our 18 GHz image based on their data. There was no evidence for spatial variations in the spectral index, and the data was best fit with a single power-law spectral slope of $\alpha = -1.3 \pm 0.1$ between 0.8–8 GHz.

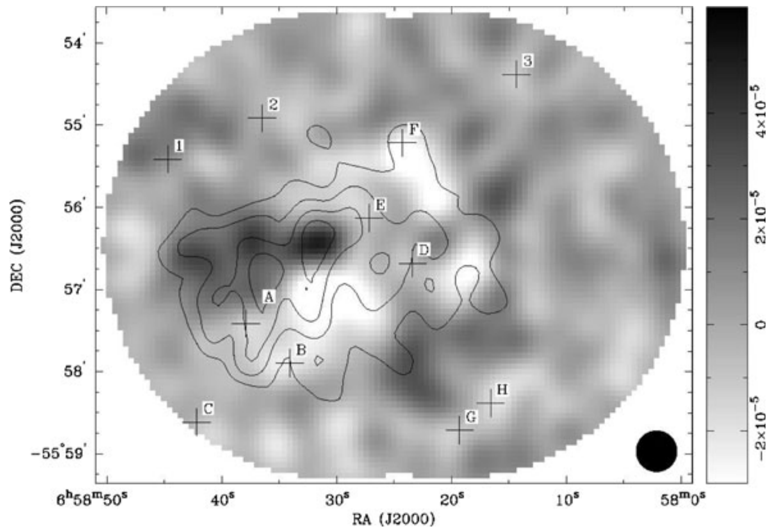

Figure 1. Grey scales represent the 18 GHz mosaic image of the bullet cluster with unresolved continuum sources subtracted; the image has been smoothed to a beam of FWHM 30″. Overlaid are contours representing the expected radio halo component in the 18-GHz ATCA mosaic image; contours are at 20, 40, 60 and 80 μJy beam^{-1}. Locations of discrete sources detected by Liang *et al.* (2000) are marked with cross symbols in this image.

The 1.344 GHz image of the radio halo[1] was corrected for the telescope primary beam attenuation at their observing frequency, an image of the radio halo component was isolated – scaled to 18 GHz adopting a spectral index of $\alpha = -1.3$, and attenuated by the mosaic gain function at our observing frequency. In Fig. 1 we show the 18-GHz image of the Bullet cluster using grey scales, *before any subtraction of the radio halo component*, with this processed image that represents the expected halo component overlaid as contours. The 18-GHz image in Fig. 1, which has been smoothed to a beam of FWHM 30″, clearly shows negative intensity values towards the central regions of the Bullet cluster. These SZE features appear to be confined within, and bounded by the lowest intensity contours of the halo component and are obvious in the 18-GHz image prior to any subtraction of the halo component, which would only enhance these SZE features. Before subtraction of any halo contribution, the 18-GHz image shows a peak in the flux density at the peak of the halo and positive 18-GHz emission towards the eastern parts of the halo. Most noteworthy is the negative peak, representing a deep SZE ‘hole’, to the south of the peak in the expected halo contribution.

The image of the Bullet cluster was convolved to a final beam of FWHM 23″.8 × 21″.4 at 80° P.A., which is the beam of the 1.344 GHz image. The halo image was then subtracted from this image and a contour 18 GHz image of the Bullet cluster, with all continuum sources including the halo subtracted, is shown in Fig. 2.

[1]The 1.344 GHz image with embedded unresolved sources subtracted was kindly provided to us by Dr. Liang.

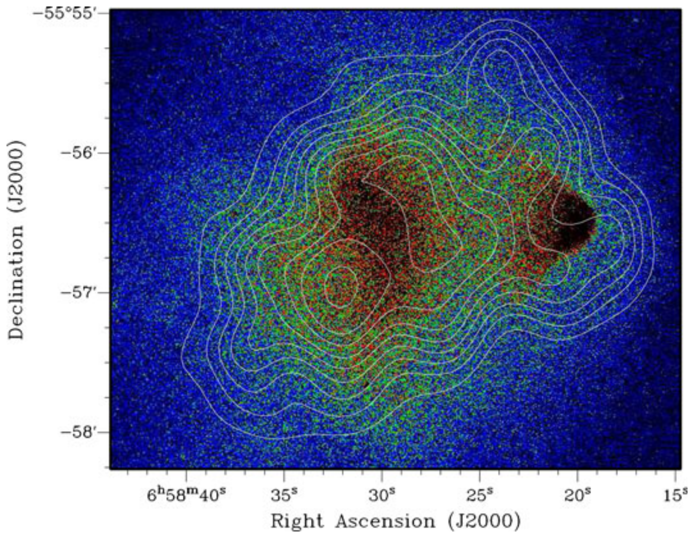

Figure 2. Contours represent the 18 GHz mosaic image of the SZE in the Bullet cluster; the image has been smoothed to a beam of FWHM 30″. Contours are at (−20, −16, −12, −8, −6, −4, −3, −2) times the image rms noise of 8.4 μJy beam^{-1}. Colours represent Chandra X-ray emission.

2.1 *Possible errors in radio halo subtraction*

Assuming an uncertainty of 0.1 in the spectral index of the halo, we infer an uncertainty of ±20% in the peak SZE dip and 5″ in its position. Over most of the SZE distribution as well, the estimated error in SZE decrement is ±20%.

A steepening in the spectral index beyond 10 GHz is possible, and is indeed expected in one model of radio halo formation. This would cause the SZ dip to reduce in amplitude, but not in size or shape. Liang *et al.* (2000) did not report any spatial variation in the spectral index, though these may exist between 10 and 16 GHz – this possibility was explored and the peak SZ dip position was found to vary by $< 5''$. This indicates the robustness of the SZ effect position.

3. A discussion of the SZE in the Bullet cluster

It is clear from Fig. 2 that the detection and the extent of the SZE is established. The sky distribution in the SZE does indeed coincide with the radio halo distribution in the western and southen parts; however, SZE is not detected towards the eastern end of the radio halo.

The deepest SZE feature is at RA: $06^{h}58^{m}32''.3$, DEC: $-55°57'03''$, and is clearly offset 35″ to the SE of the eastern X-ray emission peak.

It may be noted here that our 18 GHz ATCA image of the SZE distribution is an interferometer image and would miss larger scale extended features. We note here that Mason *et al.* (2010) and Massardi *et al.* (2010) found similar displacements of SZE dips from X-ray brightness peaks in the merging clusters RXJ1347-1145 and CL0152-1357 respectively.

4. Summary

We have presented 18 GHz observations of the Bullet cluster from the ATCA, and report robust detections of substructure in the Sunyaev–Zeldovich effect. We make reasonable assumptions about the radio halo in the cluster to extrapolate its observed properties from 0.8–8 GHz to 18 GHz and model and subtract the radio halo contribution. We image substantial substructure in SZE towards the Bullet cluster, finding a deep SZE hole that is significantly displaced from the peak in X-ray emission. The main conclusion from this work is that the intracluster gas in the merging Bullet cluster appears to have significant pressure distribution structure and peaks that differ from that in gas emission measure, galaxy and dark matter distributions. The work emphasizes the complexity in merger dynamics, and suggests that modeling the SZE contributions from cosmological clusters—for SZE cluster counts as well as SZE contributions to small-scale CMB anisotropy—is nontrivial.

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