Galactic Wings: A Case Study on the X-Shaped Radio Source in Abell 1145

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Abstract

In this project, I will study the radio source B1059+169, an astronomical object emitting radio waves found in the Abell 1145 galaxy cluster. This object is thought to be what astronomers call an Active Galactic Nucleus or AGN. Astronomers have observed that many AGN produce a pair of astrophysical jets (like the jets in a hot tub) of hot plasma that typically produce two bright radio signatures that can be observed with radio telescopes on Earth. However, the radio source B1059+169 differs from other radio AGN because it presents an atypical shape in our observations, exhibiting four bright radio signatures instead of two. This means it falls within a rare class of objects known as X-shaped radio sources. The extra pair of radio lobes, often called a “winged” signature is worthy of study, as they may reveal how these peculiar radio sources are formed.

My project explores the local environment of this radio source by measuring the X-ray emission of the surrounding gas medium utilizing data collected with the Chandra X-ray Observatory. Compared with previously collected radio and optical data, these measurements will allow me to evaluate the extent to which two prevailing theories on the formation of X-shaped sources explain the observed phenomena. The two formation mechanisms in question are the black hole coalescence model and the strong backflow model. Evidence in support of the black hole coalescence model would have implications for studying the cosmic gravitational wave background, and evidence in support of the strong backflow model would have implications for our understanding of astrophysical jets.

Background

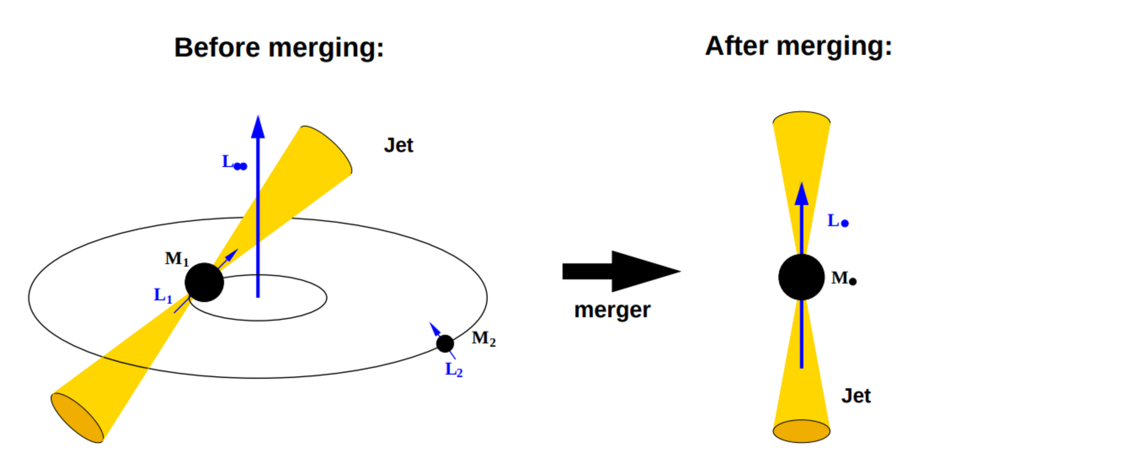


Figure 1: Illustrates the black hole coalescence model for the formation of X-shaped radio sources. The orientation of the astrophysical jets is shifted during the merger, which may explain the two pairs of radio lobes. Adapted from Zier and Biermann (2002).

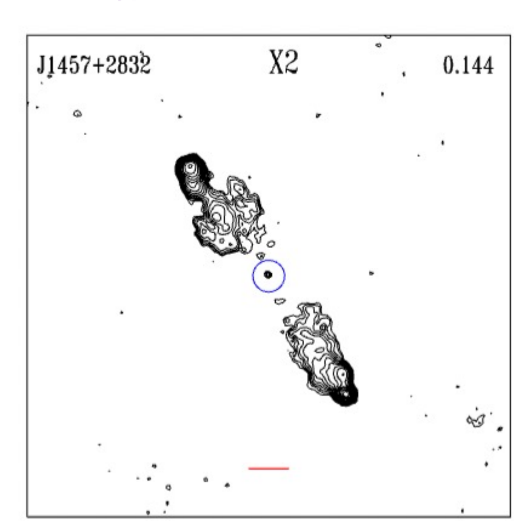
In this project I am studying an X-shaped radio source, a peculiar type of radio-loud Active Galactic Nucleus (AGN). A typical AGN produces radio emission in two parallel bursts called “radio lobes”. These radio lobes are a direct result of the morphology, or shape, of the object that emitted them. Most AGN are characterized by a pair of astrophysical jets, just like the jets in a hot tub, which produce this strong radio emission through its interaction with the Intracluster Medium (ICM), a collection of hot gas that is gravitationally bound to the galaxy cluster. Radio sources featuring a pair of bright “hotspots” at the end of their radio lobes are called Fanaroff-Riley Class II (FR-II) objects. FR-II sources, also called “edge-brightened” sources, may be easily classified by their radio morphology as seen in Figure 2. However, X-shaped radio sources differ from this expected morphology, featuring two pairs of radio lobes instead of one, as seen in Figure 3. There are two prevailing theories which aim to explain their peculiar shape, which I set out to evaluate in this case study. The first theory, illustrated in Figure 1, considers that the central AGN is not a supermassive black hole, but a binary pair of supermassive black holes. In the case where these two black holes undergo a merger event, the orientation of the jets will shift, where the pre- and post-merger signatures form the X shape. The other theory states that the source is a typical AGN whose jets are simply being bent out of shape by strong local gas pressures.

Methodology

Observations:

In this study we used imaging data at X-ray and Radio wavelengths. The data I used for this project were generated by Professor Craig Sarazin as the Principal Investigator for observations of the source B1059+169 in Abell 1145. These observations were carried out using the Chandra X-ray Observatory in cycle 18 (Seq. 801668, OBSID 19576, PI Sarazin) and the Very Large Array (PI Sarazin). These observations were carried out during CXO Cycle 18 for 55 kiloseconds using the ACIS detector between 0.3 and 10 kiloelectron-volts.

Typical FR-II Radio Source



X-shaped Radio Source

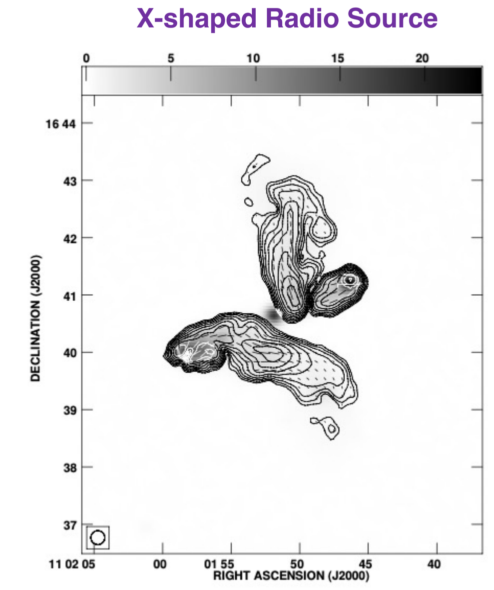


Figure 2 (Left): Illustrates a typical FR-II radio source surrounding an AGN. The compact radio contours at the ends of the radio lobes demonstrate the edge-brightening of FR-II sources. The solid red line at the bottom shows a 30 arcsecond angular scale (Capetti et al. 2017).

Figure 3 (Right): Displays the radio morphology of Abell 1145 observed in 2018 (PI Sarazin). The off-axis radio lobes form the “winged” signature which demonstrates the atypical morphology of X-shaped radio sources. (Sarazin, 2016)

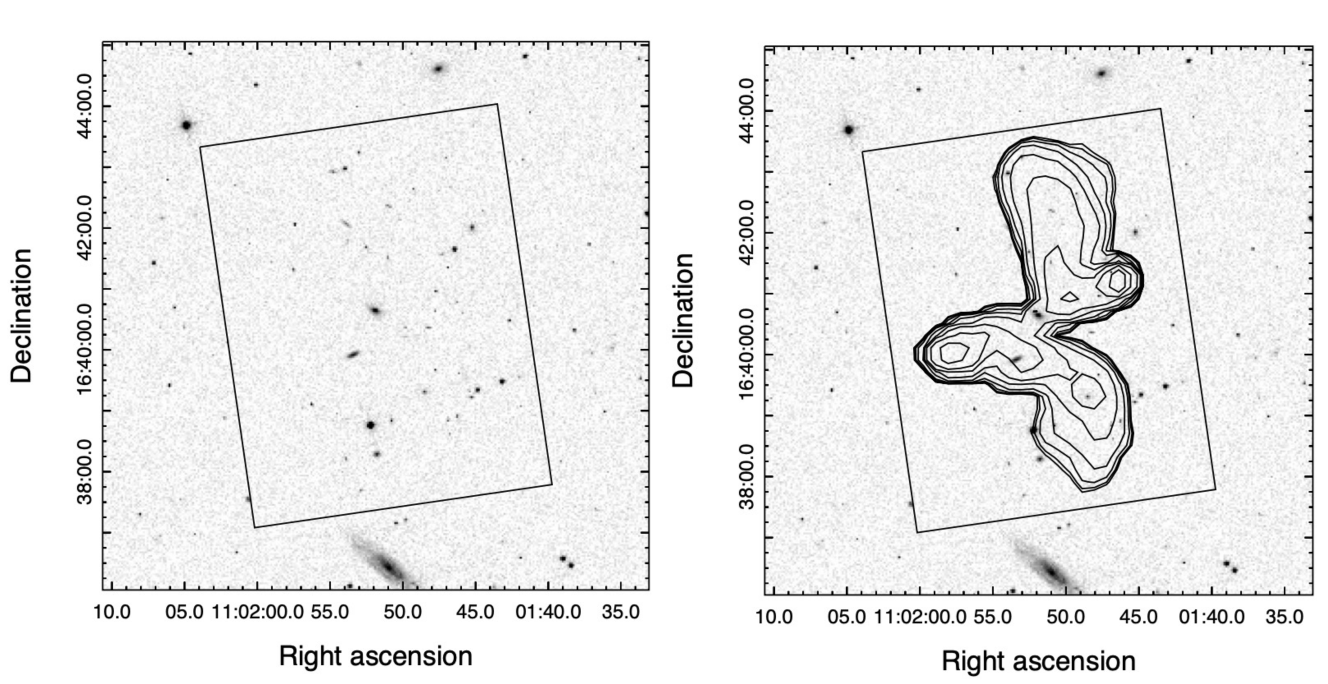
Analysis:

In astronomy, raw data must be processed before it can be used for science purposes. The following corrections and analyses were performed using the software Chandra Interactive Analysis of Observations (CIAO).

1. Standard Level-2 Pipeline, Aspect Solution
2. Separate Source & Background Emission, Create Lightcurve
3. Energy and GTI Time Filtering
4. Create Background File
5. Create Instrument Map, Exposure Map
6. Renormalize Images, Overlay Contours, Optical Comparison

To begin, our raw data from the Chandra Data Archive is run through a standard code, or “pipeline”, in order to string together a series of images taken from various angles. The main data product we obtain is called the “event file,” containing information on every photon detected by the telescope. The first main component of our analysis is to remove background flares, a source of noise across the detector related to solar activity, from the event file in order to be consistent with background files created using quiescent (inactive) background periods. To remove flares from the data we first selected data from the ACIS S3 chip and restricted its energy range to 0.5-7 keV. Then, to ensure active flares are not drowned out by source emission counts, we removed a 1’12 circular region from the center of the image. We extracted a lightcurve and ran cleaning processes to identify and remove periods of high and low counts and create a “good time interval” (GTI) file. Using specified parameters for the observation, we reprojected blank sky background data to our field of view and created new images for the source and background emission. We then generate an instrument map and reproject it to our observations to generate an exposure map (adjusted for the cleaned exposure time). Finally, our X-ray science image is renormalized by the exposure map, smoothed for display, and VLA radio contours are added.

Results & Discussion



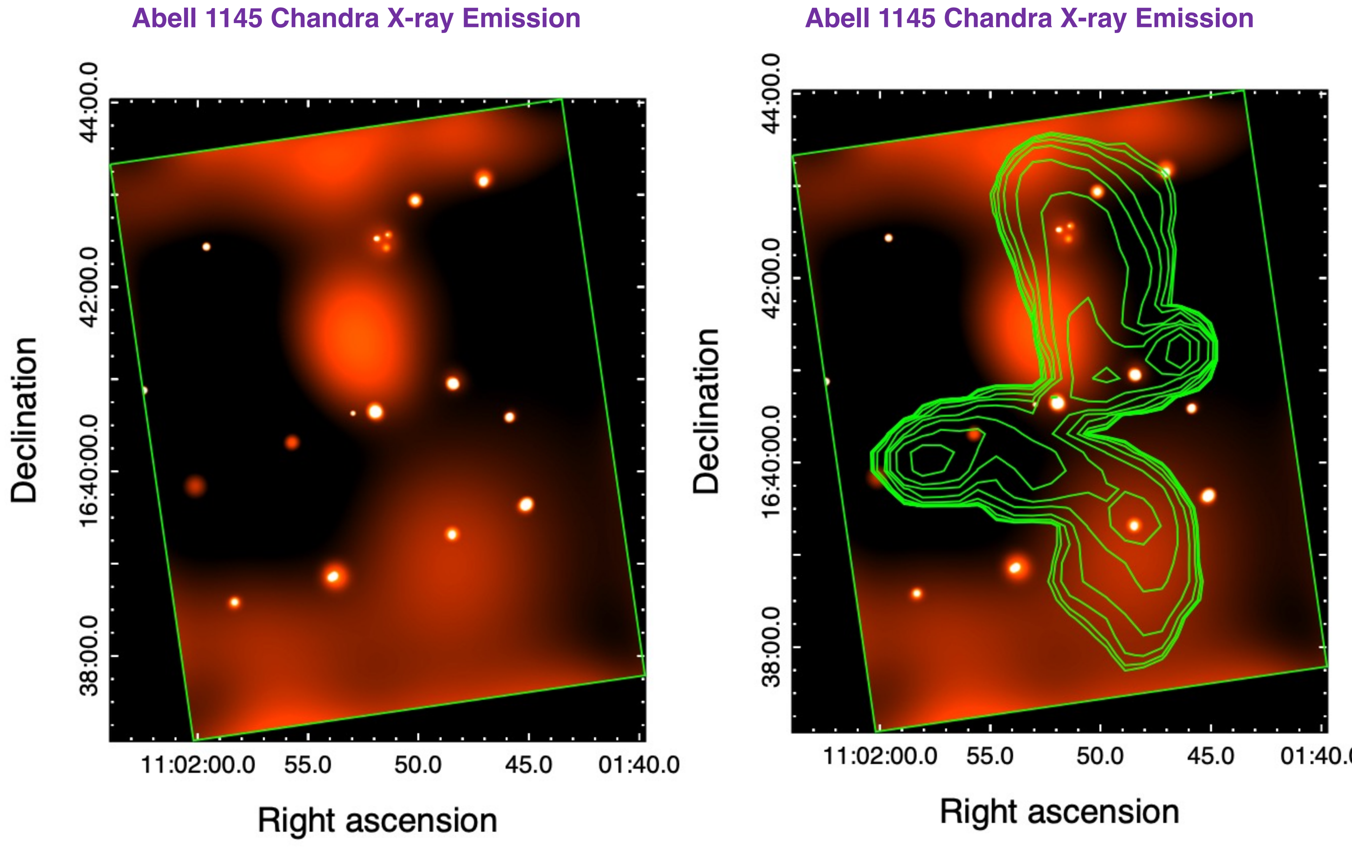


Figure 4: (Top Left) Displays an SDSS r-band optical image of Abell 1145 and the surrounding field. The rectangular region matches the coordinates of the analogous regions in all four images. (Top Right) Displays the same SDSS r-band optical image , this time with VLA radio data contours overlaid for comparison.

Figure 5: (Bottom Left) Displays processed and smoothed science image of the X-ray emission for the X-shaped radio source in Abell 1145. The glowing top and bottom edges show erroneous “edge effects”, while the glow in the center shows active X-ray emission from the ICM. (Bottom Right) Displays the same processed and smoothed science image, this time with VLA radio data contours overlaid for comparison.

As AGN are some of the brightest and most energetic objects in the universe, they emit light across the electromagnetic spectrum from radio waves to gamma rays. In our observations, the diffuse X-ray glow is caused by thermal bremsstrahlung, the deceleration of highly-energetic charged particles interacting with charged particles in the ICM. Additional thermal X-ray line emission also contributes to the observed ICM X-ray glow. These emissions are augmented by turbulent gas dynamics and the strong molecular winds blowing from the central AGN. A few of the X-ray point sources are likely AGN galaxies producing thermal emission from an accretion disk and non-thermal synchrotron emission from the galactic center. However, some point sources may be associated with background AGN outside of the cluster, or X-ray binaries, cataclysmic variables, or neutron stars falling inside or outside of the cluster. On the other hand, the radio emission from this sources is non-thermal, originating mostly from synchrotron radiation around the AGN jets and lobes or shocks in the ICM. Ionized plasma around the AGN efficiently produces radio emission due to an abundance of electrons. Combining these mechanisms, both the X-ray and radio emission is stronger where particles are accelerated and decelerated as they interact with the surrounding medium. In this way, it is clear to see why AGNs are the largest particle accelerators in the universe.

The local environment of a galaxy cluster is ideal for studying the large-scale impact AGNs have on their surroundings. The extremely hot gas in the ICM is invisible at optical wavelengths but glows brightly in the X-ray regime. This high-energy emission (or lack thereof) serves as a tracer of the energy injected into the local environment of the AGN. Noting the locations of X-ray emission can help us probe the gas dynamics within the ICM since the cluster mass distribution is closely tied to its X-ray surface brightness. In order to constrain theoretical models, the cluster thermal X-ray emission can be compared to its non-thermal radio emission. However, it is important to note that the “extended” X-ray glow is prevalent for this source solely because it resides in a massive galaxy cluster. There are very few known examples of X-shaped radio sources which belong to galaxy clusters, so the X-shaped radio source in Abell 1145 is remarkable in this regard for its location and ICM environment. Here, a simple analogy may be useful: imagine trying to draw an intricate pattern on some sand at your feet. The more sand you have to work with, the further your lines can extend, and the more noticeable your pattern will be. In this analogy, the sand is the hot ICM gas surrounding the AGN, and the pattern is the glowing diffuse thermal X-ray emission. If this radio source did not belong to a galaxy cluster, it would be like trying to see your intricate pattern with only a very small pile sand.

Examining Figures 4 and 5 we can clearly see a bright galaxy at the center of the X-shaped radio source seen in both the optical and X-ray images. This bright central X-ray point source is characteristic of an AGN due to the bright X-ray emission of infalling material on an SMBH. Two other companion X-ray point sources appear on either side of the central AGN but do not show up in the optical images. These point sources fall along the primary axis of the radio source where strong radio contours to the east and west (right and left) of the central AGN form the “active” edge-brightened radio lobes of an FR-II source. The slightly weaker radio contours to the north and south (top and bottom) trace the secondary axis of the radio source and form the “inactive” winged radio lobes. It is interesting to note that fainter X-ray point sources overlap with the north and south lobes but may or may not be imbedded in the radio lobes. In the region of the north lobe, three close X-ray point sources are resolved, whereas the optical images only show one galaxy in the same location. Most importantly, it is clear from Figure 5 that the two bright X-ray hotspots are significantly misaligned from the primary axis and very slightly misaligned from the secondary axis. This suggests that lots of thermally emitting X-ray gas is being swept away from the active radio lobes (and thus the AGN jets) forming low-pressure/low-emission regions along the primary axis of the X-shaped radio source. This is very strong evidence for the fact that AGN strongly affect their local environment on large scales.

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