Probing the non-thermal emission in Abell 2146 and the Perseus cluster with the JVLA

Marie-Lou Gendron-Marsolais1, Ph.D. candidate

J. Hlavacek-Larrondo(1), R. van Weeren(2), T. Clarke(3), H. Intema(2), H. Russell(4), A. Edge(5), A. Fabian(4), M. Olamaie(6), C. Rumsey(4), L. King(7), B. McNamara(8), D. Fecteau-Beaucage(1), M. Hogan(8), M. Mezcua(9), G. Taylor(10), K. Blundell(11), J. Sanders(12)

(1)University of Montreal, (2) Leiden Observatory, (3) Naval Research Laboratory, (4) University of Cambridge, (5) Durham University, (6) Imperial College London, (7) University of Texas, (8) University of Waterloo, (9) Institut of Space Sciences, (10) University of New Mexico, (11) University of Oxford, (12) Max-Planck-Institut fur extraterrestrische Physik

1-Introduction

Jets created from accretion onto supermassive black holes release relativistic particles on large distances. These strongly affect the intracluster medium (ICM) when located in the center of a brightest cluster galaxy. The hierarchical merging of subclusters and groups, from which clusters originate, also generates perturbations into the ICM through shocks and turbulence, constituting a potential source of reacceleration for these particles. Apart from jets, other forms of diffuse non-thermal radio sources in galaxy clusters includes:

1. **Relics:** diffuse extended sources found at the cluster's outskirt
2. **Halo:** Mpc scale diffuse emission found found in disturbed/non cool core clusters
3. **Mini-halo:** kpc scale diffuse emission detected so far in about thirty relaxed/cool core clusters[1]

We present deep multi-configuration low radio frequency observations from the Karl G. Jansky Very Large Array of two unique clusters[2,3] (Perseus & Abell 2146), probing the non-thermal emission from the old particle population of their AGN outflows. With the recent update of the facilities with the EVLA project, the resolution and sensitivity of these data provide a detailed and extended view of their radio structures.

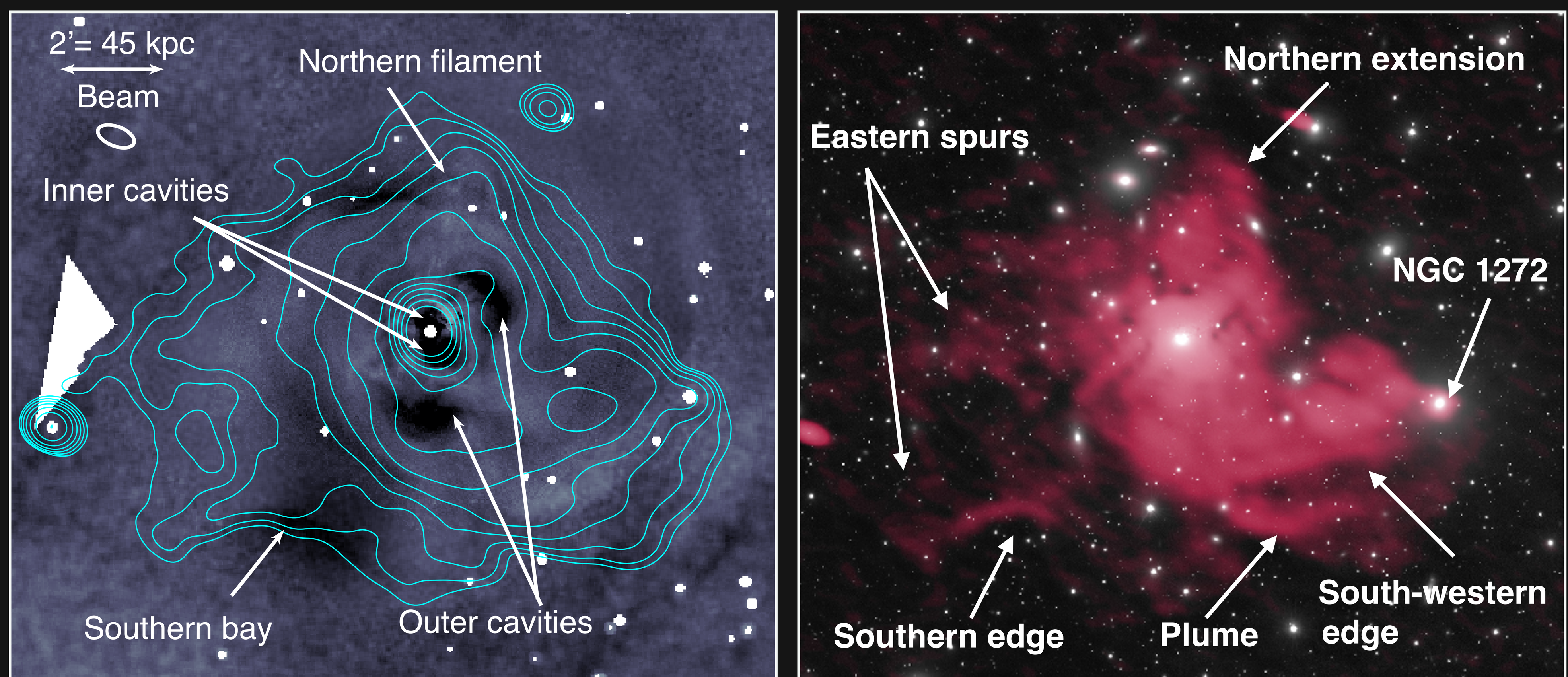

***Figure 1 - Left:** Chandra composite fractional residual image[11] (0.5-7 keV, 1.4 Ms exposure) with JVLA B-array 270-430 MHz contours from 5σ = 1.75 mJy/beam to 1 Jy/beam overlaid with the radio image beam. **Right:** The mini-halo emission surrounding NGC 1275 (JVLA B-array 270-430 MHz, in pink) overlaid on SDSS i-band image. The composite win the Public Prize of the national competition "Science Exposed » of the Natural Sciences and Engineering Research Council of Canada (french-language component).*

3-Results: Perseus

Perseus is the X-ray brightest cluster in the sky[9]. It is a nearby relaxed cool core cluster hosting a mini-halo[10]. X-ray observations have shown a succession of cavities created by the jets of the central supermassive black hole, pushing away the gas and leaving buoyantly rising bubbles filled with radio emission[11].

- Several new structures have been identified in our JVLA 230-470 MHz observations (see Fig. 1, and the recent NRAO press release). The new JVLA facilities have produced an order of magnitude deeper image than the previous 330 MHz VLA data with a higher resolution than the previous WSRT images of the mini-halo.
- Mysterious filamentary spurs of emission are found, similar to radio relics, but no shocks corresponding with the position of the filaments are known. The large-scale shape (curving counterclockwise, elongated in the direction of the cavity system) and fine structure show a correlation of the mini-halo emission with both the sloshing motion and the relativistic jets of the AGN. Mini-halos are therefore not simply diffuse, uniform radio sources, but rather have a rich variety of complex structures.
- Comparison with the deep Chandra X-ray images shows that the mini-halo is enclosed mostly behind the western sloshing cold front, which qualitatively supports the hypothesis of reacceleration of pre-existing electrons by turbulence[12]. However, fainter emission is also seen beyond, as if particles are leaking out.
- The emission avoid the southern bay, an intriguing feature behaving like a cold fronts but with the opposite curvature (possibly caused by a Kelvin-Helmholtz instabilities[13], see the recent NASA press release).
- Once fully reduced and merged, the complete A+B+C+D configurations 230-470 MHz JVLA datasets (including upcoming 4h from director's discretionary time proposal 17A-475 and 5h with regular proposal, both PI: Gendron-Marsolais) will provide a legacy dataset of this iconic system.

2-JVLA Datasets & Data reduction

Data reduction with CASA (*Common Astronomy Software Applications*):

- Manual and automatic identification of RFI (*flagdata* and *Aoflagger*[4])
- Imaging with *Clean* : use of multi-scale multi-frequency synthesis-imaging algorithm[5]
- number of Taylor coefficients greater than one, W-projection algorithm with a grid mode *widefield*[6], multi-scale cleaning algorithm[7] and mask limiting regions where emission was expected[8]
- Imaging self-calibration: use of amplitudes and phases gain corrections from data to refine calibration

	Perseus (z = 0.0183)	**A2146 (z = 0.232)**
Frequency	P-band (230 - 470 MHz)	L-band (1-2 GHz)
Datasets	5 h (B-array)	2.4h (B-array) + 7.4h (C-array) + 1.3h (D-array)
Beam size	22.1″ x 11.3″	14.1″ × 13.5″
RMS	350 μJy/beam	12 μJy/beam

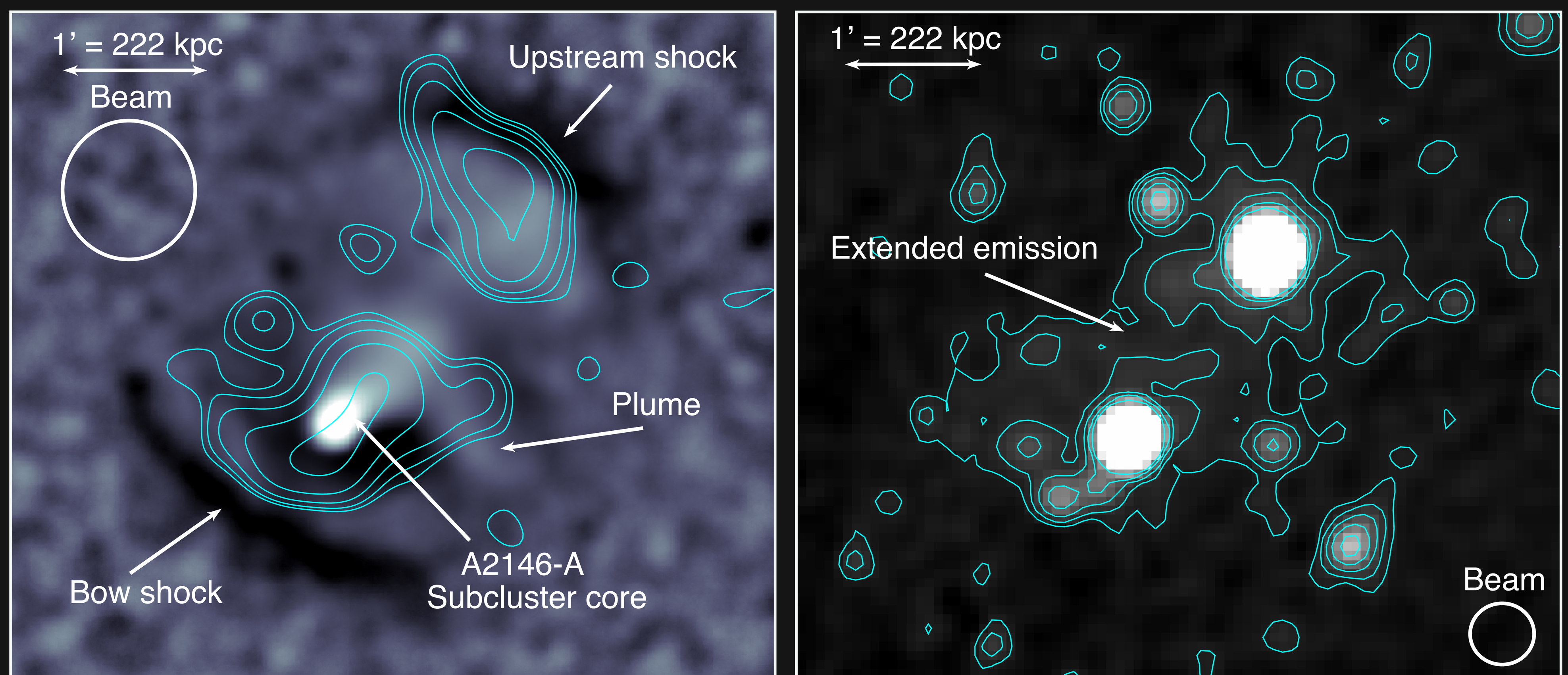

***Figure 2 - Left:** Unsharp-masked Chandra image[15] (0.3 – 7.0 keV, 420 ks exposure) with point source subtracted 1 – 2 GHz JVLA image contours starting at 3σ = 0.7 mJy/beam. **Right:** Low-resolution 1 – 2 GHz image combining all datasets, revealing the presence of extended radio emission centered on A2146.*

4-Results: Abell 2146

Abell 2146 is one of the rare clusters undergoing a spectacular merger in the plane of the sky with a similar structure to the Bullet cluster[14]. The resulting bow and upstream shock fronts are detected at X-ray wavelengths[15]. Deep GMRT 325 MHz observations failed to detect extended radio emission[16].

- Our extremely deep multi-configuration JVLA 1.4 GHz observations (totalling 11.1 hrs of on source time) have revealed for the first time the presence of a faint structure extending to 850 kpc in size, elongated along the merger axis and strongly confined between both the bow and upstream X-ray shock fronts (see Fig. 2). These observations reach a noise level (10μJy/beam) more than an order of magnitude deeper than previous observations.
- The extended emission consists of one component associated with the upstream shock and classified as a radio relic, and one associated with the subcluster core, consistent with a radio halo bounded by the bow shock.
- Theses structures have some of the lowest radio powers detected thus far in any cluster: $P_{1.4GHZ,\ halo} = 2.4 \pm 0.2 \times 10^{23}$ W Hz^{-1}, $P_{1.4GHZ,\ relic} = 2.2 \pm 0.2 \times 10^{23}$ W Hz^{-1}
- Confinement of the halo within the X-ray shock fronts indicates that the merger-induced turbulence has not yet reached the cluster scale and that the halo is most likely in its early stages of formation.
- The flux measurements of the halo, its morphology and measurements of the dynamical state of the cluster suggest that the halo was recently created (~ 0.3 Gyr after core passage). This makes A2146 extremely interesting to study, allowing us to probe the complete evolutionary stages of halos.

(1) Giacintucci et al. 2017
(2) Gendron-Marsolais et al. MNRAS 2017
(3) Hlavacek-Larrondo et al. MNRAS 2017
(4) Offringa et al. 2012
(5) Rau & Cornwell 2011
(6) Cornwell et al. 2008
(7) Cornwell 2008
(8) Mohan & Rafferty 2015
(9) Forman et al. 1972
(10) Soboleva et al. 1983; Pedlar et al. 1990; Burns et al. 1992; Sijbring 1993
(11) Fabian et al. 2000, 2003, 2006, 2011
(12) Gitti et al. 2002, 2004
(13) Walker et al. 2017
(14) Markevitch et al. 2002
(15) Russell et al. 2010, 2012
(16) Russell et al. 2011