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Locating Supermassive Black Holes in Distant Galaxies via RADIO GALAXY ZOO: LOFAR Project

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This paper focuses on processes of formation and weighing of supermassive black holes, and how they can be located via the Citizen Science Project 'RADIO GALAXY ZOO: LOFAR' presented by Zooniverse. Thousands of jets and galaxies have been seen by the Low Frequency Analyzer and Recorder (LOFAR) survey, and an automatic "source finder" computer programme has identified them. This programme is not without flaws, and it occasionally separates a single radio source into numerous components. Through this project, radio astronomers require assistance in reassembling the components that the source finder programme mistakenly separated. This will allow the recreation of the entire radio source from its constituent parts. In this paper, we discuss interesting images of potential sources that were provided to us while performing the project as volunteers. So far, 208,564 classifications have been made through this project, with 26,343 finished subjects and 8,473 volunteers as of the publication of this paper. Supermassive black holes are important to detect and study because they are the engines of cosmic change. The research will also aid in the creation of a picture of how enormous galaxies, galaxy clusters, and black holes formed in the first billion years of the universe.

Keywords: Supermassive black hole, active galactic nuclei, zooniverse, citizen science, Radio Galaxy Zoo

INTRODUCTION

In the citizen science project 'Radio Galaxy Zoo: LOFAR' by the team of Zooniverse, as volunteers, we helped astronomers to locate and identify supermassive black holes at the center of galaxies. This project tells us about our sky at radio wavelengths. Almost all of the sources found in the LOFAR radio survey of the northern sky are what astronomers call Active Galactic Nuclei (AGN). They are powered by supermassive black holes in the centers of galaxies. Nearby material passes very close to these supermassive black holes and is flung out in the form of immense jets. These jets are detectable at radio frequencies, and astronomers can learn a lot about the origin and evolution of supermassive black holes by studying their radio emission (Zooniverse, 2021). The data collected by LOFAR and processed by the source-finder algorithm is then given to the public in the form of images to identify the potential hosts of supermassive black holes and classify them.

The term 'Black Hole' was coined in 1967 by the American physicist John Archibald Wheeler (European Southern Observatory, 2010). Due to the strong gravitational pull of the black holes, these are regions from which even light cannot escape once it crosses its Event Horizon. They are ten times to billions of times of the mass of the Sun (Ohkubo, 2009), at such a small space that their escape velocity becomes greater than the speed of light.

Stars that are far larger than our Sun, exceeding the Chandrashekhar limit which is 1.4 times the mass of the Sun (S. Hawking, 2016), will compress after they have used up all of their nuclear fuel, burning higher elements until they reach Iron. The core's whole mass collapses into a black hole because the gravitational pull of the star is higher than the electron degeneracy pressure (S. W. Hawking, 2006). According to Einstein's General Theory of Relativity (1915) matter curves space-time which implies that gravity affects even massless phenomena like light, because mass and energy are equivalent in Einstein's equation (S. W. Hawking, 2006).

$$E = mc^2$$

This revolutionized the concept of black holes by introducing a point called 'singularity', established by Robert Oppenheimer.

A black hole is characterized by: mass, angular momentum and electric charge. There are four types of black holes: stellar, intermediate, supermassive and miniature. This paper focuses on supermassive black holes.

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THEORY

Supermassive Black Holes

Supermassive black holes are the black holes with the largest mass (billions of times the mass of the Sun) and are found at the centers of galaxies. The galaxies that are thought to host them are known as active galaxies. They are believed to power Active Galactic Nuclei (AGN) which are so far the 'brightest' objects in the universe. Each AGN typically releases far more energy than an entire galaxy. They grow over billions of years by the constant accretion of huge plumes of gases and other matter. They are mainly found in galaxies that are having a central bulge which is thought to form due to collision and mergers between galaxies during the early universe.

The Milky Way provides the best evidence for the existence of supermassive black holes (European Southern Observatory, 2010). The black hole at the center of our galaxy named Sagittarius A* is 4 million solar masses and is 26,000 light-years away from the Earth. The best empirical evidence for the presence of a supermassive black hole is the motion of the stars in its neighborhood (European Southern Observatory, 2010). These objects may have had a role in the early universe's structure creation, triggering bursts of star formation and nucleating proto-galactic condensations (Melia, 2007).

Active Galactic Nuclei, Quasars and Relativistic Jets

The idea that the supermassive black holes are the engine drivers of quasi-stellar objects or quasars was presented by Lynden Bell in his 1969 paper titled 'Galactic Nuclei as collapsed old quasars.' The notion of Active Galactic Nuclei (AGNs) was born out of observations made in the 1960s and 1970s, primarily in the radio, ultraviolet, and optical wavelengths ("The relevance of being active", 2019). The fact that such small volumes could produce the energy of a hundred billion Suns led to their early identification as supermassive black hole radiative manifestations (Melia, 2007). Optical, infrared, and radio investigations of AGNs demonstrate that the massive masses concentrated within the narrow radius are black holes. The large Doppler shifts and gravitational red-shifts of the features disclose the enormous gravity near the event boundary for the first time. (Fabian, 1999).

Around 10% of AGNs are radio-loud, implying that the nucleus produces a relativistic outflow of materials (Fabian, 1999). This relativistic outflow's composition could be electron-proton or electron-positron. The radiated energy usually collects in the area around a black hole. Magnetic fields are thought to allow the black hole's spin energy to be harnessed and released as kinetic energy in jets.

Formation of Supermassive Black Holes

The reason for the existence of such heavy mass black holes at a time when the universe was 1 billion years old is still not clear. Their formation process is not as simple as stellar-mass black holes which are formed due to the collapse of a heavy star. Few of the notions that are believed to be the reason for the existence of Supermassive Black Holes are:

Formation during the Big Bang

It is believed that supermassive black holes came into existence at the time of the Big Bang. In order to last more than 10 billion years, supermassive black holes must be stable. Due to no thermonuclear reactions, the lepton model is steady. It is critical that the black hole be free of baryon contamination for this to continue to be the case. There can be no matter flow into the black hole in particular. This is demonstrated by a recent observation of the Milky Way's black hole. Thus, the black hole model based on the electron-positron concept necessitates a large quantity of positrons, which were only available during the Big Bang's lepton period. (Dalton, 2019)

Also, the question of how density variations, mirrored by uneven cosmic microwave background radiation, eventually condensed into supermassive black holes and galaxies is currently being researched. (Melia, 2007).

Remnants of Population III Stars

According to observations and computer simulations, the universe was populated with stars that were brighter, hotter, and more massive than the following generation when it was 200-400 million years old (European Southern Observatory, 2010). These massive stars, called as Population III Stars are thought to disseminate manufactured heavy metals through supernova explosions. A cosmic primordial gas formed shortly after the big bang is largely made up of H, He, and a small quantity of light components (Li, Be, B, etc.). The first heavier elements, such as C, O, Ne, Mg, Si, and Fe, must be synthesized early in the universe's history during the formation of the earliest (metal-free = Population III) stars (Volonteri, 2012). It's possible that they were a thousand times more massive than the Sun and collided to generate supermassive black holes.

Formed Due to the Merger of Galaxies

The central bulge in galaxies is believed to have been formed when a galaxy merged into one or more galaxies in the past (Figure 1). This causes their respective stellar/supermassive black holes to merge, resulting in the creation of supermassive black holes at their cores, as seen today.

The turbulence created at the collision's core transports the majority of the gas to the centre, where it forms new stars and feeds a central black hole or pair of black holes (Melia,

Figure 1. The Merger of Two Galaxies. The collision between two galaxies begins with the unraveling of the spiral disks. This HST image shows the interacting pair of galaxies NGC 2207 (the larger, more massive object on the left) and IC 2163 (the smaller one on the right), located some 114 million light-years from Earth (Melia, 2007).

2007).

Detection of Supermassive Black Holes

The following are the various processes that are followed for the detection of supermassive black holes:

Spectrographic Evidence

The analysis of optical and UV emission spectrum allows the study of the central mass of the object that is being orbited by a group of stars. With the added component of outflowing material from a greater distance, UV/optical broad lines appear in the accretion disc or complicated shape of the accretion disc. According to long-term monitoring of these lines, changes in the wide line fluxes are linked to flux changes in the continuum. This yields a mass scaling relation that allows us to estimate the mass of a supermassive black hole using the continuum and broad emission line characteristics from a single-epoch spectrum of the AGN (Ilic and Popovic, 2014). Thus, it helps in the detection of supermassive black holes.

Spin Detection

The geometry of the X-ray Fe Kα line can be used to determine the spin of the supermassive black hole (Ilic and Popovic, 2014). The Fe Kα line is normally short, having a line energy of 6.4 keV. However, if it originates from a relativistic accretion disc of an AGN, it gets larger and its profile gets altered due to kinematical effects. Kinematical effects such as Doppler boosting and gravitational redshift, as well as line widening, are frequently seen in Seyfert galaxies' (those having active nuclei) spectra. Comparing observed and predicted Fe K line profiles can offer critical information about the black hole's spin since the angular momentum of the supermassive black hole has a significant impact on the broad line profile. (Ilic and Popovic, 2014).

Weighing of Supermassive Black Holes

The following are the various processes that are followed for the weighing of supermassive black holes:

Motion of Gas

Using the kinematics of the gas orbiting a black hole, one can measure its central mass. In some cases, the circling gas emits MASER - Microwave Amplification by Stimulated Emission of Radiation (a source of stimulated spectral line emission is an astrophysical MASER (Humphreys, 2011) that acts as an alternative dynamical signal for the central mass (European Southern Observatory, 2010). The circumstellar envelopes of evolved stars, molecular clouds/star forming regions, active galactic nuclei, supernova remnants, and comets all emit maser radiation (Humphreys, 2011).

Miyoshi et al. (1995) used radio interferometry and observed a disk of dense molecular material of a spiral galaxy NGC 4258. At speeds of up to 650 miles per second, the disc was orbiting the galaxy's nucleus (Melia, 2007). Sufficient radiation is produced through this disk which excites water molecules condensation and leads to strong maser emissions at radio wavelengths. However, not all galactic nuclei can be detected with masers.

Reverberation Mapping

The central engine irradiates clouds of gas around the nucleus, resulting in a spectrum with emission lines indicating the plasma's ionized state (Melia, 2007). The lines emitted from the central source are broad, from which the detection of direct radiation including some time lag is measured. Also, in the broad-line region, there is indirect radiation which is detected by the clouds. This method is known as reverberation. The mass of the supermassive black hole then can be calculated by combining the distance between the gas clouds and their estimated width (European Southern Observatory, 2010).

Motion of Stars

Performing the kinematic studies of stars orbiting the central object is the best method to determine the mass of a supermassive black hole (Figure 2). The center of our galaxy is the best evidence of this method. For far-away galaxies, clear identification of a group of stars is not possible but an approximation can be used to trace the kinematics.

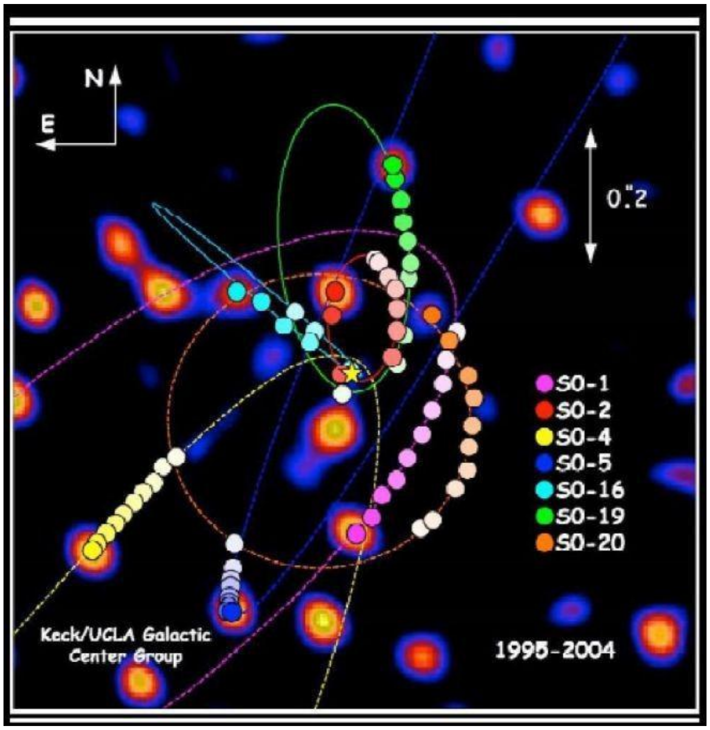

Figure 2. Motion of Stars. The positions of stars surrounding the Milky Way's centre have been calculated. The rings depict annual measurements of the location of various stars recorded with the W. M. Keck Telescopes' infrared observations (Hickox, 2011).

Low-Frequency Array (LOFAR)

LOFAR is currently the world's largest radio telescope which is working at radio-frequencies of 250 MHz. Developed by ASTRON (Netherlands Institute for Radio Astronomy) in 2012, this radio telescope consists of a large network of small antennas working simultaneously. The dipole antenna stations in the interferometric array are spread across the Netherlands and other European nations (ASTRON, 2021).

Working on the principles of interference, the dishes receive the radio signals which are collected and then processed by a Blue Gene/ P Supercomputer. High-resolution images are produced which are further used for performing projects such as the detection of black holes/ jet pairs, and the study of phenomena like solar storms. There are two types of antennas: Low Band Antennas (LBA) that operate between 10 and 90 MHz, and High Band Antennas (HBA) that operate between 110 and 250 MHz (ASTRON, 2021).

Thus, the RADIO GALAXY ZOO: LOFAR PROJECT not only aids in the finding of supermassive black holes at the center of galaxies, but also assists scientists in the creation of a picture of the early universe. The processes of formation and weighing of supermassive black holes helps in understanding the co-evolution of galaxies and black holes in cosmic time.

METHODOLOGY

The images captured by LOFAR and processed by the source finder algorithm are then shown to participants on the Zooniverse Citizen Science platform for further classification.

Training Process: Knowing the Interface

Figure 3 depicts what the window screen looks like.

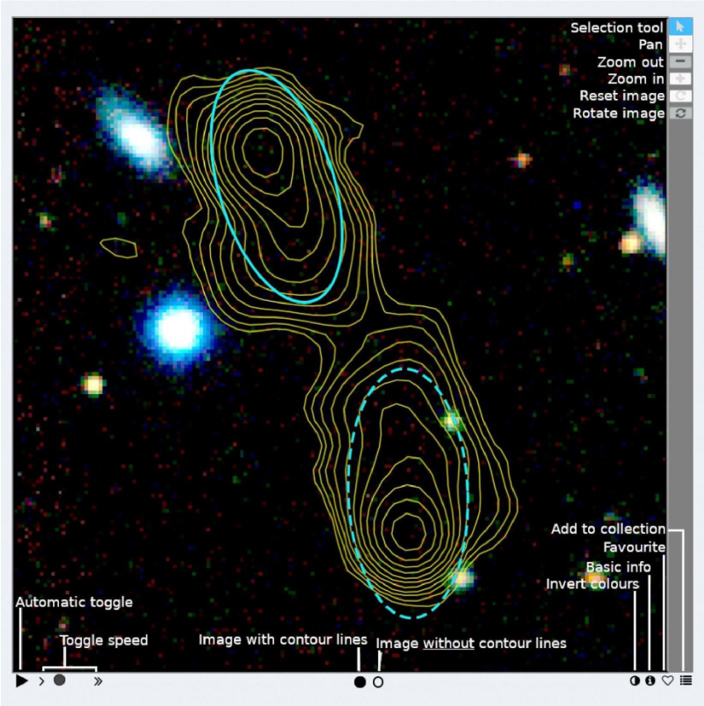

Figure 3. Knowing the Interface. The figure is a representation of what the Zooniverse's platform looks like for this particular project. The buttons and navigations provided at the corners perform various functions (Zooniverse, 2021).

Observing the Contour Lines

The yellow lines here are the contour lines which are showing the detection of radio emissions (Figure 4). The background image is taken using an optical telescope. The range of a source's radio emission is substantially greater than that of its optical emission (Zooniverse, 2021).

The Blue Ellipses

The blue ellipses give information about the surrounding regions of the radio emissions that are being observed (Figure 4). One ellipse with a solid blue line will always exist. This is in relation to the radio source that is now being investigated (Zooniverse, 2021).

Steps for Source Classification

The following steps must be followed for the source classification purposes on the Zooniverse RADIO GALAXY

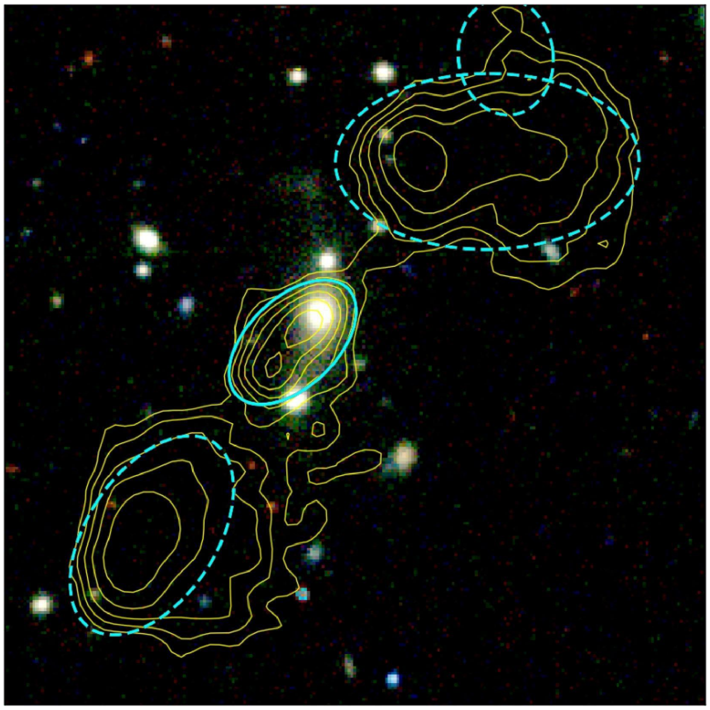

Figure 4. Contours and Blue Ellipses. The contour lines in this figure are yellow, and they show the detection of radio emissions. Blue ellipses give us information about the areas where the radio emissions we're looking at are coming from (Zooniverse, 2021).

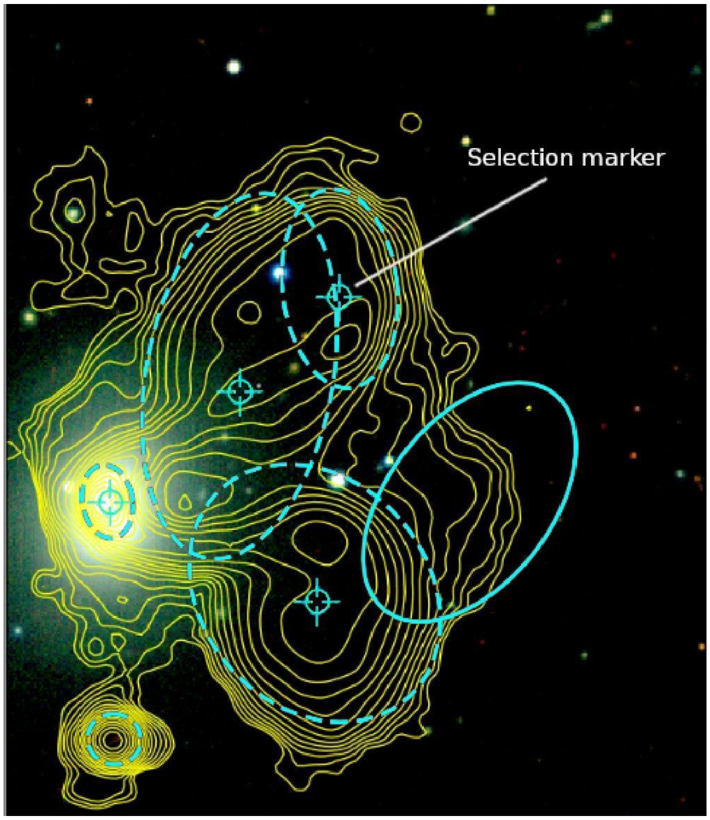

Figure 5. Marking of Ellipses. Looking at the dispersion of contour lines in the figure, the marker is placed inside the dashed ellipses that are believed to be surrounding parts of the solid ellipse (Zooniverse, 2021).

ZOO: LOFAR project's platform:

Marking Ellipses

The marker is placed inside of the dashed ellipses which are considered as the neighboring regions of the solid ellipse by looking at the spread of contour lines (Figure 5).

Marking the Optical Counterpart

One has to identify the single source from which the contour lines seem to have originated known as optical counterpart (Figure 6). On the detection of more than one source, all need to be marked.

The image can be viewed in three types - with contour lines, without contour lines, and as radio images for better detection.

In some problematic images, it may not be possible to identify the optical counterparts. This could be because of high magnification, blending issues or missing images.

Guide

For simplicity while classification, Figures 7-10 are representative of a decision tree made by authors for hands-on classification.

Apart from these, there are:

1) Complex Cases: One can view multiple radio counterparts in the optical image. The lobes seem to come from different sources.

2) Too Zoomed: One will view the extended radio source i.e. crossing the boundaries of a given optical image. In such cases, no optical source needs to be selected.

3) Artefacts: These are the radio contours that seem to have no real origin. They look like 'explosions' that are brighter near the radio sources and start to faint as they look away. The bright sources not visible in the image area can also lead to creation of artefacts.

4) Blends: When the source finding algorithm links two or more radio sources wrongly within a single blue ellipse, a blend occurs (ASTRON, 2021). There may be more than one 'optical source' and we need to select them all and classify the image as 'blend'.

5) Missing Images: Whole of the data is missing from the optical images.

RESULTS AND DISCUSSION

This section contains the analysis of images that were being classified by us as a part of this project (Figure 11).

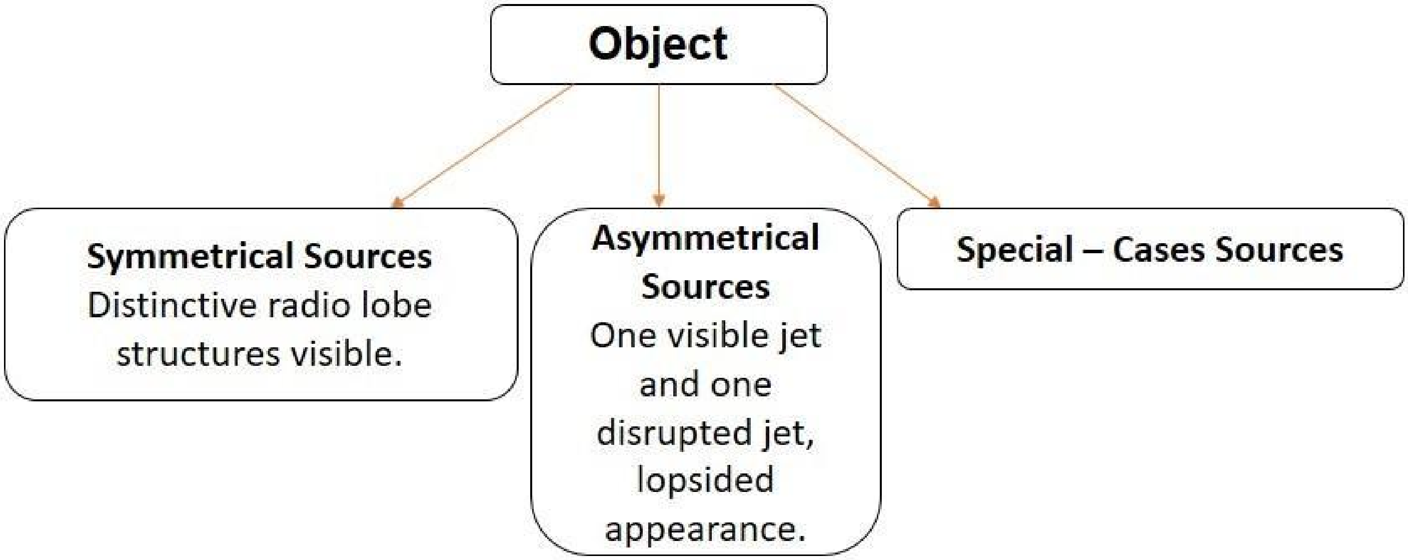

Figure 7.

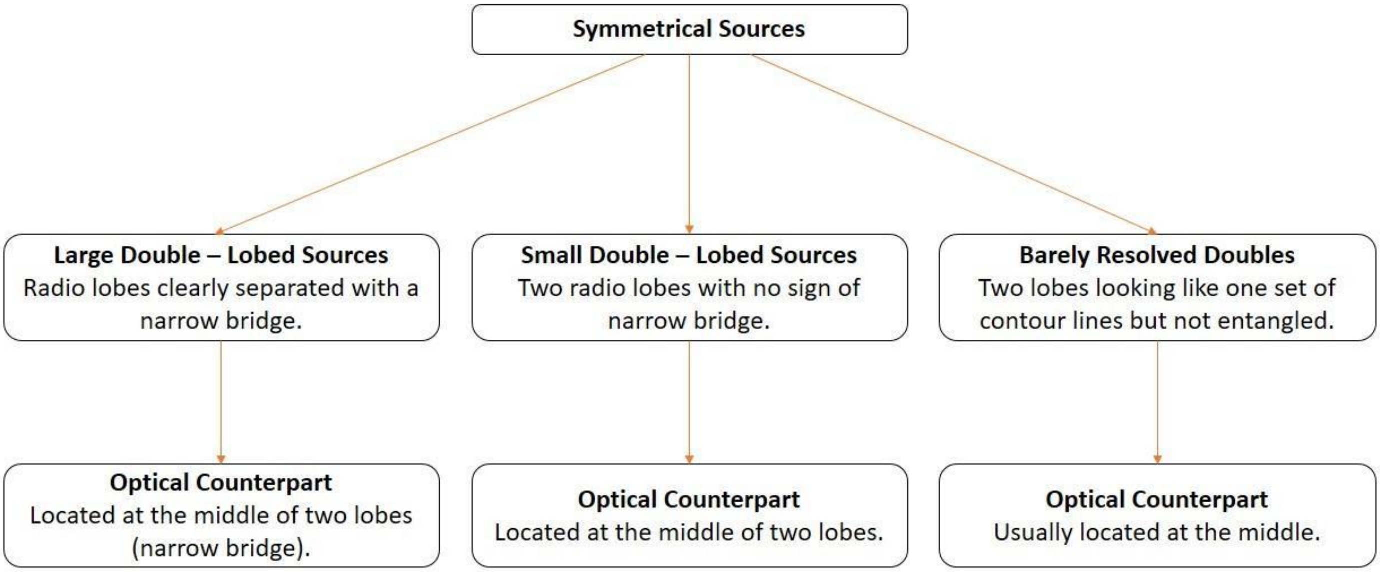

Figure 8.

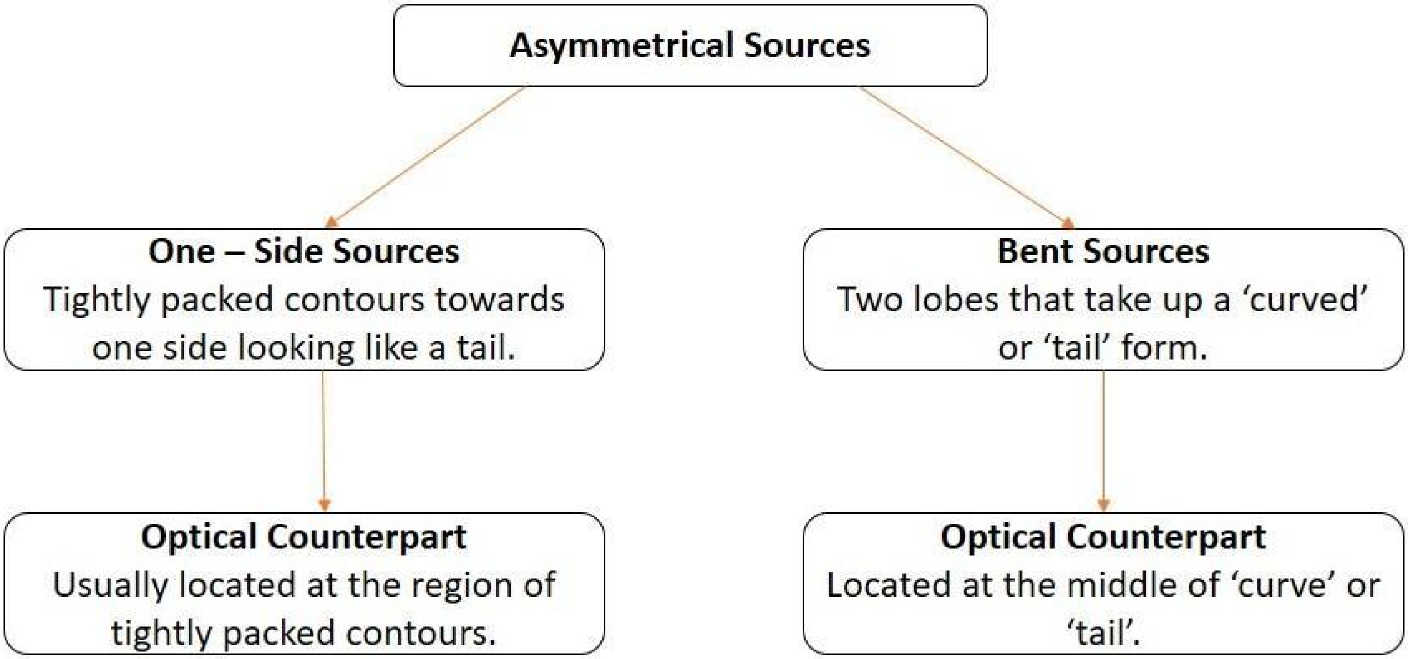

Figure 9.

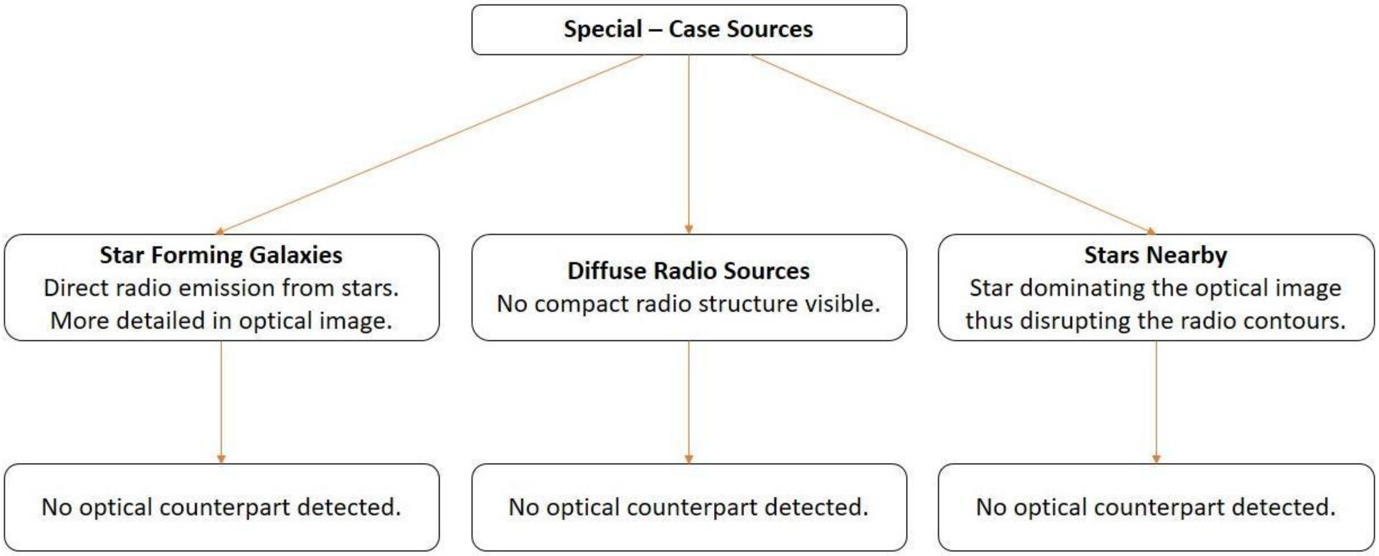

Figure 10.

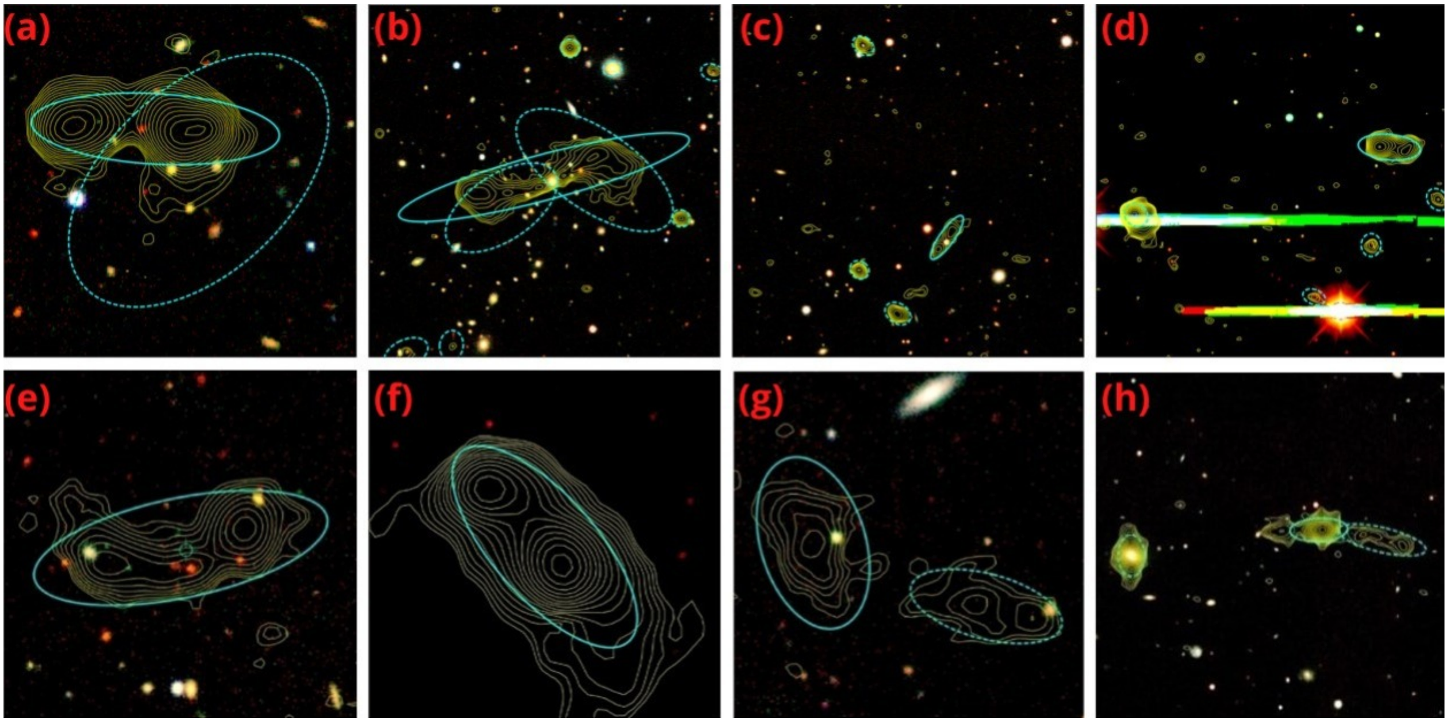

Figure 11. Classified Images. (a) This is the case of Barely Resolved Double Lobed Symmetrical Source. No particular optical counterpart can be located in it as the source is farther away. The set of contour lines tell us about the strength of the source. More compact the contour lines, more is the strength. **(b)** This is the case of Small Double-Lobed Source as the two lobes are touching each other through a narrow bridge. The optical counterpart is located in the middle. **(c)** This is the case of an Artefact because the radio contours seem to have no real origin. No particular optical counterpart can be detected. **(d)** This is the case of Nearby Stars and Artefacts. Due to the disruption of radio emissions from its potential source due to a nearby star, we are not able to locate the optical counterpart. **(e)** It is a case of Blend because here the contours seem to be mixed up with each other due to presence of two or more radio sources. **(f)** This is a Diffuse Radio Source. There is no optical counterpart. It should not be mixed with 'blend' because there is only a single radio source. It should also not be classified as 'missing image' because not all the data from the optical image is lost. **(g)** This is the case of Large (Unconnected) Double Lobed Sources. This is possible because the two lobes might be very far apart. No optical counterpart is detected. **(h)** This is the case of Two Different Set of Contours from Two Different Sources. The contour emission towards left has an optical counterpart in the middle. The opposite set of contour lines (towards right), on the other hand, has no optical counterpart (Zooniverse, 2021).

CONCLUSION

The citizen science project 'Radio Galaxy Zoo: LOFAR' helps to detect and locate the supermassive black holes at the centers of large galaxies. They are processing basic algorithms using the data collected by LOFAR in radio-wavelengths. LOFAR is a predecessor of the Square Kilometre Array (SKA) and is expected to transform the scale and scope of astronomical studies around the world. As volunteers to this project, we have demonstrated a few of the classifications we performed. The classifications were made only after proper understanding of the methodology of the project. The analysis of images is a step towards further understanding the physics of black holes. The classifications made by citizen scientists are vital for future machine learning studies since they serve as training data for automatic decision tree classifiers. With the provided metadata, better models of detection can be developed to derive further information about supermassive black holes and create models of how enormous galaxies, galaxy clusters, and black holes formed in the first few billion years of the universe. The project however, does have some limitations. It is predicted that out of a total of 5 million sources, only roughly 150,000 are acceptable for classification in the region that is eventually planned for completion. Each of these 150,000 targets requires five separate views from participants, which means that each target must be presented to five people before an appropriate classification can be created. Despite the fact that the majority of the data needed to create the radio pictures is present, all 150,000 are not uploaded at once. The reason for this is that there is an attempt to complete one section of the sky before going on to the next because human inspection

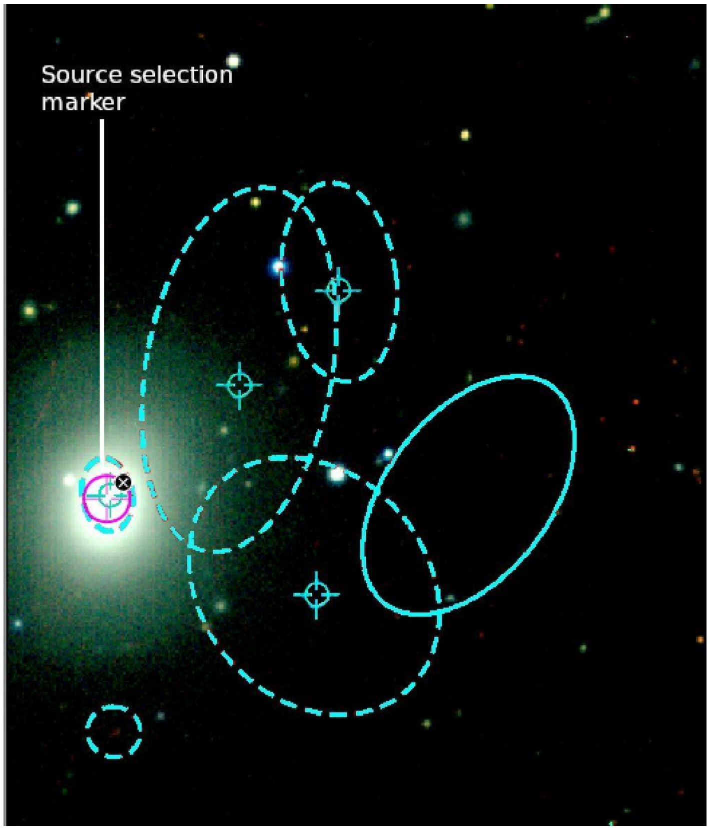

Figure 6. Marking the Optical Counterpart. The optical counterpart must be identified as the only source from which the contour lines appear to have originated as depicted in the figure (Zooniverse, 2021) .

needs time and surety. There are many faint and difficult to detect sources too. Thus, tackling the sky bit by bit will provide better classification than uploading all the targets to be classified at once. This is done by limiting the amount of live objects (the image of targets that are uploaded on the platform for classification) at any given time, because the images shown to volunteers are chosen at random from a pool of images.

This study has a wide range of implications. Radio astronomers require assistance in reassembling the components that the source finder programme misidentified. This will allow it to recreate the entire radio source from its individual components. Astronomers are also trying to figure out what galaxy is causing the radio emission. These galaxies may be viewed at visible wavelengths and provide additional information to aid astronomers in determining distances to radio sources.

Recognized as the most destructive forces in nature, supermassive black holes are also cosmic control mechanisms. They regulate star formation, nucleate proto-galactic condensations and half of the radiation produced after the Big Bang may be attributed to them (Melia, 2007). They are the engines behind the enormous energy output of quasars which permit us to study accretion and photoionization physics of supermassive black holes due to their flaring or fading nature. Their formation processes tell us about the nature of the early universe. They also help us to understand the dynamics of the galaxies.

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CONFLICTS OF INTERESTS

The authors declare no conflicts of interests.

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