SUMMER 2020

ASTRO
IIT KANPUR

FUN SPACE PROJECTS

Exoplanets
Radio Galaxies
Asteroids

ASTRONOMY CLUB IITK

Contents

Chapter 1

Exoplanets

1.1 Objectives

- To answer the question of "What is an Exoplanet", and how we find one based on the astronomical data available.
- To introduce the field of data analysis in astronomy.
- Gain in-depth knowledge of how scientists find an exoplanet by analyzing the photographic data.
- Learn more about Exoplanets by studying various methods of their detection.
- Contribute towards the astronomical research by examining the data on the open-source platform, Zooniverse.

1.2 Theory

1.2.1 Exoplanets

An exoplanet is a planet outside our solar system, usually orbiting another star. We begin the search on familiar ground. The need for water is non-negotiable. So astronomers search the cosmos for similar environments.

Around almost every star, including our sun, we can draw a band of potential habitability: the right distance and temperature for liquid water to exist. Both stars and planets come in many types and sizes, and the interplay of these factors determines the extent and influence of this "habitable zone." The safest bet might be sun-like stars, with planets of comparable size and comparable orbits to Earth's.

And when we find life, how will we know? When we analyze light shot by a star through the atmosphere of a distant planet—a technique known as spectroscopy—the effect looks like a barcode. The slices missing from the light spectrum tell us which constituents are present in the alien atmosphere. The pattern of black gaps indicating methane, another, oxygen could be a strong argument for the presence of life.

1.2.2 The Kepler Mission

In 1995, NASA's Kepler Space Telescope detected a rocky, Earth-sized world outside our solar system, the planet 51 Pegasi b. It kicked off what might be called the "classical" period of planet hunting. Hundreds of exoplanets were discovered using Wobble method. Then a new space telescope, NASA's Kepler Space Telescope, launched in 2009 settled into an Earth-trailing orbit.There is a bulk of more than 3,300 confirmed so far, using a new method, the transit method.

The Kepler mission faced its own skeptical audience. Four times, NASA rejected the designs proposed, failure of two reaction wheels on the spacecraft ended its primary mission in 2013. The Kepler science team devised a fix: using the pressure of sunlight to stabilize one axis of the telescope. The instrument was rechristened 'K2' and continues to discover planets.

The Hubble Space Telescope and NASA's Spitzer Space Telescope has helped to chart and characterize many, including puzzling out details of planetary atmospheres. Astronomers say the future of exoplanet exploration is all about direct observation by expanding and sharpening our ability to capture actual images of distant planets.

1.2.3 The TESS Mission

The Transiting Exoplanet Survey Satellite (TESS) is a space telescope for NASA's Explorers program, designed to search for exoplanets using the transit method in an area 400 times larger than that covered by the Kepler mission. It was launched on April 18, 2018 atop a Falcon 9 rocket and was placed into a highly elliptical 13.7-day orbit around the Earth. The first light image from TESS was taken on August 7, 2018, and released publicly on September 17, 2018.

The primary mission objective for TESS was to survey the brightest stars near the Earth for transiting exoplanets over a two-year period. The TESS satellite used an array of wide-field cameras to perform a survey of 85% of the sky. With TESS, it was possible to study the mass, size, density and orbit of a large cohort of small planets, including a sample of rocky planets in the habitable zones of their host stars.

1.2.4 Methods of Detection

- **Transit Method:** When a planet passes directly between an observer and the star it orbits, it blocks some of that star's light. For a brief period of time, that star actually gets dimmer. It's a tiny change, but it's enough to clue astronomers into the presence of an exoplanet around a distant star. A 'light curve' is a chart of the level of light being observed from the star. When a planet passes in front of the star and blocks some of its light, the light curve indicates this drop in brightness.

- **Radial Velocity Method:** The planet's gravitational force has an effect on its host star. The planet causes the star to wobble around in its orbit, and as the planet moves to and fro, the light waves compress together and then stretch out, changing the color of the light we see. This change in color is called 'redshift', and scientists can use it to see if an object in the sky is moving towards us or farther away.

- **Astrometry:** Planets cause their stars to wobble around in space. The wobble is visible as changes in the star's apparent position in the sky. Scientists take a series of images of a star and some of the other stars that are near it in the sky and compare the distances between these reference stars and the star they're checking for exoplanets. Astronomers can analyze the movement for signs of exoplanets.

- **Direct Imaging:** Astronomers can take pictures of exoplanets by removing the glare of the stars they orbit. The instruments designed to directly image exoplanets use various technologies like coronagraph and startshade to block out the light of stars that might have planets orbiting them.

- **Gravitational Microlensing:** Gravitational microlensing happens when a star or planet's gravity focuses the light of another, more distant star, in a way that makes it temporarily seem brighter. Astronomers can't predict when or where these lensing events will happen. So they have to watch large parts of the sky over a long period of time. When they record a star getting brighter and then dimming in the pattern of lensing objects, they analyze the data to get information about the estimated size of the star.

1.3 Data Analysis (The Transit Method)

One of our primary goals from the Planet Hunters TESS project is to find out more about the diversity of planets. To do this we will be making use of the transit method. As a planet passes in front of (or transits) its parent star, it blocks out a small amount of the star's light and we see a dip in its lightcurve.

Transits are usually a few low points, usually in a U-shape, spanning a few hours to about a day. The depth of these transits encodes the size of the planet. This helps in determining the size of the planet. The radius of the planet can be determined by the given equation:

$$R_p = R_* \sqrt{Depth} \tag{1.1}$$

where,

- R_p denotes radius of the planet
- R_* denotes radius of the star
- *Depth* denotes the transit depth

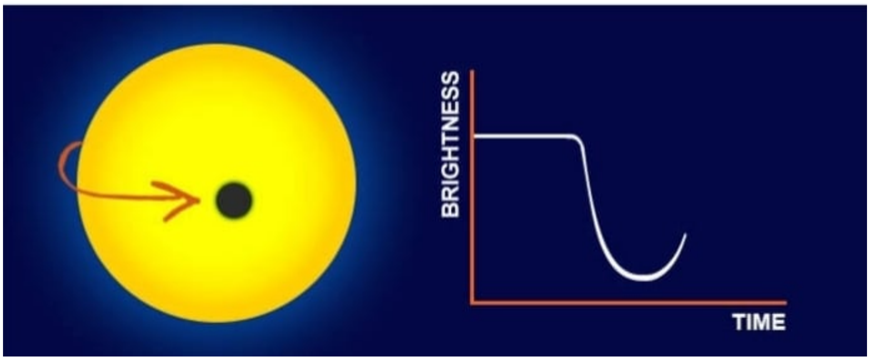


Figure 1.1: The variation in lightcurve as the planet blocks different light from different regions of the stellar surface.

As in the example given below the dips in the lightcurve indicates a planet transits. We were required to look for several such points on the light curve and identify the transits. We took an average of 30 photos to analyse the data. Depending on how far the planet is from the star and how many planets are in the system, we may see one or many transits in the star's lightcurve.

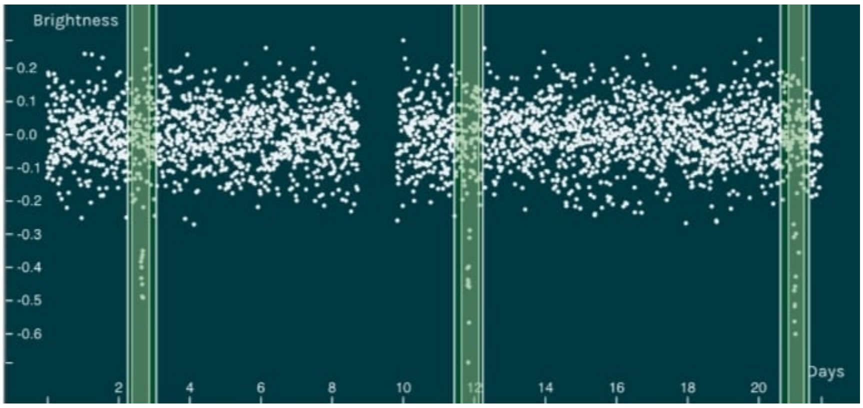


Figure 1.2: A sample lightcurve from Zooniverse. The green regions depict transits.

Depending on how far the planet is from the star and how many planets are in the system, we may see one or many transits in the star's lightcurve.

As in the example below, uneven spacing indicates that there are multiple planets.

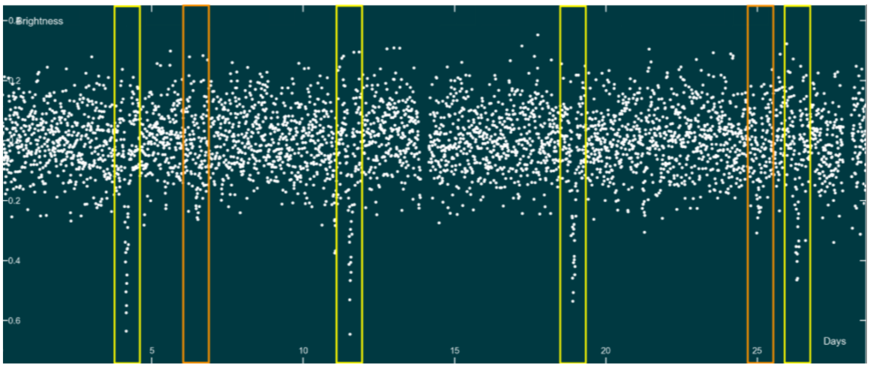


Figure 1.3: Light-curves depicting multiple planets.

1.3.1 Challenges faced

In the beginning, it can be quite tricky to find the planet transits, and there are a number of phenomenons that affect a planet transit. Here are a few difficulties we faced while analyzing the images.

- **Starspots:** Stars often have patches on their surfaces that are significantly dimmer than the rest of the surface - these are known as Starspots (or Sunspots in the case of the Sun). As stars rotate, these spots move around with them, going in and out of our view and thus resulting in variable lightcurves. The change in brightness due to starspots tends to be slow and smooth, typically occurring over a couple of days. This differs from dips in the lightcurves due to transiting planets, which typically last a few to tens of hours. The scale of starspots can range from rapid to much more gradual.

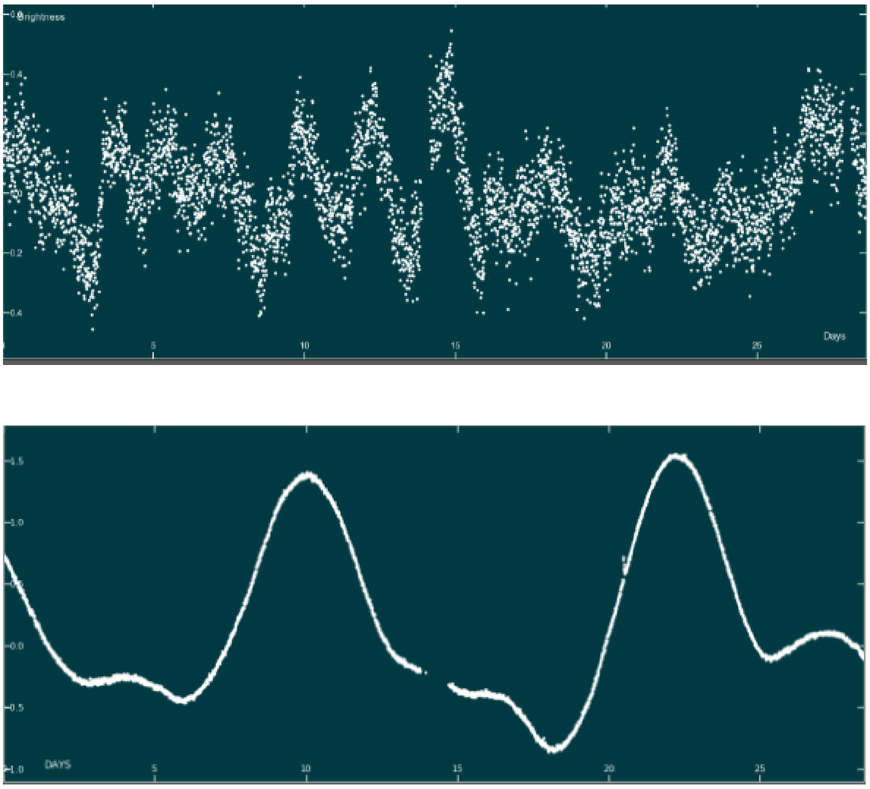


Figure 1.4: Variation due to star spots.

- **Pulsating Stars:** To complicate things further, certain stars have been found to pulsate. This means that they periodically increase and decrease in brightness. These variations can be very rapid and can make transiting planets very difficult to see. These can have a structured, repeated shape.

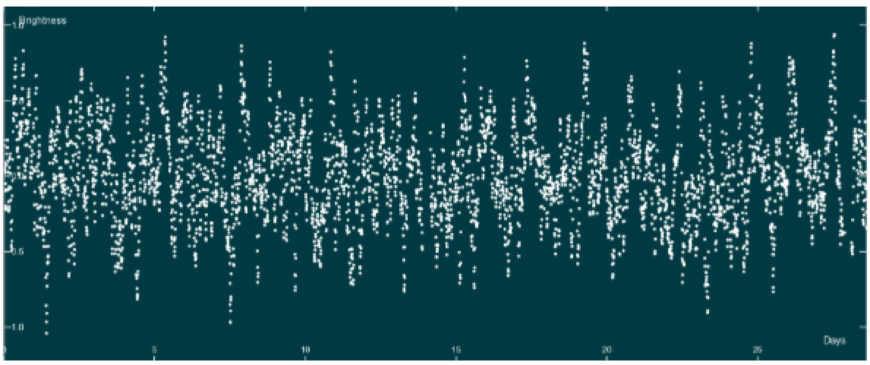


Figure 1.5: Periodic variation in lightcurve due to pulsating star.

- **Systematic Effects:** There are some systematic effects that can be seen in multiple lightcurves. Sometimes it shows up as a set of an unusually scattered point over this time range.

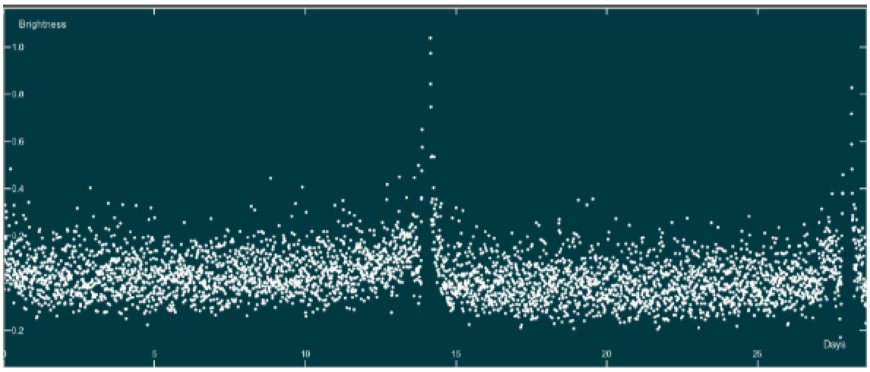


Figure 1.6: The unusual flux value can be seen in this plot. It is due to some systematic error which at times creep in.

- **Eclipsing Binaries:** Most stars are not alone, but instead exist in pairs or even triplets that orbit around one another. When one star passes in front of the other we see a dip in the lightcurve, known as an eclipsing binary. Transits due to eclipsing binaries tend to be more V-shapes, whereas transits due to plants are more U-shaped.

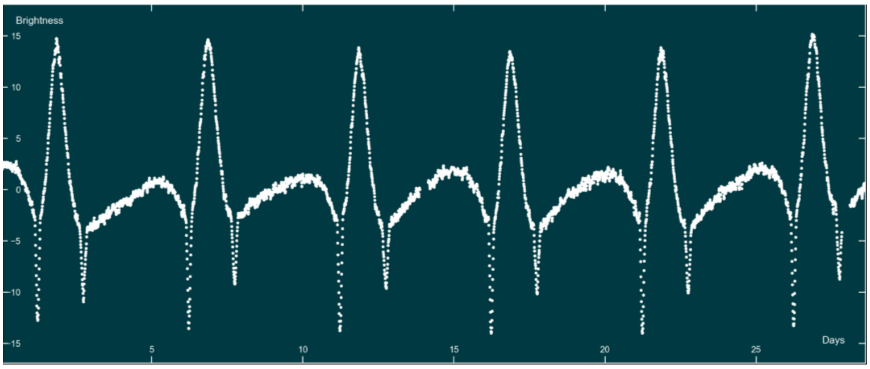


Figure 1.7: When another star eclipses the host star, a dip in light curve is seen which is usually greater than the depth due to planetary transit.

1.4 References

- The Physical Universe- An Introduction to Astronomy by Frank Shu
- https://www.cfa.harvard.edu/ avanderb/tutorial/tutorial2.html
- https://www.zooniverse.org/projects/nora-dot-eisner/planet-hunters-tess
- https://www.nasa.gov/tess-transiting-exoplanet-survey-satellite
- https://en.wikipedia.org/wiki/Transiting_Exoplanet_Survey_Satellite
- https://www.nasa.gov/mission_pages/kepler/overview/index.html

Chapter 2

Radio Galaxies

2.1 Objectives

1. To gather basic understanding of observational astronomy and introduce the field of data analysis in astronomy
2. Gain insight into the world of professional astronomy and its applications and learn how scientists analyse photometric data
3. Discover new concepts of astronomy and understand their significance
   - Learn more about Active Galactic Nuclei and their various properties, classifications and their unification model
   - Study basics of Radio Galaxies and understand meaning of terms such as Flux Density, Luminosity etc.
4. Comprehend to work as a part of a team and gain valuable leadership qualities and learn team work
5. Contribute to an innovative open source project and help astronomers in their enlightening research

2.2 Theory

2.2.1 Active Galactic Nuclei (AGN)

- An AGN is a compact region inside at the center of a galaxy that has much higher luminosity over at least some portion of the electromagnetic spectrum. Such excess non-stellar emission has been observed in the radio, microwave, infrared, optical, ultra-violet, X-ray and gamma ray wavebands.
- A galaxy hosting an AGN is called an 'active galaxy'. The non-stellar radiation from an AGN is theorized to result from the accretion of matter by a supermassive black hole at the center of its host galaxy.

Classes of AGN

AGNs are conventionally divided into 2 subclasses: Radio-Loud and Radio-Quiet based on their radio luminosities

Radio-Quiet AGN

- Low-ionization nuclear emission-line regions (LINERs): Only show weak emission and no other signatures of AGN
- Seyfert Galaxies: Earliest class of AGN to be discovered and show optical range nuclear continuum emission. Seyfert 1s show strong broad emission lines while Seyfert 2s do not

- Radio Quiet Quasars: Quasars or Quasi-stellar objects (QSO) are a class of AGN that have optical luminosities greater than that of their host galaxies and outshine their hosts. They often appear like stars in their optical images hence the name.

Radio-Loud AGNs

- Radio Loud Quasars: They behave exactly like radio-quiet quasars with the addition of radio emission from a (sub)relativistic jet
- Blazars (BL Lac objects or OVV quasars): Class of quasars with extreme variability of their luminosities. It is theorised that their relativistic jet is pointed towards line-of-sight which amplifies their variability
- Radio Galaxies: These objects show nuclear and extended radio emission and are very luminous at radio wavelengths with luminosities upto 10^{39} W between 10 MHz and 100 GHz

Unification model of AGNs

Unified models propose that different observational classes of AGN are a single type of physical object observed under different conditions. The currently favoured unified models are 'orientation-based unified models' meaning that they propose that the apparent differences between different types of objects arise simply because of their different orientations to the observer. We will not be covering it in depth as the image is self-explanatory (see below)

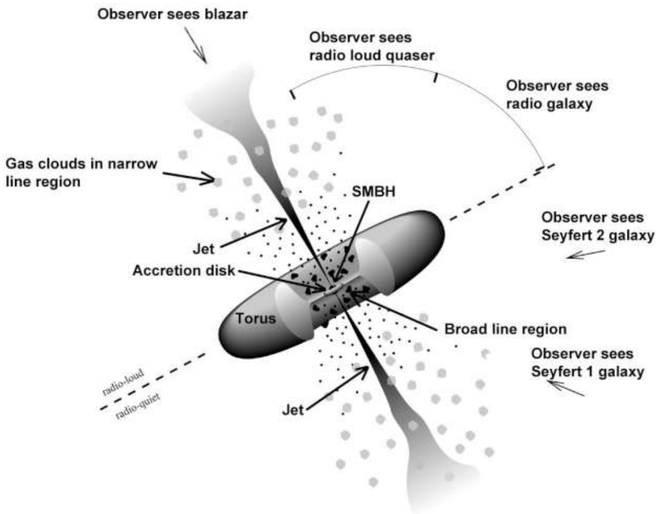


Figure 2.1: Unification model of AGNs

2.2.2 LOFAR Survey and Radio Galaxy Zoo

The ongoing LOFAR HBA 120-168MHz wide-area survey referred to as the LOFAR Two-metre Sky Survey (LoTSS) aims to survey the whole northern sky at the full resolution of 6 arcseconds and will detect over 10 million radio sources, mostly star-forming galaxies but with a large proportion of active galactic nuclei.

While the international LOFAR team consists of more than 200 astronomers from 18 countries,it is simply too small to take on this daunting task of identifying which radio structures belong to which host galaxy. Therefore, LOFAR astronomers are asking the public to help. In the context of the citizen science project **'LOFAR Radio Galaxy Zoo'**, the public is asked to look at images from LOFAR and images of galaxies and then associate radio sources with galaxies.

The survey is now 47% complete with the help of 4537 volunteers who have made 437,236 classifications of 75,110 subjects with now only 79,530 subjects remaining[1].

2.3 Overview of the Topics Covered

We referred the book **'The Physical Universe'** by **Frank Shu** and covered the following topics in our group discussions:

- **Shapley-Curtis debate:** This was a debate between 2 astronomers Shapley and Curtis in 1920 about whether distant spiral nebulae were part of the Milky Way or independent galaxies.
- **Classification of galaxies:** We learnt about the different types of spiral and elliptical galaxies, their spectroscopic features, stellar populations, etc.
- **Distribution of light and mass in regular galaxies:** We read about surface photometry, velocity dispersions in elliptical galaxies and rotation curves of spirals and delved into the related math to some extent.
- **Active galaxies and their types (special focus on radio galaxies):** We also covered the different types of active galaxies: seyferts, N galaxies, radio galaxies, quasars etc.
- **Supermassive black holes:** The primary aim of our project was to analyse data used to identify locations of supermassive black holes.

The above topics gave us an idea of what we were doing, relation of these black holes to active galactic nuclei, the observational efforts to detect the supermassive black holes etc.

2.4 Data Analysis

Radio Galaxy Zoo: LOFAR was designed to look for supermassive black holes that power active galactic nuclei. Nearby material passes very close to these supermassive black holes and is flung out in the form of two immense jets. These jets are visible at radio wavelengths and observing this radio emission can tell astronomers a lot about the formation and evolution of supermassive black holes.

In some cases, LOFAR also picks up nearby galaxies where much star formation is going on. In this case, we do not see radio jets but the shape of the radio emission follows the shape of the nearby galaxy closely. To visualise this, it shows the radio emission as yellow lines (called *contours*) in the foreground and the image from an optical telescope in the background.

1. **Reassembling radio sources:** The source finder program was designed to identify radio sources from the images collected by LOFAR. However, it is not always accurate and sometimes splits 1 source into multiple components. The analysts (we) need to associate the components so the program can reconstruct the full radio source. *(see Figure 2)*
2. **Finding active galactic nuclei:** We also need to identify from the image, the galaxy that powers the radio emission. These galaxies can be seen at visible wavelengths, and provide additional data to help astronomers determine, for example, the distance to the observed radio source. Therefore, by observing the image found with an optical telescope of the same region, we can find the host galaxy. *(see Figures 3 and 4)*

2.5 Observations and Conclusions

2.5.1 Radio Images classified

On average, 24 images of different radio sources were classified by each individual doing the project. These classifications helped in understanding radio sources in a better way and avoiding common mistakes while analyzing and identifying radio sources.

[1]data accurate as of 09/07/20

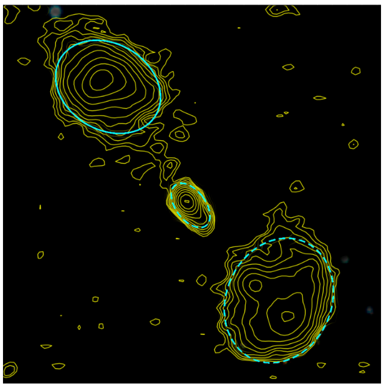


Figure 2.2: In this image, we can see a pair of radio jets found by the LOFAR telescope. The radio emission is visualised as yellow lines (contours) and the blue ellipses surround what the source finder thinks are separate sources. The finder has incorrectly divided the source into 3 components, and we can fix that by associating them.

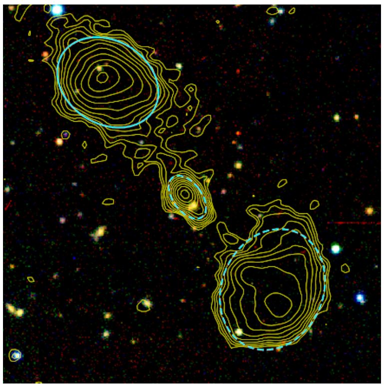


Figure 2.3: The image of the same region taken with an optical telescope shows many galaxies and other radio sources. The host galaxy is the one visible in the background as a bright source between the 2 lobes.

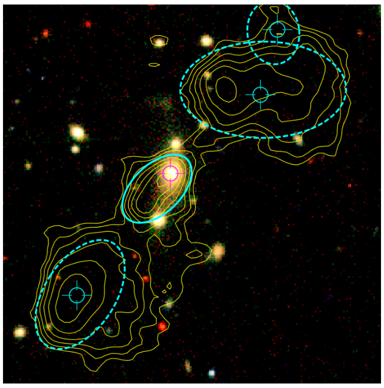


Figure 2.4: **Completed Analysis**: The blue pointers indicate the dotted ellipses which are also a part of the radio source and the purple pointer indicates the possible host galaxy as found by the optical telescope. The galaxy is in the middle of the 2 lobes.

2.5.2 General difficulties faced

Classifying radio images can be tricky sometimes and one might face some problems initially. Here are a few difficulties which we handled with the help of Field Guide feature and tutorials:

1. **Asymmetric sources:** Sometimes the radio emission doesn't have a double-lobed symmetric structure and seems to erupt from the optical source in just one direction. This can happen when the radio jet is pointing directly towards us, or when the jets are swept into a tail on one side of the optical host by external shocks or winds. A good strategy for identifying the

radio source is to look in places where the radio contours are packed tightly together.

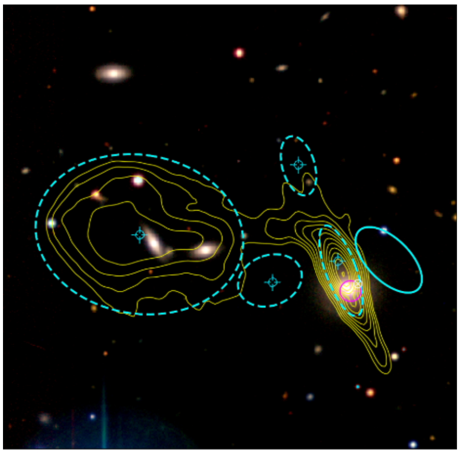


Figure 2.5: Asymmetric Sources

2. **Artefacts:** These are very spread out and chaotic radio contours that cannot be associated with a radio source(no real origin).These are produced due to radio noise from bright radio sources. Image given below is an example of artefacts around a bright point-source that make it look like the source is exploding.

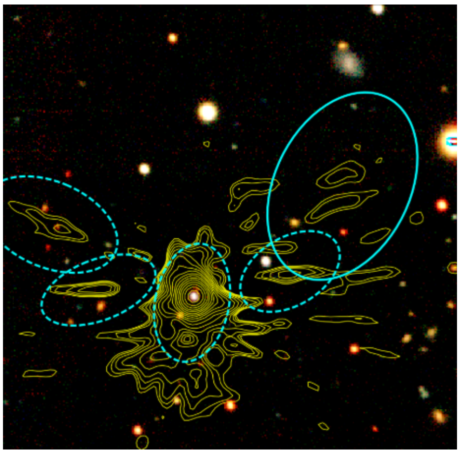


Figure 2.6: Artefacts

3. **Blends:** Blends happen when the source finder algorithm incorrectly associates two or more different radio sources within a single blue ellipse.

4. **Too Zoomed in Image:** When the radio contours extend beyond the borders of the image and look like they may show one or more components of a larger radio source. The image given below is too zoomed in and therefore we cannot find its radio source.

5. **Image Missing:** This kind of problem arises when a part of or entire optical image of the captured region is missing. In this case it is not possible to locate the host galaxy emitting the radiation.

6. **Others:** Some radio images can't be analyzed due to some obstruction or unknown reason. These kinds of images were discussed online, among the large community working on the LOFAR Radio Galaxy Zoo project, to understand them better.

2.5.3 Conclusion

We started with the concept of a Supermassive Black Hole (SMBH) and worked our way towards Active Galactic Nuclei (AGNs) and Radio Galaxies. We classified several Radio Galaxies on Zooniverse and contributed to an international research. We learned to work as a team and had lots of

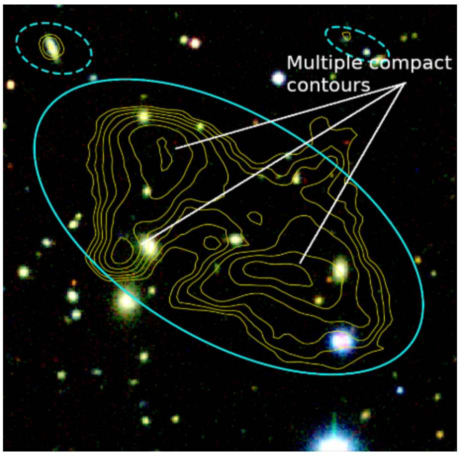


Figure 2.7: Blends

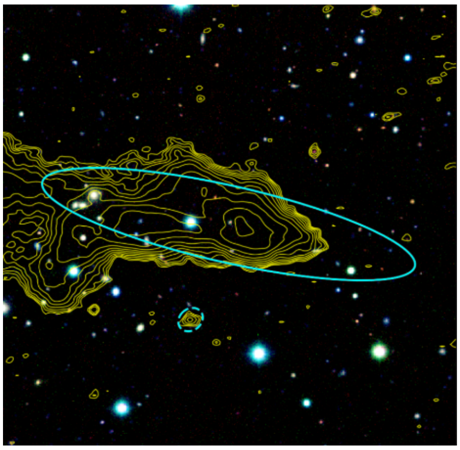


Figure 2.8: Too Zoomed in Image

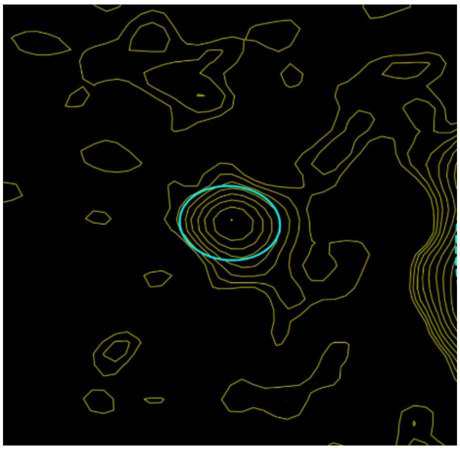


Figure 2.9: Image Missing

fun discussions and made our own theories on how the universe works. Overall it was a learning curve for us and it was major stride towards our career paths. The Fun Space Project now come to a conclusion. See you next year!

2.6 References

1. en.wikipedia.org/wiki/Radio_galaxy
2. en.wikipedia.org/wiki/Active_galactic_nucleus

3. lofar-surveys.org/surveys.html
4. zooniverse.org/projects/chrismrp/radio-galaxy-zoo-lofar

Chapter 3

Asteroid Hunting

3.1 Objective

- To gain more knowledge about Asteroids and their characteristics.
- To understand the formation of asteroid trails, their significance.
- To identify asteroid trails in archival images from Hubble Space Telescope, and gain information about data analysis.

3.2 Theory

What is an asteroid?

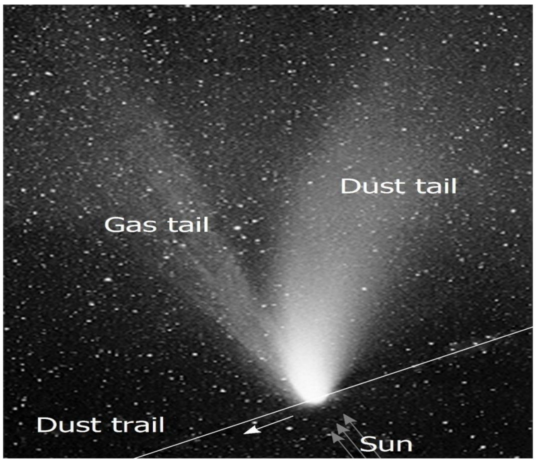
Asteroids are small, rocky objects that orbit the sun. Although asteroids orbit the sun like planets, they are much smaller than planets.
There are lots of asteroids in our solar system. Most of them live in the main asteroid belt—a region between the orbits of Mars and Jupiter.

Some characteristics of asteroids:

Asteroids aren't all round like planets. They have jagged and irregular shapes. Some asteroids are hundreds of miles in diameter, but many more are as small as pebbles.
Most asteroids are made of different kinds of rocks, but some have clays or metals, such as nickel and iron.

Formation of asteroid trails:

Sometimes when we are observing stars in the Milky Way or in far away galaxies asteroids orbiting the Sun a few tens or hundreds of millions of kilometres away happen to pass through the observed field and appear in the foreground of telescope images. These appear curved due to an effect called parallax. As the Hubble Space Telescope orbits around Earth and images a patch of the sky for a certain amount of time, asteroids will appear to move along an arc with respect to the more distant background stars and galaxies. Because of this parallax effect, asteroids that were closer to us at the time appear passing more rapidly, and thus leaving longer trails in the images, compared to more distant objects.



3.3 New Things Explored

- Knowledge of platforms that support people-powered research like Zooniverse.
- Understanding the way observations given by several people helps International Astronomical Union's Minor Planet Center to compute the orbits and update the ephemerides of asteroids to better predict their future trajectories.

3.4 Data Analysis

The data analysis part of any astronomy based object has three basic principles:

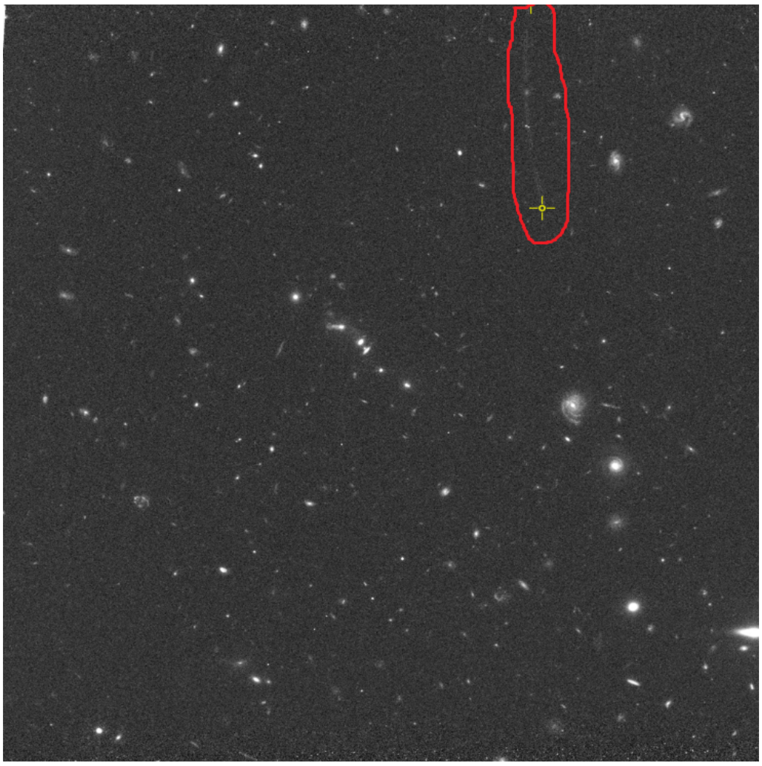
1. Capturing Image
2. Study Of Image
3. Results

1. Capturing Image

The images taken for the analysis are sky shots taken at different points of the world and are collective at the site zoouniverse.org.
The image is taken by the exposure of that part of sky through which asteroid passes and is further processed.

2. Study Of Image

The image processed is accessed by anyone at the zoouniverse site and we can identify the asteroid trails in the image.
The asteroid trails are seen as narrow curves in the image, bright or dull, depending upon the light captured. The curvedness in the trail is due to an effect called parallax effect. As the telescope revolves around the Earth, while imaging on certain patch of the sky for a certain amount of time, asteroids will appear to move along an arc with respect to the more distant background stars and galaxies. Because of this parallax effect, asteroids that were closer to us at the time appear passing more rapidly, and thus leaving longer trails in the images, compared to more distant objects.



As in this image, the asteroid trails is been marked and we can clearly see the length of the trail, which is much larger than meteor.

3. Result

This image contains traces of asteroid trails.

3.5 Data Record

- Total Students uploaded the images : 10
- Total images uploaded : 134
- Average no of images uploaded : 13

3.6 Challenges

- **Differentiating between meteor and Asteroid Trails**
  Meteors also produce trails but generally their trails are shorter than asteroid trails, but sometimes can confuse to be same.
- **Understanding trail curvature in the image**
  As the telescope revolves around, the path of the trail becomes curved rather than a straight line due to the parallax effect, and hence closer asteroids gives longer trails.
- **Identifying trails in crowded image when taken in the plane of Milky Way**
  Sometimes the image becomes too bright due to crowd in the image when taken along the plane of Milky Way. This is because more no of star are present in the background which makes it difficult to identify trails.
- **Differentiating between cosmic rays and asteroid trails**
  Cosmic rays are image artifacts caused by high energy particles hitting the detectors. They produce bright, sharp, narrow and shorter trails in the images which can be mistaken with

asteroid trails. To distinguish between asteroids and cosmic ray trails can be sometimes challenging, although, in the vast majority of cases the cosmic ray trails are shorter and appear irregular . Asteroid trails, on the other hand, have a smooth appearance and uniform brightness.

- **Missing data across the images**
  It is just the split between two CCDs that happened to fall inside the image cut-out, and is shown as a white band.
- **Stellar X-shaped spikes**
  Sometimes the star not present in the field, gives trail-like spikes which can be confused with asteroid trails.
- **Strong Gravitational lenses**
  These are curved arcs around massive galaxy clusters. They can have the appearance of asteroid trails, but usually there is more than one arc, with the same curvature.
- **Satellite trails and CCD Defect**
  Satellite also gives asteroid-like trails, but their trails are wider, straighter and are across the image. Also, CCD defect gives narrow and straight lines(black or white) which can also be mistaken as asteroid trails.

3.7 References

- https://en.wikipedia.org/wiki/Asteroid
- https://www.zooniverse.org/projects/sandorkruk/hubble-asteroid-hunter

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