Time-Varying Multi-Wavelength Spectroscopy of the Highly Variable AGN OJ-287

Principal Investigator: Mr. Zachary Stone
Institution: Stony Brook University
United States
Electronic mail: zachary.stone@stonybrook.edu

Scientific category: QUASAR ABSORPTION LINES AND IGM
Scientific keywords: ABSORPTION LINES, SPECTROSCOPY, BLACK HOLES, BL LAC OBJECTS AND BLAZARS, VARIABILITY
Instruments: STIS Proprietary period: 12

Cycle 11 primary orbits: 10
Cycle 11 parallel orbits: 0

Abstract

The quasar known as OJ 287 is known for being one of the most highly variable and well-observed AGN in the Universe. This object can vary on timescales as short as minutes, while the longest period of its luminosity fluctuations is only 12 years. Such a short timescale would produce profound effects on its environment on short time scales, seeing as its central mass and light curve allude to a binary of supermassive black holes. To observe this variation, a spectrum of the target must be taken to see changes in composition of the galaxy overtime. Furthermore, spectroscopy on a distant quasar would also be able to tell us about the material in its surrounding intergalactic medium (IGM). The object's surrounding environment could tell us more about the composition of the galaxy, how it formed, how it evolves, and how it interacts with its environment. This proposed spectroscopy also suggests ten different types of gratings and filters, spreading across the UV to the optical, to be in order to obtain a larger view of the system which OJ 287 resides. This wide variety of absorption lines to be observed combined with the small time between observations will grant us a view on how OJ 287 changes in multiple wavelengths on short scales. Short scale composition and IGM changes could allude to the complex dynamics of the jet at the center of the target's host galaxy, as well as the effects of general relativity due to the black hole binary.

	Investigator	Institution	Country
PI:	Mr. Zachary Stone	Stony Brook University	United States
CoI:			

Total number of investigators: 2

Observing Summary:

Target	RA	DEC	V	Configuration,mode,aperture spectral elements	Total orbits	Flags
OJ 287	80 54 48.9	20 06 31	15.43	STIS/NUV-MAMA SPECTROSCOPIC G140M(1567), G230M (1769), G230M(1851), G230M(2014), G230M(3055)	7	
OJ 287	80 54 48.9	20 06 31	15.43	STIS/CCD SPECTROSCOPIC G430M(3423), 3430M(3680)	3	
				Grand total orbit request	10	

■ Scientific Justification

One of the more contemporary areas of research involving extragalactic astronomy is that of quasars and active galactic nuclei. These highly luminous centers of galaxies can tell us many different aspects of stellar dynamics, evolution, and formation. By observing these objects, we can not only directly measure the properties of their host galaxies, but also the supermassive black holes in their centers. Black holes have been observed in almost all observations of active galactic nuclei. Using the fact that black holes accrete matter at highly-relativistic speeds, we can measure the radial velocities of matter near AGN to acquire an estimate of the spin of the black hole of its host galaxy. Furthermore, we can acquire the mass of the black hole of the host galaxy by using information from the luminosity and radial velocity of the AGN. Another widespread property of AGN is the presence of a relativistic jet. The centers of galaxies are so compact and contain such a large amount of angular momentum that they spew material out from the center in the form of a jet. This jet can be imaged directly in many cases. While the cause and dynamics of these jets vary from galaxy to galaxy, they can tell us of the dynamics of the center of the galaxy and how it might have formed.

In addition to acquiring information about the properties of the matter in the galaxies hosting the AGN, we can also observe properties of matter intervening on our line of sight to the galaxy. The highly luminous photons emitted from AGN will be absorbed by intergalactic dust, exciting their atoms in a characteristic fashion. For example, Hydrogen atoms exhibit Lyman-α emission and absorption at photon wavelengths near 1216 Å due to the excitation of its electron to its first excited state. From this characteristic absorption, we may probe the composition of intergalactic material, as well as material in the galaxy.

In addition to the broad field of AGN, there is also a subset named the BL Lac objects. These types of AGN are highly variable, with some oscillating between several degrees of magnitude. These oscillations are mainly due to the dynamics of the AGN and the galaxy itself, and can be used to compare to relevant computational modeling of galaxies. These objects are also not very radio loud, meaning they do not show significant features in their spectra in longer wavelengths. BL Lac objects have been able to tell us about many of the dynamics that occur in galaxies and the environments around them. They are very signature in their spectra in that they usually exhibit two peaks. These peaks are byproducts of the high energy astrophysics occurring in their jets and accretion disks. These humps are determined by the processes governing synchrotron radiation in the center of the galaxy and the efficiency by which relativistic particles travel through the jet and in the accretion disk (Falomo et al., 2014). The characteristic spectra of these objects can also tell us of the black holes in their center: how they move, how they evolve, and their mass. This black hole is assumed to be the engine which powers the relativistic jet that is characteristic of these BL Lac objects. The variability in the luminosity of BL Lac objects is namely due to the dynamics of the creation and fueling of the jet.

One of the more interesting examples of BL Lac objects is OJ 287, which varies by about 3 magnitudes at most. This AGN is suggested to be a binary of two black holes, with the larger of the two being one of the most massive black holes observed in general, having a mass of approximately 18.35 $\times 10^9$ solar masses. It can be shown that the light curve of this object displays a double peak at its maximum in its 11-12 year cycle, suggesting a binary supermassive black hole. The strongest theory for the explanation of this double peak in the light curve is strong interaction between the two highly compact objects, creating two bursts of material. In this interaction, the smaller of the two black holes would be orbiting the larger one. In this orbit, the smaller black hole would impact the accretion disk of the larger black hole twice in each orbit, creating two distinct bursts of energy (Dey et al., 2019).

In prior studies, time series analysis and spectra have been made of this object. This proposal seeks to acquire a larger and broader spectrum of OJ 287 in the near-UV and optical. Seeing as this is a BL Lac object, there would be little to no variation in its spectrum past the near- or medium-IR. Consequently, the most interesting and variable part of the spectrum would be the UV and optical wavelengths. The higher energy wavelengths also contain valuable information on the dynamics of the jet and the relativistic particles produced by it. By obtaining more information on the spectrum of this object, we can probe the galactic and intergalactic material along our line of sight. In doing so, we will be able to see the effects of this black hole binary on its surrounding environment. This binary may have distorted the intergalactic medium around it in a distinct way, which would be seen in the inferred column density of material along that line of sight. Furthermore, the metalicity of the material near and far from the galaxy would be able to tell us of the age of the galaxy, how long this current binary may have been sustained for, and how this current binary formed. A lower than usual column density of a certain material may mean that the binaries have sweeped out that material in their binary orbits. The smaller supermassive black hole in this binary is known to have a relatively high eccentricity of approximately .65. This would make the system more prone to suddenly pushing or attracting certain materials in its environment. The nature of the emission/absorption lines could also tell us of the formation of the binary system, as well as the formation of its host galaxy. The distribution of material near the galaxy could inform us if this galaxy is a result of a galaxy merger, or some other astrophysical phenomenon.

The implications of the results of this object in general have had, and continue to have, applications to many different topics in astronomy. OJ 287 has been observed as having these very bright outbursts since 1880. Therefore, however uncertain, there is a plentiful amount of data for this system, sparking many different areas of research. Furthermore, this binary of supermassive black holes is very much related to the field of general relativity. The characteristic light curve for this object would need to be explained by general relativity, as a binary of supermassive black holes is an extreme from a gravitational standpoint. This system would prove to be highly relativistic, and affect gravity surrounding it in a very characteristic way. General relativity is needed to understand the two flares that occur in the luminosity, as they are purely driven by gravitational means. The jet from the central black hole, which provides the light curve for this galaxy, would need to be explained by various models of galactic dynamics and compact object physics. Seeing as these binary black holes are supermassive, they would be emitting large amounts of synchrotron radiation, due to their strong gravity and short orbital period. The jet would be very compact due to the large amount of mass in the center of the galaxy, but also be affected by the dynamics of the binary black hole system. This system could also be instrumental in determining the mechanisms which create and fuel jets in AGN. If this large gravitational interaction between the two black holes has altered the effects of the jet in any way, it could signal to the processes behind the engine that causes it.

Multi-wavelength spectroscopy of this object could aid in all of these areas of research, especially those heavily focused on AGN. The characteristic absorption of the IGM (intergalactic medium) paired with the spectrum from the galaxy itself could tell us a lot about the composition of the galaxy, as well as its surrounding environment. If the metalicities of these two regions match, we would expect the formation of this binary system to either be a result of the formation of the galaxy or galactic dynamics. However, if a portion of the composition of either of the two astronomical objects did not match, there might have been a merger of galaxies. This would be clear if the surrounding material from the IGM did not match the material from a portion of the galaxy, showing that it either was formed in the galaxy, or there was a galaxy merger. The composition of the galaxies and the surrounding IGM would allow for more accurate models of general relativity, galaxy formation, galaxy dynamics, black hole dynamics, and AGN jet dynamics.

This spectroscopic observation will be able to complement much of the data that has been taken before, as well as tell us more information about the dynamics of the target. The spectroscopy done to observe the IGM and AGN will tell us much about its composition. Another implication of this data that will be received is important to galactic evolution. By observing the composition overtime, on small scales, we will be able to see small scale galactic evolution. OJ 287 is a very extreme system, having two supermassive black holes exerting very large amounts of gravity and radiation. Therefore, this large amount of energy added to the system should have a profound effect on its host galaxy. This system has been known to vary on all timescales, including hours and minutes. Therefore, seeing the composition change in very small timescales would be able to tell us many new things about galactic evolution. Observing the ionization of the surrounding gas in the IGM on small timescales could also tell us the electromagnetic effects of this system on its environment on small and large scales. A spectroscopic time series analysis could be done to observe changes in galactic composition on small scales, greatly aiding in the creation of galactic models of formation and evolution. Small scale changes in the composition, or simply the spectrum in general, may also tell us of the dynamics of the jet, as well as the mechanism which creates it.

Description of the Observations

The observations proposed for this proposal mainly make use of the instruments involved in STIS, namely its CCD and near-UV MAMA detectors. To mainly acquire data for the important emission and absorption lines representative of QSO (quasar) spectra, certain narrow-band UV and optical filters were selected. The most commonly detected absorption lines in QSO spectra are Lyman-α, Carbon-4, Magnesium-2, Carbon-2, Silicon-4, Magnesium-1, and Iron-2. OJ 287 has a recorded redshift of z=.3, meaning these absorption lines would only be at wavelengths 30% larger than they would be at z=0. This only shift these lines by about 300-1000 Åor so, meaning they fall directly into the wavelength ranges of the filters chosen. These wavelengths are all in the optical and near-UV as well, making full use of the telescope's instrumentation. These absorption lines can be seen in the following chart:

Absorption Line	λ[Å] (z=0)	λ[Å] (z=.3)
Ly-α	1216	1580.8
C-II	1335	1735.5
Si-IV	1394	1812.2
Si-IV	1403	1823.9
C-IV	1548	2012.4
C-IV	1551	2016.3
Fe-II	2382	3096.6
Fe-II	2600	3380
Mg-II	2795	3633.5
Mg-II	2802	3642.6
Mg-I	2852	3707.6

Table 1: Wavelengths of typical AGN absorption lines for z=.3

Seeing as this object is relatively bright compared to other QSOs, it will need a lower exposure time to achieve a high signal-to-noise ratio (STN). Using the exposure time calculator for STIS, provided by STScI, we can compute the exposure times needed to obtain spectra at different wavelengths in each of the filters chosen. The table below illustrates each of the exposure times calculated and each of the filters used.

λ[Å] (z=.3)	Grating / Central λ[Å]	Exposure Time [s]
1580.8	G140M (1567)	402
1735.5	G230M (1769)	2700
1812.2	G230M (1851)	645
1823.9	G230M (1851)	606
2012.4	G230M (2014)	215
2016.3	G230M (2014)	217
3096.6	G230M (3055)	396
3380	G430M (3423)	56
3633.5	G430M (3680)	27
3642.6	G430M (3680)	18
3707.6	G430M (3680)	11

Table 2: Description of each of the filters used for each absorption line, as well as the exposure time needed to reach a STN of 10.

When putting in parameters to determine the exposure time, I had assumed a STN of 10, being sufficient to distinguish features in the spectrum. Furthermore, I assumed a flux normalized to 10^{-15} erg cm^{-2} s^{-1} Å^{-1} at 2000Å for the shorter wavelengths, and 3000Å for the longer wavelengths. It was also reasonable to assume that the spectrum of this QSO would behave like other QSOs, allowing the calculations to be based off of spectral distributions of QSOs centered on both $\sim$1700Å and $\sim$ 3300Å. Nearly all of these absorption lines lie near the central wavelengths of these gratings, making the throughput for most of these observations fairly standard. This also assumes that the extinction is that of the diffuse Milky Way, and that background from Earth shine, the zodiacal light, and air glow are all average.

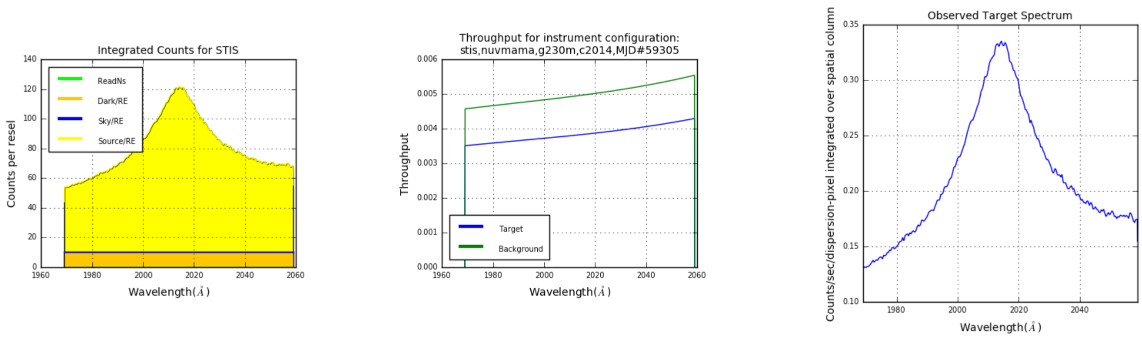

Figure 1: Examples of exposure time calculations done by STScI using the G230M (2014) grating

Totaling all of the exposure times of each of the different absorption wavelengths grants us 5293 seconds, which is approximately 89 minutes. Seeing as the calculations show the exposure times to be small for larger wavelengths, increasing the exposure on the shortest two by 20 seconds could prove useful. This would then bring the total telescope time needed to 90 minutes. However, due to the inclination of the telescope, the target will be obstructed for about 53 minutes every orbit. This leaves only approximately 43 minutes per every 96 minute orbit to be used for observations. Combining this with the exposure time calculated earlier, a total of two orbits of continual observations would be needed to obtain data for each filter. However, in order to properly sample the spectrum of this object, more than one sample is needed for each filter. Using Gaussian counting statistics, we see that the uncertainty in the data acquired is proportional to the number of datasets acquired, as $\sigma \propto 1/\sqrt{N}$. Therefore, a sample of 5 datasets for each filter will reduce the uncertainty in the data by about .44. This also allows for the measure of the variation of OJ 287 over the period of 5 orbits. This brings the orbit request total to 10 orbits. This does not account for the time taken to direct the telescope, calibrate the detectors, and find the target, but this can all be done while the telescope passes through the SAA.

In addition to the focus on the multi-wavelength view of OJ 287, there is also a focus on the variability of OJ 287 overtime. OJ 287 varies on short and long timescales, meaning that many dynamics within its system move very quickly. Therefore, it would be remiss to ignore the changes to the spectrum of OJ 287 on short time scales. Therefore, the observations for this proposal, of which there are three, should be relatively close to one another. This proposal focuses on the change in OJ 287 every hour. It is known that OJ 287 varies on periods as short as 30 minutes (Kushwaha, 2020). Therefore, these five observations would have to be in subsequent orbits, as to see the change in spectrum, and therefore IGM and composition. The delay between observations in two bands may be hours long, but the interim period between observations in the same band will be the same from observation to observation. Therefore, the period of obtaining measurements will be constant, even if the measurements of each band could be separated by hours.

Special Requirements

This object is known to be quickly varying, having a period in its luminosity of 11-12 years. Seeing as the turnaround time for observations that are considered non-disruptive are around a month, and this target varying over a little more than a decade, requesting these observations be non-disruptive should not make a difference on the data, if this were the only relevant timescale. It has been shown that OJ 287 varies in flux on timescales of all sizes. It is shown that its luminosity varies on an overall cycle of 11-12 years, but also has changes within hours and minutes. In the optical, there has been changes in luminosity having a period of approximately 32 minutes. Therefore, in order to have an accurate representation of the spectrum of OJ 287, these observations should be taken at the same time. This causes the observation to take place in subsequent orbits, as to limit the time between each observation. The telescope has an orbit of 96 minutes, and 53 minutes of this orbit are useful for observing OJ 287. Therefore, this observation should be scheduled in subsequent orbits, so that the timescale on which the observations are made are relatively close to the timescales on which OJ 287 varies. If two observations are made in subsequent orbits, an observation in one band would take place every three hours. Seeing as OJ 287 varies on many different timescales, this should prove no issue to the data being taken. This also assumes that data would be taken from the STIS/NUV-MAMA detector and the STIS/CCD detector in the same orbit. This is not specifically required by the data, but by the time constraint provided by the short scale variability of OJ 287. These two detectors would need to take data in the same orbit to have data that is separated on the order of an hour in time. Seeing as the observations taken by NUV-MAMA are substantially longer, I have proposed they observe for 7 orbits. The observations taken by the CCD will be very short, so I have tentatively scheduled them for 3.

■ Coordinated Observations

■ Justify Duplications

Prior studies of OJ 287 have mainly been used to create time-series analyses of its variation in brightness. These observations have been the source of many innovations in this field of astronomy and astrophysics. However, in order to fully understand the complete system, which OJ 287 is a part of, one must observe all of its dynamics. The variation in luminosity only gives a partial answer as to what is occurring within this system. Kushwaha (2020) has recently done a summary of observations of OJ 287 in various wavelengths, showing that the flux from OJ 287 varies across almost all wavelengths overtime. Therefore, in order to see the changes in composition overtime, spectroscopic time series analysis must be done. Seeing as this system has small scale fluctuations in luminosity, changes in composition need to be accounted for on small timescales. Consequently, this observation has two direct purposes. The first is to observe the changes in spectra of OJ 287 on very small timescales, meaning within hours or days. The second is to simply obtain a multi-wavelength perspective of the system which this AGN lies, and measure the IGM surrounding it, as well as its effect on its environment due to its jet and extreme gravity. This combination offers a unique opportunity for gathering data about the dynamics of OJ 287, even if both multi-wavelength spectroscopy and time-series on short scales have already been observed separately.

■ Previous HST Programs

References

L. Dey et al. The unique blazar oj 287 and its massive binary black hole central engine. *Universe*, 5(5):108, 2019. doi: 10.3390/universe5050108.

R. Falomo, E. Pian, and A. Treves. An optical view of bl lacertae objects. *Astron. Astrophys. Rev.*, 22(1):73, 2014. doi: 10.1007/s00159-014-0073-z.

P. Kushwaha. A multi-wavelength view of oj 287 activity in 2015-2017: Implications of spectral changes on central-engine models and mev-gev emission mechanism. *Galaxies*, 8 (1):15, 2020. doi: 10.3390/galaxies8010015.