Alessondra (Sondy) Springmann is an intern in the SULI Program at Stanford Linear Accelerator Center, where she researches host galaxy shapes of X-shaped radio sources. She studied astrophysics as an undergraduate at Wellesley College, Wellesley, Massachusetts. Ms. Springmann is a member of the American Astronomical Society, and the Society of Physics Students. She grew up in Point Reyes Station, California, and she enjoys photography, cooking, sailing, aikido, fire poi, frisbee, and hiking.

C.C. (Teddy) Cheung is a postdoc at the Kavli Institute for Particle Astrophysics and Cosmology at Stanford University. He received his Ph.D. from Brandeis University in 2004, for work on relativistic jets in active galactic nuclei, and continues research on cosmic radio sources. He came to Stanford as a Karl Jansky fellow of the National Radio Astronomy Observatory, after an initial year at the Massachusetts Institute of Technology on the same fellowship.

HOST GALAXIES OF X-SHAPED RADIO SOURCES

Alessondra Springmann and Chi Cheung

ABSTRACT

Most radiation from galaxies containing active galactic nuclei (AGNs) is emitted not by the stars composing the galaxy, but from an active source at the galactic center, most likely a supermassive black hole. Of particular interest are radio galaxies, active galaxies that emit much of their radiation at radio wavelengths. Within each radio galaxy, an AGN powers a pair of collimated jets of relativistic particles, forming a pair of giant lobes at the end of the jets and thus giving a characteristic double-lobed appearance. A particular class of radio galaxies has an "X"-or winged-shaped morphology: in these, two pairs of lobes appear to originate from the galactic center, producing a distinctive X-shape. Two main mechanisms have been proposed to explain the X-shape morphology: one being a realignment of the black hole within the AGN and the second positing that the radio jets are expanding into an asymmetric medium, causing backflow and producing secondary wings. By analyzing radio host galaxy shapes, the distribution of the stellar mass is compared to the differing model expectations regarding the distribution of the surrounding gas and stellar material about the AGN. Results show elliptical host galaxies with an orthogonal offset between the semi-major axis of the host galaxy and the secondary radio wings, which lends support to the hydrodynamical model. However, results also show circular host galaxies with radio wings, making the realignment scenario a more likely model to describe the formation of these X-shaped radio sources.

INTRODUCTION

Among the largest and most prevalent structures in the Universe are extragalactic radio sources, emitting strongly in the radio portion of the spectrum. Thousands of these objects exist, ranging in size from approximately 50 kiloparsecs across (approximately 150,000 light-years) to 100 kiloparsecs (300,000 light-years). These radio sources are composed of relativistic plasma jets traveling at high speeds and emitting synchrotron radiation (relativistic electrons moving through weak magnetic fields). Extragalactic radio sources contain a central host galaxy from which two jets are emitted. As the jets interact with the surrounding intergalactic medium, a pair of giant radio lobes forms. Figure 1 shows Cygnus A, a typical extragalactic radio source approximately 100 kiloparsecs across, which exhibits a central host galaxy (blue), collimated jets, and radio lobes (both red).

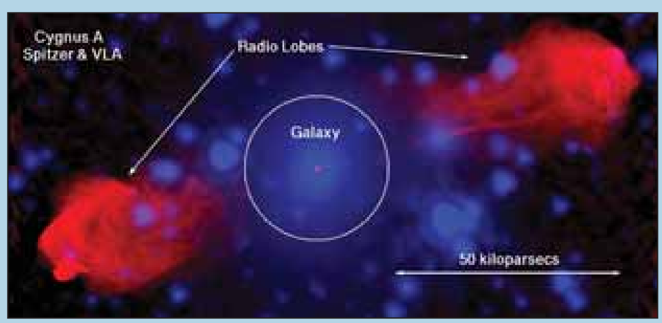

Figure 1. Extragalactic radio source Cygnus A. The host galaxy is imaged in the optical band shown in blue at the center, while the radio jets and lobes are shown in red. The total size of Cygnus A is 100 kiloparsecs across, approximately 300,000 light-hears. The optical image of the host galaxy is courtesy of the Spitzer Space Telescope and the radio image was taken with the Very Large Array, courtesy of the National Radio Astronomy Observatory/Associated Universities, Inc..

In addition to being large, coherent structures, extragalactic radio sources are also highly energetic. The energy output of typical extragalactic radio sources is 10^{44} ergs/second, with some sources having total energies up to 10^{59} ergs/second. (Our Sun, in comparison, has a luminosity of 10^{33} ergs/second, making it 11 orders of magnitude less energetic than Cygnus A.) The majority of radio galaxies emit most of their radiation not from the stars, gas, and dust composing the galaxy, but from the active source at the center, an active galactic nuclei (AGN), widely believed to be a supermassive black hole [1].

Thousands of these extragalactic radio sources resemble the canonical object, Cygnus A, in that they possess one pair of radio jets. Three decades ago approximately a dozen radio galaxies displaying two sets of jets emitting from the central supermassive black hole, forming a distinctive "X"-shape were known [2]. Over the past three decades, the number of known sources possessing the X-shaped morphology has grown to over a hundred candidates, allowing for more detailed studies of these objects, particularly regarding their shape and origin. Figure 2 shows double radio source 3C315, which displays a distinctive X-shaped morphology.

Astronomers propose that this distinct shape may be the result of a recent collision or merger between two supermassive black holes, which can produce the extra set of jets and lobes. Another explanation is that the main jets expanded into an asymmetric medium, generating an additional pair of radio lobes.

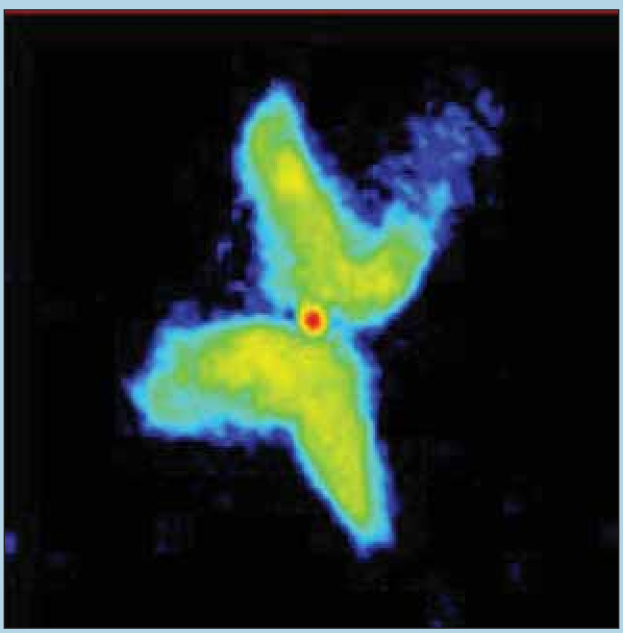

Figure 2. 3C 315, an extragalactic radio source with two pairs of jets, from Leahy and Williams [7].

Hydrodynamical simulations by Capetti et al. in Figure 3 show that as a jet, aligned parallel to the semi-major axis of an elliptical galaxy[1], propagates into the surrounding gas distribution, two major jets form, and smaller wings will form orthogonal to the major jets, producing X-shaped radio lobes [3].

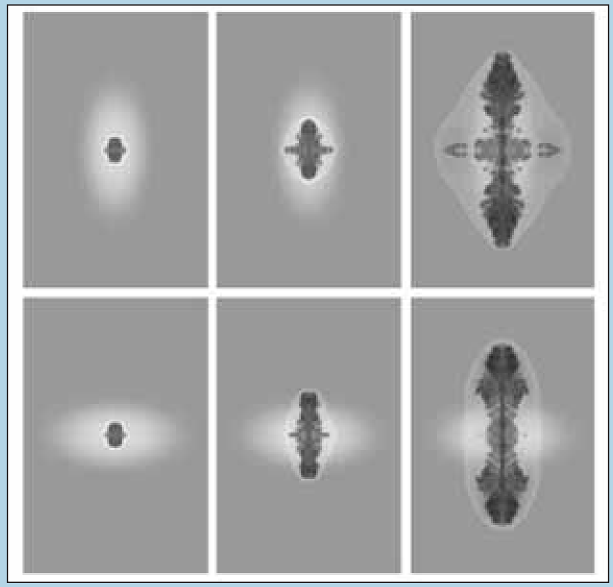

Figure 3. Hydrodynamical simulations performed by Capetti et al. [3]. These numerical simulations show density images representing the evolution of the radio-source in the stratefied medium of the host galaxy. The top panels refer to the case when the jet is oriented parallel to the major axis of the gas distribution, while the lower panels to the case when the jets are parallel to the minor axis. The white represents the distribution of gas about the host galaxy, while the dark gray represents the expanding radio jets.

From the x-ray observations performed by Kraft et al. of the gas surrounding elliptical galaxies, it is known that stellar light is an efficient way of probing gas distribution, as the distribution of gas around a host galaxy follows the distribution of stars in the galaxy [4]. Thus, a galaxy with an elliptical distribution of stars will have an elliptical distribution of surrounding gas. Wing formation is most pronounced in elliptical galaxies, with the main set of jets forming parallel to the major axis of the galaxy. Studying a small set of host galaxies, Capetti et al. found that many elliptical galaxies have a small set of "wings", which align orthogonal to the semi-major axis of the host galaxy, as shown in their simulations and in Figure 5 [3].

In this paper, the ellipticity of the galaxies that play host to the X-shaped jets, is investigated to determine if galaxies with more elliptical distributions of gas have X-shaped jets. Using the ellipse package for Image Reduction and Analysis Facility (IRAF)[2] to model the elliptically-shaped isophotes, or regions of equal brightness, of the galaxies, the ellipticity and extent of the host galaxies and

[1]An elliptical galaxy is an ellipsoid, or a three-dimensional ellipse, as shown in Figure 4. Viewed from Earth, it appears as an ellipse in the sky.

[2]IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

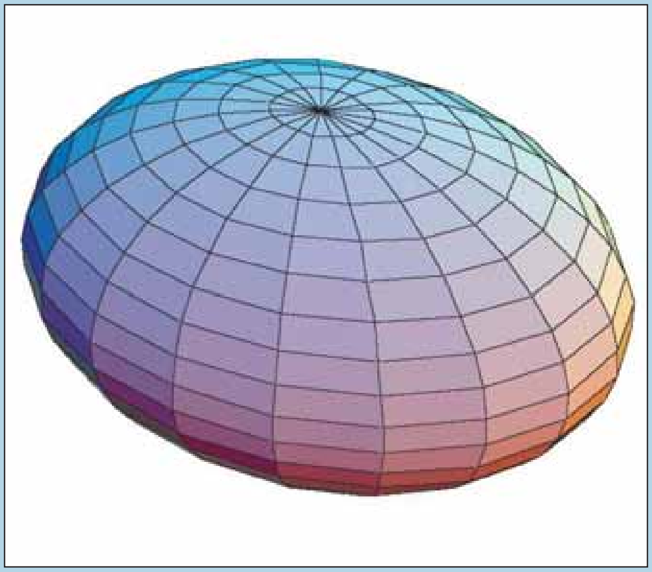

Figure 4. A model of an elliptical galaxy as a three-dimensional ellipse, ro ellipsoid. When viewed from Earth it appears to be a flat ellipse .

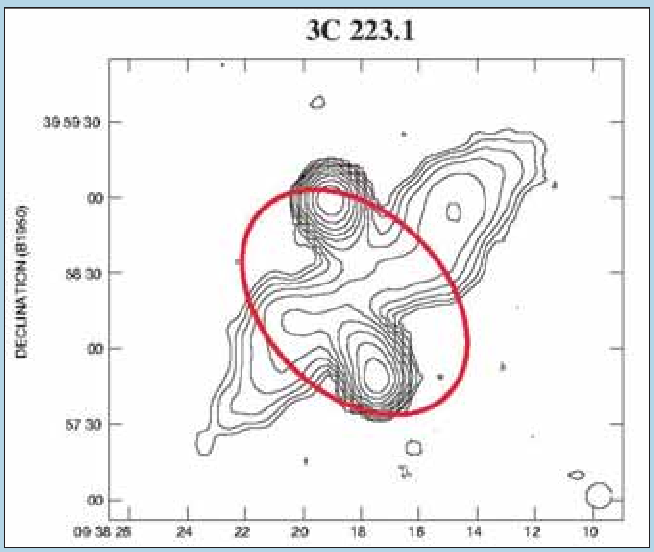

Figure 5. Superposition of the host galaxy shape (not to scale) onto the radio image maps for X-shaped source 3C 223-1. Superposition by Capetti et al. [3], with radio maps from Dennett-Thorpe et al. [8].

compared was determined to radio galaxy morphology. These results can be compared to the results of previous studies (such as those carried out by Capetti et al. [3]) with an expanded sample of X-shaped radio sources.

METHODS OF ANALYSIS

Images of the host galaxies of nine X-shaped extragalactic radio sources were collected by the Sloan Digitized Sky Survey. The images are 56-second exposures taken in the r-band filter, which has a central wavelength of 6,280 Ångstroms. All objects imaged are

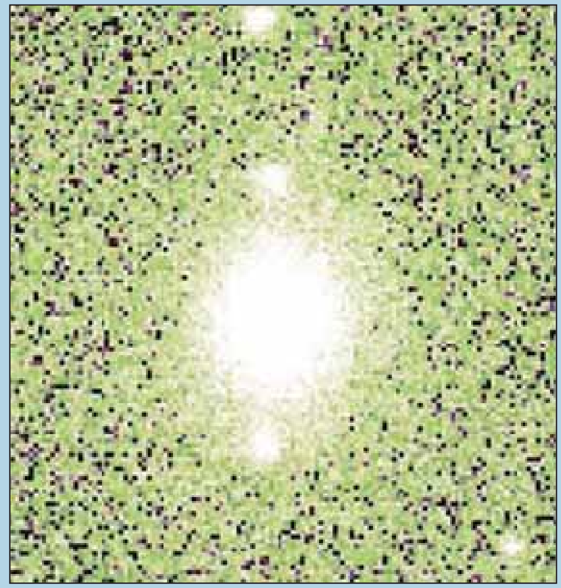

Figure 6. Detail of J0813+4347, an ellipitcal host galaxy imaged in the *r*-band by the SDSS telescope.

18th magnitude[3], or brighter in the r-band, as dimmer objects would otherwise not be sufficiently resolved. The pixel scale of the CCD is 0.4 arcseconds and the seeing for each image is approximately one arcsecond. A sample source image, the host galaxy of source J0813+4347, is shown in Figure 6.

Elliptical isophotes, or regions of equal brightness, of these host galaxies were fitted by the ellipse routine of the Space Telescope Science Data Analysis System (STS-DAS)[4] isophote package for IRAF. The isophote fitting methods are described in Jedrzejewski [5]. The center and length of the outermost elliptical isophote's semi-major axis are specified by the user, then the software plots successively smaller isophotes on the image, as seen in Figure 7. Information pertaining to the isophote plots, such as the semi-major axis of the isophote in pixels, ellipticity of the isophote[5], and position angle of the isophote relative to north in the image are written to a table. A routine called bmodel then converts this table to a model of relative isophotal intensities and sizes, which can then be subtracted from the original image to judge the goodness

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[3]The magnitude scale is a logarithmic scale that describes the relative brightness of stars, with the star Vega (α Lyrae) defined as having magnitude 0.

[4]STS-DAS is a product of the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc. for the National Aeronautics and Space Administration.

[5]Ellipticity is defined as f =1 – a/b, where a is the semi-major axis of the ellipse, and b is the semi-minor axis of the ellipse. An ellipse with f = 0 is a circle.

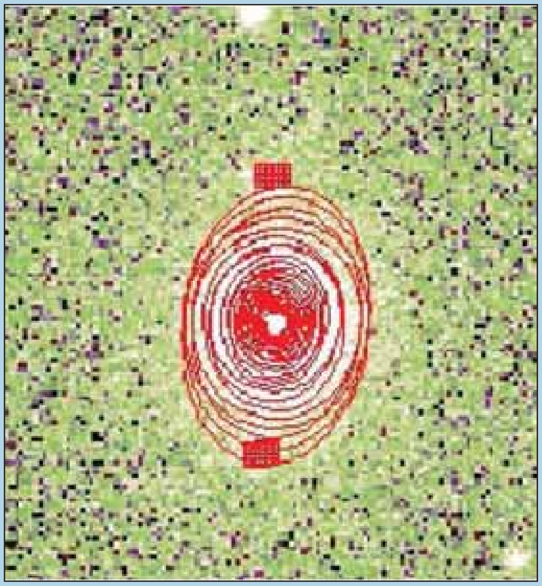

Figure 7. Isophotes fitted to J0813+4347 by the ellipse routine of the SDS-DAS package for IRAF.

of the isophote fits. Figure 8 shows the isophote model subtracted from the background image and indicates that the isophote model matches the intensity of the host galaxy, leaving minimal residual background on the image.

The position angles of the radio lobes and wings of the actual X-shaped sources were measured from data taken by the Very Large Array (VLA)[6]. The difference between the position angles of the host galaxies' semi-major axes and the position angles of the radio wings of the X-shaped sources are shown in Table 1 with the values for the ellipticities of host galaxies calculated from the isophote fits calculated from the ellipse routine.

RESULTS

Galaxy parameters (position angle of the main set of radio jets, position angle of the radio wings, position angle of the host galaxy in the optical, ellipticity of the host galaxy, and offset between the radio wing position angle and the optical host galaxy position angle) were measured for four known X-shaped sources from the literature and five new objects with a distinct X-shape found by Cheung [2].

The distribution of host galaxy ellipticities for these nine sources (in blue) is compared to a sample of "normal" (not X-shaped) host galaxies of extragalactic radio sources analyzed by Capetti et al. (white) is shown in Figure 9 [3]. Some of these host galaxies are highly elliptical; however, approximately two thirds of these objects have ellipticities consistent with the host galaxy being circular. Capetti found that the host galaxies of X-shaped sources tended to be highly elliptical [3], which is contrary to this study's finding that the host galaxies of these X-shaped objects range from being circular to highly elliptical. It appears that the host galaxy need not be highly elliptical to cause wing formation in these cases.

Although the ellipticities of these host galaxies show no specific trend toward either high or low ellipticity, the offset between the host galaxy optical semi-major axis position and that of the radio wings tends to be approximately orthogonal for six out of nine objects for which exist VLA observations, as shown in Figure 10.

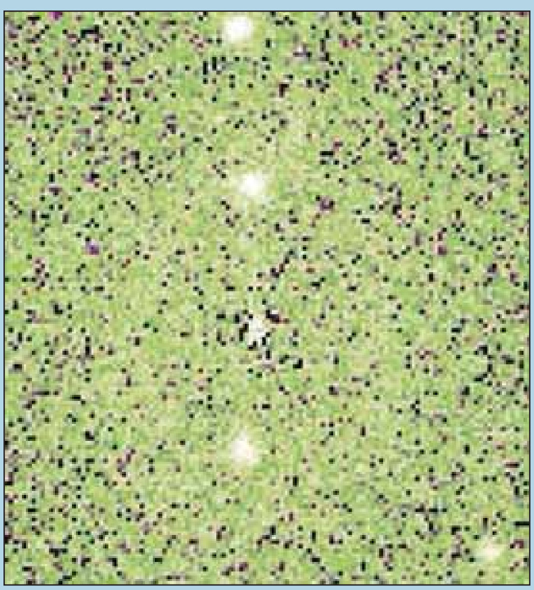

Figure 8. The J0813+4347 image with the isophote model subtracted from the data image. The original galaxy has been completely removed, except for the bright point at the center (the host galaxy AGN).

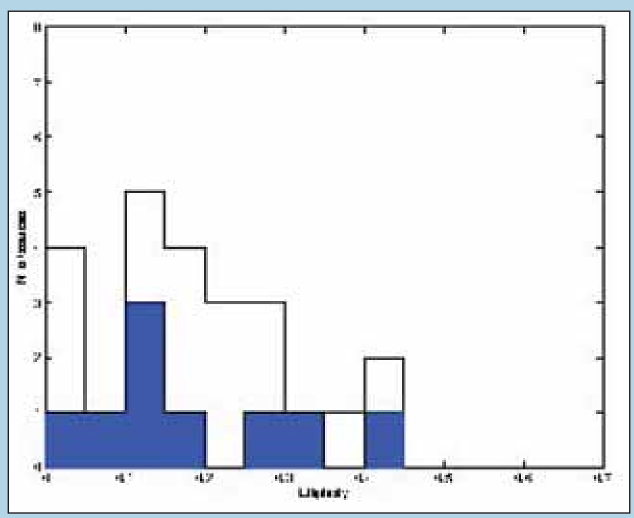

Figure 9. A histogram of the ellipticities of the host galaxies of X-shaped sources. The white histogram are the "control" objects from Capetti et al. and the blue histogram are the host galaxies of X-shaped radio sources [3].

[6]VLA data courtesy of the National Radio Astronomy Observatory/Associated Universities, Inc.

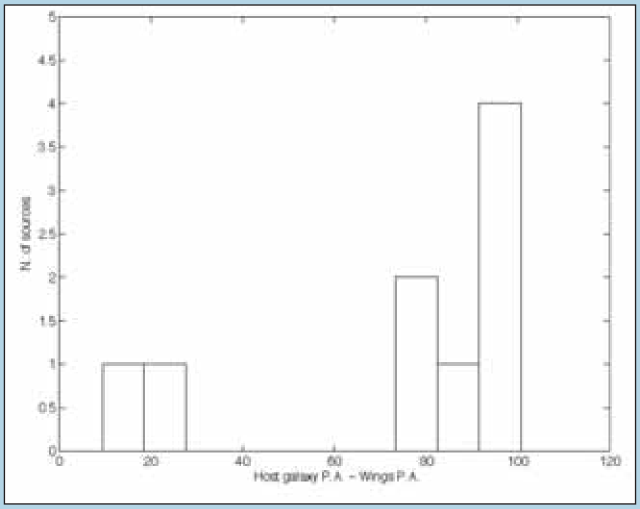

Figure 10. A histogram of the position angle offsets between the semi-major axis of the host galaxies and radio wings of the x-shaped radio sources. Approximately two thirds of the sources show an offset of 90 degrees.

With the position angles of the radio lobes and wings taken from the VLA data in Table 1, there appears to be little connection between the ellipticity of the host galaxy and the presence of radio wings orthogonal to the semi-major axis of the host galaxy. This is evidenced by objects with low ellipticities (less than 0.12) and an approximately orthogonal offset between the radio wings and optical semi-major axis of the host galaxy.

However, host galaxy position angles can only be measured if they are highly elliptical (for ellipticities greater than 0.12), which produces low-confidence measurements of the isophotal position angles of the semi-major axes of the host galaxies.

Comparing the host galaxy position angle to the wing position angle, the difference in these angles are clustered around 90°, i.e. the position angles are orthogonal, consistent with the findings of Capetti et al. However, unlike Capetti, galaxies with circular isophotes play host to X-shaped radio sources.

CONCLUSIONS

Host galaxy ellipticities from nine sources are plotted in Figure 9. Some of these host galaxies are highly elliptical, having ellipticity values of over 0.12; however, four of these objects have ellipticities consistent with being circular. The ellipticities are compared to a sample of normal radio galaxies from Capetti et al. and the distributions are indistinguishable (Figure 9), contrary to the findings of Capetti [3]. Simulations performed by Capetti show that an elliptical distribution of gas about a host galaxy produces the main lobes and auxiliary wings seen in X-shaped sources. The host galaxy need not be highly elliptical to for there to be secondary wings in extragalactic radio sources.

X-ray observations performed by Kraft et al. of 3C 403, an X-shaped source, found that the optical position angle of the host galaxy follows the X-ray gas distribution [4].

Therefore, in at least one X-shaped source, it is known that the gas follows the star distribution of the galaxy, and thus, if the galaxy appears elliptical in the optical band, it is likely elliptical in its gas distribution. According to Capetti, if the stellar light follows the distribution of gas around the galaxy, is elliptical, and is on a scale much larger than that of the host, comparable to the size of the X-shaped lobes and wings, then the double morphology of the X-shaped radio galaxies will form as the main set of jets expand into the surrounding gas [3].

Several of the host galaxies sampled show circular isophotes, contrary to the findings of Capetti. This can be resolved if the orientation effects of the host galaxy are consistent. A galaxy with the form of an ellipsoid viewer from its most circular side will appear to have circular isophotes as a consequence of the observer's position. However, it is unlikely that a galaxy having the shape of a spheroid (an ellipsoid with two axes equal in length) would have a spherical side facing Earth. It is more likely that, although our results for J0831+3219 agree with deeper observations by Ulrich et al., the data from the Sloan Digital Sky Survey is "shallow", or that the objects were not sufficiently exposed to obtain a high enough signal to noise ratio in order to resolve the elliptical isophotal structure of these host galaxies [6].

We compared our measurements with much deeper data taken at longer exposures for one well-studied, low-ellipticity object, J0831+3219 [6]. As our values for ellipticity and position angle of the host galaxy are consistent with Ulrich's, this demonstrates that the Sloan Digital Sky Survey data is valid and comparable to "deeper", or longer-exposure observations.

The model proposed by Capetti might have difficulty explaining the circular hosts of these X-shaped sources, however, it should not be immediately discounted. There are a number of papers, including Capetti, which describe hydrodynamical situations that lead to X-shaped source formation supported by data and simulations.

Other models exist that propose that the formation of secondary wings in extragalactic radio sources due to the realignment of the central supermassive black hole of a host galaxy, due perhaps to galactic mergers, but they lack significant simulations or data to reinforce their predictions. In order to verify whether the Capetti or black hole realignment model most accurately describes the creation of X-shaped extragalactic radio sources and further understand the formation of these objects, more simulations of galactic mergers should be performed, in addition to additional observations of both the host galaxies and X-shaped sources.

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