Active Galactic Nuclei and Super-Massive Black Holes

What will you learn in this Lab?

In this lab, we will measure the mass of super massive black holes and compare their total mass to that of the galaxy they lie within. To measure their masses we will examine variations in the light observed.

What do I need to bring to the Class with me to do this Lab?

- A copy of this lab script
- A pencil
- A scientific calculator
- A ruler or protractor
- Graph paper

1. Introduction

A black hole is a region of space so dense that nothing, not even light, can escape its gravitational pull. Black holes come in a variety of sizes, from masses similar to the sun to over a billion times greater. While the sun-like mass black holes can be found anywhere in and around a galaxy, the super massive ones are found in the centers of nearly every galaxy known today. This lab will focus on measuring the mass of the super massive variety using two techniques and comparing it to the mass of the host galaxy.

Because of the nature of all black holes, we can not see them against the background of space. However, since black holes found at the center of galaxies are extremely massive, they attract a lot of gas, dust and stars, which are found in great numbers at the center of galaxies. The material then spirals in toward the center, accelerating and heating up as the material is compressed more and more. The temperature of the material may reach millions of degrees and is capable of radiating enormous amounts of energy.

A fraction of the material falling toward the black hole is actually shot out along the poles of the black hole forming jets. These jets are comprised of material traveling nearly the speed of light, extending up to millions of parsecs away from the galaxy. The jets can interact with material far outside of the galaxy, and like a tractor pushing a load of snow, the material gets compressed causing it to heat up. The results are lobes of material which are bright at radio wavelengths.

The presence of the super massive black hole, and the material falling inward results in a galaxy with an active center. We call these *Active Galactic Nuclei* or AGN for short. There are many varieties of AGNs: Quasars, Seyfert galaxies and radio galaxies. The main difference is the orientation at which we view the objects. Quasars resemble stars, however this is because the jet of material from the black hole is pointed directly at the Earth like a flash light in your face, and it easily outshines surrounding the host galaxy. Seyfert galaxies are typically spiral galaxies which exhibit fluctuations in brightness in the center. Radio galaxies are typically elliptical galaxies which show the most massive and brightest jets of gas.

2. Procedure

In the following sections you will measure some physical properties of black holes and their surroundings.

2.1. Exercise I

While a black hole cannot emit light, material just on its surface can glow extremely bright which is called an AGN. In this section, we will investigate the observational requirements of measuring such a phenomena.

M87 is a fairly nearby, extremely massive galaxy which is known to harbor a supermassive black hole of 3×10^9 $M_\odot$. The famous work of Albert Einstein gives us a relationship between a black hole's mass and its radius:

$$r_\bullet = 3\times10^5 M_\bullet \tag{1}$$

where $M_\bullet$ and $r_\bullet$ are the mass and radius of the black hole in $M_\odot$ and cm respectively. This galaxy is $D=2\times10^7$ pc from the Milky Way, therefore we can calculate the angle that the black hole subtends:

$$\theta = 4.12\times10^5\times\frac{r_\bullet}{D}, \tag{2}$$

in arcseconds. Therefore, if material was collecting at the black hole's surface, then we require an angular resolution of θ to see the material.

While the world's largest optical telescopes are ≃10 m in diameter, radio telescopes can be effectively many times larger using the technique of *interferometry*. Interferometry

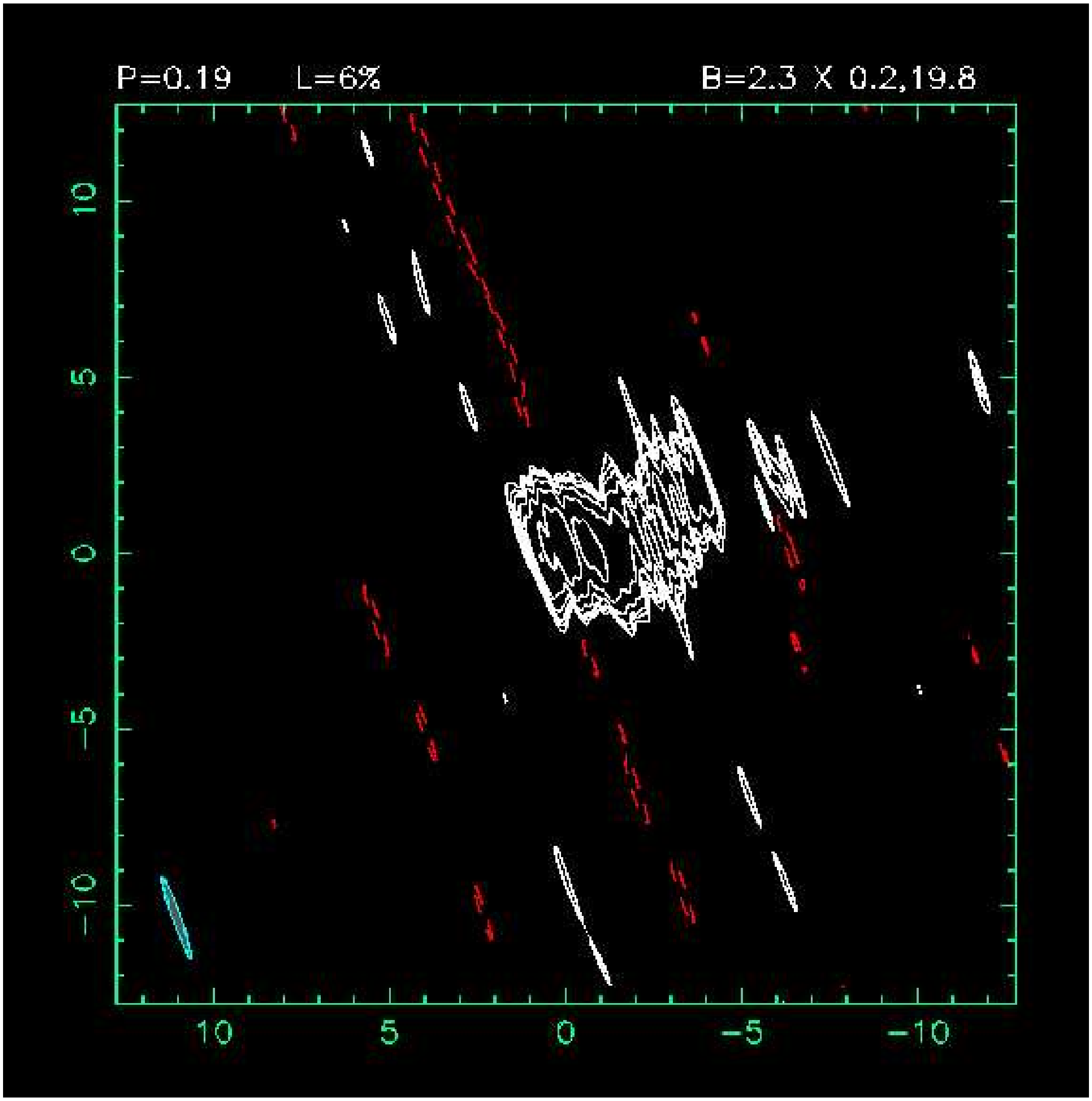

Fig. 1.— VSOP observation of the nucleus of M87. The putative black hole in the center of M87 is at the coordinate $(x, y) = (0, 0)$, and the jet is the seen extending toward to upper right of this figure. The elongated white ellipses are unresolved objects and are hence observed as point-sources. Each tick-mark along the axes is 1 milliarcsecond. *Image courtesy of H. Hirabayashi et al. 2000, Publications of the Astronomical Society of Japan, 52, 997.* More details can be found at: www.vsop.isas.jaxa.jp

uses several small telescopes separated by many kilometers to achieve a net resolution many times better than for a single facility. The largest interferometer, VSOP, orbits the Earth at a distance of 38,000 km with a total baseline of $B = 78,000$ km. This facility observes the Universe with a wavelength of $\lambda = 6$ cm. You have already seen that the resolution of an observation is related to both the wavelength and baseline:

$$\phi = 2.5 \times 10^5 \frac{\lambda}{B}, \tag{3}$$

in arcseconds. This angle ϕ is the smallest angle your telescope can resolve. Anything smaller than this will be detected as a single, point-like object, a *point-source.*

Figure 1 is an actual image from the orbing VSOP observatory. The center object is the core of the galaxy. The white ellipses are point-sources (described above) which have this shape since the telescope's orbit is an ellipse. Using a ruler or a straight-edge, measuring the shortest width of 3–6 point-sources from the VSOP observation. The scale given on the x and y axes are in milliarcseconds. Compute the average of your trials. How does this estimate compare to theoretical value given by equation (3)?

2.1.1. Questions

1. How did the theoretical and observed values of the VSOP resolution compare?

2. What was the resolution required to resolve material on the surface of the black hole?

3. We know that material is falling onto the surface of this black hole, with the VSOP observation can it be directly observed? Why or why not?

4. If not, can you think of a way to resolve it? *Hint*– Astronomers are constantly trying to build larger and larger telescopes.

2.2. Exercise II

As we have seen, it is straight-forward to calculate a black hole's mass once its radius is known. Since direct radial measurements (like in Exercise I) can be a daunting task, we must find another way to measure the size of a black hole. This is achieved through the use of a *light curve.* A light curve is a plot of an object's change in brightness over a given timespan. Most AGNs are observed to flicker due to material falling across the *event horizon* of the black hole. Since light curves are fairly easy observations to make, many AGN have been observed in this way.

In this section will we estimate the mass of the black hole from the light curves of several AGNs. For each of the following plots, you should measure the time it takes to go from a maximum to a minimum and back to the next maximum. This should be done at least 3 times for each object. Record these results in Tables 1–5. Average the times and black hole sizes.

For the black hole's radius, assume that the emitted light comes from the black hole's diameter. Therefore, the radius is:

$$r_\bullet = 14.4 \times t, \tag{4}$$

where t is measured in hours and $r_\bullet$ is in *astronomical units* (AU), the mean distance between the Earth and the Sun. Then using a similar relationship as equation (1) we can calculate the mass:

$$M_\bullet = 5 \times 10^7 \times r_\bullet, \tag{5}$$

where $r_\bullet$ is measured in AU and $M_\bullet$ is measured in solar masses ($\mathrm{M}_\odot$).

2.2.1. Questions

1. What is the typical time scale you measured (give as an approximate value)?

2. What is the typical mass of the black holes measured (give as an approximate value)?

2.3. Exercise III

Now we will compare the mass of supermassive black holes to the mass of their host galaxies. The majority of the light emitted from a galaxy comes from its constituent stars. From detailed stellar studies, we know that a star's mass is directly proportional to its luminosity. Therefore, if we know a galaxy's distance and brightness, we can infer its mass. Since the *redshift* of a galaxy can be related to its distance, we arrive at an expression for

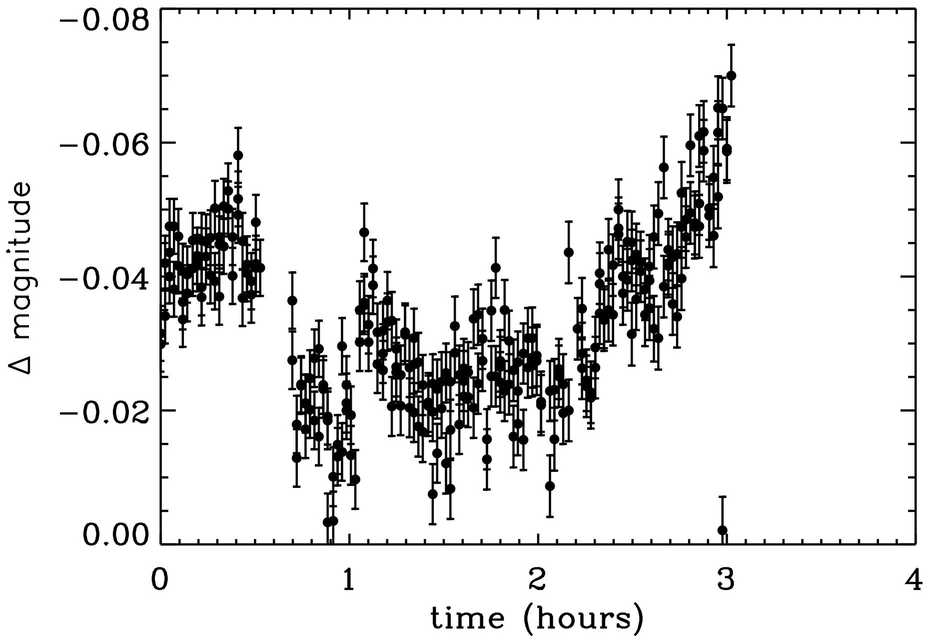

Fig. 2.— Light curve of Perseus A.

Table 1. Data table for Perseus A.

	Time-Span (hr)	Δmag (mag)	$r_\bullet$ (AU)	$M_\bullet$ ($M_\odot$)
Trial 1	__________	__________	__________	__________
Trial 2	__________	__________	__________	__________
Trial 3	__________	__________	__________	__________
Trial 4	__________	__________	__________	__________
Trial 5	__________	__________	__________	__________
Average	__________	__________	__________	__________

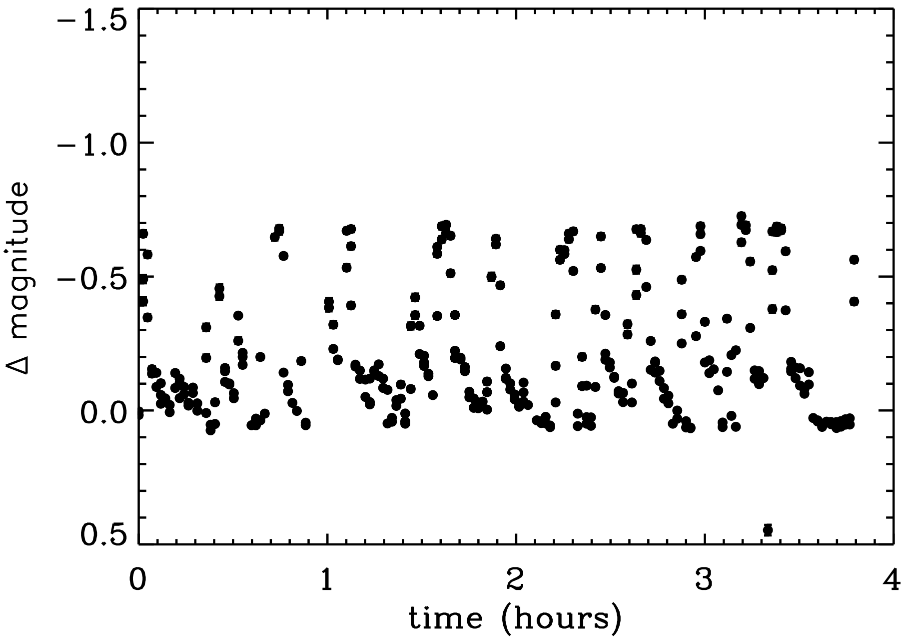

Fig. 3.— Light curve of Markarian 421.

Table 2. Data table for Markarian 421.

	Time-Span (hr)	Δmag (mag)	$r_\bullet$ (AU)	$M_\bullet$ ($M_\odot$)
Trial 1				
Trial 2				
Trial 3				
Trial 4				
Trial 5				
Average				

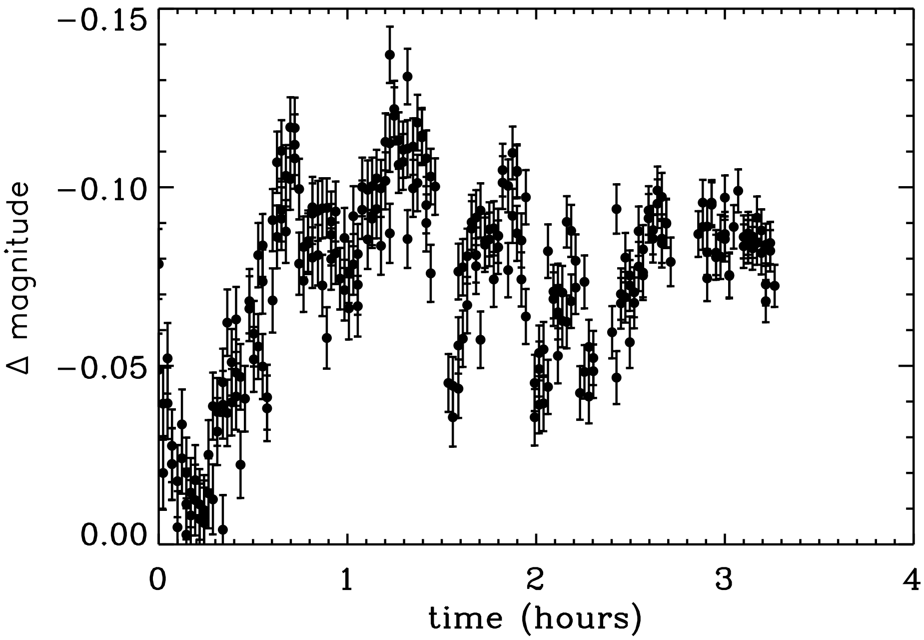

Fig. 4.— Light curve of Markarian 501.

Table 3. Data table for Markarian 501.

	Time-Span (hr)	Δmag (mag)	$r_\bullet$ (AU)	$M_\bullet$ ($M_\odot$)
Trial 1	__________	__________	__________	__________
Trial 2	__________	__________	__________	__________
Trial 3	__________	__________	__________	__________
Trial 4	__________	__________	__________	__________
Trial 5	__________	__________	__________	__________
Average	__________	__________	__________	__________

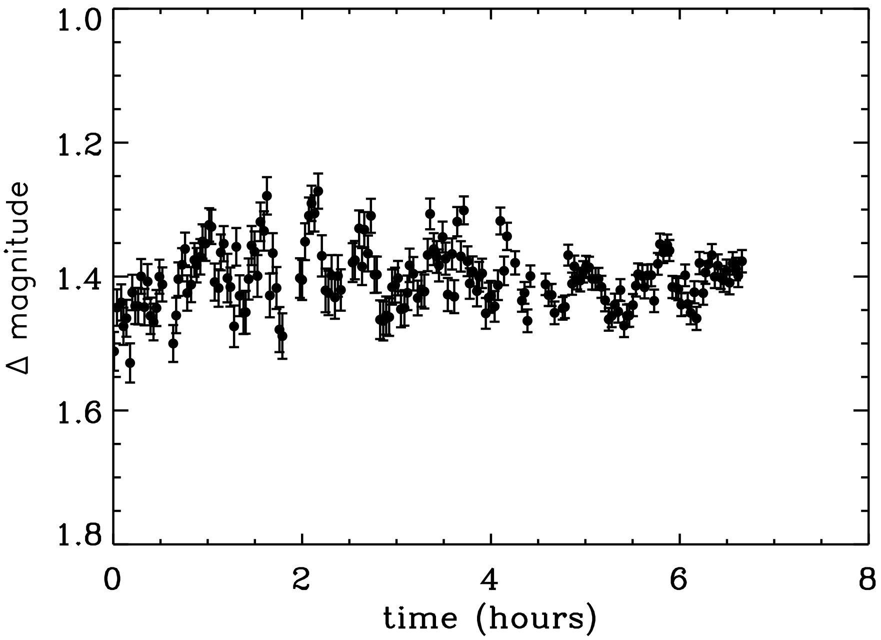

Fig. 5.— Light curve of OJ287.

Table 4. Data table for OJ287.

	Time-Span (hr)	Δmag (mag)	$r_\bullet$ (AU)	$M_\bullet$ ($M_\odot$)
Trial 1				
Trial 2				
Trial 3				
Trial 4				
Trial 5				
Average				

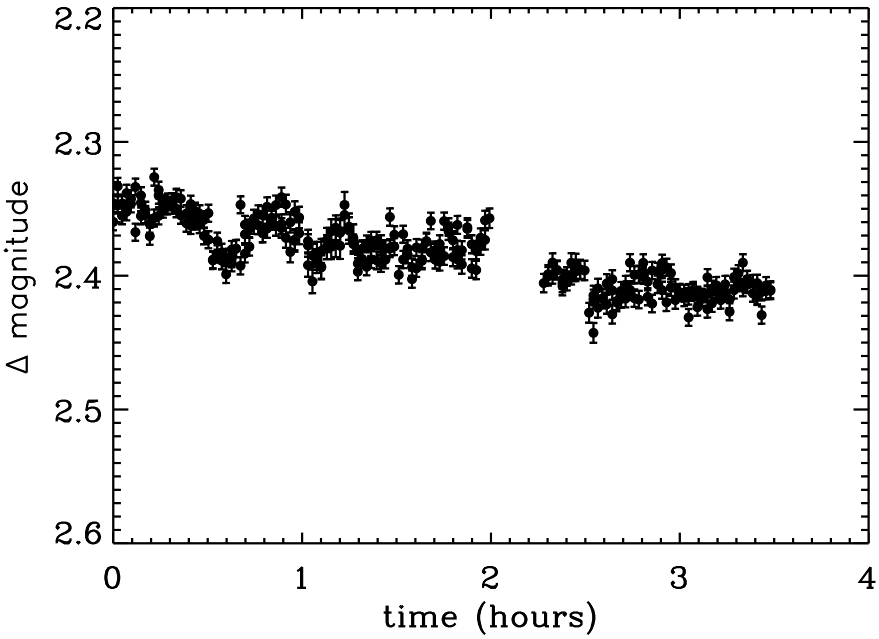

Fig. 6.— Light curve of S5 0716+71.

Table 5. Data table for S5 0716+71.

	Time-Span (hr)	Δmag (mag)	$r_\bullet$ (AU)	$M_\bullet$ ($M_\odot$)
Trial 1				
Trial 2				
Trial 3				
Trial 4				
Trial 5				
Average				

the mass of the host galaxy:

$$M = 10^{17} \times 10^{-0.4*m} \times \left(\frac{z}{1+z}\right)^2 , \qquad (6)$$

where m is the magnitude and z is the redshift. In Table 6, you will find magnitudes and redshifts for the AGN host galaxies. Compute the host galaxy masses from equation (6) and the given data and record your results.

To look for correlations between the black hole and host galaxy mass, we will plot the results. Plot the mass of the black hole (y-axis) against the mass of the galaxy (x-axis). Since the values of the galaxy and black hole masses are so large, we will plot the log-base-10 of each quantity so that the plot is of a manageable size. The Milky Way is about 10^{10} $M_\odot$ and contains a supermassive black hole in its center that is about 10^7 $M_\odot$, put this data point on your plot. Draw the "best-fit" line to the observations (be sure **NOT** to connect the dots). Measure the slope and "y-intercept" from your figure.

2.3.1. Questions

1. What is the typical mass of a galaxy (give as an approximate value)?

2. What relationships do you see in your plot? What was the slope?

3. How does the Milky Way compare to the other galaxies you studied? Would you say that the Milky Way is special, why or why not?

Table 6. Host Galaxy Data

			Host Galaxy		Black Hole	
AGN	Magnitude (mag)	Redshift (z)	Mass ($M_\odot$)	$\log_{10}$(Mass) $\log_{10}(M_\odot)$	Mass ($M_\odot$)	$\log_{10}$(Mass) $\log_{10}(M_\odot)$
Perseus A	12.6	0.018				
Markarian 421	13.3	0.030				
Markarian 501	14.2	0.033				
OJ287	14.0	0.310				
S5 0716+71	14.0	0.300				