XMM-Newton Observations of the Southeastern Radio Relic in Abell 3667

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ABSTRACT

Radio relics, elongated, non-thermal, structures located at the edges of galaxy clusters, are the result of synchrotron radiation from cosmic-ray electrons accelerated by merger-driven shocks at the cluster outskirts. However, X-ray observations of such shocks in some clusters suggest that they are too weak to efficiently accelerate electrons via diffusive shock acceleration to energies required to produce the observed radio power. We examine this issue in the merging galaxy cluster Abell 3667 (A3667), which hosts a pair of radio relics. While the Northwest relic in A3667 has been well studied in the radio and X-ray by multiple instruments, the Southeast relic region has only been observed so far by Suzaku, which detected a temperature jump across the relic, suggesting the presence of a weak shock. We present observations of the Southeastern region of A3667 with XMM-Newton centered on the radio relic. We confirm the existence of an X-ray shock with Mach number of about 1.8 from a clear detection of temperature jump and a tentative detection of a density jump, consistent with previous measurements by Suzaku. We discuss the implications of this measurement for diffusive shock acceleration as the main mechanism for explaining the origin of radio relics. We then speculate on the plausibility of alternative scenarios, including re-acceleration and variations in the Mach number along shock fronts.

Key words: acceleration of particles – shock waves – galaxies: clusters: individual: A3667 – X-rays: galaxies: clusters

1 INTRODUCTION

The growth of structure at large scales is driven by violent, energetic mergers of galaxy clusters. These events result in turbulence and shocks that propagate throughout the cluster volume. Observations of diffuse synchrotron emission in clusters indicate that some fraction of the energy generated by merger events is transferred into non-thermal components, including magnetic fields and cosmic rays, in the intracluster medium (ICM) (for recent reviews, see e.g., Feretti et al. 2012; Brunetti & Jones 2014). X-ray observations reveal that the hot thermal plasma that makes up the ICM in merging clusters is generally highly disturbed, as indicated by surface brightness discontinuities and complicated temperature profiles (e.g., Markevitch & Vikhlinin 2007).

Diffuse radio emission from clusters is typically classified by morphology (Feretti et al. 2012). Radio halos are characterized by ~Mpc-scale, unpolarized emission that tends to be centered on the center of the cluster, and are thought to be the result of turbulence throughout the ICM. Radio relics are found near the outskirts of merging clusters, often in pairs on opposite sides of the cluster, and tend to be highly elongated and moderately polarized at the 15 – 30% level. Radio relics are some of the best evidence for the existence of merger shocks in clusters (e.g., Ensslin et al. 1998; Brüggen et al. 2012).

If radio relics are the result of shock-driven particle acceleration, then these shocks should also be identifiable in X-ray observations of the ICM via a surface brightness discontinuity and corresponding temperature jump at the location of the shock. However, identification of these shocks is hampered by the fact that they are often in the outskirts of clusters, where the thermal gas density is low and the X-ray emission is therefore faint.

A fruitful approach to identify merger shocks so far has been to perform deep X-ray observations of clusters with radio relics. While there are currently over 50 observed radio relics, only a handful of those have an associated temper-
ature jump or surface brightness discontinuity observed in the X-ray band that suggests a shock front (recently, e.g., Akamatsu & Kawahara 2013; Eckert et al. 2016; Sarazin et al. 2016). In contrast, there are also several clusters with detected X-ray shocks that are not associated with radio relics (although they do host other diffuse radio emission such as halos; e.g. the western shock of the Bullet Cluster: Markevitch et al. (2002); Shimwell et al. (2014); A520: Markevitch et al. (2005); Vacca et al. (2014); A2146: Russell et al. (2010); Hlavacek-Larrondo et al. (2017)). Additionally, several shocks were found in merging clusters via surface brightness and temperature jumps in the Chandra archive by Botteon et al. (2017); however, none of these appear to be associated with radio relics (and only some host radio halos).

Abell 3667 (hereafter A3667; \(z = 0.0556 \pm 0.013\)) is a well-known merging cluster in the southern hemisphere that hosts a pair of radio relics to the Northwest (NW) and Southeast (SE) (Rottgering et al. 1997; Johnston-Hollitt 2003; Carretti et al. 2013; Hindson et al. 2014; Riseley et al. 2015). X-ray observations of the central region of the cluster indicate that it is highly disturbed with a prominent cold front (Vikhlinin et al. 2001; Briel et al. 2004; Datta et al. 2014; Ichinohe et al. 2017). The NW relic is one of the most powerful observed radio relics (Feretti et al. 2012) and the encompassing region has been extensively studied in the X-ray. XMM-Newton (hereafter, XMM) and Suzaku observations indicate the existence of a shock front at the location of the NW relic (Finoguenov et al. 2010; Akamatsu et al. 2012; Sarazin et al. 2016). However, the SE relic region has only been observed in the X-ray band so far with Suzaku (Akamatsu & Kawahara 2013). A temperature jump was measured with Suzaku at the location of the SE relic, suggesting the presence of a weak shock with a Mach number of 1.75 ± 0.13 (Akamatsu & Kawahara 2013). However, due to the broad PSF of Suzaku, point sources were not excluded from that analysis, which could lead to over- or underestimates of the cluster temperature profile across the relic region. Additionally, discontinuities in the surface brightness are critical to confirm the existence and specific location of a shock front. The resolution of Suzaku is too poor to have a shock front. The resolution of Suzaku is too poor to have a corresponding surface brightness jump and pinpoint the location of the shock front, which is not typically possible from a spectral analysis of the temperature jump alone. We show in Figure 1 a mosaic of all publicly-available XMM observations of A3667, including this new SE observation, overlaid with the radio relics as observed with the Sydney University Mongolo Sky Survey (SUMSS) (Bock et al. 1999; Mauch et al. 2003).

This paper is structured as follows. In Section 2, we outline the observation and data reduction strategy. In Sections 4 and 3, we describe the spectral and spatial analysis procedures, respectively. In Section 5, we discuss the results of spectral and spatial fitting. Finally, we conclude in Section 6. We use a cosmology with the following parameter values: \(\Omega_M = 0.3, \Omega_k = 0.7, H_0 = 70 \, \text{km s}^{-1} \, \text{Mpc}^{-1}\). For these values, at a redshift of 0.0556, 1″ = 1.08 kpc. Unless otherwise noted, uncertainties are reported at the 68% confidence level.

2 OBSERVATION AND DATA REDUCTION

We present here the analysis of a new observation of the SE relic region in A3667 with XMM, to provide independent confirmation of the existence and strength of this X-ray shock first discovered by Akamatsu & Kawahara (2013) and to test the viability of DSA as the prevailing mechanism for accelerating electrons at the shocks associated with radio relics. With this new observation, we can confirm the low Mach number estimate from Suzaku via a temperature jump and exploit the high spatial resolution of XMM to identify a corresponding surface brightness jump and pinpoint the location of the shock front, which is not typically possible from a spectral analysis of the temperature jump alone. We show in Figure 1 a mosaic of all publicly-available XMM observations of A3667, including this new SE observation, overlaid with the radio relics as observed with the Sydney University Mongolo Sky Survey (SUMSS) (Bock et al. 1999; Mauch et al. 2003).

3 SPATIAL ANALYSIS

3.1 Filtered Images

A surface brightness discontinuity is one of the strongest indicators of a shock front, coupled with a spectral analysis. However, no discontinuity is obvious from a visual inspection

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1 Redshift from the NASA Extragalactic Database (NED).

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\[ \text{A} \]
We model the thermal electron density with a broken power law:

\[ n_2(r) = \frac{r}{r_{\text{shock}}}^{-\alpha_2}, \quad r \leq r_{\text{shock}} \]

\[ n_1(r) = n_0 \left( \frac{r}{r_{\text{shock}}} \right)^{-\alpha_1}, \quad r > r_{\text{shock}} \]

(1)

where \( n_0 \) is the electron number density normalization, \( C \equiv n_2/n_1 \) is the shock compression ratio, \( r_{\text{shock}} \) is the shock radius, and \( \alpha_1 \) and \( \alpha_2 \) are the power law indices of the post- and pre-shock regions, respectively.

We use the ProfiFit package\(^3\) (Eckert et al. 2011) for fitting. ProfiFit uses the technique in Appendix A of Owers et al. (2009) to numerically project the density profile above along the line of sight to the surface brightness. The functional form of the actual model that is fit with ProfiFit is given by:

\[ S(r_L) = \text{norm} \int n(r)^2 \, dl + \text{const}; \]

(2)

where \( S(r_L) \) is the surface brightness along the projected 2D radius \( r_L \), \( \text{norm} \) is the normalization, \( n(r) \) is the 3D density profile given in Equation 1, and \( \ell \) is the line-of-sight such that \( r^2 = r_L^2 + \ell^2 \). There are a total of six model parameters: the normalization and an optional constant background term (both in units of surface brightness, counts s\(^{-1}\) arcmin\(^{-2}\)) and four additional parameters from the density profile: the shock compression ratio \( C = n_2/n_1 \), the shock jump radius \( r_{\text{shock}} \), and the two power law indices \( \alpha_1 \) and \( \alpha_2 \). The data are grouped into bins with a minimum signal-to-noise of 5 and are logarithmically spaced, varying in size from about 10-30 arcsec across the region considered.

The surface brightness profile and best-fit model is shown in Figure 4. The signal-to-background ratio is relatively low, especially in the region outside of the relic, so the overall fit is somewhat poor with a reduced \( \chi^2/\text{dof} = 51/27 \approx 1.9 \). The best-fit value for the compression ratio is: \( C = 1.4 \pm 0.2 \). The best-fit shock radius is at the outer edge of the radio relic, \( r_{\text{shock}} = 15.5 \pm 0.2 \) arcmin in Figure 4. This corresponds to \( r \sim 10.5 \) arcmin in Figure 7. However, a broken power law does yield the best fit compared to a single power law (\( \chi^2/\text{dof} = 67/29 \); this is a power-law fit directly to the surface brightness and not to the density). An F-test reveals that the improvement of the broken power law fit to the density over a single power law fit to the surface brightness is at the 2 sigma level, i.e. it has an associated chance probability of 2.5% (the F-statistic is 4.2).

The sector was chosen to optimize both the size of the jump and overall quality of the fit. Varying the bin size or minimum signal-to-noise did not significantly change the quality of the fit or parameter values. The length of the sector did have an impact on the fit. Outside the sector shown in Figure 3, the surface brightness profile flattens out towards the SE. This is likely due to cluster emission becoming fainter than the sky background, as was also seen in the spectral fitting of the outer regions. The outer edge of the

\[ \text{http://www.iasf-milano.inaf.it/~eckert/newsite/Proftit.html} \]
Figure 2. Left: GGM filtered image, $\sigma = 16$, 0.5 – 4 keV. The two white ellipses mark the locations of the “plateau” (center of image) and the “mushroom” (towards the northwest) features described in Section 3.1. Right: Same as left, but with SUMSS contours overlaid.

Figure 3. XMM image of the SE observation of A3667, 0.5 – 4 keV, smoothed with a Gaussian kernel with a FWHM of 10 arcsec. The white contours show the southern relic with the same contour levels as in Figure 1. The solid black sector shows the region used to extract the surface brightness profile. The dashed black line indicates the best-fit position for the shock radius. The dashed wedge towards the northwest of the image is shown to indicate the origin in Figure 4; that is, the point of the wedge corresponds to $r = 0$. The coordinates of this point are (20h13m04.32s, −56d57m0s). The straight dashed black line cutting through the wedge labeled “Spectral Region 1” marks the location of the beginning of the spectral regions in Figure 5 and $r = 0$ on Figure 7. The black “+” shows the position of the point source PMN J2014-5701 and the black “x” marks the position of SUMSS J201330-570552, discussed in Section 5.2.

sector was chosen by eye to be where this transition appears to occur. The inner edge of the sector does not strongly affect the best-fit values of the fit, but does affect the overall quality of the fit. When a constant background term is added to Equation 1 and left free, the formally best-fit value is negative, which is unphysical. If this constant term is forced to be zero or positive, the best-fit value is consistent with zero. The $2\sigma$ upper limit on a constant background term is $< 1.5 \times 10^{-4}$ counts s$^{-1}$ arcmin$^{-2}$. This value is consistent with the count rate of the sky background estimated from the spectral fit in Section 4.

We can relate the Mach number, $M$, and compression...
Table 1. Background model components

| Component | $\Gamma$ | $kT$ | Normalization |
|-----------|---------|------|---------------|
| LHB       | –       | 0.184 ± 0.001 | (1.84 ± 0.02) × 10^{-6} |
| GH        | –       | 0.63 ± 0.02   | (3.5 ± 0.1) × 10^{-7}   |
| CXB       | 1.41    | 5.6 ± 0.2     | (5.6 ± 0.2) × 10^{-7}   |
| RESP      | 0.76 ± 0.03 | –      | (1.9 ± 0.1) × 10^{-3}   |

X-ray temperatures have units of keV. The normalizations are in XSPEC units: \( \frac{10^{-14}}{\text{cm}^2 \text{ph} \text{s}^{-1} \text{keV}^{-1}} \int n_e n_H dV \), where \( D_A \) is the angular diameter distance to the source, \( z \) is the redshift, and \( n_e \) and \( n_H \) are the electron and hydrogen densities (cm\(^{-3}\)). The spectral index for the CXB was kept fixed. The RESP normalization listed is for the pn detector, region 7. The other normalizations are scaled to this value by the flux in a given detector and region reported by the ESAS command `proton_scale`, and vary in the range \((0.5 - 2) \times 10^{-3}\).

ratio, \( C \), assuming \( y = 5/3 \), using the Rankine-Hugoniot jump conditions:

\[
M = \left( \frac{3C}{4 - C} \right)^{1/2}.
\]

For our best-fit value of \( C = 1.4 ± 0.2 \), this yields \( M = 1.3±0.1 \). The uncertainties reported are purely statistical and do not take into account systematics due to sector choice.

4 using the abundance table from Anders & Grevesse (1989)

5 www.atomdb.org

Figure 5. XMM image of the SE region of A3667, 0.5 – 4 keV, smoothed with a Gaussian kernel with a FWHM of 10 arcsec. Overlaid in black are the regions used in spectral fitting. The dotted black line marks the location of the best-fit shock radius from the spatial analysis. The white contours show the southern relic (with the same contour levels as in Figure 1).

law in our fit. In order to better constrain these background components, we include an additional spectrum from the ROSAT All-Sky Survey from an annulus of 1 – 2° around the center of A3667. This spectrum was extracted using the X-ray Background Tool\(^6\) provided by NASA’s HEASARC. The normalizations for these components are left free. The spectral index for the CXB is fixed to 1.41 (De Luca & Molendi 2004), while the temperatures for the LHB and GH were left free. For the absorbed components, the X-ray column density is fixed to \( n_H = 4.31 \times 10^{20} \) cm\(^{-2}\), reported by the Leiden/Argentina/Bonn (LAB) Survey (Kalberla et al. 2005). We also initially included a cool (~ 0.1 keV) absorbed component to represent cooler Galactic emission (Snowden et al. 2004), but the normalization for this component was consistent with zero after fitting. For the column density reported here for this observation, this component is likely fully absorbed. The best-fit parameters for these components, fit simultaneously across all regions, are listed in Table 1.

We include a number of additional instrumental background components. Two constants are included: one fixed to the solid angle for each region and detector, and another left free to account for small variations in the inter-detector calibration, linked across regions but left free across detectors. Gaussian emission lines that correspond to the Al Kα and Si Ka instrumental fluorescence lines are added for the MOS1 and MOS2 detector at 1.49 keV and 1.75 keV, and for the pn detector at 1.49 keV. The line energies are fixed, the widths fixed to 0, and the normalizations left free for each region and detector.

We also include a separate model component for any residual soft proton emission (RESP) in the form of a power law that is not folded through the instrument effective area, following the ESAS cookbook. The spectral index and nor-
We show the spectra and best-fit models for regions 1–6 in Figure 6. We plot the cluster temperature profile in Figure 7. The cluster temperatures and normalizations can be found in Table 2. This profile is roughly consistent with the temperature profile measured by Suzaku by Akamatsu & Kawahara (2013), which used different spectral regions and background modeling.

There is a clear change in the slope of the temperature profile between regions 1–3 to 4–6. We can estimate the strength of the shock from the post- and pre-shock temperature change. Assuming a specific heat ratio of $\gamma = 5/3$, the Rankine-Hugoniot jump conditions yield:

$$\frac{T_{\text{post}}}{T_{\text{pre}}} = \frac{5M^2 + 14M^2 - 3}{16M^2},$$

(4)

where $M$ is the Mach number, and $T_{\text{post}}$ and $T_{\text{pre}}$ are the post- and pre-shock temperatures, respectively. However, from Figure 7, it is not exactly clear where the edge of the shock front actually is. X-ray observations of relic regions in general suffer from projection effects, which may be responsible for smearing out the edge of a shock (Skillman et al. 2013; Hong et al. 2015). If we take the trailing edge of the relic (region 4) to be post-shock with $T_{\text{post}} = 5.0^{+0.5}_{-0.6}$ and leading edge (region 6) to be pre-shock with $T_{\text{pre}} = 2.7^{+0.8}_{-0.6}$, the Mach number is then $1.8^{+0.5}_{-0.4}$. Within these statistical uncertainties, the estimate of the Mach number from the surface brightness is consistent with this estimate from the temperature jump (see however Sarazin et al. 2016 for a discussion of issues that can lead to discrepancies in Mach number estimates from surface brightness vs temperature profiles). We show this value along with estimates of the Mach number the surface brightness analysis and from other X-ray and radio observations, in Table 3.

As seen in Figure 5, the shock front as inferred from the spatial analysis lies partially in regions 5 and 6. This provides further motivation for choosing to measure the Mach number between regions 4 and 6. This edge is also marked by a vertical, dashed blue line in Figure 7 and lies at the leading edge of the radio relic (this line was measured by drawing a straight line from the center of the NW edge of spectral region 1 to the center of the arc in Figure 5, which is located at the beginning of spectral region 6.)

If we instead take region 3 as the post-shock region, the Mach number is $2.4^{+0.6}_{-0.4}$, which is higher than but consistent with our previous estimate as well as the estimate from Suzaku and from DSA estimates. We therefore take our previous value, measured between regions 4 and 6, as a conservative estimate.

As an independent check on this estimate, we also measure the temperatures in two regions that essentially split the relic in two non-overlapping halves lengthwise. We did not use the location of the density break to decide on these regions; we instead used only the shape of the radio emission to divide the relic region in half. As labeled in Figure 5, the post-shock region covers part of region 3 and the whole of region 4, and the pre-shock region covers all of region 6, and part of region 7, while region 5 is split between them. We show these regions in Figure 8. We find very similar temperatures to the ones listed in Table 2. The temperatures of the post- and pre-shock regions (regions B and C) are $5.8^{+0.8}_{-0.7}$ keV and $3.2^{+1.0}_{-0.7}$ keV, respectively. The temperature in region A is $6.3^{+0.3}$ keV. In region D, the normalization of the cluster emission is again consistent with 0 within 3σ. The Mach number in this case, using the temperatures measured...
Figure 6. Observed spectra with best-fit model components for the first six regions with nonzero cluster emission. For clarity, only the spectra for the MOS2 camera are shown; the spectra from the MOS1 and pn cameras look similar. Also for visual clarity, the black data points are grouped into bins with a minimum signal to noise ratio of 5. The plots are labeled in the same way as Figure 5. The solid black line is the model sum. The solid dark blue line is the cluster emission. The dotted green line is the CXB. The dashed orange and dash-dotted yellow lines are the LHB and GH, respectively. The solid pink line is the RESP. The RASS spectrum is not shown. The instrumental line fits at 1.49 keV and 1.75 keV are also not shown as separate model components, but are included in the overall fit.

5 DISCUSSION

5.1 Comparing estimates of the shock strength

We summarize our estimations of the Mach number of the SE shock in A3667 in Table 3. Under the assumption of DSA, the Mach number is related to the radio spectral index as follows:

\[ M = \left( \frac{2\alpha_{inj} + 3}{2\alpha_{inj} - 1} \right)^{1/2}, \]

where the radio injection spectral index, \( \alpha_{inj} \), is related to the electron injection spectral index, \( \delta_{inj} \), via \( \alpha_{inj} = (\delta_{inj} - 1)/2 \), with \( dN/dE = E^{-\delta_{inj}} \) and \( S_{\nu} \propto \nu^{-\alpha_{inj}} \). In planar shocks, the radio injection index can be related to the volume integrated radio spectral index, \( \alpha_{int} \), via \( \alpha_{int} = \alpha_{inj} + 0.5 \) (Ginzburg & Syrovatskii 1969). However, this may not be a valid approximation for cluster shocks, which simulations suggest might be more spherical (e.g., Kang 2015a,b).

Ideally, the radio injection spectral index would be obtained directly from the detection of a gradient across the relic in a spatially-resolved spectral index map. However, this is often not possible due to the limited resolution in available observations. Observations of the SE relic with MWA by Hindson et al. (2014) did not display a spectral index gradient across the relic. Therefore, to calculate the Mach number, we will use the reported integrated index of \( \alpha_{int} = 0.9 \pm 0.1 \) measured over the 120 – 226 MHz range, with the acknowledgement that this is likely a lower limit on the Mach number. In this case the estimated Mach number is \( M = 2.45 \pm 0.26 \). An integrated spectral index of \( \alpha_{int} = 1.2 \pm 0.2 \) was measured at higher frequencies between 843 MHz and 1400 MHz, by Johnston-Hollitt (2003), where some evidence for a spectral gradient across the relic was found. A flatter spectral index of \( \sim 0.5 - 0.7 \) was measured at the outer edge of the radio relic. If we take the injected spectral index to be \( \alpha_{inj} = 0.7 \pm 0.2 \), the inferred Mach number would be \( M = 3.3 \pm 1.5 \). As is the case for several other relics with detected X-ray shocks, the shock strength estimated from DSA using the radio spectral index is higher than estimates from X-ray observations, but consistent with the X-ray measurements within 2\( \sigma \). This discrepancy suggests that DSA is too simplistic to explain the nature of

\[ \text{MNRAS 000, 1–10 (2017)} \]
particle acceleration at cluster shocks. We discuss alternative scenarios in the next section, 5.2.

A3667 is the second example of a double-relic cluster with deep X-ray observations that hosts one powerful relic and strong shock (the NW relic in this cluster) and one weaker relic and shock (the SE relic). These characteristics are also observed in CIZA J2242.8+5301 (the Sausage Cluster; Akamatsu et al. 2015). An upcoming study indicates that a third cluster, A3376, displays this behavior as well (Urdampilleta, et al., in prep). This behavior is likely driven by the specific dynamics of the cluster merger event. Simulations suggest that A3667 is post-merger (Roettiger et al. 1999; Datta et al. 2014). Optical observations support this and indicate that the merger axis is close to the plane of the sky (Johnston-Hollitt et al. 2008). Further analysis of the mass structure would help to confirm this scenario.

5.2 Particle Acceleration at Radio Relics

The acceleration of particles at shocks in astrophysical systems is typically attributed to DSA. However, it is generally assumed that DSA is not efficient for weak shocks \( M \lesssim 3 \), because the injection into the DSA process is inefficient (Kang et al. 2012). Moreover, there appears to be a critical Mach number \( M = \sqrt{C} \) (corresponding to a compression ratio of \( C = 2.5 \)), below which cosmic-ray acceleration is not supported energetically (Vink & Yamazaki 2014). Indeed, shocks induced by coronal mass injections indicate that energetic particles are accelerated for all shocks above \( C = 2.5 \) (Giacalone 2012), whereas for lower compression ratios the situation appears to be more complicated. However, for the shocks in the solar system, the accelerated particles, though quite energetic, are generally still sub-relativistic. In fact, the critical Mach number reported in Vink & Yamazaki (2014)

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7 See also the conference presentation Urdampilleta et al. 2017: https://www.cosmos.esa.int/documents/332006/1402684/IUrdampilleta_t.pdf
X-ray Analysis of the A3667 SE Relic

6 CONCLUSION

We present new observations of the SE relic region of the merging cluster A3667. We find a clear temperature jump across the radio relic, consistent with previous observations from Suzaku. We find weak evidence for a corresponding surface brightness discontinuity. We interpret these discontinuities, along with the presence of the radio relic, as evidence for a shock, and estimate a shock strength of $M = 1.8$, consistent with previous X-ray and radio estimates. This cluster is another example of a system with one powerful radio relic and strong X-ray shock and one weak relic and shock.

This low Mach number is not consistent with the idea that for diffusive shock acceleration to accelerate particles the Mach number has to be $M > 2$. Possible solutions to reconcile DSA with the presence of non-thermal electrons at a level that should have already been detected by Fermi ($Vazza & Brüggen 2014$), or else require unrealistically large magnetic fields and/or cosmic ray proton-to-electron number ratios ($Vazza et al. 2015$). Particle-in-cell simulations indicate that protons and electrons are accelerated differently depending on the shock geometry ($Guo et al. 2014a,b; Caprioli & Spitkovsky 2014$). When taken into account in simulations of relics in clusters, this effect can alleviate the tension between the expected gamma-ray emission and observed upper limits in certain cases ($Wittor et al. 2017$). The already-mentioned possible presence of a fossil population of cosmic ray electrons could also alleviate this problem ($Vazza & Brüggen 2014$).
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