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## **X-ray spectroscopy of merging galaxy clusters**

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## X-ray study of Abell 3365 with XMM-Newton

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### *Abstract*

We present an X-ray spectral analysis using *XMM-Newton*/EPIC observations ( $\sim 100$  ks) of the merging galaxy cluster Abell 3365 ( $z = 0.093$ ). Previous radio observations suggest the presence of a peripheral elongated radio relic to the east and a smaller radio relic candidate to the west of the cluster centre. We find evidence of temperature discontinuities at the location of both radio relics, indicating the presence of a shock with a Mach number of  $\mathcal{M} = 3.5 \pm 0.6$  towards the east and a second shock with  $\mathcal{M} = 3.9 \pm 0.8$  towards the west. We also identify a cold front at  $r \sim 1.6'$  from the X-ray emission peak. Based on the shock velocities, we estimate that the dynamical age of the main merger along the east-west direction is  $\sim 0.6$  Gyr. We find as well that the standard shock acceleration scenario from the thermal pool is consistent with the electron acceleration mechanism at the eastern radio relic. In addition, we study the distribution of the temperature, iron (Fe) abundance and pseudo-entropy along the merging axis. Our results show that remnants of a metal-rich cool-core can partially or totally survive after the merging activity. Finally, we find that the merger can displace the metal-rich and low entropy gas from the potential well towards the cold front as suggested by numerical simulations.

## 3.1 Introduction

Galaxy clusters are the largest virialized structures in the Universe and grow hierarchically via accretion and merging of less massive subclusters. During this merging process, turbulence, shocks and cold fronts (CF) arise in the hot intra-cluster medium (ICM) as a result of the strong merging activity (Markevitch & Vikhlinin 2007). Cold fronts delimit the boundary between the infalling subcluster's cool dense gas and the hot cluster atmosphere. Shocks are large scale structures that propagate along the hot ICM out to the cluster outskirts, where they are usually found. Both can be detected by temperature and density discontinuities in the ICM via spectral analysis and X-ray surface brightness (SB) edges, respectively. Moreover, shocks present a discontinuity as well in the pressure distribution, while cold fronts maintain it uniform across the edge (Vikhlinin et al. 2001). Shocks in galaxy clusters (typically characterized by a Mach number  $\mathcal{M} \leq 3-5$ ) are thought to (re)accelerate electrons in the ICM via first-order Fermi diffusive shock acceleration (hereafter DSA, Bell 1987; Blandford & Eichler 1987). These relativistic particles may produce non-thermal synchrotron emission in the form of radio relics in the presence of an amplified magnetic field. These radio features are elongated, polarized and steep-spectrum ( $\alpha < -1$ , being  $S_\nu \propto \nu^\alpha$ ) structures located usually at the cluster periphery (for a theoretical and observational review, respectively, see Brunetti & Jones 2014; van Weeren et al. 2019). Turbulence generated in the merger may also (re)accelerate particles generating unpolarized cluster-wide radio phenomena known as radio haloes (Brunetti et al. 2001; Feretti et al. 2012; van Weeren et al. 2019).

Nowadays the number of shock detections in merging galaxy clusters is increasing (for recent works, e. g. Akamatsu et al. 2017; Thölken et al. 2018; Urdampilleta et al. 2018; Di Gennaro et al. 2019; Botteon et al. 2019a). In some cases these shocks appear at the same or similar location as radio relics (see Table 1 of van Weeren et al. 2019). The study of the shock-relic connection and their radial distribution throughout the ICM improves our understanding of the dynamical stage of the cluster. Moreover, a detailed spectral analysis along the merging axis, including a study of their metallicity distribution, can provide valuable information on the chemical evolution and dynamical history of the merged ICM (Urdampilleta et al. 2019).

In this paper, we analyse the temperature and surface brightness discontinuities in the outskirts and central ICM of Abell 3365 (Abell et al. 1989, hereafter A3365), together with the temperature, Fe abundance, and pseudo-entropy distribution along the main merging axis. For this purpose we use observations taken by the *XMM-Newton* satellite. A3365 is a nearby ( $z = 0.093$ , Struble & Rood 1999) multi-merging galaxy cluster detected in X-rays by *ROSAT* and named as RXC J0548.8-2154 (Böhringer et al. 2007). A3365 has  $M_{500} = 1.7 \times 10^{14} M_\odot$  obtained from X-ray observations (Lovisari & Reiprich 2019). Based on this value and using the self-similar quantities described in Appendix A of Arnaud et al. (2010), we estimate  $r_{500} = 0.81$  Mpc =  $7.82'$  (at this redshift) and  $T_{500} = 3.14$  keV. A3365 hosts one radio relic at the east (hereafter relic E) and one radio relic candidate at the west (hereafter relic CW) discovered in the NVSS survey and observed by van Weeren et al. (2011a) with the VLA and WSRT at 1.4 GHz. As described by van Weeren et al. (2011a) relic E and relic CW have an angular extension of  $5.5'$  or 560 kpc and  $2.3'$  or 235 kpc, respectively at this

redshift (see Fig. 3.1).

A3365 consists of three subclusters (Golovich et al. 2018), see Fig. 3.1. They all have similar redshift, and the main components 1 and 3 are separated by a distance of 9'. They are considered as part of the same merging system (Golovich et al. 2018) named along this paper as A3365. The mass ratio between these two main subclusters is 5:1, respectively (Bonafede et al. 2017). The most massive component 1 has itself two sub-components. The X-ray emission peak (hereafter 1b) is displaced by 2.5' towards the west from sub-component 1a. The recent spectroscopic survey by Golovich et al. (2018) shows that A3365 contains 150 cluster members, is located at a redshift of  $0.09273 \pm 0.00028$  and has a velocity dispersion of  $981 \pm 58$  km/s. The red sequence distribution suggests that the merging system is formed by three subclusters (see their Fig. 25 for more details): one is coincident with A3365\_1a towards the east, an other is in a similar position as A3365\_3, in the middle, and the last one is towards the west (hereafter A3365\_2), see Fig. 3.1. Golovich et al. (2018) suggest that the main merging activity occurred along the east-west direction, where A3365 has crossed the A3365\_1a subcluster, stripping the gas of both subclusters in the east-west direction, highly disturbing the ICM, and forming the cometary tail towards the east. The spatial distribution seems to suggest that the merger between A3365\_1a and A3365\_3 is associated with the relic E. However, there is not a clear connection of this merger with the relic CW, suggesting that it might have a different origin. Golovich et al. (2018) also explain that A3365\_1a shows two bright galaxies, which may indicate an ongoing merging activity. Finally, A3365\_2 seems to advance towards A3365\_3 and might be an indication that it has still not merged. Here we use *XMM-Newton* to investigate the merging scenario in more detail.

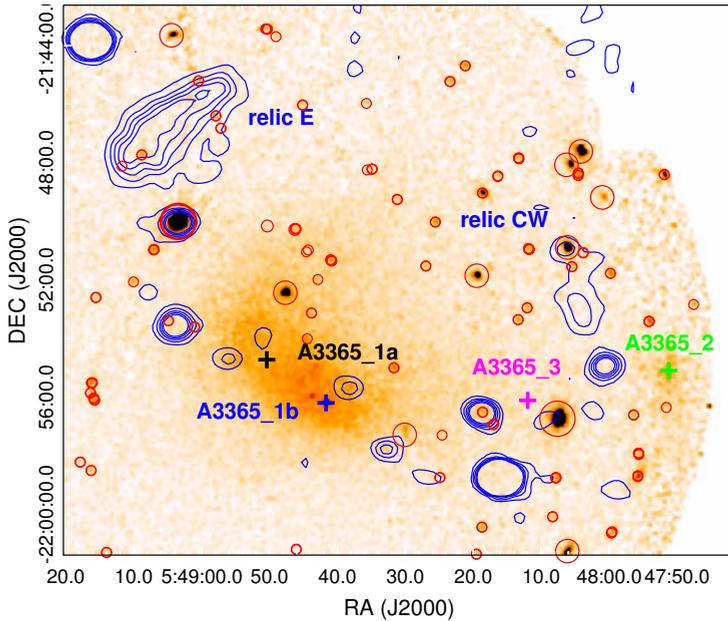
For this analysis, we use the values of protosolar abundances ( $Z_{\odot}$ ) reported by Lodders et al. (2009). We assume cosmological parameters  $H_0 = 70$  km/s/Mpc,  $\Omega_M = 0.27$  and  $\Omega_{\Lambda} = 0.73$ , respectively, which give 104 kpc per 1 arcmin at  $z = 0.093$ . All errors are given at  $1\sigma$  (68 %) confidence level unless otherwise stated and all the spectral analysis made use of the modified Cash statistics (Cash 1979; Kaastra 2017a).

**Table 3.1:** Observations and net exposure times.

Sequence ID	Name	Position (J2000) (RA, Dec.)	Observation starting date	M1 (ks)	M2 (ks)	pn (ks)
0760970101	A3365-p1	(05:48:47.00, -21:54:34)	2016-03-29	71	75	65
0677181301	A3365-p2	(05:48:50.38, -21:54:43)	2011-09-02	27	27	26

## 3.2 Observations and data reduction

The two available *XMM-Newton* observations of A3365 are listed in Table 3.1. Both data sets are reduced using the *XMM-Newton* Science Analysis System (SAS) v17.0.0, with the



**Figure 3.1:** XMM-Newton smoothed image of A3365 in the 0.5–2 keV band. Red circles are the point sources that have been removed. VLA 1.4 GHz radio contours are shown in blue. The centre of the three subclusters: A3365\_1a, A3365\_2 and A3365\_3, identified by Golovich et al. (2018) are marked with black, magenta and green crosses, respectively. The X-ray emission peak is shown with a blue cross, A3365\_1b.

calibration files from June 2018. For this analysis we use only the observations of the EPIC instrument, containing the MOS and pn detectors. We first apply the standard pipeline commands `emproc` and `eproc`. Next, we filter the soft-proton (SP) flares by building Good Time Interval (GTI) files. For this process we use the method detailed in Urdampilleta et al. (2019) and extensively explained in Appendix A.1 of Mernier et al. (2015). We identify and exclude the point sources in the complete FOV with a circular region of  $10''$  radius (see Fig. 3.1), except where higher radii are needed to cover larger sources (see Appendix A.2 of Mernier et al. 2015). We use the SAS task `edetect_chain` for this purpose. We keep the single, double, triple and quadruple events in MOS (`pattern`  $\leq 12$ ) and only the single pixel events in pn (`pattern` = 0). We also correct the out-of-time events from the pn detector.

### 3.3 Spectral analysis

In our spectral analysis of A3365, we assume that the observed spectra include the following components: optically thin thermal plasma emission from the ICM in collisional ionization equilibrium, and the background consisting of the local hot bubble (LHB), the Milky Way halo (MWH), the cosmic X-ray background (CXB), the hard particle (HP) background

and residual soft-protons (SP). The models used for each of the background components are detailed in Urdampilleta et al. (2019) and Mernier et al. (2015). The estimation of the sky background components (LHB, MHW and CXB) is obtained from a *ROSAT* observation of an offset annulus surrounding A3365, using the X-ray Background Tool<sup>1</sup>. The parameters of the SP components are obtained fitting the total FOV ( $r = 15'$ ) EPIC spectra, where the ICM *cie* (SPEX) model parameters are also left free. The best-fit parameters of the background components for each observation are listed in Table 3.2. The emission models are corrected for the cosmological redshift and absorbed by the galactic interstellar medium. We adopt the weighted total hydrogen column density  $N_{\text{H,tot}} = 2.94 \times 10^{20} \text{ cm}^{-2}$  (Willingale et al. 2013)<sup>2</sup>.

**Table 3.2:** Best-fit parameter values of the total background estimated for the A3365-p1 and A3365-p2 observations.

	$Norm^a$	$kT$ (keV)	$\Gamma$
MWH	$0.10 \pm 0.10$	$0.17 \pm 0.02$	–
LHB	$0.46 \pm 0.07$	0.08 (fixed)	–
CXB	$1.81 \pm 0.22$	–	1.41 (fixed)
A3365-p1			
SP MOS1	$1.32 \pm 0.13$	–	$1.40 \pm 0.02$
SP MOS2	$2.01 \pm 0.17$	–	$1.40 \pm 0.02$
SP pn	$4.88 \pm 0.67$	–	$0.88 \pm 0.03$
A3365-p2			
SP MOS1	$1.65 \pm 0.37$	–	$1.40 \pm 0.02$
SP MOS2	$2.19 \pm 0.22$	–	$1.40 \pm 0.02$
SP pn	$5.05 \pm 0.25$	–	$1.40 \pm 0.10$

<sup>a</sup> For LHB and MWH norm in units of  $10^{70} \text{ m}^{-3} \text{ arcmin}^{-2}$   
 For CXB norm in units of  $10^{50} \text{ ph s}^{-1} \text{ keV}^{-1} \text{ arcmin}^{-2}$   
 For SP norm in units of  $10^{45} \text{ ph s}^{-1} \text{ keV}^{-1} \text{ arcmin}^{-2}$

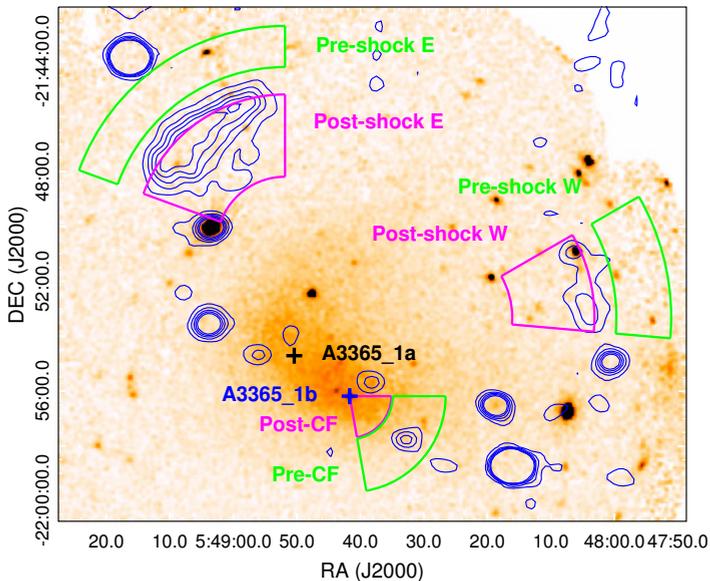
The spectral analysis software used in this work is SPEX<sup>3</sup> (Kaastra et al. 1996, 2017c) version 3.05.00 with SPEXACT (SPEX Atomic Code and Tables) version 3.05.00. We fit simultaneously the spectra of the MOS (energy range from 0.5 to 10 keV) and pn (0.6–10 keV) detectors. We apply the method of optimal binning (Kaastra & Bleeker 2016). A single temperature plasma is assumed for all the sectors in this study. We leave as free parameters the temperature,  $kT$ , the metal abundance,  $Z$ , and the normalization,  $Norm$ . All metal

<sup>1</sup><https://heasarc.gsfc.nasa.gov/cgi-bin/Tools/xraybg/xraybg.pl>

<sup>2</sup><http://www.swift.ac.uk/analysis/nhtot/>

<sup>3</sup><https://www.sron.nl/astrophysics-spex>

abundances are tied to the Fe abundance. We account for the effect of systematic uncertainties related to the  $\pm 10\%$  variation in the normalization of the sky background and non X-ray background components (Mernier et al. 2017; Urdampilleta et al. 2019). The contribution of these systematic uncertainties is further included in our analysis and results.



**Figure 3.2:** Same as Fig. 3.1, indicating spectral extraction regions. The green sectors represent the pre-shock and pre-cold front regions of relic E, relic CW and CF. The magenta sectors are the post-shock and post-cold front regions. The center of A3365\_1a and A3365\_1b are marked with black and blue crosses.

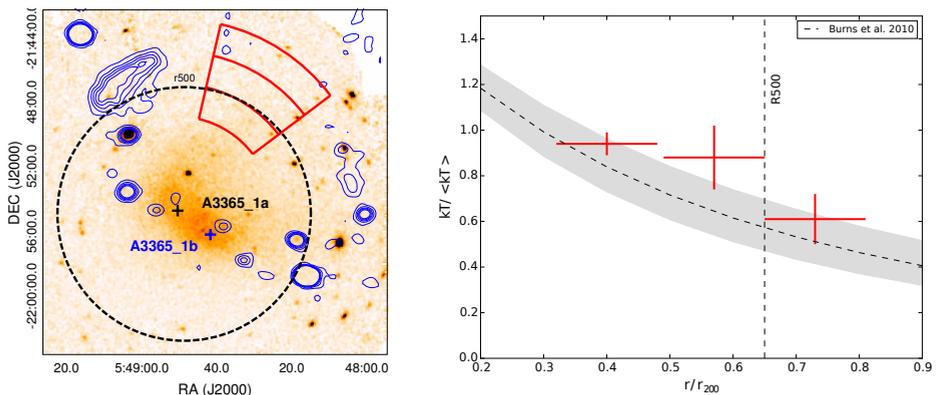
### 3.4 X-ray surface brightness profile

In order to confirm the evidence of shocks and cold fronts characteristic of merging galaxy clusters, the presence of SB profile discontinuities should be found at the same location as temperature discontinuities. We adopt a broken power-law density profile to describe the density. Assuming spherical symmetry, the density distribution is given by:

$$\begin{cases} n_2(r) = n_0 \left( \frac{r}{r_{\text{sh}}} \right)^{-\alpha_2} & r \leq r_{\text{sh}} \\ n_1(r) = \frac{1}{C} n_0 \left( \frac{r}{r_{\text{sh}}} \right)^{-\alpha_1} & r > r_{\text{sh}} \end{cases} \quad (3.1)$$

where  $n_0$  is the model density normalization,  $r$  is the radius from the centre of the sector,  $r_{\text{sh}}$  is the discontinuity location,  $\alpha_1$  and  $\alpha_2$  are the power-law indices. At the location of the

SB discontinuity the downstream (post-shock or post-CF) density,  $n_2$ , is higher by a factor of  $C = n_2/n_1$  compared with  $n_1$ , the upstream (pre-shock or pre-CF) density. This factor  $C$  is known as the compression factor. We assume that the X-ray emissivity is proportional to the density squared ( $S_X \propto n^2$ ) and integrate the cluster emission along the line of sight in the 0.5–2 keV energy band. For the sky background we fit the X-ray SB distribution with a constant model at large radii and we subtract it. Once the soft proton contribution and the instrumental and sky backgrounds are subtracted and all the point sources are removed we fit the X-ray SB, leaving all model parameters listed above free to vary.



**Figure 3.3:** *Left panel:* Same as Fig. 3.1, showing extraction regions for the 'relaxed' direction of the cluster (orthogonal to the merging axis) in red. The black dashed circle represents  $r_{500}$ . The center of A3365\_1a and A3365\_1b are marked with black and blue crosses. *Right panel:* The temperature distribution of the red sectors compared with the Burns et al. (2010) 'universal' profile for relaxed clusters. The gray shaded area shows the  $1\sigma$  scatter.

## 3.5 Results

### 3.5.1 Thermodynamical properties at the location of the radio relics

The diffuse radio emission in the A3365 outskirts (see Fig. 3.1) was classified as a radio relic in the east and a candidate radio relic in the west by van Weeren et al. (2011a), as described previously in Section 3.1. In this work, we investigate the possible presence of shocks associated with these radio relics analyzing the thermodynamical properties of the hot ICM. In order to search for a possible temperature discontinuity, we perform a spectral analysis of the post-shock and pre-shock E and CW regions, assuming that the candidate shocks are located at the external edge of the respective radio relics. We maintain a separation between upstream and downstream regions of  $\approx 1'$  to avoid any photon leakage from the brighter region. The Fe abundance is fixed to  $0.3 Z_{\odot}$  in these regions. The best-fit parameters for the post and pre-shock regions at the relics E and CW are shown in Table

3.3. They both show a significant drop of the temperature. Shocks are characterized by higher temperature and pressure in the post-shock (downstream) than in the pre-shock (upstream) region. The temperature jumps ( $kT_{\text{post}}/kT_{\text{pre}}$ ) are  $4.6 \pm 1.4$  and  $5.5 \pm 1.2$  for E and CW, respectively.

**Table 3.3:** Best-fit parameters for the post and pre-shock regions at the relic E and relic CW shown in Fig. 3.2.

	$kT$ (keV)	$Norm$ ( $10^{70} \text{ m}^{-3} \text{ arcmin}^{-2}$ )	C-stat/d.o.f.
Relic E			
Post	$4.45 \pm 1.08$	$1.10 \pm 0.07$	883/1009
Pre	$0.97 \pm 0.16$	$0.89 \pm 0.04$	1097/1024
Relic CW			
Post	$4.72 \pm 0.90$	$2.12 \pm 0.10$	1056/933
Pre	$0.86 \pm 0.10$	$0.33 \pm 0.07$	960/923

We have also analyzed three regions (see red circular sectors in Fig. 3.3 *left*) orthogonal to the merging axis. We have compared their radial temperature profile with the 'universal' distribution of Burns et al. (2010) for relaxed clusters. For that purpose, we assume the location of A3365\_1a as the centroid, the average temperature  $T_{500} = 3.14$  keV, and  $r_{200} \sim 0.65r_{500} = 12'$  (Reiprich et al. 2013). As shown in Fig. 3.3 *right*, the temperature profile in this direction presents a smooth decrease and is consistent with the expected distribution for relaxed clusters.

Additionally, we have determined the SB profile from circular sectors with the same angular appearing as the post and pre-shock E (centre at RA =  $5^{\text{h}}48^{\text{m}}51^{\text{s}}85$ , Dec. =  $-21^{\circ}50'41''48$ ) regions in the east and post and pre-shock W (RA =  $5^{\text{h}}48^{\text{m}}29^{\text{s}}04$ , Dec. =  $-21^{\circ}53'18''19$ ) in the west, shown in Fig. 3.2. The SB in these peripheral regions is too shallow, so the extracted profiles are mainly dominated by the background. Due to this low SB and reduced integration time, we are not able to detect SB discontinuities and obtain the best-fit parameters based on these SB profiles.

Furthermore, we can calculate the average density,  $n$ , in the post and pre-shock regions because  $Norm \propto 1.2n^2V$ .  $V$  is the emitting volume projected along the line-of-sight (LOS). We assume that only the sphere between the maximum and minimum radius corresponding to each circular sector contributes to the emission (Henry et al. 2004; Mahdavi et al. 2005). We estimate  $V$  as  $V = 2SL/3$ , with  $L = 2\sqrt{(R_{\text{max}}^2 - R_{\text{min}}^2)}$ , and  $S$  the area of the sectors in the plane of the sky.

For the relic E, we estimate  $n_1 = (1.63 \pm 0.05) \times 10^{-4} \text{ cm}^{-3}$  and  $n_2 = (1.64 \pm 0.04) \times 10^{-4} \text{ cm}^{-3}$ . At face value, this does not support the presence of a strong shock as indicated by the temperature jump. However, these measurements represent emission-weighted averages over a (presumably) steep radial gradient in both the post and pre-shock regions that

is unresolved (that is to say, the current signal to noise only allows for a single integrated measurement for each region). This, and complicated projection effects due to an aspherical shock front shape, could mask the presence of such a shock; in this case, the shock would be easier to detect in the temperature profile, where the radial gradient is relatively shallower than the density gradient.

For the relic CW, the density values are  $n_1 = (0.97 \pm 0.10) \times 10^{-4} \text{ cm}^{-3}$  and  $n_2 = (2.41 \pm 0.06) \times 10^{-4} \text{ cm}^{-3}$ . In this case, the compression factor is  $C = 2.5 \pm 0.3$ . This value is lower but close to the  $C$  derived from the temperature discontinuity described in Table 3.6. For the CW relic, therefore, both the density and temperature profiles show evidence for the presence of a shock.

### 3.5.2 Substructure in the central ICM

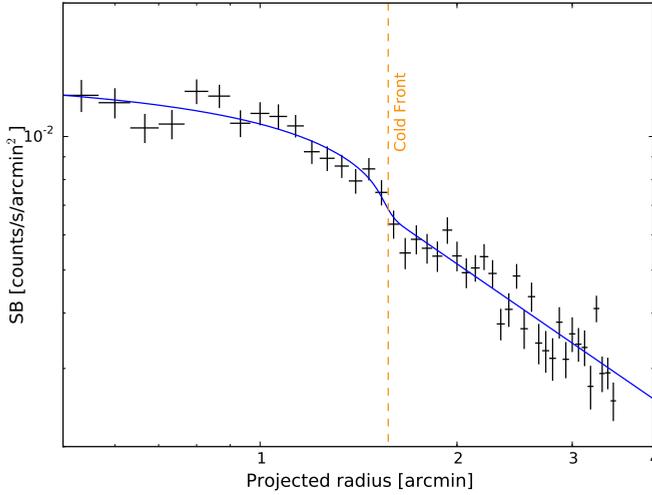
We search for the X-ray SB discontinuity in different edges of the bright and disturbed ICM. We find a clear discontinuity in the western side, close to the X-ray peak. We use for the X-ray SB profile analysis a circular sector centred on the X-ray peak, with exactly the same shape as the post-CF (magenta) and pre-CF (green) regions together, see Fig. 3.2. The radial X-ray SB profile obtained is shown in Fig. 3.4. The best-fit parameters of the model show a discontinuity at  $r_{sh} = 1.57 \pm 0.05$  arcmin with a compression factor value of  $C = 1.33 \pm 0.08$ . At this same location, we measure the temperature in the post-CF ( $r = 0' - 1.57'$ ) and pre-CF ( $r = 1.57' - 3.5'$ ) regions (see Fig. 3.2 and Table 3.4) and we obtain a temperature jump of  $T_1/T_2 = 0.79 \pm 0.05$ . Using the temperature jump and the compression factor, we obtain a pressure ratio of  $P_1/P_2 = 1.05 \pm 0.09$ , consistent with a constant pressure value across the edge. This proves that the X-ray discontinuity found in the disturbed ICM edge is a cold front.

**Table 3.4:** Best-fit parameters for the cold front regions shown in Fig. 3.2.

	$kT$ (keV)	$Z$ ( $Z_\odot$ )	C-stat/d.o.f.
Post-CF	$2.62 \pm 0.10$	$0.59 \pm 0.09$	962/913
Pre-CF	$3.30 \pm 0.17$	$0.25 \pm 0.08$	1039/1003

### 3.5.3 Temperature and Fe abundance distributions along the merging axis

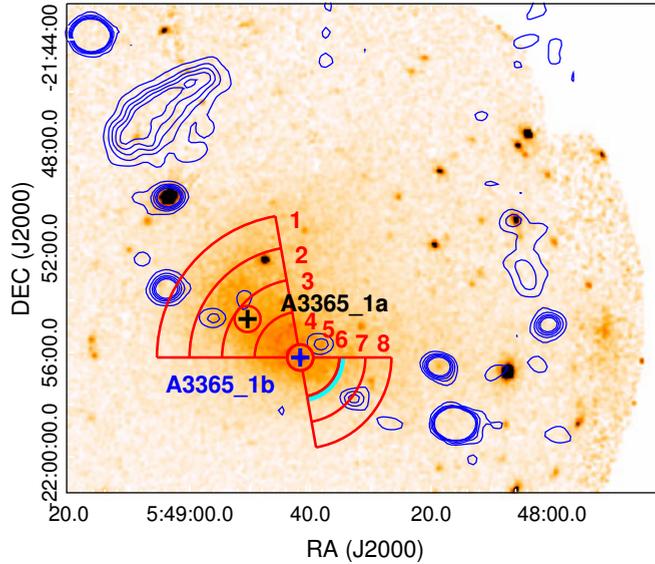
As shown in Fig. 3.5, we cover the disturbed ICM elongation with circular sectors following the X-ray emission in the east-west direction. We dedicate two circles to the subcore of the main subcluster, A3365\_1a, and X-ray peak (A3365\_1b). We fit the cluster emission and the background spectra, excluding the point sources as explained in Section 3.3. We use the X-ray emission peak as the centroid for our temperature and abundance distributions along the merging axis (see Fig. 3.6).



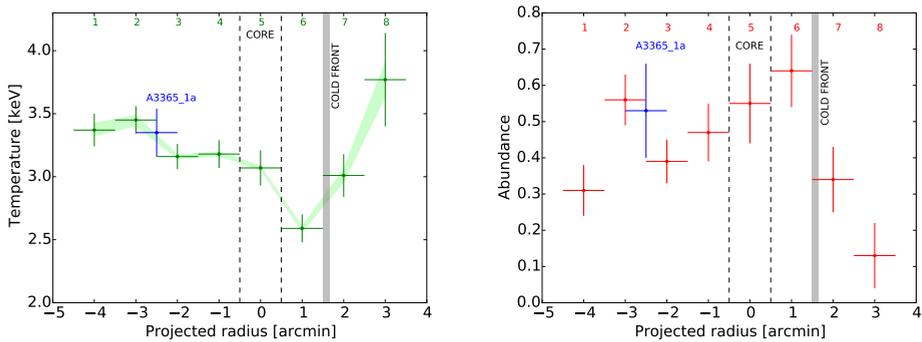
**Figure 3.4:** Radial X-ray SB profile across the cold front in the 0.5-2.0 keV band using the XMM-Newton observations. The profile is corrected for exposure, background and soft protons, and point sources are removed. The best-fit model is shown in blue and the vertical dashed orange line represents the estimated position of the cold front.

**Table 3.5:** Best-fit parameters for A3365 regions shown in Fig. 3.5.

Region	Radius (')	$kT$ (keV)	$Z$ ( $Z_{\odot}$ )	$Norm$ ( $10^{70} \text{ m}^{-3} \text{ arcmin}^{-2}$ )	C-stat/d.o.f.
1	$-4.0 \pm 0.5$	$3.37 \pm 0.13$	$0.31 \pm 0.07$	$10.12 \pm 0.27$	1077/1006
2	$-3.0 \pm 0.5$	$3.45 \pm 0.11$	$0.56 \pm 0.07$	$13.46 \pm 0.33$	1022/999
3	$-2.0 \pm 0.5$	$3.16 \pm 0.10$	$0.39 \pm 0.06$	$18.16 \pm 0.43$	1092/996
4	$-1.0 \pm 0.5$	$3.18 \pm 0.11$	$0.47 \pm 0.08$	$24.92 \pm 0.79$	967/922
5 (A3365_1b)	$0.0 \pm 0.5$	$3.07 \pm 0.14$	$0.55 \pm 0.11$	$25.97 \pm 0.10$	927/880
6	$1.0 \pm 0.5$	$2.59 \pm 0.11$	$0.64 \pm 0.10$	$14.90 \pm 0.65$	941/893
7	$2.0 \pm 0.5$	$3.01 \pm 0.17$	$0.34 \pm 0.09$	$8.63 \pm 0.36$	1014/927
8	$3.0 \pm 0.5$	$3.77 \pm 0.37$	$0.13 \pm 0.09$	$4.25 \pm 0.19$	1046/935
A3365_1a	$-2.5 \pm 0.5$	$3.35 \pm 0.19$	$0.53 \pm 0.13$	$17.44 \pm 0.76$	929/884



**Figure 3.5:** Same as Fig. 3.1, where the red sectors represent the regions used for the temperature and abundance distributions. The cyan line shows the location of the cold front. The centre of A3365\_1a and the A3365\_1b are marked with black and blue crosses.



**Figure 3.6:** *Left panel:* The temperature distribution of A3365 along the merging direction. *Right panel:* The abundance distribution of A3365. The shaded area in the left panel represent the systematic uncertainties. Systematic errors on abundance are much smaller than statistical and thus not shown in the right panel.

The best-fit parameters of the temperature and abundance distributions are presented in Table 3.5. Sectors one to five, which are contained in the cometary tail, have a uniform temperature distribution between 3–3.5 keV. However, the temperature clearly decreases downstream of the cold front, increasing with a significant gradient in the cold front upstream region. The abundance distribution shows some signatures of two enhanced peaks, one associated with the main subcluster core, A3365\_1a, and the other one with the cold

front downstream region, both with values close to  $\sim 0.6 Z_{\odot}$ . The gas located just behind the cold front is displaced from the central potential well by the internal dynamical forces of the cold front (Heinz et al. 2003). These same effects have been already observed in Abell 3667 and Abell 665 (Lovisari et al. 2009; Urdampilleta et al. 2019).

## 3.6 Discussion

### 3.6.1 Shock jump conditions and properties

Based on the temperature jump found in the A3365 merging galaxy cluster outskirts, we report the presence of two X-ray shock candidates associated with the relic E and relic CW. Here we present the shock properties (the Mach number,  $\mathcal{M}$ , the compression factor,  $C$ , and the shock velocity,  $v_{\text{shock}}$ , among others), see Table 3.6.  $\mathcal{M}$  and  $C$  are calculated from the Rankine-Hugoniot jump condition (Landau & Lifshitz 1959) assuming that all of the dissipated shock energy is thermalized and the ratio of specific heats (the adiabatic index) is  $\gamma = 5/3$ :

$$\frac{T_2}{T_1} = \frac{5\mathcal{M}^4 + 14\mathcal{M}^2 - 3}{16\mathcal{M}^2}, \quad (3.2)$$

$$C = \frac{n_2}{n_1} = \frac{4\mathcal{M}^2}{\mathcal{M}^2 + 3}, \quad (3.3)$$

where  $n$  is the density, and the indices 2 and 1 corresponds to post-shock and pre-shock regions, respectively.

The Mach numbers estimated from the temperature discontinuities described in the previous section are  $\mathcal{M}_E = 3.5 \pm 0.6$  and  $\mathcal{M}_{CW} = 3.9 \pm 0.8$ . The presence of shocks with  $\mathcal{M} \gtrsim 3.0$  is uncommon in galaxy clusters, with only few examples known until now (CIZA J224.8+5301, Akamatsu et al. 2015; 'Bullet', Shimwell et al. 2015; 'El Gordo', Botteon et al. 2016b; A665, Dasadia et al. 2016a; A3376, Urdampilleta et al. 2018).

The sound speed at the pre-shock regions is  $c_{s,E} \sim 508 \text{ km s}^{-1}$  and  $c_{s,W} \sim 479 \text{ km s}^{-1}$ , assuming  $c_s = \sqrt{\gamma k T_1 / \mu m_p}$  where  $\mu = 0.6$ . The shock propagation speed  $v_{\text{shock}} = \mathcal{M} \cdot c_s$  for the east and west is  $v_{\text{shock},E} = 1800 \pm 300 \text{ km s}^{-1}$  and  $v_{\text{shock},W} = 1900 \pm 300 \text{ km s}^{-1}$ , respectively. If we assume that the eastern shock is generated by the merger of A3365\_1a and A3365\_3 and it is moving with a constant velocity, we can calculate the dynamical age of the merger. The projected distance between A3365\_1a and the relic E is  $\sim 10'$ , which means  $\sim 1.04 \text{ Mpc}$  at  $z = 0.093$ . Thus, the time required to reach the actual position is  $\sim 0.6 \text{ Gyr}$ . We do the same exercise with the shock in the west assuming that is generated by the same merger. In this case, the distance between A3365\_1a and relic CW is  $\sim 11' = 1.17 \text{ Mpc}$ , resulting in a time of  $\sim 0.6 \text{ Gyr}$ . The upper limit of the merging time using the downstream gas velocity is in both cases  $\sim 2.0 \text{ Gyr}$ . Therefore, both shocks required the same time to propagate from the core passage up to their current location. In addition, we have no evidence of additional physical processes or mechanisms for the generation of the western shock. This might suggest that the possible origin of both shocks is the merger between A3365\_1a and A3365\_3.

As we explain in Section 3.1, DSA is based on first order Fermi acceleration and considers that there is a stationary and continuous injection. It accelerates relativistic electrons following a power-law spectrum  $n(E)dE \sim E^{-p}dE$  with  $p = (C + 2)/(C - 1)$ , producing a radio synchrotron emission whose emissivity depends on the frequency as  $S_\nu \propto \nu^\alpha$ . The two power law indexes  $p$  and the radio injection spectral index  $\alpha$  are related  $\alpha = -(p-1)/2$ . From our analysis we estimate the injection spectral index values of  $\alpha_E = -0.68 \pm 0.06$  and  $\alpha_W = -0.64 \pm 0.03$ . Unfortunately there are no available spectral indices derived from radio observations for their comparison to date. Future radio observations are needed to confirm these results.

### 3.6.2 Shock acceleration efficiency

Recent studies have demonstrated that the low efficiency of the DSA mechanism for low- $\mathcal{M}$  shocks ( $\mathcal{M} \leq 2-2.5$ ) is not enough for the electron acceleration to proceed from the thermal pool (for observational evidences on radio relics, Botteon et al. 2019b and theoretical arguments, Vink & Yamazaki 2014, Ha et al. 2018 and Ryu et al. 2019). For this reason, alternative mechanisms have been proposed lately, as for example the re-acceleration of pre-existing cosmic ray electrons (Markevitch et al. 2005; Kang et al. 2012; Fujita et al. 2015).

**Table 3.6:** Shock properties at relic E and relic CW.

	Mach No. $\mathcal{M}^a$	$v_{\text{shock}}$ (km s $^{-1}$ ) <sup>b</sup>	Compression $C^c$	Power-law slope $p^d$	Spectrum index $\alpha^e$
E	$3.5 \pm 0.6$	$1800 \pm 300$	$3.2 \pm 0.2$	$2.36 \pm 0.11$	$-0.68 \pm 0.06$
CW	$3.9 \pm 0.8$	$1900 \pm 300$	$3.3 \pm 0.2$	$2.28 \pm 0.05$	$-0.64 \pm 0.03$

<sup>a</sup>  $\mathcal{M}$  is obtained from eq. (3.2).

<sup>b</sup>  $v_{\text{shock}} = \mathcal{M} \cdot c_s = \sqrt{\gamma k T_1 / \mu m_p}$

<sup>c</sup>  $C$  from eq. (3.3).

<sup>d</sup>  $p = (C + 2)/(C - 1)$

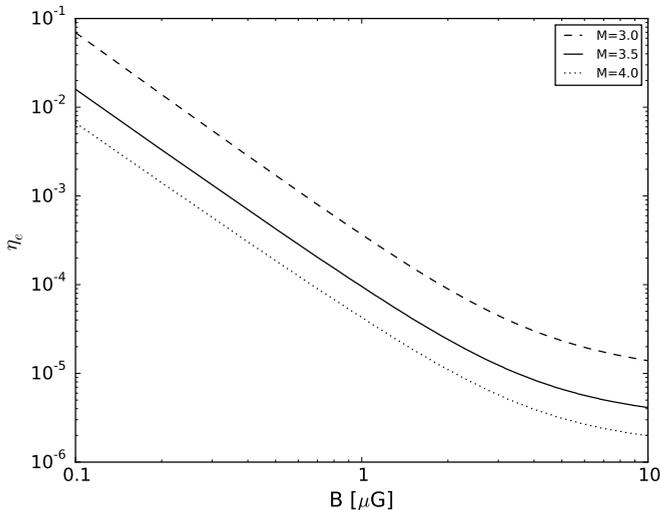
<sup>e</sup>  $\alpha = -(p - 1)/2$  predicted

In this case, if we assume DSA as the shock acceleration mechanism of the thermal electrons in radio relics, the electron acceleration efficiency,  $\eta_e$ , can be defined as the amount of kinetic energy flux at the shock moving at  $v_{\text{shock}}$ , which is converted into relativistic electrons and produces the synchrotron luminosity  $L_{\text{sync}}$  of the radio relic. Both parameters,  $\eta_e$  and  $L_{\text{sync}}$ , relate as (Brunetti & Jones 2014):

$$\eta_e = \left[ \frac{1}{2} \rho_1 v_{\text{shock}}^3 \left( 1 - \frac{1}{C^2} \right) \frac{B^2}{B^2 + B_{\text{CMB}}^2} S \right]^{-1} \Psi(\mathcal{M}) L_{\text{sync}}, \quad (3.4)$$

where  $\rho_1$  is the total upstream density,  $C$  the compression factor,  $S$  the shock surface,  $B_{\text{CMB}} = 3.25(1+z)^2$  and  $B$  are the magnetic field equivalent for the Cosmic Microwave Background radiation and the magnetic field for the radio relic in  $\mu\text{G}$ , respectively.  $\Psi(\mathcal{M})$  represents the ratio between the energy flux injected in 'all' particles and those only visible in

radio (for a more detailed description of the computation and equations see Botteon et al. 2019b).



**Figure 3.7:** Electron acceleration efficiency,  $\eta_e$  as a function of the magnetic field,  $B$ , for  $\mathcal{M} = 3.0, 3.5$  and 4.0.

Figure 3.7 shows the electron acceleration efficiency,  $\eta_e$ , as a function of the magnetic field,  $B$ , at the relic E. Radio data needed for the calculation of the electron acceleration efficiency in the relic WC are not available in the literature, therefore we only calculate it for relic E. We assume  $S_{1.4\text{GHz}} = 38.9$  mJy,  $S = \pi \times ((LLS/2)^2) = \pi \times ((644/2)^2)$  kpc<sup>2</sup> being  $LLS$  the radio relic largest linear size (see Nuza et al. 2017), the temperature and electron density in the downstream region are  $kT_d = 4.45$  keV and  $n_d = 1.64 \times 10^{-4}$  cm<sup>-3</sup>, respectively. The density in the upstream region is obtained from the Eq. (3.3). We obtain  $\eta_e$  values for three different Mach numbers of  $\mathcal{M} = 3.0, 3.5$  and 4.0. In the case of  $\mathcal{M} = 3.5$ , for  $B > 0.4$   $\mu\text{G}$ , the electron acceleration efficiency due to the shock is  $\eta_e \lesssim 10^{-3}$ . Therefore, in this case the standard DSA scenario cannot be excluded, where efficiencies of this order are expected for weak shocks (Brunetti & Jones 2014; Caprioli & Spitkovsky 2014; Hong et al. 2014; Ha et al. 2018). These results also agree with the recent findings of Botteon et al. (2019b) and Botteon et al. (2016b) for 'El Gordo' cluster, which suggest that DSA of thermal electrons is a valid mechanism in the case of shocks with high Mach number ( $\mathcal{M} \gtrsim 3$ ).

### 3.6.3 Cold front properties

We find evidence of X-ray SB and temperature discontinuities at the western edge of the highly disturbed ICM associated with a cold front. This front is perpendicular to the merging axis and moves presumably in the east-west direction, as shown in Fig. 3.2. It confines a cool and dense gas cloud moving through a hotter ambient gas (Markevitch & Vikhlinin

2007; Vikhlinin et al. 2001). The velocity of this cool gas cloud can be estimated using the density and temperature values derived from the X-ray SB and temperature discontinuities (Landau & Lifshitz 1959; Vikhlinin et al. 2001; Ichinohe et al. 2017; Urdampilleta et al. 2018). For that purpose, we assume that the cool gas is a spherical body moving through in the ambient gas.

The ratio of pressures between the stagnation point (index 0, where the fluid  $v = 0$ , in front of the blob) and the free stream (index 1) can be expressed as a function of the gas cloud speed  $v$  (or equivalently the Mach number assuming  $\mathcal{M}_1 = v/c_s$ , where  $c_s$  is sound velocity of the free stream) (Landau & Lifshitz 1959):

$$\frac{p_0}{p_1} = \begin{cases} \left(1 + \frac{\gamma-1}{2} \mathcal{M}_1^2\right)^{\gamma/(\gamma-1)} & (\mathcal{M}_1 \leq 1), \\ \left(\frac{\gamma+1}{2}\right)^{(\gamma+1)/(\gamma-1)} \mathcal{M}_1^2 \left(\gamma - \frac{\gamma-1}{2\mathcal{M}_1^2}\right)^{-1/(\gamma-1)} & (\mathcal{M}_1 > 1), \end{cases} \quad (3.5)$$

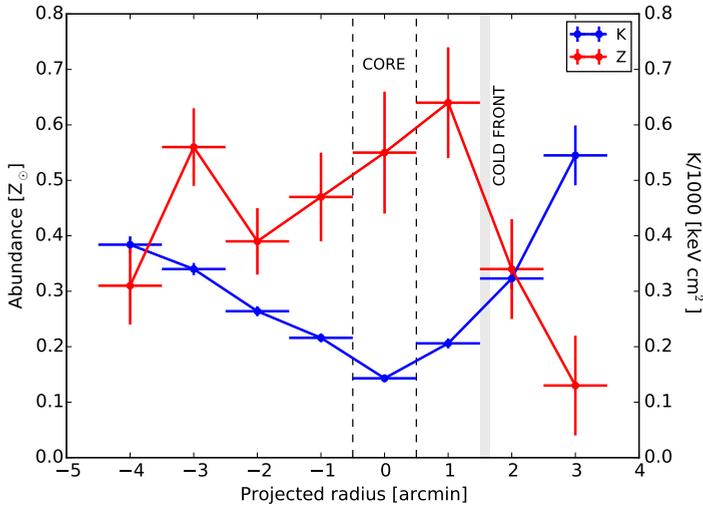
where  $\gamma = 5/3$  is the adiabatic index.

The gas dynamic parameters at the stagnation point cannot be measured directly. However, the pressure in the downstream region of the cold front has a similar value as the stagnation pressure as explained by Vikhlinin et al. (2001). For this reason, we assume  $T_0 = 2.62 \pm 0.10$  keV as the temperature downstream the cold front and  $T_1 = 3.30 \pm 0.17$  keV as the free stream region, upstream (Vikhlinin et al. 2001; Sarazin et al. 2016). The density of these regions is calculated from the best-fit parameter of the broken power-law model described in Section 3.4 and shown in Fig. 3.4. The pressure inside the cold front is  $p_0 = T_0 \times n_0 = (7.7 \pm 1.0) \times 10^{-3}$  keV cm $^{-3}$  and outside  $p_1 = T_1 \times n_1 = (4.2 \pm 0.6) \times 10^{-3}$  keV cm $^{-3}$  (both densities are calculated at the average point of the downstream and upstream regions). Thus, the pressure ratio is  $p_0/p_1 = 1.9 \pm 0.4$ , which corresponds to a subsonic Mach number of  $\mathcal{M}_1 = 0.92 \pm 0.07$  in the free stream. This value is consistent with the cold front in A3376 ( $\mathcal{M}_1 = 1.2 \pm 0.2$ , Urdampilleta et al. 2018) and slight higher than A3667 ( $\mathcal{M}_1 = 0.70 \pm 0.06$ , Ichinohe et al. 2017). The sound speed in this region is  $c_{cf} = \sqrt{\gamma k T_1 / \mu m_p} = 937 \pm 24$  km s $^{-1}$  with  $k T_1 = 3.30 \pm 0.17$  keV, giving the velocity of the cool gas cloud as  $v_{cf} = 862 \pm 69$  km s $^{-1}$ .

### 3.6.4 Pseudo-entropy distribution

We aim to better understand the thermal history of the disturbed ICM of A3365. For that reason, we calculate the pseudo-entropy,  $K \equiv kT \times n^{-2/3}$ , for each of the sectors described in Section 3.5.3. We use the data obtained from the spectral analysis, namely the temperature,  $kT$ , and the emission measure,  $Norm$ , to derive the density,  $n$ .

Figure 3.8 shows the pseudo-entropy distribution along the merging axis together with the Fe abundance profile. The distribution shows a clear low entropy minimum at the location of the X-ray peak of the merging system. Urdampilleta et al. (2019) observed the same behaviour in two of the merging clusters Abell 665 and 1RXS J0603.3+4214 (known as the Toothbrush cluster). This suggests that the cool-core of the progenitor subcluster has totally or partially remained after the merging activity. As a consequence, we may be in the presence of a cool-core remnant (Rossetti & Molendi 2010). Moreover, the presence



**Figure 3.8:** Scaled pseudo-entropy ( $K/1000$ ) and abundance distributions along the merging axis for A3365.

of the Fe abundance enhancement and the low temperature gas towards the contact discontinuity or cold front, supports the scenario described by the simulations of Heinz et al. (2003). As an effect of the merger, the cold dense core of the cluster is displaced from the centre of the potential well. As the velocity of the core reverses in an attempt to return to equilibrium, a shear layer is created driving the gas along the cold front backwards in the direction of the background flow. This brings the material with the lowest temperature and highest abundance from the centre of the cool core towards the cold front as shown by our results in Fig. 3.8.

### 3.7 Summary

We have presented an imaging and spectral analysis of A3365 ( $z = 0.093$ ) using *XMM-Newton* observations ( $\sim 100$  ks). The recent spectroscopic survey by Golovich et al. (2018) shows that A3365 is a complex merging system formed by three subclusters. Moreover, previous radio observations (van Weeren et al. 2011a) suggest this merging galaxy cluster hosts a radio relic to the east and a radio relic candidate to the west of the merging cluster centre.

In this work, we detect abrupt temperature jumps across both radio relic edges, suggesting the presence of two shocks associated with them in the cluster outskirts. For these shocks, we estimate the Mach number and the shock velocity based on the temperature jump, being  $\mathcal{M} = 3.5 \pm 0.6$  and  $v_{\text{shock}} \sim 1800 \pm 300 \text{ km s}^{-1}$  for the shock in the east, and  $\mathcal{M} = 3.9 \pm 0.8$  and  $v_{\text{shock}} \sim 1900 \pm 300 \text{ km s}^{-1}$ , for the shock in the west. Assuming that

they are moving with constant velocity, the time since core passage is  $\sim 0.6$  Gyr for both shocks. This might suggest that they originate in the same merger between A3365\_1a and A3365\_3. For the relic E, we compute the shock acceleration efficiency as a function of the magnetic field in the relic and we find that DSA scenario is a possible acceleration mechanism. Similar results have been found for shocks with  $\mathcal{M} \gtrsim 3$  as 'El Gordo' (Botteon et al. 2016b) and A3376 (Botteon et al. 2019b).

We also confirm by temperature and surface brightness discontinuities the presence of a cold front at  $r \sim 1.6'$  from the X-ray emission peak in the merging direction. It delimits a cool gas cloud moving with  $\mathcal{M} \sim 0.9$  and a speed of  $v \sim 860 \text{ km s}^{-1}$ .

In addition, we obtain the temperature, Fe abundance and pseudo-entropy distribution in the highly disturbed central parts of the ICM along the merging axis. We find signatures of two abundance peaks, one is coincident with A3365\_1a ( $\sim 0.6 Z_{\odot}$ ), and the other is located towards the cold front ( $\sim 0.6 Z_{\odot}$ ), displaced from the potential well. This is consistent with the simulations by Heinz et al. (2003), which suggest that the shock passage can affect the internal dynamics of the cool gas and move the low entropy and metal rich gas towards the cold front. Finally, and in line with previous results shown in e.g. (Urdampilleta et al. 2019), the pseudo-entropy distribution shows a relative low entropy minimum, which might suggest that remnants of the metal-rich cool-core can survive partially or totally after the merging activity.

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*"Hegoak ebaki banizkio,  
nerea izango zen,  
ez zuen alde egingo.  
Bainan, honela  
ez zen gehiago txoria izango,  
eta nik txoria nuen maite."*

*- Joxean Artze, Txoria txori*