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Cavity Detection Tool (CADET)

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X-ray cavities

X-ray cavities are remnants of past radio-mechanical AGN activity and can be observed as surface brightness depressions in hot atmospheres of clusters, groups, and massive galaxies. They are products of the interaction between outflows of relativistic plasma (jets) and ambient hot X-ray emitting gas. For nearby radio galaxies, the energy released in these relativistic jets is dominant over the energy expelled by electromagnetic radiation and for the most powerful outflows it can be comparable to power output of a typical quasar (10^{46} erg s^{-1}). Cavities can deposit significant amounts of this energy and then slowly dissipate through sound waves and turbulent flows as they rise in the surrounding medium. By measuring volumes of cavities and surrounding pressure, the total energy as well as the corresponding mechanical jet power required for their inflation can be estimated.

X-ray cavities, just like radio lobes, typically come in pairs and originate in a single relativistic outflow. The observations show that cavities are discrete separate bubbles rather than continuous funnel-like structures and for many galactic systems even multiple generations of cavities are observed (Figure 1). X-ray cavities come in various shapes and sizes, but usually they are approximated by rotational ellipsoids assuming axial symmetry around the galactocentric direction. Typically, cavities are inflated approximately at the speed of sound on timescales of tens of millions of years and may reach up to hundreds of kiloparsecs in size.

Figure 1. NGC 5813 with 3 prominent pairs of X-ray cavities. Credit: Randall 2015.

Current detection methods

Cavities are filled purely with nonthermal relativistic plasma not emitting any X-ray photons. On X-ray as well as Sunayev-Zeldovich observations, they are therefore detectable as surface brightness depressions. Current X-ray observations, however, suffer from low count statistics and well defined X-ray cavities were so-far detected only in tens of sources. Usually, cavities are therefore visually detected from smoothed raw or residual images (obtained by subtracting a best fitting beta model, Figure 2) and their extent is estimated by manually overlaying the cavities with ellipses. We note, however, that such approach can be highly inaccurate, prone to biases and especially problematic for poor-quality data.

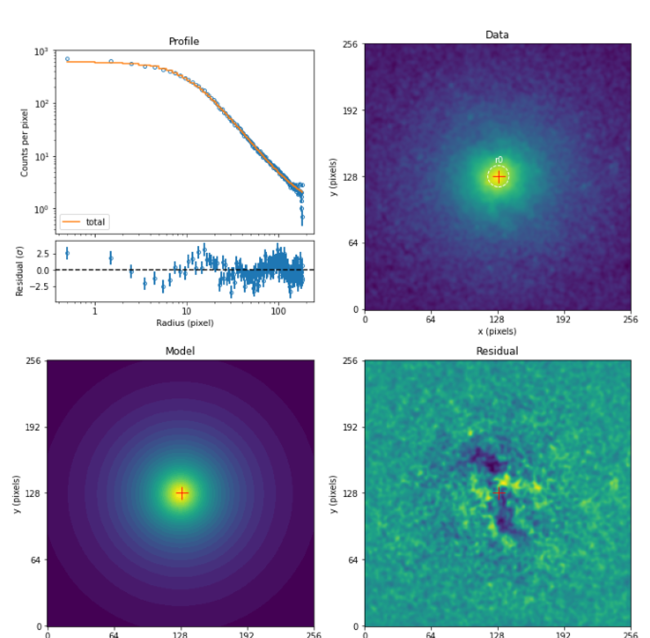

Figure 2. Interactive beta-modelling tool [1].

[1] https://github.com/tomasplsek/Beta-modelling

Cavity Detection Tool (CADET)

The Cavity Detection Tool (CADET) is a **machine learning** pipeline trained for detection and size-estimation of X-ray cavities on images observed by current and future X-ray satellites such as the *Chandra X-ray Observatory or* ***Athena***. The CADET pipeline is composed of a convolutional neural network (CNN) producing pixel-wise predictions and a DBSCAN clustering algorithm that decomposes predictions of the CNN into individual cavities (Figure 3). Instead of training the pipeline using real X-ray data, we generated a large sample of artificial models of galaxies with cavities and trained the network using simulated **mock images**.

Architecture

1. **Input image**: X-ray image with removed and filled point sources cropped and binned to 128x128 pixels
2. **CNN**: Convolutional neural network [2] composed of 5 Inception-like convolutional blocks
3. **Pixel-wise prediction**: Prediction image of 128x128 pixels with values ranging from 0 to 1
4. **DBSCAN**: Clustering algorithm decomposing pixel-wise predictions
5. **Cavity prediction**: Coordinates of pixels belonging to individual X-ray cavities

Figure 3. Schematic picture of the architecture of CADET pipeline.

Artificial data

Artificial training images were simulated to resemble real X-ray images of early-type galaxies. The gas distribution of artificial galaxies was approximated using a **beta-model** [1] and cavities were produced by cutting off a pair of **rotational ellipsoids**. Parameters of both beta-models and X-ray cavities were sampled from their measured distributions obtained from an analysis of 72 nearby early-type galaxies. Mock surface brightness maps, generated by summing the 3D galaxy models across one axis, were convolved with *Chandra* on-axis PSF and noised using Poisson statistics to resemble real low-count X-ray images.

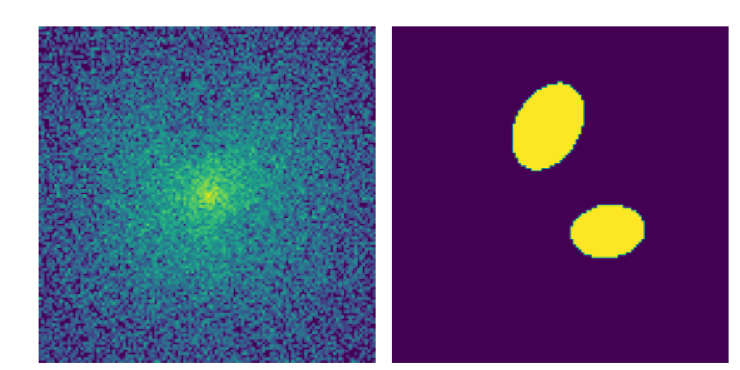

Figure 4. Left: mock image, right: cavity mask.

Training & Testing

The CADET pipeline was trained for 16 epochs using 2^{19} **simulated images** in total. The training was performed using various parameters of the CNN as well as of the training data (e.g. X-ray cavities in 50% vs 100% of images). Training of a single network including on-the-fly data generation was performed on NVIDIA GeForce RTX 3080 (10 GiB) and lasted 8 hours.

To select the optimal combination of hyper-parameters, we generated a set of 10^4 mock images and compared the performance of individual networks. The same set of images was also used to test the prediction accuracy of the final pipeline by comparing reconstructed cavity volumes to their true values (Figure 5). To test the network also qualitatively using real *Chandra* data, we picked 3 images with well-defined X-ray cavities and visually compared CADET predictions with expected cavity extent (see Figure 6).

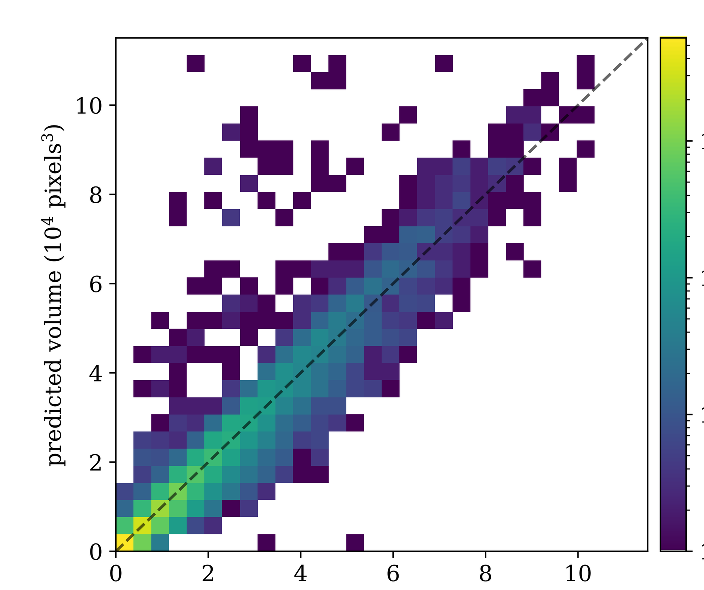

Figure 5. Predicted vs true cavity volumes.

Application on real *Chandra* images

The CADET pipeline was applied on a sample of 72 real *Chandra* images. All images were probed on multiple scales and cavity predictions were only taken as valid if present on at least two different scales. The significance of detected cavities was tested both using azimuthal count statistics on given real images as well as by simulating images with similar properties and measuring accuracy of predictions (Figure 7). After excluding insignificant or spurious false detections, at least one pair of X-ray cavities was detected for 56 sources, 6 of which are new previously undetected cavity candidates.

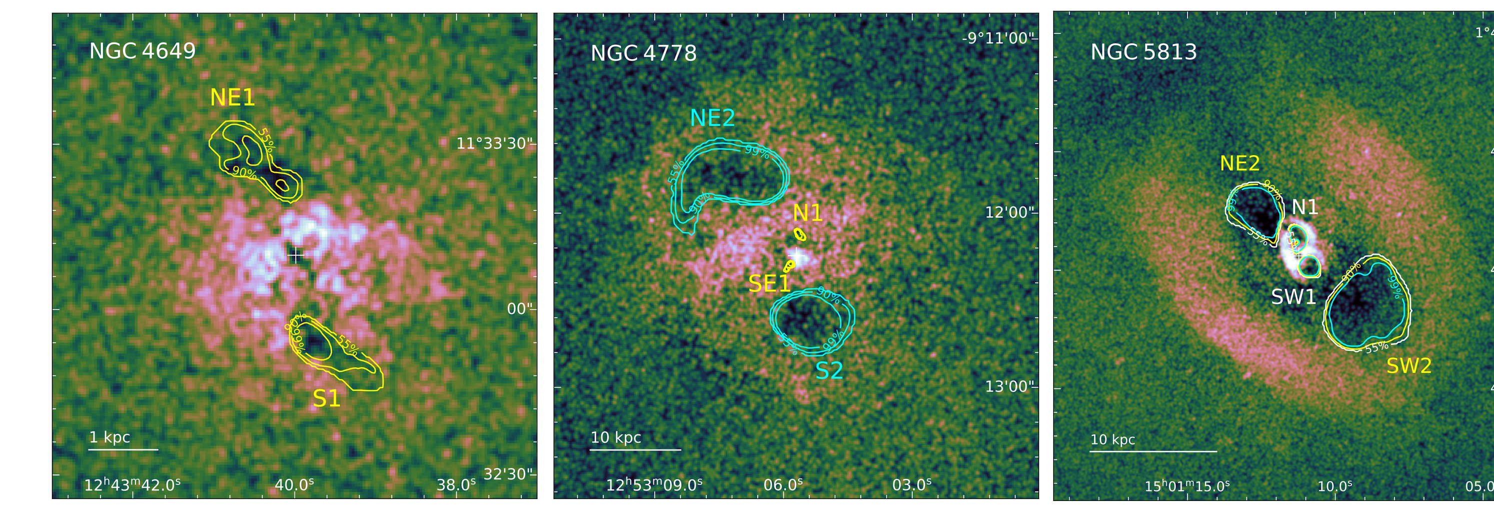

Figure 6. Real X-ray images overlaid by contours of CADET predictions.

Prediction significances

To test the accuracy and significance of CADET predictions for real images, we simulated mock images with identical properties as the given input image (parameters of the beta model, number of counts) and measured the relative cavity area error for a grid of possible cavity radii and distances (Figure 7).

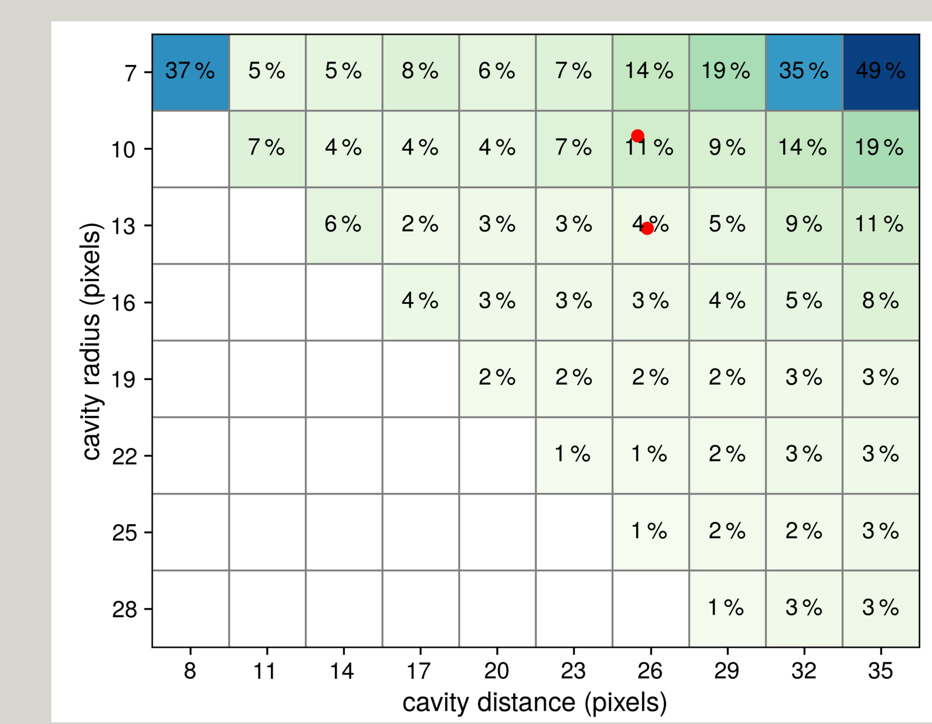

Figure 7. Relative area error heatmap for various cavity radii and distances. This simulation was generated for parameters of NGC 4649 and corresponding X-ray cavities detected by CADET are marked with red points.

References

[1] A. Cavaliere and R. Fusco-Femiano. X-rays from hot plasma in clusters of galaxies. *Astronomy & Astrophysics*, 49:137–144, May 1976.

[2] Stanislav Fort. Towards understanding feedback from supermassive black holes using convolutional neural networks. *arXiv e-prints*, art. arXiv:1712.00523, December 2017.

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