Primary Research Concerning Active Galactic Nuclei(AGN)

Yixian Chen
Dep of Physics, Tsinghua University
Email: yx-chen17@mails.tsinghua.edu.cn

Abstract

In this thesis I will conclude my work and learnings during the summer SRT(Students Research Training) project: "Research Concerning High-Energy Radiations of AGN".This project mainly serves as an elementary briefing and training program for actual astronomical research. The work consists of two parts:

- Reviewing considerable amount of papers and journal articles,understanding the fundamental features and principals of Active Galactic Nuclei and becoming acquainted with certain advanced frontier research of Astrophysics concerning AGNs
- Learning important programming skills for data-processing such as **Linux** and **Python**. Exerting important softwares such as Fermi Scitools run on Linux operating systems for astronomical research(In this case, drawing light curves etc.). Learning documentation preparation system **LaTeX**

Hereby discussing them separately in details.

Present Situation of AGN Study

Early Explorations

In the early 20th century, astronomers have already discovered certain anomalies-unusual emission lines-in photographic observations of nearby galaxies, though their nature had not been understood.

In 1943, Carl Seyfert (1911-1960) described observations of a collection of nearby spiral galaxies having bright nuclei that were sources of unusually broad emission lines NGC 1068, NGC 4151, NGC 3516)(C.K.Seyfert,1943). The luminosity of a nucleus can be 10-100 billion L_{sun}, comparable to the luminosity of the rest of the galaxy as whole, their host galaxies are later known as **Seyfert Galaxies**.

In the 1950s, radio astronomy began to thrive, and scientists discovered some of the nearby elliptical galaxies to be active radio-sources emmitting out radio jets and forming enormous radio lobes on either directions, later named **Radio Galaxies**. Around the same period, radio surveys had detected a number of bright and compact objects coincided with faint stellar-like objects whose spectrum showed unusual, broad emission lines and did not seem to correspond to the lines of any known stellar objects, named **Quasars**. In 1963, from the redshift measurements of 3C279, Maarten Schmidt(1929-) realized the broad spectral lines were highly shifted lines of Hydrogen, and the redshift measurements indicate these quasars were highly luminous objects at enormous distances, centers of violent activity in the heats of colossal galaxies(M.Schmidt,1963). Eventually, quasars and their less luminous cousins(including Seyfert and Radio Galaxies and other stellar objects such as Blazars whose introductions I shall omit) were given a more general name **Active Galactic Nuclei/AGNs**.

Enquiring into the nature of their high luminosity, scientists discovered the radiation to be of gravitational origin rather than stellar—there should be a massive black hole accretion mass in the center of an AGN(Although by which time "Black Hole" was yet to be the official name for black holes, they were still referred to as "Schwarzchild throats" and event horizens as "Schwarzchild sphere"). This was first suggested by Salpeter in 1964,who calculated that with the circular velocity and binding energy in circular orbit yielding to the formulas(E.E.Salpeter,1964):

$$V_c = [GM/(r-2n)]^{1/2}, where \quad r > 3n$$

$$E = mc^2\{1-(r-2n)[r(r-3n)]^{-1/2})\}$$

And the last stable circular orbit having a diameter of $12GM/c^2 = 12n$, the maximum binding energy would be:

$$E = mc^2(1-2\sqrt{2}/3) = 0.057mc^2$$

when a cloud if gas collects around the nucleus, the power of accretion with time derivative of M(or the mass flux F) should be $0.057Fc^2$.With this principal, it only requires an effective mass flux of 0.1 M_{sun} a year for the nucleus to equal the stellar light output of the rest of the galaxy.Lynden-Bell perfected this theory with a steady gas-swallowing medel with magnetic transfer of angular momentum obeying Faraday's Law in 1969.(D.Lynden-Bell,1969)

It was interesting to know incorrect assumptions were also made during the researches. After the gravitational origin of radiation was suggested, Fowler and Hoyle suggested the red shifts might also have a gravitational origin. But Schmidt showed that this was unlikely for it would mess up the emission lines. In the 1969 paper, Lynden-Bell himself suggested that AGNs might be collapsed old Quasars, implying that quasars are something that would evolve like a

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star and should go through a process of collapsing to become a super massive black hole. In fact, quasars are also types of AGNs already containing black holes in their centers, and all the AGNs share one unified model. But first their puzzling features should be analyzed and explained to a considerable extent.

Accretion Disks

The study of accretion disks have long started before the accretion disk model of AGN was proposed. Generally, an accretion disk is formed by diffused material in orbit of a massive center body(i.e. protostars, white dwarves, neutron stars, black holes, in AGN's case a super massive black hole), fiction causes materials to slow down and fall towards the center, while the gravitation potential energy is transferred to heat and electromagnetic radiation with a very high efficiency. The frequency range of that radiation depends on the central object's mass. Accretion disks of young stars and protostars radiate in the infrared; those around neutron stars and black holes in the X-ray part of the spectrum.

If matter is to fall inwards it must lose not only gravitational energy but also lose angular momentum. Since the total angular momentum of the disk is conserved, the angular momentum loss of the mass falling into the center has to be compensated by an angular momentum gain of the mass far from the center. In other words, angular momentum should be transported outwards for matter to accrete. This condition is called the Rayleigh stability criterion:

$$\frac{\partial(R^2\Omega)}{\partial R} > 0$$

where Ω is the angular velocity of the fluid element with respect to R. However, common hydrodynamic viscosity was not enough to satisfy this condition, we need turbulence-enhanced viscosity.

In 1973, Shakura and Sunyaev proposed a α-disk model where they quantified turbulence in the gas as the source of an increased viscosity. Assuming subsonic turbulence and the disk height as an upper limit for the size of the eddies, the disk viscosity can be estimated as

$$\upsilon = \alpha c_s H = \alpha P_{tot}/\rho\Omega$$

where c_s is the sound speed, H is the FWHM of the disk, and α is a free parameter between zero (no accretion) and approximately one which can be determined from observation data, and nearly everything essential of the disk model can be described in terms of α. In the standard Shakura-Sunyaev model, viscosity is also assumed to be proportional to the total pressure with $p_{tot} = \rho c_s^2$.(N.I.Shakura & R.A.Sunyaev,1973)

Magnetorotational instability is another machanism which could generate angular momentum transport. Two radially neighboring particles in the disk are connected by magnetic field like a spring, however the (Keplerian)velocity of the inner particle is larger than the outer one. When the spring is stretched, the inner particle decelerates and falls towards the center, while the outer particle accelerates and escapes. The new criterion for accretion under this instability is:

$$\frac{d\Omega^2}{dlnR} > 0$$

The problem with this machanism is that with the rapid increase of the distance between particles, the magnetic field diffuses and material dissipates quickly. So further researches must be made to see why the accretion disk's observed rate of fusion dominates that of fusion when as far as we know viscosity and magnetic diffusivity have almost the same order of magnitude in magneto-rotationally turbulent disks.(Balbus and Hawley,1991)

These theories were mainly developed based on black hole accretion disks, but most of the physical process and thesis applies to AGN SMBH accretion as well.

Kip Thorne, the 2016 Nobel Prize winner, is one of the first to give the AGN accretion disk model a full relativistic treatment. Following is a simulation of how this disk would appear based on he and Page's calculation.The back of the disk is distorted into a perpendicular plane, the relativistic rotation speed needed for centrifugal equilibrium in the very strong gravitational field near the black hole produces a strong Doppler **redshift** on the receding side whereas there will be a strong **blueshift** on the approaching side.(Page & K.S.Thorne,2006)

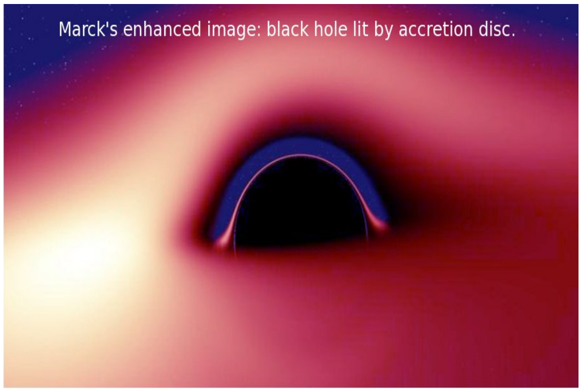

Figure 1: Simulation by J.A.Marck

Relativistic Jets

Just like the jets in Herbig-Haro objects formed by accretion disks around young stellar objects, the interaction of BH and disk gives rise to powerful jets on either side of the disk. Magnetic fields accelerate charged particles to relativistic speeds, forcing them to effuse from weak spots in the center of the highly condensed gas disk.

In certain Radio Galaxies we observed only one radio jet though both radio lobes, the cause of which is a simple relativistic **beaming effect**: the photons emitted by the jet moving away from the observer tends to focus in the small space angle around the jet.

Early observation has shown the velocity of the jets of certain AGNs(3C345,M87)has exceeded the speed of light. This phenomenon, later referred to as the **Superluminal**

Motion, is merely an optical illusion. Suppose the angle between the velocity of the jet(incoming) and the direction of observation is θ, the *appeared* velocity of the jet moving perpendicularly across the celestial sphere would be:

$$v_{app} = \frac{v\sin\theta}{1-\beta\cos\theta}$$

For a fixed β, the maximum appearance velocity would be:

$$v_{app,max} = \frac{v}{(1-\beta^2)^{1/2}}$$

where

$$\cos\theta = \beta$$

Therefore, when β and θ both approximates zero, we might observe appearance velocities far greater than the speed of light.(Rees,1966)

Spectrum

The AGNs have very unique spectrums.Here is a typical Spectral Energy Distribution(**SED**) of AGN.It has conspicuous bulges around the IR and blue regions. Apart from those, the SED mostly yield to power law distributions, A.K.A:

$$F(or \quad S)_v \propto v^{-\alpha}$$

The power law distributions can be explained by electron synchrotron in strong magnetic fields: the smooth curve is the result of the superposition of the seperate SEDs of a whole group of electrons being accelerated.

NATURE. VOL. 223. AUGUST 16. 1969

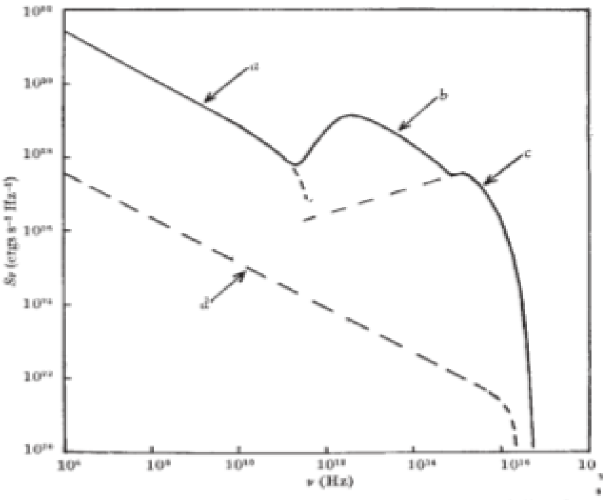

Fig. 1. The emitted spectrum of disk and synchrotron radiation for the standard model. The flux from Sagittarius *A* is weaker by a factor 100, indicating only 1 per cent efficiency of the proton synchrotron. *a*, Proton synchrotron; *b*, outer disk; *c*, central disk; *d*, electron synchrotron.

Figure 2: A typical power spectrum and its components

The Power Spectral Density(**PSD**) of an AGN is roughly the SED taken time derivative (in a period of time), and could show a great deal of information about the variability of the object in different wavenlengths.

Unified Model of AGNs

Ever since the discovery of different classifications of AGNs, efforts have been made to unravel the intrinsic properties which caused their differences. By the 90s, the Strawhat Person Model(**SPM**) was formulated in which there are only two basic types of AGN—radio loud/radio quiet—that vary in intrinsic luminosity and all other observed properties for classification are ascribed to **orientation**(R.Antonucci,1993). Despite a few exceptions and anomolies, astronomers have strong faith in this model, in a 1993 session of IAU, astronomer Antonucci even mentioned that they had formed a religion called the "Unification Church"(R.Antonucci,1994).

Gradually, scientists have developed a basic picture of a supermassive black hole surrounded by an accretion disk into a more sophisticated and exact model which attempts to explain all types of AGNs by different observational orientations. (FIGURE 3)

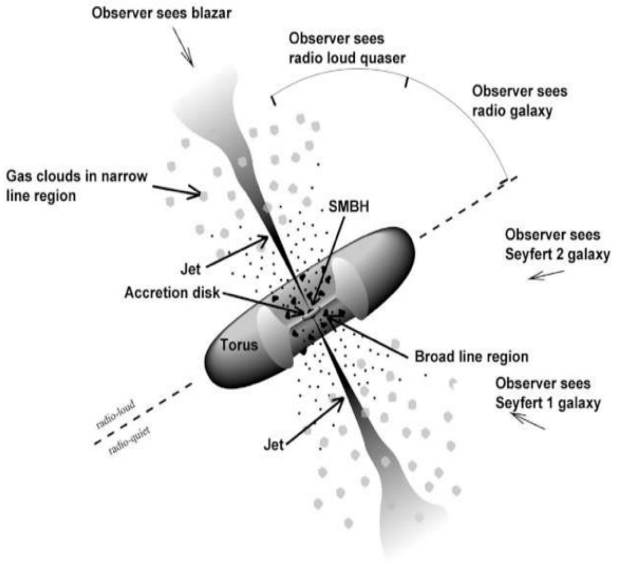

Figure 3: Unified Model of AGNs, https://fermi.gsfc.nasa.gov/science/eteu/agn/

As we can see, in this unified model, the Super Massive Black Hole is not only surrounded by the accretion disk but also, at a farther distance, a large torus of gas and dust consisting of material that is feeding the central engine itself. Other more rarefied gas form a Broad Line Region(**BLR**) and a Narrow Line Region(**NLR**) isotropically around the SMBH. When viewed from different angles, the AGN model would have diversed spectropic properties, E.g:

- When the AGN is viewed from an angle parallel with the accretion disk, due to heavy absorption of visible light and photons with smaller wavelength by the dust torus, the observer will recieve strong radiation from radio wavelength and the shape of jets on both sides of the disk would be most conspicuous, therefor this AGN will show features of Radio Galaxies.

- When viewed from the direction of one of the jets, the AGN's compact and extremely luminous center is most likely to be observed in details, showing the characteristics of a blazar or quasar.
- When viewed from the sides, the observer would see different types of Seyfert Galaxies and maybe quasars depending on the intrinsic radio-loudness of the AGN and which region(NLR/BLR) is exposed more to the observer.

Principally, this model has already been accepted by more and more astrophysicists, but still needs and is indeed undergoing further testing and revising with observational data. Here's a question that I didn't find a clear answer: According to observation, Seyfert galaxies are mainly **spiral** galaxies and radio galaxies are mostly **elliptical** galaxies, which is quite wierd. While they are theoretically categorized by the observed orientation, is there a intrinsic connection between the orientation and the shape of the galaxies?

X-Ray Variability

Decades ago, scientists have already discovered that the X-ray variability is a very important parameter for AGNs, somehow intrinsically connectedd with the Black Hole Mass and the luminosity of the object.

In 1993, Lawrence and Papadakis tried to fit a power law model to observation datas of certain AGNs,:

$$log[P(\upsilon)] = log[A(10^4\upsilon)^{-\alpha} + C]$$

where A is called the PSD amplitude and C is constant due to Poisson noise which dominates at high frequency. The fitted A seems to anti-correlate with luminosity and the α values are mainly 1-2 with a mean of 1.55. But later, scientists including Papadakis himself have adopted a better hypothetical model:the 2-10KeV(X-ray) power spectrum doesn't have a fixed α, it first follows a power law of slope -2($\alpha = 2$) at high frequencies and then **flattens** to a slope of -1($\alpha = 1$,note that on the PSD with y axis as υF_υ,the tangent fattens to 0) below a so-called **break frequency** υ_{hfb} which anticorrelates well with Black Hole mass($\upsilon_{hfb} \propto 1/M_{BH}$),until(currently found in certain AGNs) a second break frequency υ_{lfb} below which it flattens to 0($\alpha = 0$). The PSD amplitude (in the frequency × power space) does not depend on mass or luminosity but is in fact about 0.02 for all AGNs.(I.Papadakis & A.Lawrence1993)

The parameter for X-ray variability **Excess Variance** σ^2_{nxs} is defined as the variance of a light curve normalized by its mean squared after correcting for the experimental noise depending on the binsize[1] of the light curve(Papadakis, 1995):

$$\sigma^2_{nxs} = \frac{1}{N\bar{x}^2}\sum_{i=1}^{N}[(x_i - \bar{x})^2 - \sigma_i]$$

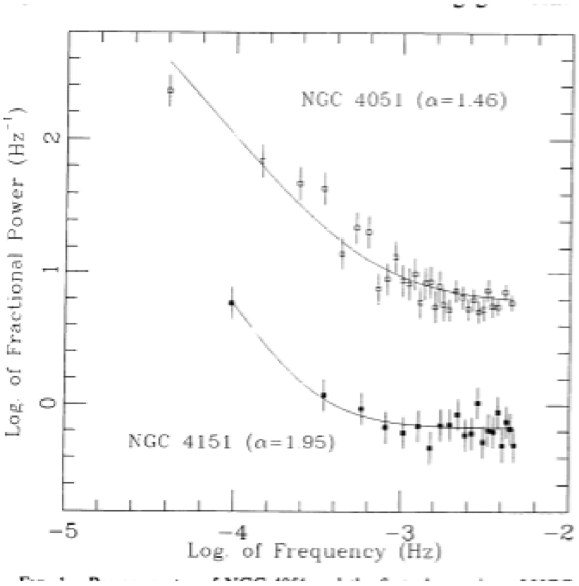

Figure 4: Some examples of typical PSD in the X-ray region for AGNs

which also can be calculated by integral over certain regions of PSD:

$$\sigma^2_{nxs} = \int_{1/T}^{1/2\Delta t} P(\upsilon)d\upsilon$$

1/T should be the lowest frequency sampled υ_{min}, and Δt is the binsize, so the upper limitυ_{max} is close to infinity for very short timescale. The result of the intergration depends on the size relation between υ_{min}, υ_{max}, υ_{hfb} and υ_{lfb}. A lot of discoveries and theories have been made concerning the σ^2_{nxs}, here are two for example:

- Scaling of Black Hole Mass: Under the assumptions of a universal PSD amplitude and that $M_{BH} \propto 1/\upsilon_{hbf}$, when $\upsilon_{min} > \upsilon_{hbf}$ and the second break is negligible, the intergration yields that:

  $$M_{BH} = C(T - 2\Delta t)/\sigma^2_{nxs}$$

  In 2004, Nikolajuk and Papadakis used Cygnus X-1(we already knew the mass of which quite accurately)[2] to calibrate the C and compared the AGN black hole masses obtained by this method with those by others like reverberation mapping[3]. They found that apart from a category of AGNs called Radio-loud Narrow Line Seyfert 1(NLS1), this model fits fairly well. For the NLS1s, they found that the model would fit well with a C twenty times larger.(M.Nikolajuk et al, 2010)

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[1] Data binning is a data pre-processing technique used to reduce the effects of minor observation errors. The original data values which fall in a given small interval, a binsize, are replaced by a value representative of that interval, often the central value.

[2] there is actually a problem in here: Cyg X-1 is, after all, a 20 solar mass black hole which is intrinsically different in many aspects with a Super Massive Black Hole with $10^7 M_{sun}$, the only reason they gave to justify this calibration is that the PSDs of Cyg X-1 and some AGNs are alike, which seemed a little inadequate.

[3] Reverberation mapping: a way of determining the Black Hole Mass by measuring the mean square speed $< v^2 >$ of the gas in the Broad Line Region from the Doppler broadening of gaseous emission lines, formula:$GM_{BH} = fR_{BLR} < v^2 >$, where R is the radius of BLR and f is a factor determined by the shape of BLR

- Actually, it can be proved that for soft/high state accretion around the black hole, there should rarely be a second frequency break(only in very unique circumstances), it is only in low/hard state accretion model where we might often find one. But from the observed data it is always hard to determine whether this frequency exists or not. In a 2010 paper by our professor Zhang Youhong, he took an extremely large binsize of 300 days to plot PSDs of AGNs with 14 years of data from ASM Telescope.He showed that with a binsize large enough, the dependence between the calculated σ^2_{nxs} and M_{BH} and luminosity can be used to judge which of two hard/soft model suits the case better. His actual results gave evidence for the latter.(Y.Zhang,2011)

Radio-loud Narrow Line Seyfert 1(NLS1)

Radio-loud Narrow Line Seyferts are a heated topic of current research. They are unique probes of the formation of powerful radio jets with unique multi-wavelength properties at near-Eddington accretion rates and low black hole masses. The selection criterion for NLS1 is the small width of their broad Balmer lines, $FWHM(H\beta) < 2000km/s$, their radiation output covers the whole variety of radio, infrared, X ray photons and γ bursts variabilities are considerably higher than common AGNs.Some of the features have already been explained:

- The low black hole masses can explain the small width of the BLR emission lines.
- The multi-wave emissions implies accretion at or near the Eddington limit, the L/L_{Edd} ratio is very high[4].

Therefore,it can be deduced that NSL1s maybe young or rejuvenated AGNs rapidly growing in their black hole sizes. But further infomations needs to be collected(Foschini et al, 2011).

Maybe the reader remembered that in the scaling of Black Hole Mass with σ^2_{nxs}, we had to multiply the C in the formula with a factor of 20 for the unique NLS1s to get a relatively convincing Black Hole Mass. The intrinsic nature of this factor remains to be discovered. Here's my thoughts on this: qualitively, it's true that the excess variance for NLS1s are considerably larger than normal AGNs, so the $C(T-2\Delta t)/\sigma^2_{nxs}$might give a value too small, smaller than the BH Mass. But it's also true that the BH Mass of NLS1s are smaller than average AGNs. So maybe the smallness of variance is to a larger extent?

Programming For AGN Research

In this training program, we came across various softwares run on Linux operating systems that help process data of AGNs obtained by telescopes and output results. Some of them are already widely in use in the latest researches.

Fermi Science Tools

The Fermi STools is a software that helps analyse the Fermi LAT data. It was run on command lines from the Linux Terminal, processing **FITS(Flexible Image Transport System)** format files.

FITS is an open standard for documents formatted as N-dimensional arrays (for example a 2D image), or tables, the most commonly used digital file format in astronomy. The FITS standard has special (optional) features for scientific data, for example it includes many provisions for describing photometric and spatial calibration information, together with image origin metadata.

The exploration of FITS documents with Fv Reader will be discussed later, for now I will focus on introducing how to run this software. The reader can explore for himself on https://fermi.gsfc.nasa.gov/ssc/data/analysis/software/, but I'll give a more practical and succint instruction.

- **Linux**: First, make sure you have a Linux operating system, you may install a Virtual Ubuntu Desktop server on your Mac/Windows system via Virtualbox, VMWare etc; And you may choose to adopt a dual system if your computer still has adequate internal storage. If you are using a virtual machine, please make sure you have at least 20 GBs of hard drive storage and 1 GB of internal memory for this software and others. Open the command lines by clicking terminal.
- **Installation**:Download the tar.gz pack from https://fermi.gsfc.nasa.gov/ssc/data/analysis/software/, unpack it in whatever directory you want. The recommended directory is the default home directory /home/(username), which is the default working directory " " when you open the terminal.

```
~$:gunzip   c *.tar.gz | tar xvf -
#unpacking
~$:cd home/(username)/ScienceTools-v11r5p3
    -fssc-20180124-x86_64-unknown-linux-
    gnu-libc2.23/x86_64-unknown-linux-gnu-
    libc2.23/BUILD_DIR
#entering the directory where you can run
    the configuration script
home/.../BUILD_DIR $:./configure
#configuring
home/.../BUILD_DIR $:./make
#an additional move to make sure the
    configuration is complete, the
    response should be that makefile is
    not needed anymore.
home/.../BUILD_DIR $:cd
#back to home directory
~$:gedit ~./bashrc
#opening an interface to rewrite your
    bashrc,directly write down these lines
     in you bashrc, which will allow you
    to access the fermi-init.sh with a
    simple command on the terminal:
FERMI_DIR=~/ScienceTools-v10r0p5-fssc
    -20150518-x86_64-unknown-linux-gnu-
    libc2.19-10/x86_64-unknown-linux-gnu-
    libc2.19-10
export FERMI_DIR
```

---

[4] Eddington luminosity: also referred to as the Eddington limit, is the maximum luminosity a body can achieve when there is balance between the force of radiation acting outwards and the gravitational force acting inwards. For a quasar, L/L_{Edd} can reflect the strength of its accretion

```
alias ferminit=". $FERMI_DIR/fermi-init.sh"
#close the gedit interface
~$:source ~./bashrc
#refresh the bashrc, then
~$:ferminit
#now you can access the software—nothing seems to happen at first for it doesn't have a visual interface, but you can run command lines with the Fermi ST functions now.
```

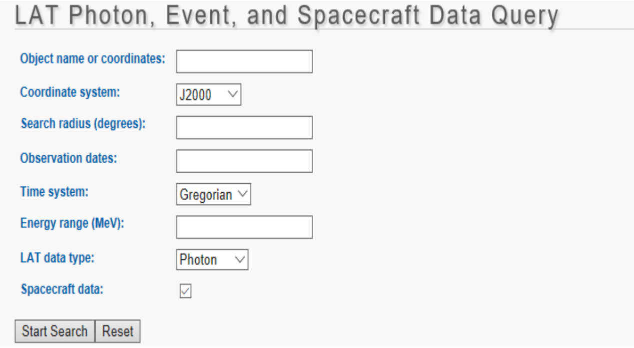
It would be better to install the ftools as well(this includes the useful FITS viewer fv). Go to https://heasarc.gsfc.nasa.gov/docs/software/lheasoft/download.html, download the General Use package for Ubuntu 16.04LTS without the Xespec.

```
~$:gunzip  c *.tar.gz | tar xvf -
#unpacking
~$:cd home/(username)/heasoft-6.24/x86_64-unknown-linux-gnu-libc2.23/BUILD_DIR
#entering the directory where you can run the configuration script
home/.../BUILD_DIR $:./configure
#configuring
home/.../BUILD_DIR $:./make
#an additional move to make sure the configuration is complete, the response should be that makefile is not needed anymore.
home/.../BUILD_DIR $:cd
#back to home directory
~$:gedit ~./bashrc
#opening an interface to rewrite your bashrc,directly write down these lines in you bashrc, which will allow you to access headas-init.sh with a simple command on the terminal:
HEADAS=~/heasoft-6.22/x86_64-unknown-linux-gnu-libc2.23
export HEADAS
alias heainit=". $HEADAS/headas-init.sh"
#close the gedit interface
~$:source ~./bashrc
#refresh the bashrc, then
~$:heainit
```

- **Extracting data**: To extract LAT photon data, you have to go to https://fermi.gsfc.nasa.gov/cgi-bin/ssc/LAT/LATDataQuery.cgi.

  Now, you can query for data with these parameters as shown in figure 5.

  Notes:


LAT Photon, Event, and Spacecraft Data Query

Object name or coordinates:

Coordinate system: J2000

Search radius (degrees):

Observation dates:

Time system: Gregorian

Energy range (MeV):

LAT data type: Photon

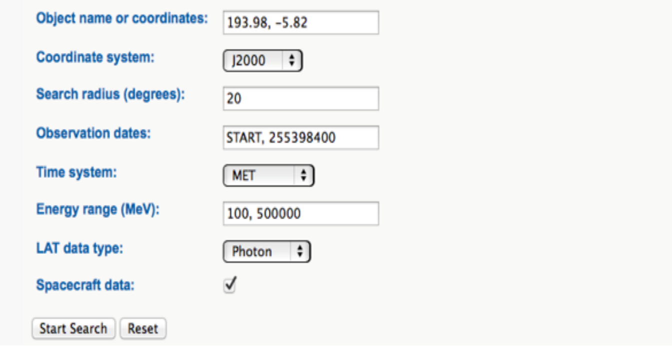
Spacecraft data: ☑

Figure 5: Data search interface

  - The coordinates (whether Equatorial or Galactic) have to be in degrees and separated by a comma. You can insert also the name of the source like 3C279, or PG1553+113. The source coordinates will be reported back to you when you retrieve the results of your query and you have to remember that when you use the Tools.
  - If a pair of coordinates are entered, you have to choose the equinox time ("J2000" or "B1950") if these were Celestial coordinates, or you have to select "Galactic" if these were Galactic coordinates. This selection is ignored if a name was given.
  - Observation dates may be specified in the Gregorian calendar system, or as a number of seconds in the **MET** system (Mission Elapsed Time, number of seconds since midnight of 1 January 2001), or as a number of days in the MJD system (Modified Julian Days, floating-point number of days since midnight of 17 November, 1858). Http://heasarc.gsfc.nasa.gov/cgi-bin/Tools/xTime/xTime.pl is available should you need to convert your time to a different format.

    The starting date may be replaced by the string 'START' (as in this example), to indicate the earliest available data. The ending date may be replaced by the string 'END', to indicate the most recent available data.
  - The Spacecraft data selection is enabled by default and is usually a very large FITS file. If you do not wish to download the "Spacecraft" data file, remember to uncheck this selection.The spacecraft file from START to END can be **reused** in data processing.

  In the tutorial we use this set of parameters as figure 6.


Object name or coordinates: 193.98, -5.82

Coordinate system: J2000

Search radius (degrees): 20

Observation dates: START, 255398400

Time system: MET

Energy range (MeV): 100, 500000

LAT data type: Photon

Spacecraft data: ✓

Figure 6: 3C279

  Then, download the FITS files to your home memu. There should be 3 files with their names ending with

"PH00""PH01""SC00",for convenience, we could rename the long strings just like that, leaving only four letters.These are photon data files of the blazar 3C279.

- **Preparing data i.e.3C279** Data preparing consists of two steps:
  - (gtselect): Used to make cuts based on columns in the event data file such as time, energy, position, zenith angle, instrument coordinates, event class, and event type.
  - (gtmktime): In addition to cutting the selected events, gtmktime makes cuts based on the spacecraft file.

  To make this tutorial brief and simple I will only introduce some arguments for the functions above and how to execute them in bash.

```
~$:ls *PH* > events.txt #create an input
    file for multiple photon FITS file ,a
    text which lists all files with "PH"
    in its name
~$:gtselect evclass=128 evtype=3 infile=
    @events.txt outfile=3
    C279_region_filtered.fits ra = 193.98
    dec = −5.82 rad = 20 tmin=START tmax
    =255893400 emin=100 emax=500000 zmax=
    90
```

  The auguments above are, in order: event class(mostly 128 for source), event type(mostly 3), input and output file, the RA and DEC for new center of observation,radius if acceptance cone, maximum and minumum time and energy, maximum apparent zenith angle.

  Two method of running this function: putting all the arguments in the command line separated with a sapce and press enter, or just run gtselect and press enter and input whatever argument the command line then asks for.

  Then, we run a gtmktime:

```
~$:gtmktime scfile=SC00.fits filter="(
    DATA_QUAL>0)&&(LAT_CONFIG==1)" roicun=
    no evfile=3C279_region_filtered.fits
    outfile=3C279_region_filtered_gti.fits
```

  Arguments: spacecraft files, filter expression(DATA_QUAL - quality flag set by the LAT instrument team (1 = ok, 2 = waiting review, 3 = good with bad parts, 0 = bad),LAT_CONFIG - instrument configuration (0 = not recommended for analysis, 1 = science configuration)), apply ROI-based zenith angle cut(usually no),event and output file.

  Now, we have a fully prepared data file **3C279_region_filtered.fits**.

- **Processing data i.e. Burst** Here is a tutorial for drawing a light curve for a γ burst, introducing another function:
  - gtbin:bin the photon data into a map and a lightcurve

```
~$:wget https://fermi.gsfc.nasa.gov/ssc/
    data/p6v11/analysis/scitools/data/
    exploreLATDataGRB/LAT_explore_GRB.tgz
~$:tar xvfz LAT_explore_GRB.tgz #extract
    the files
~$:cd /home/(usename)/LAT_explore_GRB #
    enter directory
~/LAT_explore_GRB$:gtselect evclass=128
    infile=grb_events.fits outfile=
    GRB081916C_lc_events.fits ra= 121.8
    dec= −61.3 rad= 10 tmin=243216266 tmax
    =243218266 emin=30 emax= 300000 zmax=
    180 # run a gtselect
~/LAT_explore_GRB$:gtbin algorithm = LC
    evfile = GRB081916C_lc_events.fits
    outfile = GRB081916C_light_curve.fits
    scfile=NONE tbinalg = LIN tstart =
    243216266 tstop = 243218266 dtime = 10
     #run a gtbin
```

  Arguments for gtbin: Type of output file(this case light curve), event and output file, spacecraft file, algorithm for defining time bins, the start and finish time, the binsize. Now, we have a light curve data file **GRB081916C_light_curve.fits**.

- **Processing data i.e. AGN light curve with variability** Here is a tutorial for drawing a light curve for a AGN with a typical periodic variability, introducing another function:
  - gtexposure:Given a "counts" light curve, this function computes the exposure (cm^2/s) associated with each time bin,allowing for a light curve in photons/s to be computed. This might take hours.

  First, we search for the data of AGN PG 1553+113 on the LAT data extract page. The necessary parameters are given in the following gtselect commands(you can search for raw data in a larger region). Mind that drawing this heavily binned light curve of an AGN will require a very long observation time and a very large file, unlike the γ burst.

  After downloading the files, name all photon files as "PH0X.fits" and spacecraft file as "SC00.fits" in the home directory.

```
~$:ls *PH*.fits > pg1553.txt
~$:gtselect evclass=128 extype=3 infile=
    @pg1553.txt outfile=pg1553_filtered_1.
    fits ra=238.929 dec=11.1901 rad=1 tmin
    =239557417 tmax=523318554 zmax=90 #
    run a gtselect
~$:gtmktime scfile=SC00.fits filter="(
    DATA_QUAL==1) && ABS(ROCK_ANGLE)<90 &&
     (LAT_CONFIG==1) && (angsep(RA_ZENITH,
    DEC_ZENITH,238.929,11.1901)+1<105) &&
    (angsep(238.929,11.1901,RA_SUN,DEC_SUN
    )>5+1) && (angsep(238.929,11.1901,
    RA_SCZ,DEC_SCZ)<180)" roicut=yes
    evfile=pg1553_filtered_1.fits outfile=
```

```
    pg1553_filtered_1_gti.fits # run a
    gtmktime
~$:gtbin algorithm=LC evfile=
    pg1553_filtered_1_gti.fits outfile=
    lc_PG1553_1.fits scfile=SC00.fits
    tbinalg=LIN tstart=239557517 tstop
    =523318554 dtime=3888000 # run a gtbin
~$:gtexposure infile=lc_PG1553_1.fits
    scfile=SC00.fits irfs=P8R2_SOURCE_V6
    srcmdl="none" specin=-1.604 # run a
    gtexposure
```

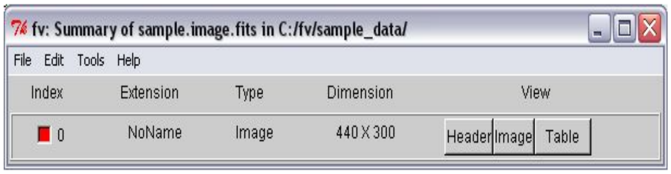
Arguments for gtexposure: input and spacecraft files, reference to the LAT Instrument response functions, XML file containing the Likelihood model for the target source, photon spectral index to use for weighting the exposure as a function of energy. Now, we have a light curve data file **lc_PG1553_1.fits**.

Fv & Ds9

After we retrieved the fits files, it's time we view them with the special softwares fv and ds9.

Fv is already included in the ftools. As introduced before, FITS is the standard format that is universally used by researchers and observatories for astronomical data files. It is important to realize that FITS is much more than just another image format, such as GIF or JPG, and that FITS files can store many different images and tables all merged into a single file. The main purpose of fv then is to provide an easy-to-use tool for examining and editing the contents of any FITS file.

Whether if you opened a fits file by clicking on it or opening it from the fv file table, you will find a summary table:


fv: Summary of sample.image.fits in C:/fv/sample_data/

Index	Extension	Type	Dimension	View
0	NoName	Image	440 X 300	Header Image Table

Figure 7: summary table

The table provides a capsule summary of the type and size of each major component in the file. These components are called Header-Data Units (HDUs) or ‘extensions’ in FITS terminology. Every FITS file must have at least 1 HDU, and this first HDU is called the Primary Array. The primary array can only contain an N-dimensional array of data (typically a 2-dimensional image), but any HDUs following the primary array may each contain either an image or a table(binary). For image files, you can view image with ds9 or POW(already included inside fv) or edit raw numbers (pixels) in the tables. For binary table files, you can produce a ”counts map” image with HIST or edit and plot the table contents with calculator or PLOT. The calculator and plotter in fv are very useful, here I will demonstrate how to use them by viewing the already processed files in the previous section.

- 3C279: Click on the Hist button for the EVENTS file in 3C279_region_filtered.fits.Select RA for the X column's drop down menu and DEC for the Y column. Select 0.1 degree for binsize. And now a picture like **figure 8** will be generated.
- GRB: Open GRB081916C_light_curve.fits, the lightcurve is in the RATE extension. Choose 'All' to view the content of that extension. The extension has 4 columns: TIME, TIMEDEL, COUNTS and ERROR. Plot the COUNTS as a function of TIME. Select 'Plot' for the RATE extension. Click on 'Time' then on 'x'. Click on 'Counts' then on 'y'. Finally click on 'Plot'. The result is as **figure 9**.
- PG1553+113: Open lc_PG1553_1.fits, open the table for the EVENTS file and add two new columns: RATE and RATE_ERROR, all 8 bytes doubles.

  Initially all the values are 0, then open the calculator, input:

  RATE = counts/exposure

  RATE_ERROR = error/exposure

  You can also execute the calculations via command lines in terminal:

```
~$:ftcalc lc_PG1553_1.fits ftcalc
    lc_PG1553_1.fits RATE 'counts/exposure
    '#input file, output file(covers), new
     parameter, the calculation of new
    parameter
~$:ftcalc lc_PG1553_1.fits ftcalc
    lc_PG1553_1.fits RATE_ERROR 'error/
    exposure'
~$:fv lc_PG1553_1.fits
```

  In the plot interface, select RATE as y axis, RATE_ERROR as y axis error, TIME as x axis, ERROR as x axis error, and you plot a discrete light curve with error values just like **figure 10**, and you can see clearly the periodic fluctuation of the count rates.

  If you do the same binning(with a smaller binsize) and exposure process to the 3C279 data previously prepared, you will also obtain a light curve somewhat like **figure 11**, but the periodic variability of the AGN is not so obvious for the sampling time is a bit too short.

Ds9 is yet another viewer of FITS files, we can use it to open the 3C279 counts map image with the very same result as figure 8, and you can conveniently adjust the color options, which I will not go into details.

FermiPy

Fermipy is a python package that facilitates analysis of data from the Large Area Telescope (LAT) with the Fermi Science Tools built on the pylikelihood interface. It uses a configuration-file driven workflow in which the analysis parameters are defined in a YAML file. Analysis is executed through a python script that calls the methods of

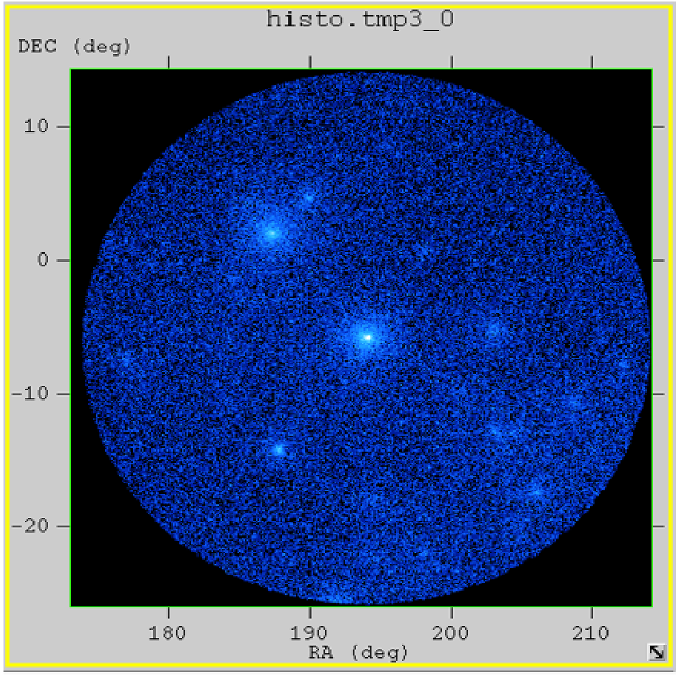


Figure 8: 3C279.fits

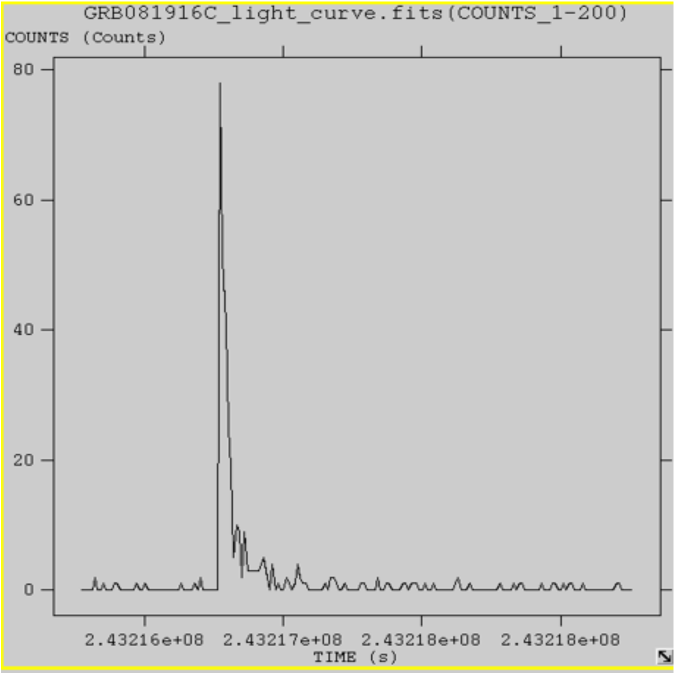


Figure 9: GRB081916C_light_curve.fits

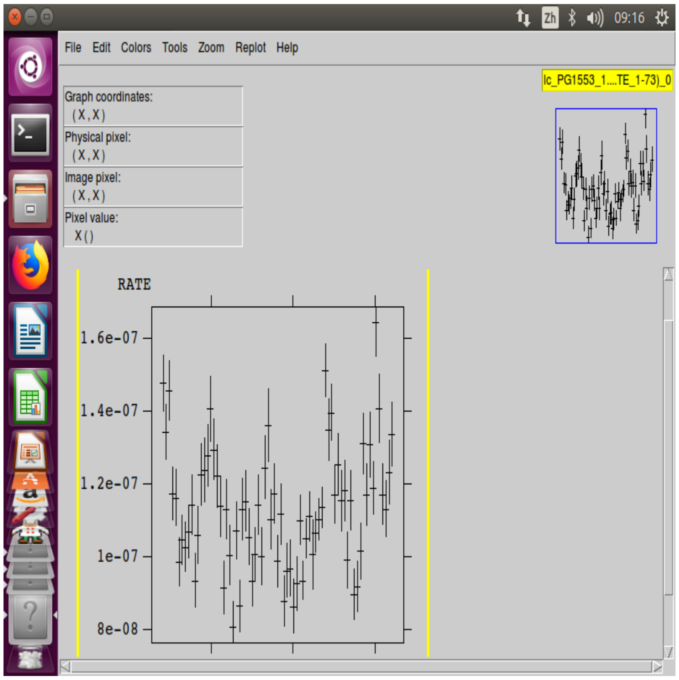
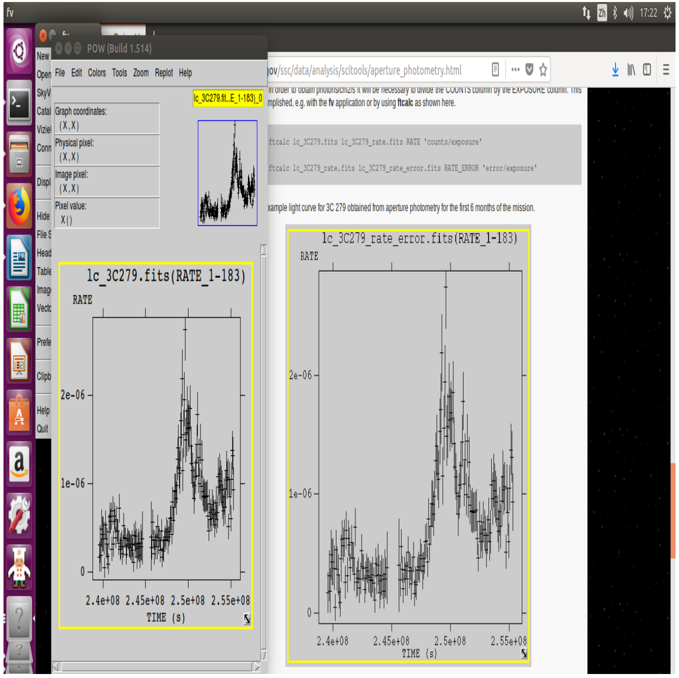


Figure 10: lc_PG1553_1.fits



jov/ssc/data/analysis/scitools/aperture_photometry.html

In order to obtain photons/cm2/s it will be necessary to divide the COUNTS column by the EXPOSURE column. This
mplished, e.g. with the **fv** application or by using **ftcalc** as shown here.

```
ftcalc lc_3C279.fits lc_3C279_rate.fits RATE 'counts/exposure'

ftcalc lc_3C279_rate.fits lc_3C279_rate_error.fits RATE_ERROR 'error/exposure'
```

xample light curve for 3C 279 obtained from aperture photometry for the first 6 months of the mission.

Figure 11: 3C279 light curve

GTAnalysis to perform different analysis operations, it's more accurate than the ordinary science tools. Official guide: https://fermipy.readthedocs.io/en/latest/index.html

- **Installation** It's recommended to use Anaconda Python to intstall FermiPy in the Linux system. (You will encounter a lot of trouble if you use pip, because you have to install pip under the python package INSIDE the science tools, and that very python is short of SSL module.)

```
~$:curl –OL https://raw.githubusercontent.com/fermiPy/fermipy/master/condainstall.sh
~$:source condainstall.sh #this script will create a new installation under $HOME/miniconda
~$:conda install fermipy
~$:curl –OL https://raw.githubusercontent.com/fermiPy/fermipy/master/condasetup.sh
~$:source condasetup.sh #initialize the ST/fermipy environment
```

- **Quickstart** The official guide is on https://fermipy.readthedocs.io/en/latest/quickstart.html, we will not go into details in this thesis, but the reader is encouraged to try this out. Figure 12 is an SED drawn out by the FermiPy function GTAnalysis.sed(Wood,2017).

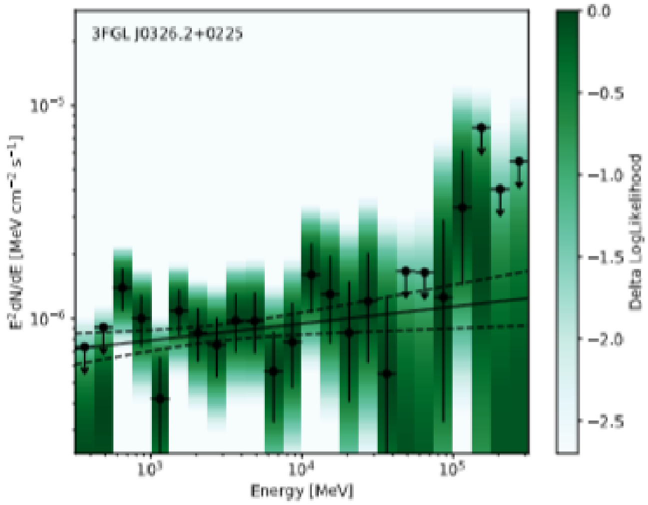


Figure 12: SED of an AGN

Conclusion

This SRT Program has been a huge opportunity for us to be introduced to the wonders of astronomical research. In this program we learned to scan and search for papers on cutting-edge projects and use softwares to process astronomical data, but most importantly, we got a glimpse of essenece of scientific research and its biggest difference from course learning: You have to explore a totally unknown region mostly by yourself, motivated by your curiosity and questions. While solving some of the problems, we generate more questions for further research.

A Summary of our Results We were interested in the properties of NLS1s, so we took some NLS1s for which we can find both the SMBH mass and the observation results of Fermi telescope. They are:

- FBQSJ1644+2619
- PMN J0948+0022
- PKS1502+036
- SBS0846+513
- 1H0323+342
- PKS2004-447

We drew the light curves with Fermi Science Tools taking 300-day-bin as in (Zhang. 2010), and plotted their excess variances(and average) with respect to Black Hole masses with Python.

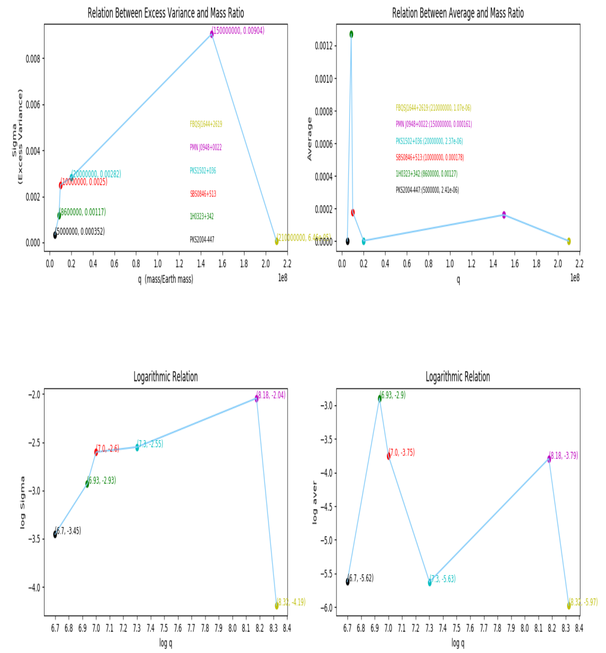


Figure 13: Results

Acknowledgments

The author wants to thank very much for Professor Zhang Youhong of Tsinghua University for initiating this SRT program and providing a lot of help in AGN paper searching and solving problems about Linux programming. Also, he wants to thank Academician Doug Lin from University of Santa Cruz for sparing some time for brief discussions on his projects concerning AGNs.

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