Project Report

PPr801

Detection and Study of Characteristics of Quasars Using SDSS

Submitted by

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CERTIFICATE

This is to certify that the reading project entitled ”Detection and Study of Characteristics of Quasars Using SDSS” is done by **Laxmi Prasoon Barik** under my guidance and supervision during January 2024 to May 2024 for the 8th Semester Project **PPr801** of Integrated M.Sc. in Physics at Center for Basic Sciences, Pandit Ravishankar Shukla University, Raipur, Chhattisgarh, India.

To the best of my knowledge and belief, this dissertation embodies the work done by the candidate.

Supervisor

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I offer my sincere thanks to everyone who has, directly and indirectly, helped me in the completion of my project.

I sincerely behold the blessings of my parents for supporting me.

Laxmi Prasoon Barik

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1 Introduction

First recognition quasars was made in 1963 by Maarten Schmidth. It was named 'Quasi-stellar radio source (QSR)' or 'Quasi-stellar object (QSO)', meaning that they resemble stars in their point-like appearances. However their spectra is very different from the spectra of a star. The emission lines are same as other astronomical sources but extremely red-shifted. We can conclude that they are highly luminous in order to be seen at such large distances. Their optical spectra are similar to Seyfert 1 galaxies, with prominent broad lines but rather weaker narrow lines. 10 % are strong radio sources i.e. radio loud. Some prefer to refer radio-quiet quasars as QSO. [1]

We can say that a quasar is a remote, very luminous AGN buried in a galaxy of normal luminosity. In other words, they are cores of galaxies where the central engine is a supermassive black hole. It gives light in all wavelengths. Due to its high magnetic field, the particles are trapped and spin at very high velocities around it. The heating effect takes place and jets are formed along its poles in radio waves and X-rays which can be seen from a large distance. [2]

Discovery of quasars is a landmark in observational astronomy. Its history dates back to world war II with the beginning of radio astronomy. Due to their unusual spectra, 3C273 and 3C48 were studied in detail by astronomers after the release of 'Third Cambridge Catalogue' prepared by Mullard Radio Astronomy Observatory at University of Cambridge. It was found that their spectra was significantly redshifted. H_α line has rest wavelength at 656.3 nm but it was observed at about 760.0 nm. This is about 15% shift. Yet they were luminous enough to be seen at such a distance and to be mistaken as starsdue to their compactness. This lead to the development of the term Quasi-stellar Objects(QSO) or quasars. [3] [4]

For comparison the apparent magnitude of 3C273 is 13. It is approximately 10^{12} times brighter then the sun. Figure [1] shows an image of 3C273 taken by Hubble Space Telescope at 850-1700 nm. [5]

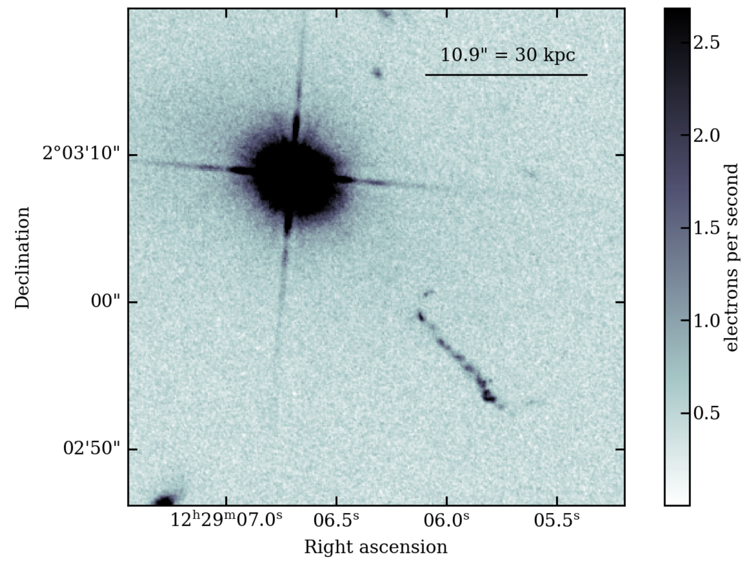


Figure 1: HST image of 3C 273 at 850-1700 nm. It has a peak brightness of 28606 e/s. Image combines four exposures providing a total of 37 second integration time. [5]

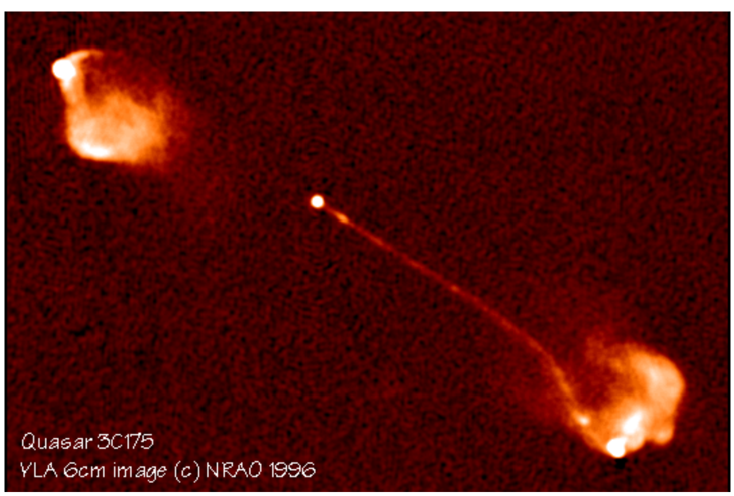


Figure 2: Quasar 3C175 at z = 0.768. The two jets are clearly visible. Source: Radio images from the NRAO's Very Large Array [6]

2 Structure and Power Source

2.1 Structure of Quasars

Quasars are essentially powered by gravitational accretion onto supermassive black holes. The difference between AGN and other galactic nuclei is that AGN accretes a few solar masses of matter each year. After accretion disk, There are clouds of gas moving at high velocities around their inner structure. They are responsible for broad emission lines of hydrogen and ions from other atoms which are used to distinguish quasars from other celestial objects. Some quasars have radio jets. Jets are highly collimated beams of plasma which is propelled out along the rotational axis of accretion disk at high speed. It can reach speed close to the speed of light. Since they are highly energised, they are observed at X-ray and radio wavelengths. Appearance of quasars depends on which way they are oriented with respect to our line of sight.

2.2 Power source of Quasars

For many years the enormous energy output from quasars was a puzzling question to astronomers. This can be called energy-redshift problem. The value of redshift tells us that they are at enormous distance from Earth. But their observation tells us that they are luminous enough to be mistaken like a star. So what exactly is providing enough energy to quasars.

2.3 Energy-redshift problem

There are only a few energy sources producing enough energy to power a quasar. The best explanation is a supermassive black hole which functions as central engine for many galaxies. A black hole is a massive body where nothing, even light, can escape from its gravitational influence. A black hole can be either rotating or non-rotating based on its rotation. Their redshift and extreme luminosity rises many possible explanations but non of them is convincing. Further gravitational lensing of quasars has shown that they are at cosmological distances. Thus, they are indeed radiating a large amount of flux.

Nuclear fusion of hydrogen in stars convert only 0.7% of the hydrogen nuclei but matter falling into black hole can radiate about 10% of its rest

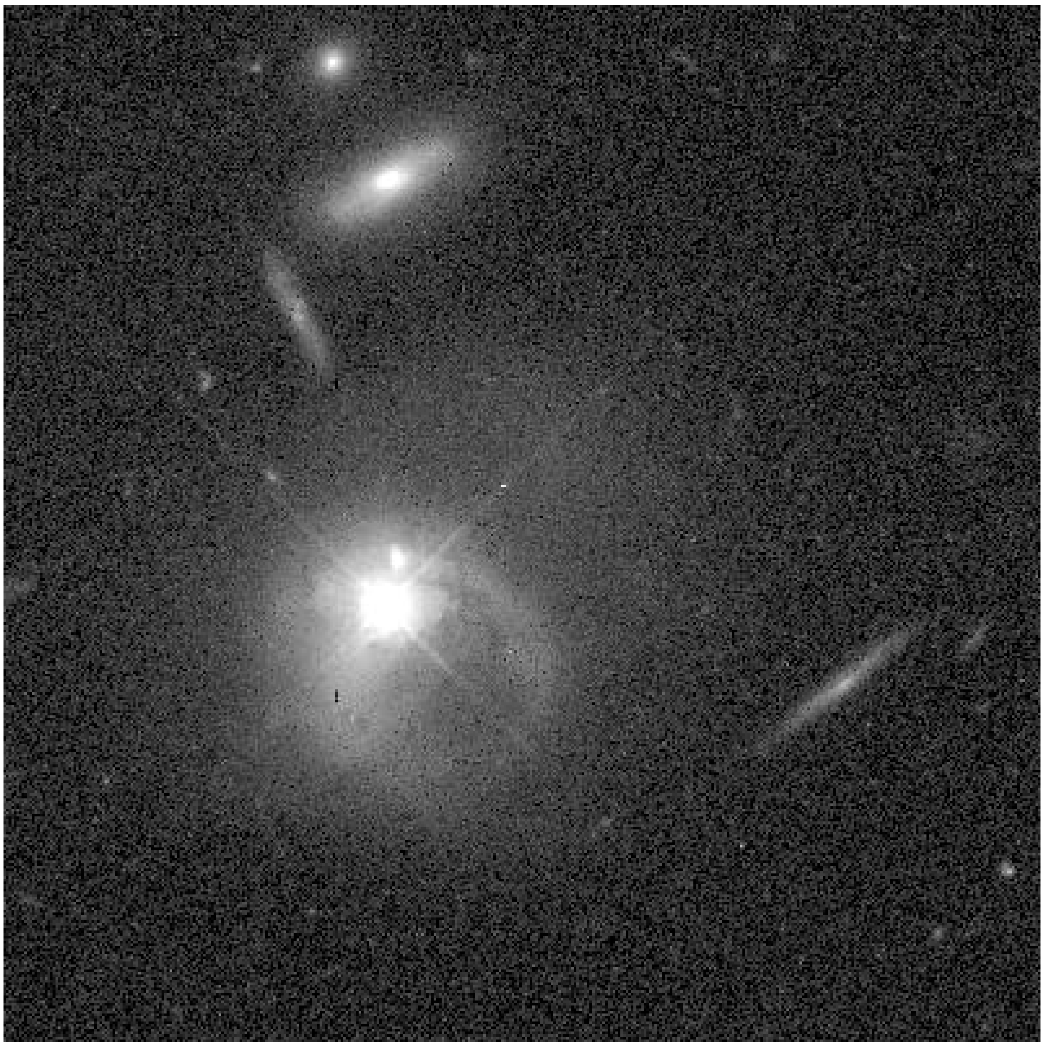


Figure 3: PKS 2349, Merger between a quasar and galaxy. Image taken with Wide Field Planetary Camera-2, credit: John Bahcall, Institute for Advanced Study, NASA[7]

mass energy. Thus we can calculate the luminosity of an accreting black hole as:

$$L = 0.1Qc^2$$

where Q is the mass accretion rate i.e. rate at which matter is falling.

However, the Eddington limit defines the maximum luminosity(L_E) that a black hole can have based on its mass:

$$L_E/W = 1.3 \times 10^{31} \times (M/M_{\odot})$$

The central part of our galaxy has luminosity around $10^{38}W$ which gives the corresponding mass of the black hole to be approximately $7.7 \times 10^6 M_{\odot}$. [1]

The observed luminosity of quasars requires supermassive black holes with masses around $10^8 M_{\odot}$. This supports the need for such massive objects in Active Galactic Nuclei(AGN).

This supports the argument that power source of quasars are supermassive black holes acting as AGN. Moreover, the successful explanation of many detailed radio galaxies has made astrophysicists confident of the model placing massive black hole in the center of a galaxy though there origin is still uncertain.

3 Looking and Comparing surveys

3.1 Data Selection

This is the most crucial part as selecting incorrect or contaminated image can lead to false results. I have used VLA FIRST archive server and SDSS's visible-light image using its Navigation tool and compared their image. SDSS image was of high resolution therefore we can clearly see the difference between each pixels. 7

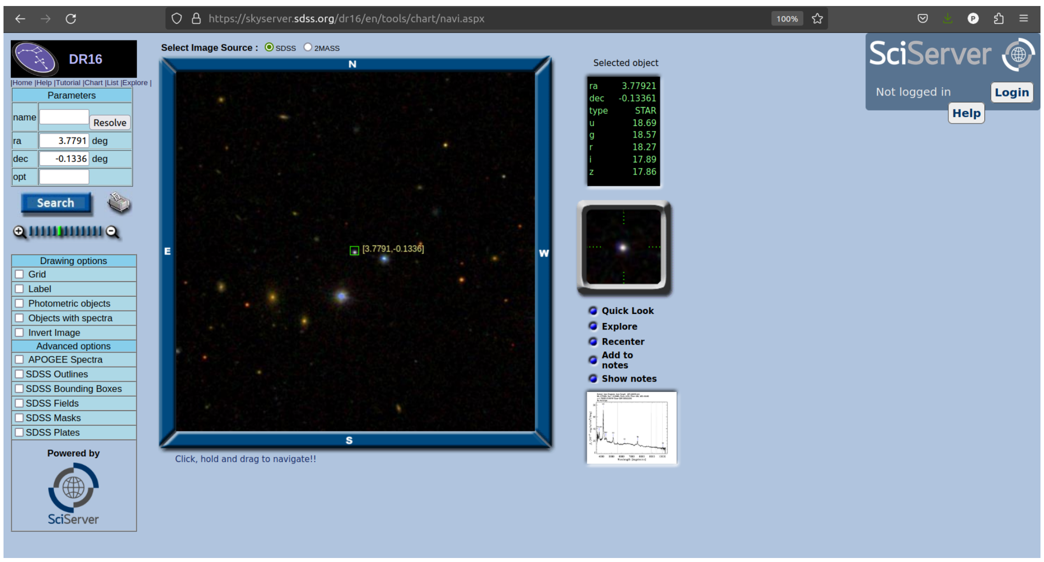


Figure 4: An interface of SDSS Navigation tool. Putting RA and dec in degrees gives output.

For SDSS Navigation tool, both RA and dec is to be mentioned in degrees while VLA FIRST archive server uses RA in hours and dec in degrees. Both images should have same image size in arcminutes for comparison purpose. In SDSS Navigation tool, we can get spectra in different bands. Both servers provide images in FITS format. Images in GIF format can also be downloaded.

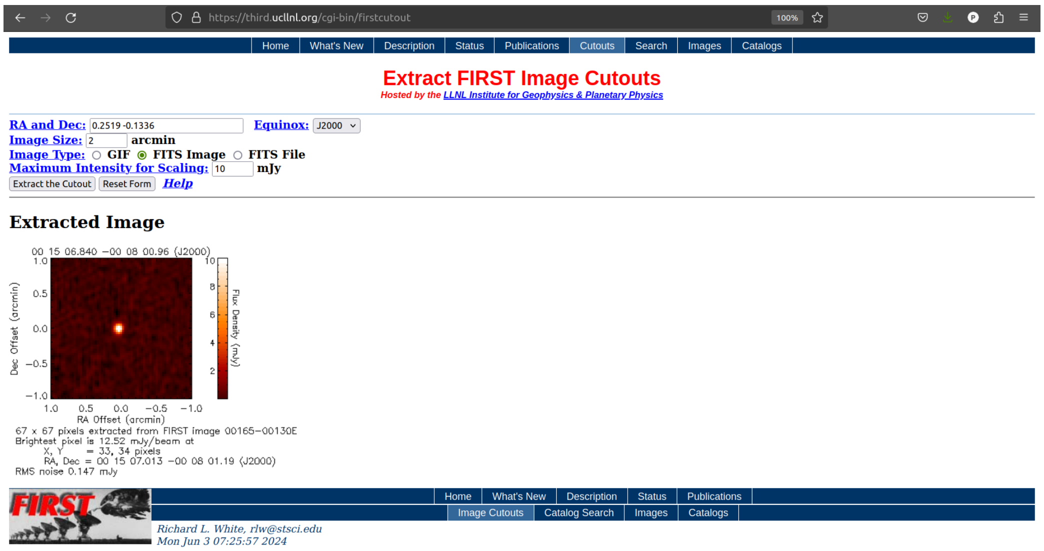


Figure 5: An interface of the VLA FIRST archive server. Putting RA(hours) and dec(degrees) gives output.

3.1.1 FITS file and tool used for comparison: DS9

FITS stands for Flexible Image Transport System. It is standard data format used in astronomy and astrophysics. This format is used for transport, archival storage and analysis of scientific data set. Multiple images can be stacked in one FITS file.

A standard FITS file consists of several components:

1. Primary Header Data Unit: It consists of two parts.

    (a) Header containing metadata about the file and data it is holding. Such as OBSERVAT(Name of observatory where the data was taken), BITPIX(Specifies number of bits per data pixel) etc.

    (b) Data array which is multi-dimensional array of the data values. It is optional. Eg. NAXIS,NAXIS1 etc.

2. Extensions: It contains multiple extensions.

    (a) Image extensions used to store additional images or data array which is related to primary data.

   (b) Table extensions divided into two types: ASCII tables stored in plain text format and binary tables stored in binary format.

3. Header containing essential metadata in the form of keyword-value pairs. Components such as processing history and comments are included in this part.

4. Data: It can be either data array or table.

SAOImage DS9 is an astronomical application which is used for imaging and visualization. It supports various files such as FITS and binary tables, region manipulation and many scale algorithms, multiple frame buffers and colormaps. It is developed by the Smithsonian Astrophysical Observatory. Installation and opening two files for comparison is the first task done using standard process using either terminal or software itself. After opening two images, we can synchronize the frames. It is done using 'Match Frames' command under 'Frames'. Parameters such as wcs, scale and color can be compared. After comparison we save our current frame to export the comparison as an image.

3.1.2 Using contours

Detailed comparison between images can be made through another method. This is by using contour parameters. In contour setting, we get several options for generating contours:

1. Levels: They are values of image intensity at which contours are drawn.

2. Smooth: Smoothing function can be applied for reducing noise in the image.

Contours can be saved in ds9 thus allowing the user to apply the same contour parameters to multiple files.

3.1.3 IRAF and PyRAF

IRAF stands for Image Reduction and Analysis Facility. It is a software system for analysis of astronomical data supported by National Optical Astronomy Observatory(NOAO). It was initially developed in 1980s at NOAO. Originally, it was designed to support ground-based telescopes but over the

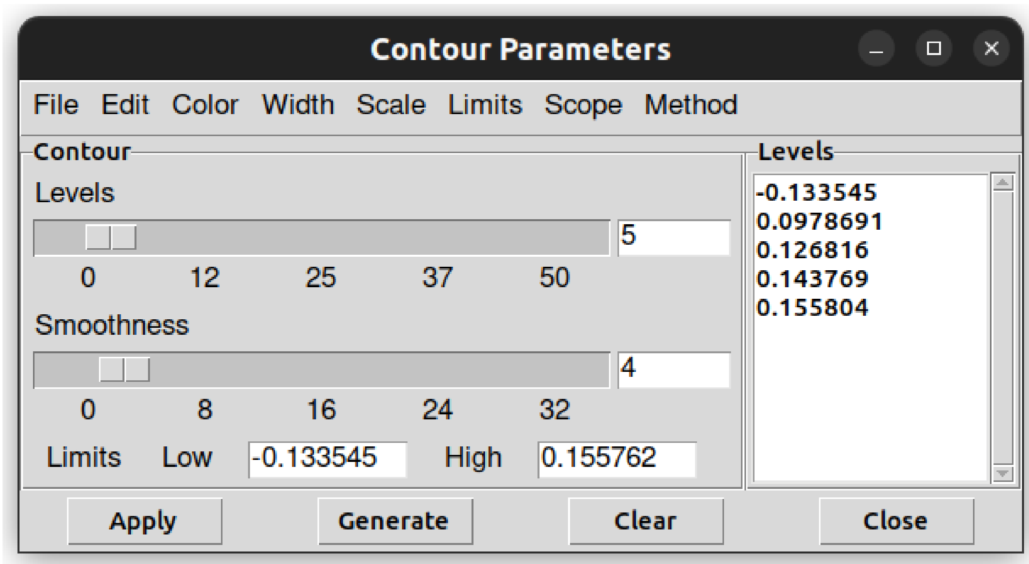


Figure 6: Contour parameters in ds9: levels and smoothness are set.

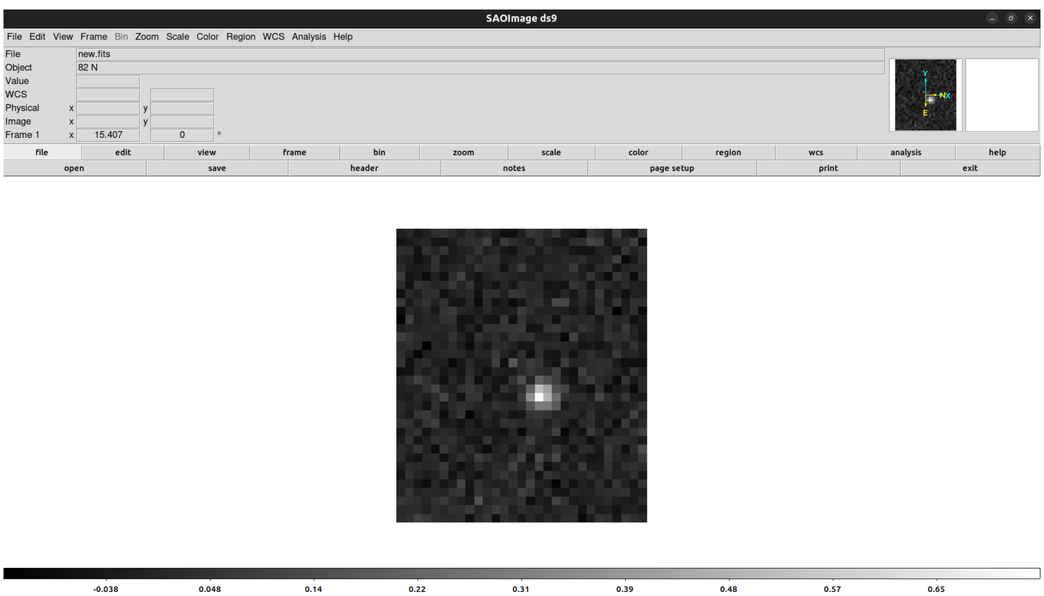


Figure 7: SAOImage ds9: An interface of ds9

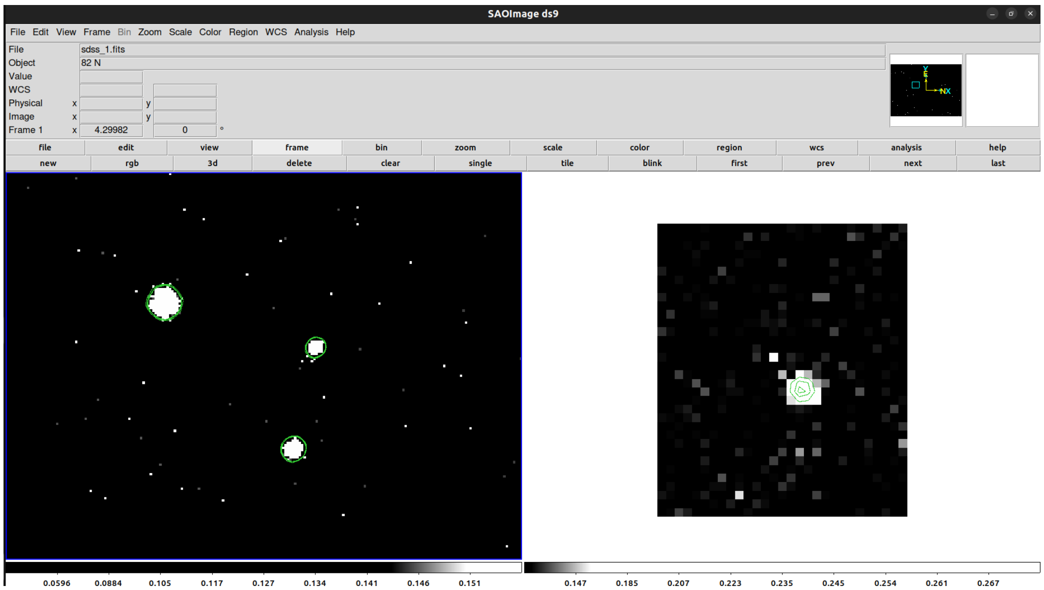


Figure 8: Contour parameters are applied in ds9 and can be seen in both frames.

years, it has evolved to include space-based observatories. It is an open-source software therefore astronomical community has made significant contributions. The key features of IRAF is image processing such as image alignment, calibration and combining two images, S=spectral reduction such as extracting and analyzing spectra and photometry and astrometry. IRAF is task oriented i.e. it is organized into ”tasks” which are individual scripts.

PyRAF is a command language for IRAF base on Python language. It allows importing Python modules into IRAF instead of IRAF CL. Using IRAF and PyRAF, we can crop our fits file into desired pixels or coordinates for comparison. It uses scripting for performing tasks.

There are certain commands like

```
iraf.imcopy(f"{original fits file}{crop region}", croppped fits)
```

which helps to manage tasks. The above command crops the original fits file in given croping region and gives output as cropped fits file.

I have used PyRAF for matching two FITS file using this command.

3.2 Example

Comparison of image obtained from two different surveys at different wavelengths:

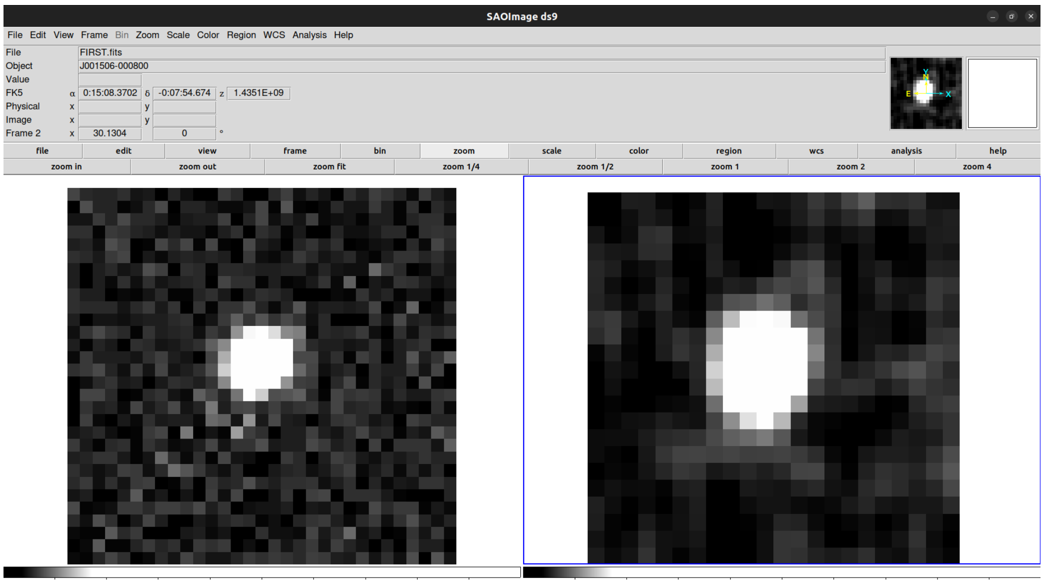


Figure 9: Comparison between two images obtained from different surveys at different wavelengths: (a)SDSS (b)VLA FIRST at RA=3.7791° and dec=-0.1336 ° and 2 arcminutes

4 Spectra Comparison

Every astronomical object has a unique spectrum. Spectra can be compared in order to learn certain properties such as composition of the object.

4.1 Spectra of Various objects

The first spectrum[10] is of a typical galaxy. The secod spectrum[11] is of a typical star and the third spectrum[12] is of a typical quasar. [8]

The spectrum can be compared by analyzing their key features.

1. **Galaxy Spectrum:** It shows a mix of absorption emission lines where $H\alpha$ and $H\beta$ lines are prominent. It also has strong presence of oxygen(O III), sulfur(S II) and Nitrogen(N II) lines which indicates the presence of ionized gas in the galaxy. The continuum shows less variation compared to other spectra which shows that various stellar populations are contributing in its spectrum.

   The galaxy spectrum contains thermal radiation from stars(absorption lines) and non-thermal radiation from ionized gas(emission lines).

2. **Star Spectrum:** It shows prominent absorption lines along hydrogen(H), calcium(Ca II) and magnesium(Mg). There are other metal lines which are present like iron(Fe) and sodium(Na). The continuum is smooth in comparison to others with gradual decrease in intensity from shorter to longer wavelengths.

   Its continuum decreases in intensity from blue to red wavelengths which is a typical blackbody radiation. It shows presence of thermal radiation sources.

3. **Quasar Spectrum:** Its spectrum is dominated by strong broad emission lines of hydrogen(H), carbon(C IV), magnesium(Mg II) and oxygen(O III). The continuum is relatively flat which shows a mix of thermal emission from accretion disk around supermassive black hole and non thermal emission. The redshift in the emission lines is are significant which refers that they are very far away from Earth.

   The spectrum is dominated by broad emission lines. This is due to high-velocity gas near the supermassive black hole though there are some non-thermal radiation from jets around the black hole.

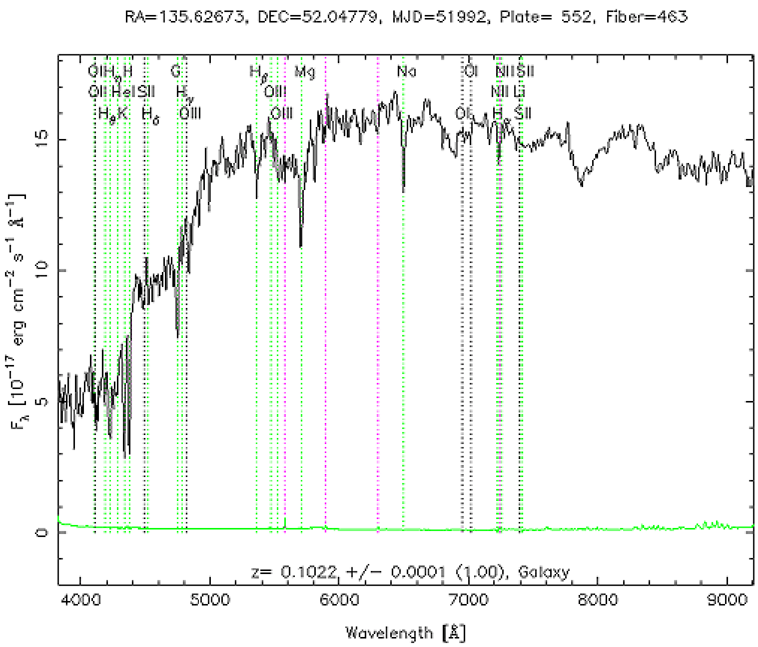


Figure 10: Spectrum of a galaxy

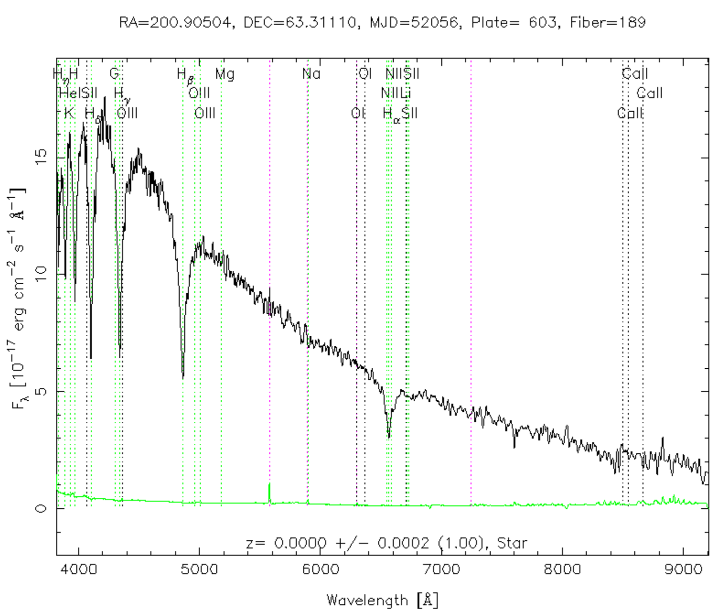


Figure 11: Spectrum of a star

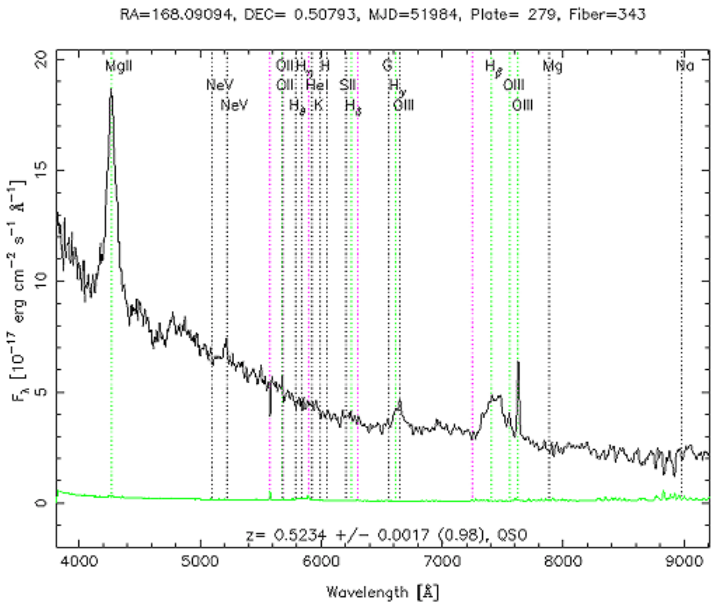
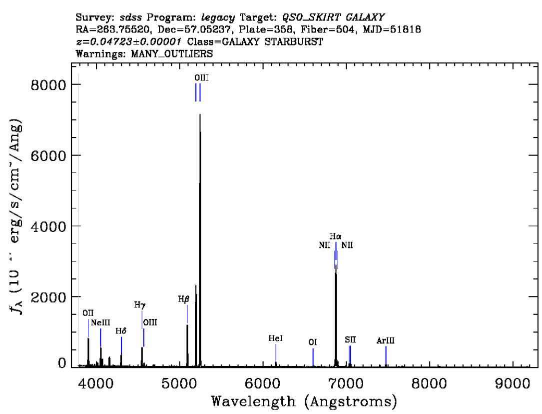


Figure 12: Spectrum of a quasar

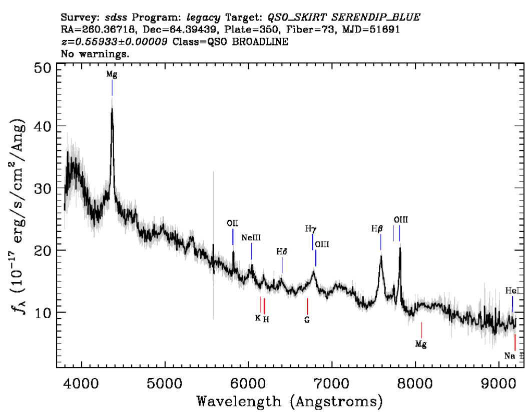
4.2 Spectra of Some Quasars

There is spectrum of six different quasars each of which is at different distance. They all have different redshits which is mentioned in the spectrum itself.

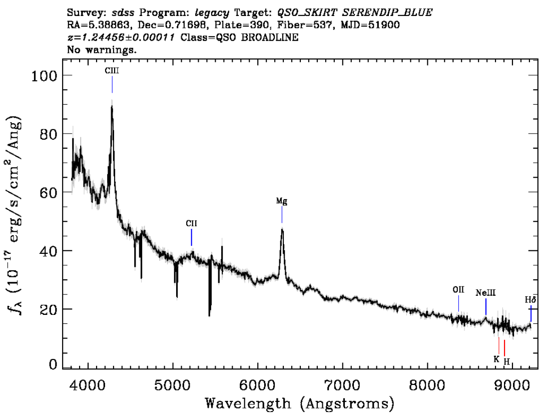
Each of them has emission peak at different wavelength due to different values of redshift. For example (d) has Ly_α peak between 4000-5000 A^o with F_λ at $60 f_\lambda \times 10^{-17} erg/s/cm^2/Ang$, (e) has the peak at 6000 A^o with F_λ at $16 f_\lambda \times 10^{-17} erg/s/cm^2/Ang$ and (f) has the peak at 7000-8000 A^o with F_λ at $11 f_\lambda \times 10^{-17} erg/s/cm^2/Ang$. This means the peaks shifted towards right i.e. longer wavelengths.



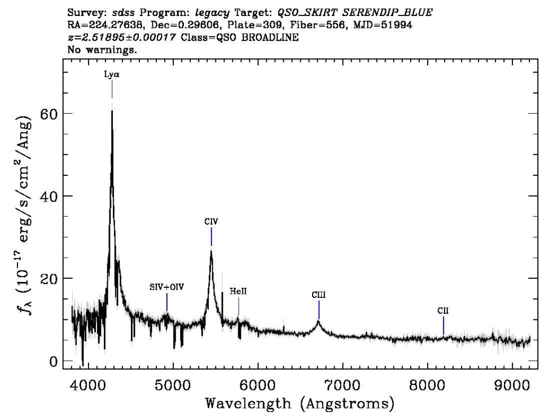
(a)



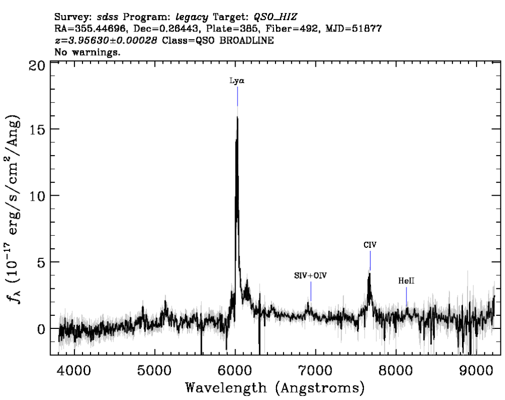
(b)



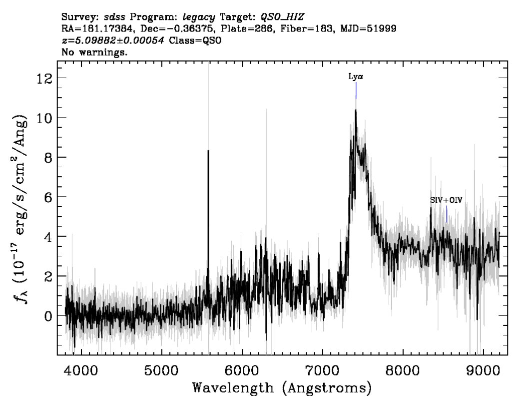
(c)



(d)



(e)



(f)

Spectra from various sources arranged according to their redshift values. [9]

The values of redshift for the spectra are: (a)z=0.04723, (b)z=0.55933, (c)z=1.24456, (d)z=2.51895, (e)z=3.9563, (f)z=5.09882.

(a) with z=0.04723 is the nearest object with prominent lines OIII, H_γ, H_β, H_α, NII, OII, NeIII, HeI, SII, and ArIII. They are much closer to their rest wavelengths. It shows a clear H_α line indicating strong starburst activity. (b) with z=0.55933 has prominent lines Mg, OII, NeIII, H_δ, H_γ, H_β, OIII, HeI, and Na. (c) with z=1.24456 hs prominent lines CIII, Mg, OII, NeIII, and H_δ. They are significantly redshifted. Each spectra shows broad emission lines which is expected from a spectrum of a quasar.

5 Using SDSS in finding Quasars

Sloan Digital Sky Survey(SDSS) is one of the most ambitious astronomical surveys ever conducted. It uses a dedicated 2.5 meter wide-anle optical telescope at Apache Point Observatory in New Mexico since 2000. It has surveyed hundreds of millions of objects.

It captures images in five optical bands(u, g, r, i, z). Due to redshift, quasars exhibit distinctive colors. By plotting color-color diagrams, we can classify quasars. They have unique color signatures across different filters. They appear as point sources.

They have very high redshift values due to their distance from us. They exhibit strong, broad emission lines(such as hydrogen Ly_{α}, C IV) which are their key indicators.

Till date, it has identified and cataloged over 500,000 quasars. It proves to be an essential resource in the area of astronomy and astrophysics particularly giving insights into large scale structure of the universe and its evolution. It has identified a large number of Broad Absorption Line(BAL) quasars. It helps in studying the winds from quasars.

SDSS has discovered some of the farthest quasars ever seen. These discoveries provide insights into the formation of supermassive black holes and early universe. SDSS has helped in refining the quasar luminosity function which is a function describing the number density of quasars as function of redshift and luminosity. It has also helped in studying the spatial distribution of quasars and its clustering properties. The long exposure study also helps in understanding the variability of quasars over time.

The data collected by the survey is periodically released as Data Release(DR) catalogues. The latest is DR18 which is the fifth phase of SDSS. Part of SDSS-III, Baryon Oscillation Spectroscopic Survey(BOSS) is focused on measuring large-scale structure of the universe and extensive quasar obervations to map distribution of matter via Lyman alpha forest. Lyman alpha forest refers to a series of absorption lines seen in the spectra of distant quasars and galaxies which are caused by the intervening clouds of neutral hydrogen in intergalactic medium(IGM). When Lyman alpha lines are plotted in quasar spectrum, they appear as "forest" of closely spaced liens, primarily on blue side of the quasar's Lyman-alpha emission lines.

6 Understanding characteristics

6.1 Relation between colors and redshifts

I have plotted various color vs redshift curve using python from the data set downloaded from SQL Search tool in dr16 under SDSS.

The SQL Query used is:

```
select top 4000
objid, modelmag_u, modelmag_g, modelmag_r, modelmag_i, modelmag_z,z

from
SpecPhoto

where
class='QSO'
```

The code used for plotting the scatter plot is:

```
# Import necessary libraries
import pandas as pd
import matplotlib.pyplot as plt

# Define the path to the excel file
file_path = '/home/laxmi/color.xlsx'

# Read the excel file into a Data Frame
df = pd.read_excel('/home/laxmi/color.xlsx')

# Extract the columns for plotting
x = df['u-g']
y = df['z']

# Plot the data
plt.figure(figsize=(10, 6))
plt.scatter(x,y)
#plt.plot(x, y, marker='o', linestyle='-')
```

```
plt.xlabel('color(u-g)')
plt.ylabel('redshift(z)')

plt.legend(["data_points"], loc="lower right")

plt.title('Plot between color and redshift')
plt.grid(True)
plt.show()
```

Similarly we can plot many other curves. There seems to be a relation between them however any concrete result can not be made from the data set. Detailed analysis can be made using color-color diagram. [10]

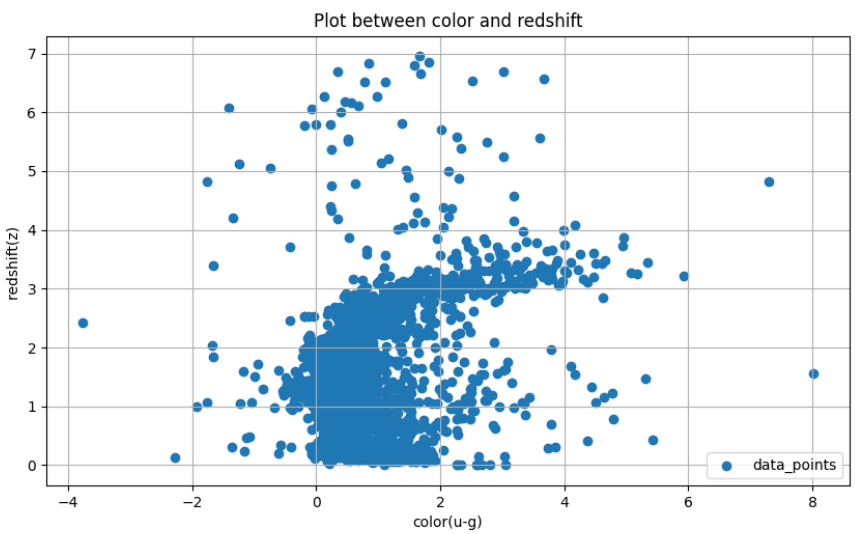


Figure 13: Color-redshift plot between u-g value and redshift(z): Though there is some randomness but most of the values lie between 0-2 in a straight beam.

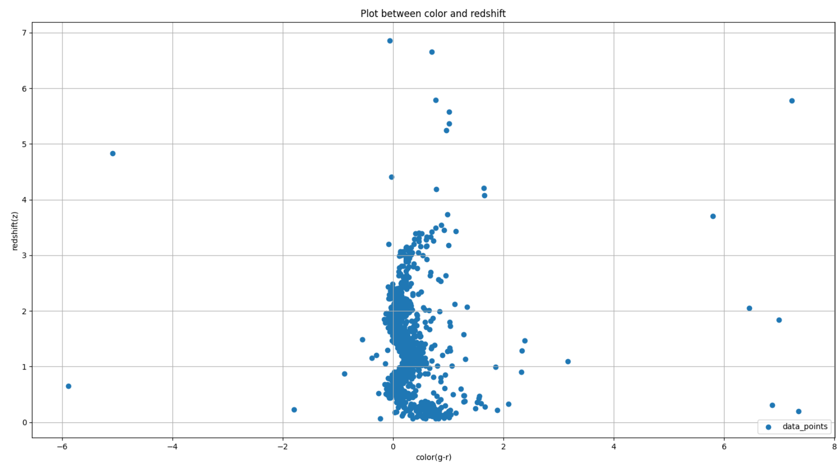


Figure 14: Color-redshift plot between g-r value and redshift(z): Similar to u-g vs z graph, most of the values lie between 0-2.

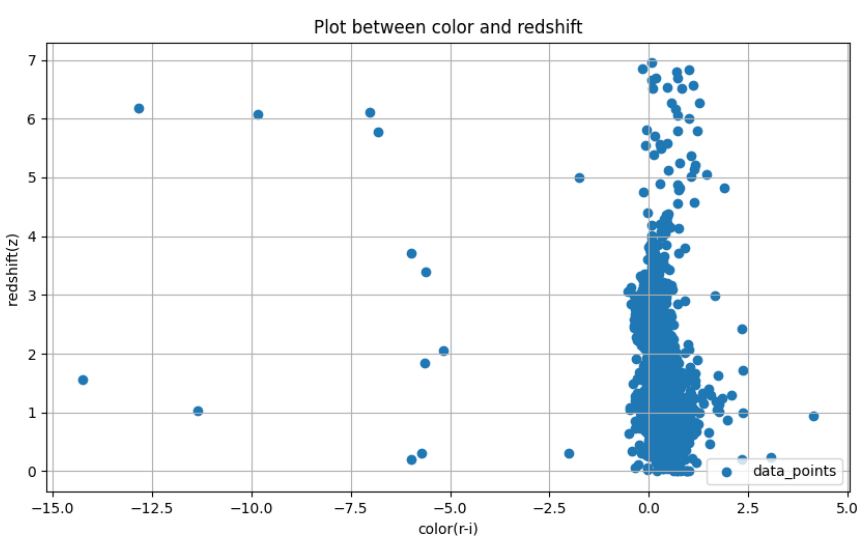


Figure 15: Color-redshift plot between r-i value and redshift(z): Most of the values lie near 0 to 2.5 in a straight path.

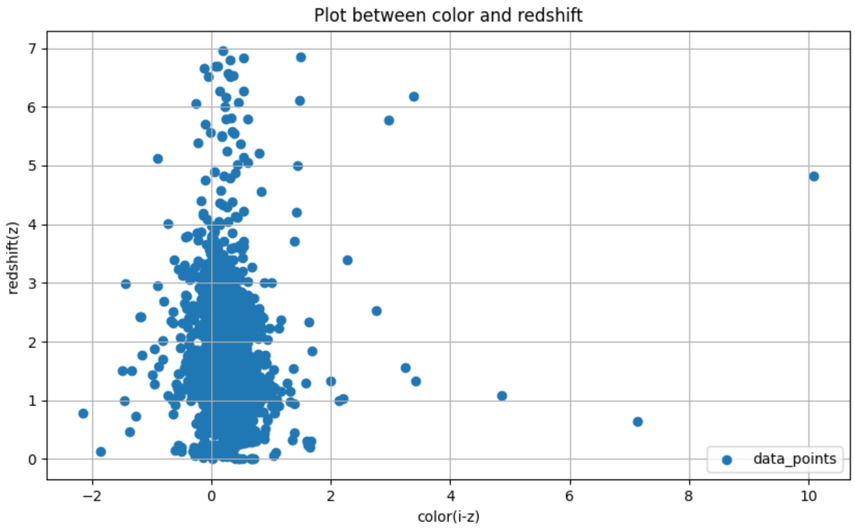


Figure 16: Color-redshift plot between i-z value and redshift(z): Most of the values lie around -1 to 1

6.2 Relation between color-color

Color-color diagrams are very important in study of quasars. They help in identifying quasar candidates, determining redshifts and understanding their environments. In u-g vs g-r diagram, quasars are separated since they have strong ultraviolet excess (high u-g) in and different optical slopes(g-r). g-r vs r-i diagram helps in further distinguishing quasars from stars and galaxies. High-redshift quasars (z greater than 2.2) can be identified. They tend to have redder g-r and bluer r-i colors compared to low-redshift quasars.

i-z vs r-i diagram is useful for quasars at redshift around 3 where the Lyman-alpha forest starts affecting i-band.

In SDSS such criteria are used. For example, in SDSS quasars are typically selected by using a combination of color cuts such as u-g greater than 0.4, g-r less than 1.0.

I have plotted graph between color-color values of different bands using 4000 quasars in python.

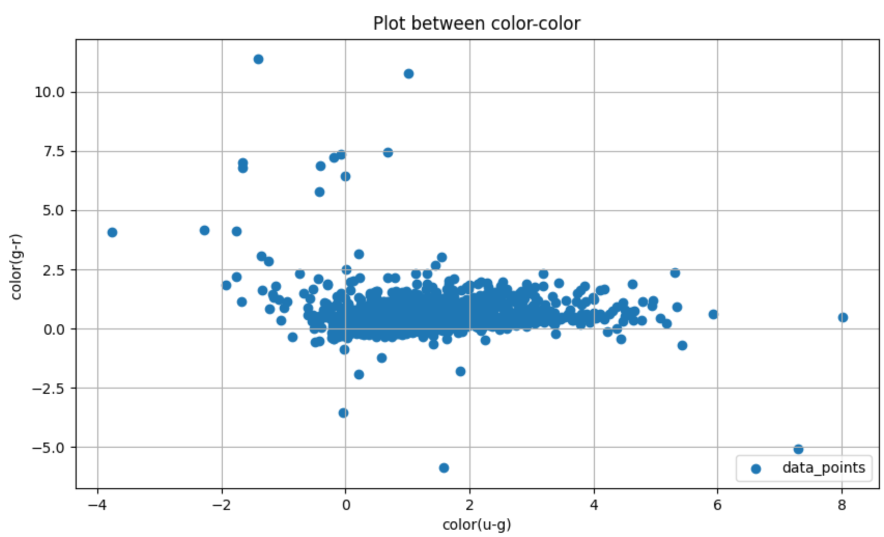


Figure 17: Color-color plot between u-g value and g-r value: straight line behavior of x-axis can be seen. Most of the data is in between -1 to 4.

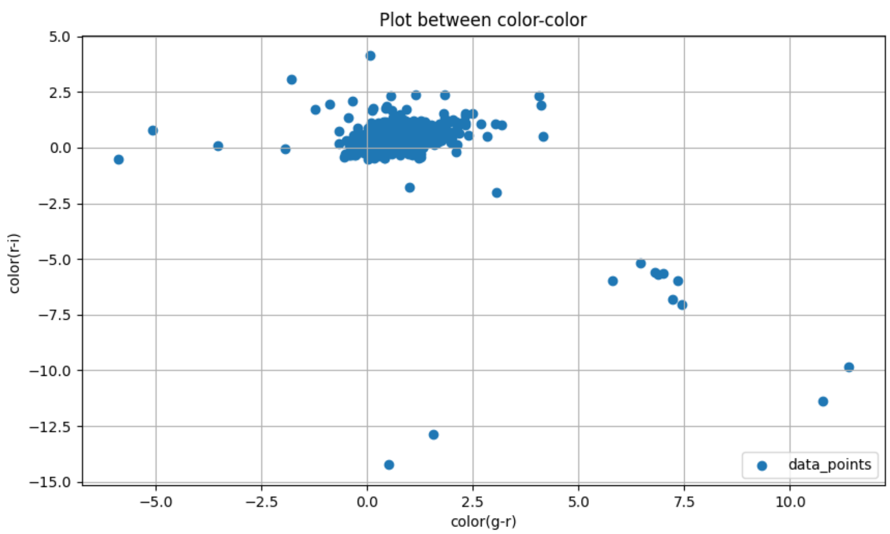


Figure 18: Color-color plot between g-r value and r-i value: Apart from a thick straight line behaviour, we can see the clumped data between -1 to 2.5

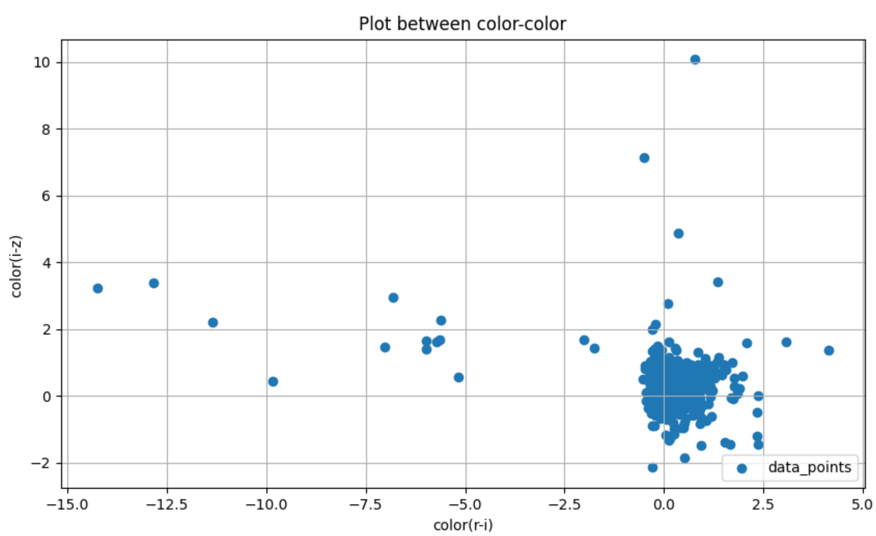


Figure 19: Color-color plot between r-i value and i-z value: the data points are clumped in region of square -2 to 2

7 Challenges and Future Prospects

Study of quasars presents several challenges for astrophysicists:

1. Starting with their discovery, they exhibit a wide range of properties which makes them hard to identify.
2. There is problem of contamination of the data from other astronomical objects like galaxies and stars.
3. Since their spectra is extremely red shifted , it is difficult to detect them using optical telescope therefore it requires x-ray or radio telescopes.
4. They exhibit variability on a wide range of time-scale therefore they require long-term monitoring. Since they are very distant, high-resolution spectroscopy is often required.

The area of studying quasar is quite challenging but it holds answer to many questions. Some fundamental aspects like the evolution of universe can be understood using quasars. There is no quasar within our vicinity. Thus we can say that no new quasar has formed recently. This is yet to be explained fully. Formation of supermassive black holes at the centre of galaxies is also an unexplained topic. There is a lot to be discovered in the future.

By taking some measures, this area can be further understood. Creating filters for primary classification of objects and focusing on those objects which are quasar candidate can increase the efficiency in measurement. Using advanced numerical simulations can provide great help for understanding quasars. [11]

Modern day telescopes and instruments such as James Webb Space Telescope(JWST), Extremely Large Telescopes(ELTs) and Square Kilometre Array(SKA) will definitely enhance our understanding of quasars. The development of theoretical models and their simulations can also provide great insights into their characteristics.

8 Summary

SDSS provides various compatible tools for analysis of many astronomical objects. Study of stars, galaxies, black holes, supernovae etc can be done by the data provided by SDSS. Quasars are one of the fascinating area in modern day astrophysics for research. It has been over half a decade since the discovery of first quasars.

I have used SDSS to extract the data of some astronomical objects according to either their RA/dec or Plate-Fiber values. Two separate data were taken from Faint Images of Radio Sky at Twenty-one cm(FIRST) for radio wave and SDSS for visible wavelength respectively.

I used DS9 for comparison of fits file from different bands. I have also compared spectra of different objects given in SDSS advanced project tasks. For increasing values of redshifts given in the data, the emission lines were red-shifted accordingly. Particularly Ly_α line can be used compare and infer any conclusion.

I have made color-redshift diagram for 1000 quasars which I got from running query in SkyServer's SQL Search tool. The value of redshift increases in various color parameters, though it can be said that it is a near constant line in y-axis. There are many questions which do not have certain answers yet but further research will definitely help to reach to new discoveries.

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