Basic Information

Created: 09/16/2019 • Last updated: 11/13/2019

Please complete eligibility and basic demographic information, and tell us about your high school.

Eligibility

Select the option that best describes you:

I am a high school senior living in the United States with an expected graduation date of Winter 2019 or Spring 2020 (eligible to apply)

ABOUT YOU

Your Legal Name

First Name on Your Transcript	Rohan
Middle Name on Your Transcript (optional)	(No response)
Last Name on Your Transcript	Subramani

Alternate/Nickname for Your Biography

What do you like to be called?

Rohan

Gender (optional)

Male

Preferred Gender Pronouns

he/him/his

Parent/Guardian #1

First Name	Shoba
Last Name	Viswanathan
Relationship to You	Mother

Parent/Guardian #2

First Name	Mahadevan
Last Name	Subramani
Relationship to You	Father

Step Parent/Guardian #3 (optional)

First Name	(No response)
Last Name	(No response)
Relationship to You	(No response)

Step Parent/Guardian #4 (optional)

First Name	(No response)
Last Name	(No response)
Relationship to You	(No response)

REGENERON SCIENCE TALENT SEARCH RULES CONFIRMATION

Read the Regeneron Science Talent Search Rules and Entry Instructions 2020 **document.**

- This is a required step in order for you to understand the eligibility requirements, rules regarding human and animal research and more.
- The rules document contains a helpful checklist for all applicants. We strongly recommend that you review it.

I have read, understand, and agree to abide by the Regeneron STS Rules.

SCHOOL INFORMATION

Current High School Name and College Board Code

Select your school from the list below. You may search by your high school's name, CEEB code, zip code, city or state.

Note: **If your school is not listed here, please email sts@societyforscience.org.** We are happy to add your school to this list (could take up to 2 business days). Do not select a school you do not actually attend. We typically add 100+ schools to this list each year.

336085,Yorktown High School ,Yorktown Heights,NY,10598

Where is your high school located?	I attend school in the United States or in a U.S. territory

High School Address

Confirm Name of High School	Yorktown High School
High School Address	2727 Crompond Road
High School Address 2	(No response)
High School City	Yorktown Heights
High School State	NY
High School Zip Code	10598
High School County Name	Westchester

Please provide your high school's website: https://sites.google.com/yorktown.org/yhs/home

Type of School: Public

Please select all that apply.

Are you graduating from high school early?

Are you completing your high school coursework in less than 4 years and/or graduating a year or semester early and/or choosing to forgo graduating from high school? We ask this question to verify your eligibility for Regeneron STS.

No

Current Coursework

In what classes are you currently enrolled? Enter up to eight (three are required). Grades are not needed.

1	AP Physics
2	AP Calculus BC
3	Economics
4	Science Research
5	AP Literature
6	AP Spanish
7	Wind Ensemble
8	Physical Education

Recommender Requests

Last updated: 09/19/2019

You are responsible for requesting three types of recommendations. The linked instructional documents will help you determine the best person to ask to complete each type. Recommendations are also due on November 13, 2019 at 8pm Eastern Time; materials will not be accepted past the deadline, including letters of recommendation. Visit our Application FAQ for tips and to learn more about this process.

1. **Read the instructional documents for each recommendation type below, then click the checkbox to acknowledge that you understand this process. The ability to request recommendations will then appear in your Task List on the internal home page.** You may also request a second recommendation for each type (optional); these extra recommendation tasks will appear at the bottom of your Task List.
2. It is your responsibility to remind your recommenders to submit their recommendations. You will receive an automated email when each recommender submits. If you are unsure of the status of your recommendations, feel free to email **sts@societyforscience.org** and our team will confirm.
3. TIP: Sometimes entrants decide to swap/replace/reorder their requested recommenders. We do not recommend this unless you know for sure that an adult has NOT completed a recommendation on your behalf (double check with us first). If by chance the adult has already completed the recommendation, you will delete the content and we will not be able to retrieve it. When you attempt to reorder the requests you will delete them; please note that the recommendations appear to judges and evaluation in the order they were received, and no importance is placed on order of recommendations in the review process.

Instructional Documents for Each Type of Recommendation:

1. Educator Recommendation Instructions
2. Project Recommendation Instructions
3. High School Report Instructions

Click the box below to acknowledge your understanding of this requirement.

I have read the documents above and understand that it is my responsibility to request three types of recommendations through the online application system. I will ask my recommenders to complete the required documents by the deadline, November 13, 2019.

I agree

Rules Wizard/Form Uploads

Last updated: 09/16/2019

See the Regeneron STS Official Rules for help navigating this section. If you have specific questions about your entry or need assistance with this section, please email our help account at sts@societyforscience.org.

Research that involves humans, vertebrate animals, or human or vertebrate animal tissue must adhere to Regeneron STS rules. Researchers must obtain special permissions and approvals to work with these subjects. This survey will guide all entrants to upload paperwork dependent on the topic of research. If this applies to your work, please make sure IRB and IACUC approval forms and wildlife permits are properly signed, that any surveys and informed consent documents uploaded are blank, and any other paperwork is properly completed. Exempt human and animal tissue studies will still need to upload documentation about the source of the tissue.

HUMAN RESEARCH

1. Does your project involve the use of human participants, including surveys (written, in-person or online), and/or did you test a product of your project (your invention, prototype or computer application) using human participants other than yourself?

No

2. Does your project involve the use of human tissue?	No
3. Does your project involve the use of data collected from humans (i.e. surveys, test scores, medical records, etc.) that were not collected by you nor your mentor?	No

Click "next" to proceed

ANIMAL RESEARCH

4. Does your project involve live, non-human vertebrate animals or non-human vertebrate animal tissue?

No, I did not work with non-human vertebrate animals

Select all that apply:

ADDITIONAL PAPERWORK & INFORMATION

Optional Paperwork Description

If you wish to provide additional paperwork to show approval processes from your local science fair, etc. you may do so here. Please describe what you are uploading and why in the text box, and upload your documentation in the next upload section.

(No response)

Optional Paperwork File Upload

(No response)

Science Research Description

Created: 09/16/2019 • Last updated: 11/13/2019

Tell us the basics about your project

1. Project Category

Space Science

Select the category that best fits your project. Three PhD-level evaluators with expertise in the area you choose below will review your work.

2. Project Theme

Research submitted to Regeneron STS is often interdisciplinary. Please check any of the boxes below that describe your project. This information is primarily used for media purposes and identifying future trends in categories. Please select all that apply.

: Exoplanets

3. Project Title

Enter your project title. For any symbols, please write the name of the symbol in all capital letters (ALPHA, GAMMA, etc.)
Otherwise, please use normal Title Case.

Full Project Title:	TESS Updates to Plan JWST Observations for Atmospheric Characterization of Promising Exoplanets
Short Project Title (50 characters or less):	TESS Updates for Promising Exoplanets
If the title of your project requires any special symbols or formatting (such as italics) please explain here:	(No response)

4. Where was the experimentation / research conducted?

Home

College or University

Select all that apply.

5. Please check all that apply to this research experience:

Enrolled in a science research class

6. Primary Research Location

Name of Research Location (institution, university, park, school, etc.)	Massachusetts Institute of Technology
Describe the Research Location (please include name of lab)	Kavli Institute for Astrophysics and Space Research
Was the primary research location in the United States or a US territory?	yes
Research Location City	Cambridge
Research Location State	MA
Website	https://space.mit.edu/

7. Mentors

Please provide information on the adults, undergraduate student or higher, with whom you met and worked with in any way related to your research. You will be asked to provide their contact information in Task 11.

	Prefix	First Name	Last Name	Institution (if different from above)	Job Title	Time spent with this mentor
Mentor #1	Dr.	Tansu	Daylan		Postdoctoral researcher	6 weeks of full-time work
Mentor #2	Dr.	Maximilian	Günther		Postdoctoral researcher	6 weeks of full-time work
Mentor #3						

8. How did you connect with your mentor(s)? (maximum 100 words)

I looked into places where research based on TESS data was being carried out, and found that the central hub was MIT. I emailed one exoplanet researcher, and she referred me to Dr. Daylan and Dr. Günther. They ultimately took me on as a research intern.

9. How did you get the idea for your research? (maximum 200 words)

Explain the development of your research question and/or engineering goals. Was the project assigned to you?

The idea for the project was devised by my mentors prior to my arrival, though the majority of the work after that was my own.

10. What was the duration of the research? (maximum 150 words)

Explain the amount of time you spent on the research project that you have submitted, and provide the start and end date.

I spent 6 weeks working full time at MIT (~40 hours per week), starting on July 9, 2019 and ending on August 16. After I returned home, I continued working between 5 and 10 hours per week until late October. In total, this amounted to around 300 hours of work on the project.

11. If your research was conducted as part of a larger research project or group, explain how your work is independent of this larger project. (maximum 200 words)

If there were other high school students in the group, be specific about how your work was similar to and different from other students.

I worked with two postdoctoral researchers and one other high school student. My work was independent because there were two related but separate projects, and I focused on one while the other high school student focused on the other. While my mentors helped me address any issues that arose, I collected all the data and formatted data in a manner that was readable by the computer program used. Therefore, my research was largely independent of the other work being done in the group.

12. Please attribute the support you received in each area of the research process and highlight what you claim as your own, original, unique contribution. (maximum 200 words per section)

Provide a description of what you did in sentences, more than simply stating a percentage or writing "all."

a. Developing / Initiating the purpose of the research	My mentors had the idea for this project prior to my arrival at MIT.My role in selecting the project was reaching out to mentors who I knew were studying TESS data.
b. Designing the procedures	My mentors created the software package which was used for the project, and they had the idea for how to utilize the package to analyze previous data and TESS data. I contributed revisions to the procedure. For example, I suggested that it would be more efficient and computationally feasible to avoid collecting all prior data, as the task of analyzing everything simultaneously was problematic for the software package. Instead, we collected a subset of the previous data which still provided most of the useful information. This was helpful in speeding up the process without sacrificing the reliability of the conclusions.
c. Implementing the procedure (including special techniques or the use of special equipment)	This was entirely independent. I acquired TESS data from the MAST database, and archival data from online resources and from the first authors of the papers which discussed them. I formatted the data such that our software package could read the files.
d. Gathering / Recording data	N/A: this was an automated process in this study, as the software package conducted statistical fits to data and displayed the outputs.
e. Analyzing data	As the project progressed, I analyzed the outputs more and more independently. By the end, I was able to analyze the probability distributions for each planetary characteristic entirely by myself.
f. Formulating conclusions	I interpreted the updated values of planetary characteristics independently.

13. Describe any limitations of your research. (maximum 150 words)

Because only one year of TESS observations is complete, we were only able to analyze planets which were observed during this first year. Also, due to limited time and computing power, we have only managed to study the top three planets so far.

14. Indicate any other substantive guidance received, as well as any prior research involvement or training that helped you in conducting your own work in this project. (maximum 250 words)

N/A

15. Are you related to anyone who works in the lab or environment in which you conducted your research?

No

This is permitted and students are not penalized if they are related to their mentors. However, it is imperative to disclose this information.

16. Statement of Independence

- Frequently Regeneron STS applicants perform research that is similar to that of parents, mentors, relatives, friends and/or other high school students. This is expected, since science is a cumulative process, each finding built on a previous one. The influence and assistance of those around you might be reflected in your responses to the questions above, but in some cases might be difficult to articulate because their roles are a bit less defined.
- In order to recognize the independent research of student investigators, a clear picture of the evolution of your work and the aspects that are of your own design and execution are required. We would like to give you the opportunity to reassure the evaluation committee that while the above-mentioned influences may exist, the work you have submitted is your own and not that of a parent, mentor, relative, friend or any other person.
- Failing to disclose similar or related research of which you are aware or failing to mention any person who has either closely or loosely guided you, and their relationship to you and your family, is a violation of our rules and the ethics statement you must agree to in order to submit this application, and is grounds for failure to qualify to the Regeneron STS.

Select the option below that best describes your situation:

I certify that there are no additional people who have done research in an area of science close to mine, nor is there any additional person who has closely or loosely advised me, contributed to my research or had any influence on my work.

17. Intellectual Property and Viewing Your Application

I certify that I have discussed this submission with the scientists with whom I worked and they do not have concerns regarding intellectual property. I give permission to Society staff to show my entire application, including my research report, to any of my mentors or recommenders.

18. Individual Research Projects

Combining individual research projects into team projects to submit to other competitions is against STS Rules. An individual project must remain so through competition season (June 2020). Please verify that you do not have plans to combine the research submitted to the Regeneron Science Talent Search with another high school student for a different competition.

I do not have plans to combine this research with another high school student for competition.

19. Research Report Guidelines

Read the Research Report Guidelines before proceeding to the next task, where you will upload your Research Report. The Research Report Guidelines document contains important information about the format of your research paper, naming convention, size limits, and more.

I have read the Research Report Guidelines 2020 document

TESS Updates to Plan JWST Observations for Atmospheric Characterization of Promising Exoplanets

Rohan Subramani

Abstract

The James Webb Space Telescope (JWST), scheduled for launch in 2021, may revolutionize the search for extraterrestrial life by characterizing exoplanet atmospheres. However, it is difficult to predict the correct times to observe planets with JWST; only certain locations in their orbits provide useful data for atmospheric characterization, and current knowledge of their orbits is limited. This study used the software package *allesfitter* to analyze recent data from the Transiting Exoplanet Survey Satellite (TESS) and better describe the orbits of the three most promising exoplanets for emission spectroscopy analysis (a method of atmospheric characterization): WASP-77A b, WASP-43 b, and WASP-18 b. These updates provided more precise and accurate knowledge of the planets' orbits, making it considerably easier to predict the ideal times for JWST to observe them. The one-sigma uncertainty for ideal observation time decreased by a factor of 3.02 for WASP-77A b, 14.24 for WASP-43 b, and 4.08 for WASP-18 b, which means that analyzing their atmospheres will require less time out of JWST's busy observing schedule. This contribution will facilitate atmospheric characterization in the near future, an important step forward toward the potential discovery of life on other planets.

Introduction

The scientific study of planets outside our solar system has implications for many of humanity's most burning questions: How did Earth form? Are there other planets similar to Earth? Is there life elsewhere? If yes, where? How does it develop? The drive to answer these questions has led to rapid growth in the field of exoplanet research since the first extrasolar planet was discovered in 1995 (Mayor and Queloz, 1995). With advanced techniques, telescopes, and spectrographs, researchers have now discovered over 4,000 exoplanets (NASA, 2019). Atmospheric characterization of these planets can reveal essential information about the planets themselves as well as the characteristics of the entire exoplanet population.

Review of Literature

The gases in a planet's atmosphere, and the quantities in which they exist, can provide clues towards the presence (or lack) of life (Des Marais *et al*., 2002). For example, signs of biosignature gases (gases produced by living organisms that can accumulate to detectable levels in an exoplanet's atmosphere) in a planet's atmosphere provide an indication that life may be present on the planet (Seager, 2017). Furthermore, by analyzing a relatively small number of exoplanet atmospheres, it may be possible to predict trends for the entire exoplanet population (Owen, 2019). Since the atmosphere on Earth is crucial for living organisms, this generalization would be a major step in the quest to determine the frequency of life in the universe.

The James Webb Space Telescope (JWST), scheduled for launch in early 2021, will be an extremely powerful tool for probing the atmospheres of distant planets (NASA, 2019). However, this analysis can only be conducted by observing promising planets during the correct phase of their orbits, and it is difficult to predict the timing of these ideal windows. The details of this statement will be clarified in the following sections.

Importance of Orbital Phase for Atmospheric Characterization. Orbital phase refers to the position of a planet in its orbit around its host star. A planet that is directly between its host star and Earth is said to be at Phase 0, and a planet that is directly behind its host star from the point of view of Earth is said to be at Phase 0.5. To understand why atmospheres can only be characterized at certain orbital phases, one must understand how atmospheres are characterized in the first place. One of the main methods for atmospheric characterization is emission spectroscopy (CU, 2016).

Emission spectroscopy allows for characterization of a planet's atmosphere by detecting the light emitted and reflected by a planet (including its atmosphere). The light emitted from a planet is known as thermal emission, because it is being radiated due to the heat of the planet. This radiation is approximated with Planck's law for blackbody radiation, which describes the electromagnetic emission of idealized hot objects. In addition to thermal emission, emission spectroscopy detects light from the host star that is reflected off of the planet's atmosphere. Emission spectroscopy is only possible by observing the planet before and during its secondary eclipse (Figure 1). Immediately prior to this occultation (another word for "secondary eclipse"), the emission from the star, the emission from the planet, and the reflection off the planet are all visible. The emission from the star is still dominant, so it is difficult to determine the planet's contributions. To filter out the light from the star, the secondary eclipse is observed. Since the planet is behind the star, only the star's emission is visible. By subtracting the stellar

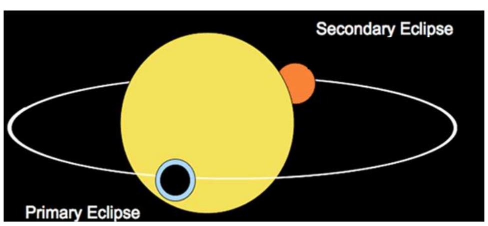

Figure 1: The primary eclipse (or transit) and secondary eclipse of a planet. Secondary eclipses allow for emission spectroscopy (Seager, 2017).

emission from the light curve that combines all three, one can obtain the combination of thermal emission and reflection from the planet. The emitted light passes through the atmosphere, and the reflected light was reflected by the atmosphere, so the composition and scale height (a measure of the size of the atmosphere; specifically, the height at which the pressure is half of what it is at the planet's surface) influence the intensities and wavelengths of light that are detected on Earth. Studying these intensities and wavelengths can therefore reveal the atmospheric characteristics when the planet is observed before and during its secondary eclipse (RIT, 2016).

Quantifying the Characterizability of a Planet's Atmosphere. Not every planet's atmosphere will be easily characterizable, even with JWST. Due to its high but limited sensitivity, an effective strategy would be to observe planets that are expected to have easily characterizable atmospheres. In order to rank planets in order of atmospheric characterizability, a previous study proposed a method called the Emission Spectroscopy Metric (ESM) (Kempton *et al.*, 2018). As the name suggests, ESM indicates how amenable a planet is to characterization with emission spectroscopy.

The calculation of ESM values follows directly from the nature of emission spectroscopy. Since the aim is to detect as much thermal emission and reflection as possible, with as little diluting starlight as possible, ESM values are biggest for large, hot planets around relatively small, cool stars. These conditions create the most contrast from the planet's signals relative to the star's signals, making the atmosphere easier to analyze. The exact numerical calculation can be seen in Equation 1:

$$\boxed{\text{ESM} = 4.29 \times 10^6 \times \frac{B_{7.5}(T_{day})}{B_{7.5}(T_*)} \times \left(\frac{R_p}{R_*}\right)^2 \times 10^{-m_K/5}} \tag{1}$$

- $B_{7.5}(T_{day})$ is the blackbody radiation predicted by Planck's law for the planet's dayside (which is visible just prior to a secondary eclipse).
- $B_{7.5}(T_*)$ is the blackbody radiation predicted by Planck's law for the star.
- R_p is the radius of the planet.
- R_* is the radius of the star.
- m_K is the magnitude of the star's emission in the K band.

Analyzing Equation 1 reveals the same concepts regarding the goals and methods of emission spectroscopy. The scale factor at the beginning (4.29×10^6) is only for normalization to a particular reference planet, and is not conceptually meaningful. The ratio of planet blackbody radiation to stellar blackbody radiation is a measure of how much contrast will be visible, as is the ratio of planet radius to stellar radius. The only conceptually important new component is the star's K band magnitude: the concept is that the more total light a telescope receives, the more easily an atmosphere can be detected. Therefore, if two planets have the same contrast with their stars, the one with the brighter star can be analyzed more easily.

Difficulties Selecting Ideal Observation Windows. Based on the two sections above, it is clear that atmospheric characterization will require knowledge of the top Emission Spectroscopy Metric targets and knowledge of the times when each of them will be undergoing secondary transits. The ESM values for known planets can be calculated without much difficulty, but predicting secondary eclipse timings is more problematic. In order to predict future transit (or secondary transit) times, there are two parameters that must be known: epoch and period. Epoch is a reference point for a time when a transit occurred (which can be used as an initial position), and period is the amount of time the planet takes to complete one orbit around its host star (which describes the subsequent motion). This information reveals future transit times because the epoch is at Phase 0, and the planet returns to Phase 0 after any integer number of periods.

The same is true for secondary transits, just with a slight offset; half a period after the epoch is Phase 0.5, and any integer number of periods after that is also Phase 0.5. The problem with this prediction method is that when determining epoch and period with data, there is uncertainty to the values that results from instrumental noise. This error compounds when trying to predict transits several years away. The uncertainty of the future transit time is equal to the error of the period multiplied by the number of periods between the observed transit and the time of prediction (Figure 2). In the case of many top Emission Spectroscopy Metric targets, discovery and follow-up analyses are outdated for these purposes; it has been several years since they were observed, which makes predictions ineffective due to the compounding effects of uncertainty in the periods (e.g. Turner *et al*., 2016). This can lead to large uncertainties for transit timings by the time these planets can be observed with JWST. This uncertainty is concerning, because JWST will have a busy observation schedule and will not be able to watch these planets for several hours without knowing exactly when the phases required for atmospheric characterization will occur.

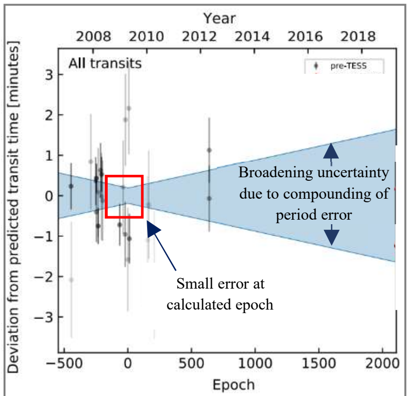

Figure 2: *Transit timing uncertainty for WASP-5b is shown in blue, broadening over time after the calculated epoch (red) due to compounding uncertainty of period (Bouma et al., 2019).*

Addressing the Problem of Compounding Uncertainty. Fortunately, the Transiting Exoplanet Survey Satellite (TESS) launched in April of 2018 offers a potential solution to this problem. It surveys large portions of the sky and, among other things, acquires new data for most previously known exoplanets (Ricker *et al*, 2014). This provides a longer baseline for calculating the period of top ESM targets, and moves the calculated epoch closer to the present day. These improved values can be visualized as transformations on Figure 2 that minimize the transit timing uncertainty in the future: the more recent epoch corresponds to a shift to the right such that the narrowest section of the shaded area is closer to the present time, and the more precise period corresponds to a compression such that the blue region does not widen as quickly towards the right side of the graph. The ultimate result is a narrower band of transit timing uncertainty for future times when the James Webb Space Telescope can observe these planets, which will help maintain an efficient observation schedule for JWST.

Problem Statement

P1. The ideal observation windows for atmospheric characterization of top ESM targets with JWST are unknown.

Objective

O1. This study aimed to minimize future transit timing uncertainties for the top three ESM targets by updating the relevant parameters using data from TESS.

Hypothesis

H1. If we utilize data from the Transiting Exoplanet Survey Satellite, then the ideal times for JWST observation of the top three ESM planets will be obtained with high precision and accuracy because TESS data combined with archival information provides a clear picture of planets' orbital history over several years (Kempton *et al*., 2018).

Methodology

Role of Student vs. Mentors

My mentors wrote the *allesfitter* code and taught me how to access and use this tool. They also wrote Python programs that I utilized, which helped automate several tasks. My roles were to gather data for the planets of interest from various sources, format the data so that *allesfitter* could read them, and prepare the *allesfitter* runs in a series of steps that allowed us to ultimately update the astrophysical parameters for each planet. My mentors and I worked together to analyze the *allesfitter* runs and fix problems that arose. I conducted this research full-time at my mentors' lab for 6 weeks last summer, and contributed 5-10 hours per week from home for 10 weeks afterwards.

Planet Selection

The first step of this project was to determine which planets would be studied. Since the goal was to use TESS data to update the characteristics top candidates for atmospheric characterization with emission spectroscopy, only transiting planets which were already observed by TESS could be analyzed. Emission Spectroscopy Metric values were calculated for all planets that fit these criteria, and the top three were selected for study. These planets, in order, were WASP-77A b, WASP-43 b, and WASP-18 b.

Data Collection and Homogenization

Data collection involved consultation of numerous data resources. For each planet, TESS data were acquired from the Mikulski Archive for Space Telescopes (MAST). The values in these files were time (the time when each observation was taken), relative flux (the amount of light received from the star, normalized so that the mean of all the out-of-transit values was 1), and flux error (a measure of how uncertain the flux value is due to imperfections of the instrument and observing conditions). For archival data, I first looked through journal articles focused on the planets I was working on and databases where the data products are often stored, and extracted the relevant data. I sent email requests to lead authors when the data were not available online. The archival data also came with varying units, often as Heliocentric Julian

Date (HJD) instead of Barycentric Julian Data (BJD) for time and magnitude instead of flux for quantity of light received. HJD to BJD conversions had to be carried out using an online converter (Eastman *et al.*, 2010), while magnitude was converted to flux using a Python program written by my mentors. Once the data collection and formatting were completed, *allesfitter* was used to determine characteristics of the planet.

Basics of *allesfitter*

This project made use of the software package *allesfitter* (Günther & Daylan, 2019), which incorporates many previously constructed packages for statistical analysis and plotting of astronomical data. These packages are ellc (Maxted, 2016), aflare1.py (Davenport, 2014), dynesty (Speagle, 2019), emcee (Foreman-Mackey *et al*., 2013), celerite (Foreman-Mackey *et al*., 2017), python (Rossum, 1995), numpy (van der Walt, Colbert & Varoquaux, 2011), scipy (Jones *et al*., 2001), matplotlib (Hunter, 2007), tqdm (doi:10.5281/zenodo.1468033), and seaborn (https://seaborn.pydata.org/index.html). For the purposes of this study, *allesfitter* was used to fit planetary models to both photometric and radial velocity data using Markov Chain Monte Carlo and Nested Sampling fits. These fits involve computerized statistical analyses of the data, and the outputs describe the characteristics of the planet.

Photometric Data. Photometric data describe the quantity of light being received from a star for a stretch of time, and comes in the previously described columns of time, flux, and flux error. Transits are particularly important for photometric analyses of planets. During transits, telescopes receive less light from the host star, and these light dips reveal several characteristics of the planet. The transit depth (the amount of light blocked) reveals the planet to star radius ratio, with larger transit depths indicating a higher ratio because large planets around small stars block more light than small planets around large stars. The amount of time between transits reveals the orbital period of the planet, because transits occur once per orbit. This indirectly provides information about how far the planet is from the star, because the farther a planet is from its star, the longer its period. Furthermore, transits provide an epoch for each planet since epoch can be any transit time of the planet. TESS and many other instruments collect photometric data, and there are several steps to fitting planetary models to this data with *allesfitter*. First, the background noise is modeled using a Gaussian Process (GP). A GP determines which fluctuations in flux are due to instrumental effects rather than planetary effects so that the planetary model only uses the actual planetary effects to narrow down the astrophysical parameters (these parameters being the characteristics of the planet, such as radius ratio, orbital period, and epoch). Figure 3 shows a planetary model fit to TESS data from WASP-77A b (the planet with the highest ESM value in this study). TESS observed more than one transit of the planet; in this plot, the data are consolidated to look like one transit in order to make the accuracy of the fit more visually apparent. The data from all the transits (the gray dots) are shifted on top of one another so that data collected from the same orbital phase are in line with one another vertically; this is known as phase-folded data. The blue dots are average values for all the fluxes within a small orbital phase window, representing the average flux when the planet is in the given position. Therefore, the entire set of blue dots is essentially an "average transit" based on all the TESS data. The red curve in Figure 3 is the best planetary model that *allesfitter* derived from the

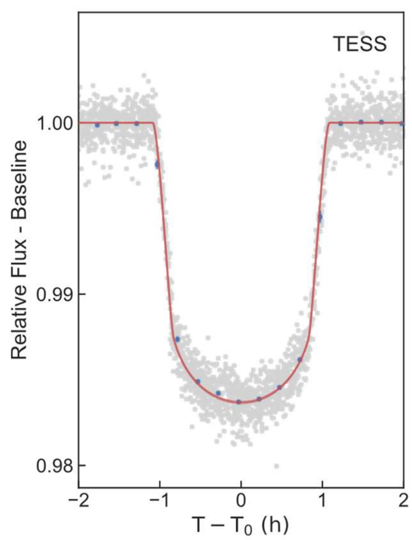

Figure 3: *Model (red) fit to the TESS photometric data (blue and gray) for WASP-77A b (R. Subramani).*

inputted data; it fits the data well because it passes almost perfectly through all the blue points. Note that besides the transit, the data and model seem to be perfectly flat. This is because, as the y-axis indicates, the Gaussian Process baseline has been subtracted to remove instrumental noise (also called red noise). Prior to this subtraction, there were many other fluctuations. Removing the red noise is essential for accurately constraining planetary parameters.

Radial Velocity (RV) Data. Stars keep planets in orbit around them due to gravity, but because all forces have equal and opposite forces associated with them, stars also feel the gravitational pull of their planets. The resulting motion is relatively small, because stars are much more massive than planets, but sometimes this motion can still be detected. The data measuring the speeds of stars due to the gravitational pull of planets are known as radial velocity (RV) data. By measuring a star's radial velocity many times, it is possible to learn how these speeds oscillate and infer the planet's qualities. For example, the star's oscillations in motion are periodic, where one cycle is equal in length to the planet's orbital period (because the planet is constantly pulling the star in different directions, eventually returning to the same place it started after one orbital period). Therefore, we can constrain period based on RV data. RV datasets describe the motion of a star over a time interval, and include the uncertainty of the instrument's readings. Figure 4 shows an example of *allesfitter* fitting a planetary model to RV data from the High Accuracy Radial Velocity Planet Searcher (HARPS) instrument for WASP-77A b. The data were not all from one orbit: these data were also phase-folded, though there are far fewer data points (the blue points are all of the data). The red curve is the expected radial velocities based on the best planetary model

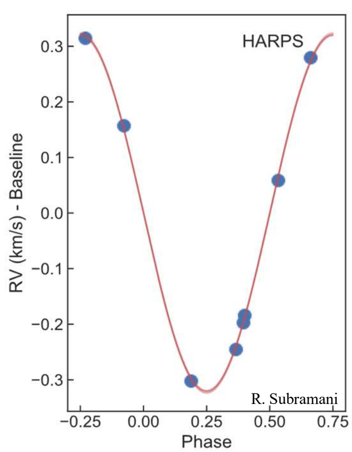

***Figure 4**: Model (red) fit to HARPS RV data (blue) for WASP-77A b (R. Subramani).*

allesfitter could derive based on the data, and it closely matches the observations. This suggests that the parameters calculated by *allesfitter* for the planetary model accurately match the characteristics of the actual planet.

All data. Once the individual instruments were run and the baselines were independently determined, a planetary model was simultaneously fitted to all of the data. The astrophysical parameters derived from this "all data" run were the most important results for each planet, providing the most accurate depiction of the planet's characteristics that could be drawn from all the observations collected.

Results

Below are the updated ephemerides for the three planets studied in this project. To reiterate, these planets are (in order of Emission Spectroscopy Metric ranking) WASP-77A b, WASP-43 b, and WASP-18 b.

WASP-77A b

WASP-77A b (Maxted *et al.*, 2013) is a Hot Jupiter on a 1.36-day orbit around a G8 V type star. It has a radius of 1.21 Jupiter radii (R_j) and a mass of 1.76 Jupiter masses (M_j). The parameters of interest were determined using *allesfitter* as described above, and the values and uncertainties for these parameters as determined by this work are compared to those from previous literature in Table 1. The values under the columns labeled "previous" were also calculated with *allesfitter* during this project, but the data from the Transiting Exoplanet Survey Satellite was not included in the fit.

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Table 1: Values and uncertainties calculated for each parameter based on previous observations and this work for WASP-77A b. The improvements which are most critical for planning JWST observations are highlighted.

Parameter	Value (previous)	Uncertainty (previous)	Value (this work)	Uncertainty (this work)
Epoch (BJD)	2455458.362	0.0001930	2456757.189	0.000286
Period (days)	1.36002835	5.002×10^{-7}	1.36002966	2.347×10^{-7}
R_p/R_*	0.1187	0.000655	0.1193	0.000239
$(R_p+R_*)/a$	0.2099	0.003857	0.2145	0.01806
cos(i)	0.0382	0.01800	0.0563	0.00561
K (km/s)	0.3206	0.00170	0.3214	0.00173

*R_p is the planet radius, R_* is the stellar radius, a is the length of the semi-major axis of the planet's elliptical orbit path, i is the angle of inclination, and K is the maximum radial velocity of the star. R_p/R_* is a planet-to-star radius ratio, $(R_p+R_*)/a$ is a ratio of combined radii to distance between planet and star, and cos(i) is a way of describing the planet's orbital plane relative to the plane of view from Earth (cos(i)=0 is a perfect transiting path, so all planets in this study have cos(i) values near 0).

WASP-43 b

WASP-43 b (Hellier *et al.*, 2011) is a Hot Jupiter planet in a 0.81-day orbit around a K7 V star. It has a radius of about 0.9 R_j and a mass of roughly 1.8 M_j. The outputs from *allesfitter* are displayed in Table 2.

Table 2: Values and uncertainties for each parameter based on previous observations and this work for WASP-43 b. The improvements which are most critical for planning JWST observations are highlighted.

Parameter	Value (previous)	Uncertainty (previous)	Value (this work)	Uncertainty (this work)
Epoch (BJD)	2455823.346	0.0000551	2456535.136	3.24866×10^{-5}
Period (days)	0.813474751	2.051×10^{-7}	0.81347412	1.741×10^{-8}
R_p/R_*	0.1608	0.000457	0.1607	0.000331
$(R_p+R_*)/a$	0.2405	0.001562	0.2422	0.001208
cos(i)	0.1400	0.00201	0.1428	0.00150
K (km/s)	0.5504	0.00395	0.5498	0.00379

This space is intentionally left blank.

WASP-18 b

WASP-18 b (Hellier *et al.*, 2009) is a Hot Jupiter on a 0.94-day orbit around an F6 star. It has a radius of about 1.2 R_j and a mass of about 10.4 M_j. Once more, the parameters of interest were determined using *allesfitter*, and the findings are listed in Table 3.

Table 3: Values and uncertainties for each parameter based on previous observations and this work for WASP-18 b. The improvements which are most critical for planning JWST observations are highlighted.

Parameter	Value (previous)	Uncertainty (previous)	Value (this work)	Uncertainty (this work)
Epoch (BJD)	2455396.413	0.0000913	2456150.517	0.0000725
Period (days)	0.94145	1.051×10^{-7}	0.94145	3.090×10^{-8}
R_p/R_*	0.0979	0.000210	0.0984	0.000107
$(R_p+R_*)/a$	0.3127	0.00499	0.3214	0.00153
cos(i)	0.0957	0.01505	0.1202	0.00368
K (km/s)	1.8212	0.00456	1.8220	0.00445

Discussion

As hypothesized, the updates with TESS data decreased the uncertainty in period for every planet studied. This makes future transit timing predictions far more accurate, and in turn makes it possible to more effectively select observation times for the James Webb Space Telescope. This is particularly important because JWST will have a busy observing schedule, and only a limited time can be dedicated to each target. The improvement in transit timing

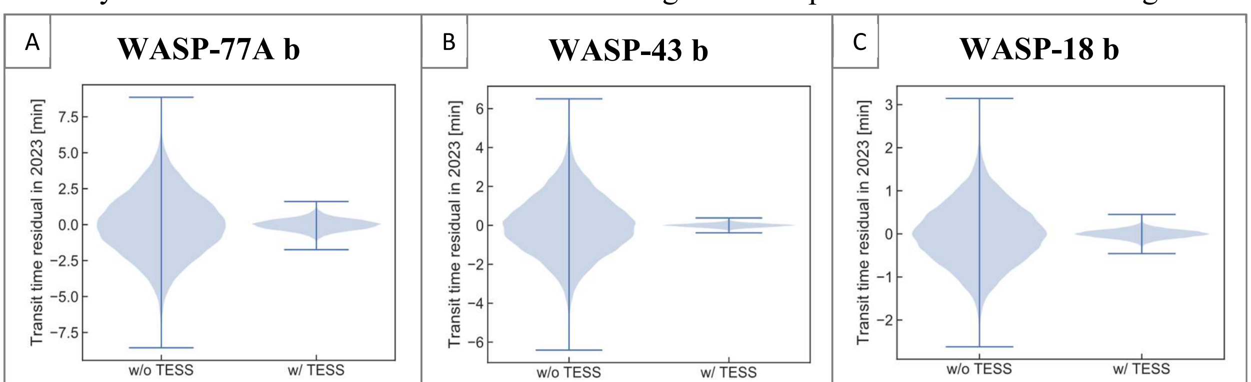

Figure 5: Transit timing uncertainty in 2023 without TESS data (on the left of each plot, representing all previous data) and with TESS data (on the right of each plot, representing the update provided by this project) for (A) WASP-77A b, (B) WASP-43 b, and (C) WASP-18 b, showing how TESS dramatically decreases uncertainty (R. Subramani).

prediction accuracy is shown in Figure 5, which contains violin plots for each of the planets analyzed in this study. The shaded regions of these violin plots are probability distributions which describe how much error there may be in the predicted transit timings. TESS data decreases the one-sigma transit timing uncertainty in 2023 (when JWST may observe these planets) by a factor of 3.02 for WASP-77A b (Figure 5A), a factor of 14.24 for WASP-43 b (Figure 5B), and a factor of 4.08 for WASP-18 b (Figure 5C).

Future Research

In this work, only the top three ESM targets were reanalyzed and updated using TESS data due to time constraints. It would be helpful to continue this work and update the parameters of many more high priority targets for atmospheric characterization, because JWST will likely be able to observe more than three targets for this purpose. Further study of the three planets which were studied here will also be beneficial, because the characteristics which make them top ESM targets make them noteworthy in other ways as well. All three have extremely short period orbits. The host star of WASP-77A b is part of a binary star system and shows signs of magnetic activity. WASP-18 b has a surprisingly high mass and density given its radius: generally, planets much larger than Earth are primarily gaseous and have low densities. Therefore, WASP-18 b may share characteristics with the class of celestial bodies known as brown dwarfs, which lie between planets and stars, because brown dwarfs can be much denser than gaseous planets. The reason these unusual circumstances are important for future research is that their impacts on planetary development are currently unknown, and more in-depth study of these three planets will serve to inform researchers about their influences. Additionally, this study only looked at previously discovered planets that were observed in TESS's first year (because only the first year of data was available), but there are many promising ESM targets that do not fit these criteria.

Many planets are being newly discovered with TESS, and some may provide even better opportunities for atmospheric characterization. Also, previously discovered planets are being observed in TESS's second year (which is currently ongoing), and these should be updated to narrow down transit time predictions as well.

Applications

Once JWST is launched in 2021 and observes these planets, the data will provide new insights into the atmospheres of Hot Jupiters. New knowledge about this interesting class of planets may help astronomers better understand the processes of planetary formation and evolution. In the coming decades, similar attempts can be made to analyze the atmospheres of Earth-like planets. This will reveal details not only about the individual planets, but about the entire population of atmospheres for all Earth-like planets. Perhaps even more importantly, these studies will make it possible to look for biosignature gases in the atmospheres which suggest the presence of life. For example, the presence of large quantities of both methane and oxygen in an atmosphere is a strong indication of life (Seager, 2017). This is the case on Earth: without biological processes, it would be impossible for the high quantities of methane and oxygen in Earth's atmosphere to coexist. There are many other biosignature gases and combinations which could similarly provide grounds to believe that life exists on other planets. A discovery of such gases would revolutionize our understanding of our place in the universe.

Conclusion

The goal of this project was to contribute to the search for extraterrestrial life by updating the characteristics (specifically, period and epoch) of top targets for atmospheric characterization using data acquired in the first year of the TESS mission. By using the software package *allesfitter*, it was possible to find the most likely characteristics for each of these planets based on previous data as well as TESS data. As hypothesized, the update provided a long baseline for *allesfitter* to work with, which allowed for considerable improvements in the precision of future transit timing predictions. This research will serve to help efficiently and accurately select observation times for atmospheric characterization with JWST, which in turn may provide new information about characteristics of the exoplanet population or even evidence of extraterrestrial life. There is great excitement in this field because such a discovery seems plausible soon, and its potential impacts cannot be overstated. Meaningful findings in the search for extraterrestrial life would expand not only the boundaries of science, but the scope of human civilization.

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Previous Research

Created: 11/05/2019 • Last updated: 11/13/2019

Tell us about your previous science research projects

1. Individual Science Projects (optional)

List any individual research projects (not class projects) to which you have contributed during high school. A project does not need to have been submitted to a competition to be listed. List projects in chronological order, starting with the most recent project on top.

	Start Date (MM/DD/YYYY)	End Date (MM/DD/YYYY)	Supervising scientist/mentors (if any)	Project Title	Competition/ Awards (if any)	Check this box if this is the project you are entering to Regeneron STS
1.	07/09/2019	08/16/2019	Dr. Tansu Daylan and Dr. Maximilian Günther	TESS Updates to Plan JWST Observations of Promising Exoplanets for Atmospheric Characterization	The competitions in which I am submitting this work have not happened yet.	✔
2.	07/16/2018	09/01/2018	Dr. James Kasting	Paleoclimate Calculations Using a 1-D Climate Model with Applications for Long-Term Planetary Habitability	1st Place in Earth and Planetary Sciences at Somers Science Fair. 2nd Place in Physics and Astronomy at Westchester Science and Engineering Fair. Honorable Mention at International Genius Olympiad.	✖
3.						✖
4.						✖
5.						✖

2. Team Science Projects

Have you ever completed research with a team member?

No

You are submitting that you have never conducted research as part of a student team project. Thanks for letting us know! Just to clarify, if you HAVE ever conducted research as part of a student team, you need to check YES and answer questions 2a-d. Even if you were a primary member of a team or conducted one portion of the research, it is still considered a part of that team project. Team research is not eligible for the Regeneron Science Talent Search, but we are curious about your past projects. If you have not conducted any team research, carry on to question 3.

3. Conference Presentations, Abstract Publications, Student-Level Publications, Paid Publications, or Future Submission Plans (optional; maximum 300 words)

Please list any conferences in which you have presented your work; instances where the abstract of your research has been published; publications in student-level, non-peer reviewed, or pay-for publication journals; and future publication plans (including articles submitted to journals, but not yet published) (If any):

Presented a poster based on the project I am submitting for Regeneron STS at TESS Science Conference 1.

4. Ph.D.-level Peer-reviewed Journal Publications

Are you listed as an author or coauthor on any scientific publications? (you may select more than one option)

I have submitted a paper/am pending publication

Describe your plans for future publication (optional).

If this research is the same as the project you are submitting to Regeneron STS, please indicate so below. (200 words max)

I will be publishing two peer-reviewed articles in a scientific journal along with my mentors based on the project I am submitting for Regeneron STS. I have not actually submitted the papers for publication yet, but they are in preparation. I will be the third author on one paper, and fourth author on the other. The papers will be submitted to and published in the Astronomical Journal.

5. Science Training Institutes, Research Progams, Summer Programs

Please list the names of programs where you have conducted research projects, science summer camps you have attended, etc. Check the box to indicate if your STS project was conducted at any of these institutions.

	Name of Program	City	State	Dates	Website	STS Project?
Program 1	Columbia Science Honors Program	New York	New York	Fall 2016 - Spring 2020	http://www.columbia.edu/cu/shp/	✖
Program 2						✖
Program 3						✖
Program 4						✖
Program 5						✖
Program 6						✖
Program 7						✖
Program 8						✖

Essay Questions

Created: 11/05/2019 • Last updated: 11/13/2019

Tell us about your project, inspiration, and impact. Do not feel pressured to meet the word limit for each question.

1. Research Project “Layperson’s Summary” (maximum 200 words)

Summarize your project in layperson’s terms, while maintaining scientific accuracy. Your explanation should be easily understandable and include background, procedures, conclusions and relevance. This summary will aid readers, including evaluators, journalists and the public.

The James Webb Space Telescope (JWST), scheduled for launch in 2021, may revolutionize the search for extraterrestrial life by characterizing exoplanet atmospheres. However, it is difficult to predict the correct times to observe planets with JWST; only certain locations in their orbits provide useful data for atmospheric characterization, and current knowledge of their orbits is limited. This study used the software package allesfitter to analyze recent data from the Transiting Exoplanet Survey Satellite (TESS) and better describe the orbits of three promising exoplanets for atmospheric characterization. These updates provided more precise and accurate knowledge of the planets’ orbits, making it considerably easier to predict the ideal times for JWST to observe them. This will make the process of analyzing their atmospheres more efficient. This contribution will facilitate atmospheric characterization in the near future, an important step forward toward the potential discovery of life on other planets.

2. Project Inspiration (maximum 200 words)

What inspired you to conduct this research project? (What is the story behind your research topic?)

In elementary school, I watched a documentary about the Hubble Space Telescope which emphasized the insignificant size of Earth in the scale of the universe. It taught me that despite the many advancements and complexities of human civilization, our exploration of the universe has been extremely limited so far. So when I joined my school’s Science Research program and was encouraged to read journal articles on a topic of my choice, I was inspired to pursue a field that is pushing the boundaries of our knowledge of the universe beyond Earth: exoplanets. Papers on a variety of topics, from newly discovered planets to habitable zone studies, intrigued me. Then, I learned about the Transiting Exoplanet Survey Satellite (TESS). This highly advanced instrument launched in April of 2018, and its acquisition of precise photometric data for countless stars makes it invaluable for discovering new exoplanets and reanalyzing previously discovered ones. I started emailing researchers working with TESS data so I could be a part of its influential mission, and eventually I was invited to join a project being carried out at MIT to recharacterize previously known exoplanets with this new data.

3. STEM Interests (maximum 250 words)

After completing your research, how has your interest in science, engineering, and/or math been clarified? What are your other STEM-related interests besides your project?

This project taught me exactly how the astrophysics research process works. Firstly, I collected data from previous studies, and while this task was not always exciting, I learned why it is worth persisting. Once in a while, an anomaly arose, and the numbers in my Excel files suddenly revealed an exciting planetary characteristic, like the presence of particles in a planet’s atmosphere that scatter UV light more effectively than visible light. This thrilling feeling is an extremely strong motivation for me to continue with scientific research. Also, my exposure to computer modeling tools gave me insight both into how results are derived and how skills like programming and statistics are vital in astrophysics research. I intend to add to my knowledge of these fields and others during my free time next summer. Further, my experiences preparing two journal articles based on my research and attending the TESS Science Conference at MIT this summer introduced me to the communication of ideas in the scientific community. At the conference, I presented a poster and listened to numerous talks given by graduate students and professors from around the world. Outside of my project and the STEM interests I describe elsewhere, I am captivated by the mysteries of the universe on its smallest and largest scales, the interplay of these scales in the earliest moments after the Big Bang, the possible existence of many universes, theories of everything (like string theory and loop quantum gravity), and the ultimate fate of the universe.

4. Project Benefits and Impact (maximum 200 words)

What benefits do you think your research will bring to the world, and/or to your field? What additional steps, and by whom, might be needed for this benefit to be realized?

While further research is required to achieve them, the potential impacts of my project are far reaching. The most immediate application is to select times for the James Webb Space Telescope (JWST) to observe promising exoplanets. Once data is available for these planets, the compositions and sizes of their atmospheres can be determined and used to better describe the entire exoplanet population. Once even more advanced space telescopes, such as the Characterizing ExOPlanets Satellite (CHEOPS), are in use, it will be possible to use similar techniques for Earth-like planets and determine not only the compositions and sizes of their atmospheres, but also whether or not there is evidence of life on those planets. Atmospheric studies may provide compelling evidence for life in the form of biosignature gases. Earth, for example, has high levels of methane and oxygen which could not coexist without biological processes. Discovering life would likely change our perception of the universe around us and energize our ventures into the great expanse beyond Earth. It is important to pursue these long-term goals in the present so that we may achieve them more quickly.

5. Your Potential as a Scientist, Mathematician or Engineer (maximum 250 words)

Address through specific and concrete examples what characteristics you have that best demonstrate your affinity and aptitude for being a good scientist. What have you done that illustrates scientific aptitude, curiosity, inventiveness and/or initiative? How does your experience suggest future success as a scientist, mathematician or engineer? What do you plan to study in post-secondary education and what occupation do you plan to pursue? What do you hope to be doing 10 years from now?

I have a deep love for science, endless curiosity about the universe, and uncommon scientific aptitude. My roles in the research I am submitting for Regeneron STS demonstrate my strengths; for example, I quickly learned how to be a useful contributor to my project despite originally being completely unfamiliar with planetary model fitting, a key process in our study. After a brief introduction from my mentors, I was able to understand the basic statistics of both Markov Chain Monte Carlo fits and Nested Sampling fits, complex topics which are typically taught in college statistics courses. As a strong conceptual learner, I was able to apply my understanding to evaluate the outputs of the planetary model fits. Once, one of my mentors was even uncertain about why a probability distribution was unusually shaped, and I was able to point out the cause. Aside from my project, many of the extracurriculars I listed in the activities section are concrete examples of my in-depth explorations of math, science, and physics specifically. Outside of these activities, my passion drives me to delve even deeper into math and science. I created a video on quantization for the Breakthrough Junior Challenge, and I practice number theory problems with some of my free time. In the next ten years, I intend to major in astrophysics in college, and then pursue a PhD and a career as a professor and/or researcher.

6. Major Scientific Question (maximum 300 words)

What is a major scientific question in your field whose answer you believe will have a significant impact on the world in the next 20 years, and why? Using examples from your own experience or research, explain how you might envision addressing the question over the next 20 years.

"Is there other life in the universe?"

This question was not formulated in the field of exoplanets, or astronomy, or even science. It has been posed since ancient times due to natural curiosity, and has been pursued in a myriad of ways. For example, the Ancient Greeks thought the universe was infinite, and supposed that this would mean there were infinite civilized worlds. In the 16th century, Nicolaus Copernicus suggested that the Sun was the center of the solar system. This led people to wonder if all the other stars we see in the night sky could be the centers of their respective solar systems, and if they could have planets with life around them. The first exoplanet discovery was in 1995, commencing a new age in the attempts to answer the driving question stated above. Today, there are over 4,000 known and confirmed exoplanets, and we have obtained knowledge regarding the sizes, compositions, and atmospheres of some of these planets. We are closer than ever to discovering life in the universe; in fact, NASA's chief scientist in 2015 stated that she expected to find "strong indications of life beyond Earth within a decade, and... definitive evidence within 20 to 30 years." More planets are being discovered than ever before using the Transiting Exoplanet Survey Satellite (TESS) and research like my own is working towards atmospheric characterization of exoplanets. I envision moving forward with this research by utilizing data from future space telescopes, such as the James Webb Space Telescope (JWST) and the CHaracterizing ExOPlanets Satellite (CHEOPS), to determine the compositions of exoplanet atmospheres which could reveal indications that life is present. It is possible that this question (which has existed for millenia) will be answered within our lifetimes.

7. "Tweet" about your project! Tell us about your project in 280 characters or less.

The Society might share this response if you are named a scholar or finalist.

Using a software package, I fitted planetary models to data for exoplanets which are promising targets for atmospheric characterization. These models improve selection of times when the atmospheres can be studied with the James Webb Space Telescope.

Activities, Interests and Awards

Created: 10/28/2019 • Last updated: 11/13/2019

Tell us about your activities, interests and awards. Do not feel pressured to meet the word limits for essay questions.

EXTRACURRICULAR ACTIVITIES, VOLUNTEERISM & EMPLOYMENT

Tell us about your extracurricular activities, volunteer work, employment, etc. We want to know more about you, your day-to-day life, how you spend your time, and why. Please select an activity type and describe your involvement in the activity. If you do not see an exact match for your activity in the list, select "other." Please do not feel pressured to use all seven activity boxes below; tell us about your favorites.

How many activities would you like to list? 7

Activity #1

Activity Type:	Other
Name of Activity (type of sport, name of club, etc):	Columbia Science Honors Program
Your Role/Leadership Roles:	Student
How many years have you participated in this activity?	4
Explain the time commitment to this activity:	2.5 hours every Saturday during the fall and spring.
Awards won/accomplishments related to this activity	N/A
Anything else you would like to share about this activity? (75 words maximum)	There is a rigorous selection process, including an all-around test of math and science, from which only select students are admitted. I was accepted in the first year I was eligible, and I have been taking high-level courses to advance my knowledge of my favorite academic subjects: physics and astronomy. My courses so far have been "Modern Cosmology", "Geometry and Topology," "Intro to Probability," "Astronomy and Astrophysics," and "Particle Physics."

Activity #2

Activity Type:	STEM-related Club
Name of Activity (type of sport, name of club, etc):	Science Olympiad
Your Role/Leadership Roles:	Team Captain as a sophomore, President as a senior.
How many years have you participated in this activity?	4
Explain the time commitment to this activity:	3-20 hours of preparation every week for about 3 months prior to the competition.
Awards won/accomplishments related to this activity	For each event, I was part of a two-person team competing against about 45 other teams. Some of my greatest accomplishments include: 1st Place in Fermi Questions. 5th Place in Wright Stuff. 8th Place in Mission Possible. 9th Place in Helicopters.
Anything else you would like to share about this activity? (75 words maximum)	Last year the team from my school nearly qualified for the State level competition, and this year we will be aiming to achieve that goal.

Activity #3

Activity Type:	STEM-related Club
Name of Activity (type of sport, name of club, etc):	Math Team
Your Role/Leadership Roles:	Captain as a senior.
How many years have you participated in this activity?	4
Explain the time commitment to this activity:	Occasional practice meetings, one competition meet each month for 6 months.
Awards won/accomplishments related to this activity	Qualified for State level as a junior with one of the top overall scores in the county.
Anything else you would like to share about this activity? (75 words maximum)	The problems in Math Team test creative problem-solving skills, which makes them the most fun type of math problems for me. I have even practiced similar, but more difficult, number theory problems on my own time because I greatly enjoy them.

Activity #4

Activity Type:	Music (Instrumental)
Name of Activity (type of sport, name of club, etc):	Alto Saxophone in Wind Ensemble, Jazz Band, and Area All-State Band
Your Role/Leadership Roles:	Section leader in Wind Ensemble and Jazz Band, the two audition-only bands in my school.
How many years have you participated in this activity?	8
Explain the time commitment to this activity:	One class period of Wind Ensemble each day, one 1.5 hour Jazz Band rehearsal each week, and regular practice outside of school to prepare for concerts. Area All-State band had three 6 hour rehearsals and a concert.
Awards won/accomplishments related to this activity	Qualifying for the Area All-State Band is an accomplishment, as it required a top score on a NYSSMA adjudication relative to others in my county.
Anything else you would like to share about this activity? (75 words maximum)	The NYSSMA adjudication I mentioned requires thorough preparation of a challenging classical solo, scales, and sight reading. I received a 99/100 on a level 6 piece (the most difficult level) in order to qualify for Area All-State.

Activity #5

Activity Type:	Volunteer Work
Name of Activity (type of sport, name of club, etc):	Appalachia Service Project
Your Role/Leadership Roles:	Safety Monitor, Team Leader
How many years have you participated in this activity?	4
Explain the time commitment to this activity:	A 2 hour meeting each month to prepare for a one week trip to the Appalachian region in the summer.
Awards won/accomplishments related to this activity	N/A
Anything else you would like to share about this activity? (75 words maximum)	We spend a week in an impoverished county in Appalachia helping make homes "warmer, safer, and drier" for those who cannot afford home maintenance. This service can sometimes help parents maintain custody of children who would otherwise be taken away by Child Services due to the unacceptable living conditions. Aside from the fulfilling work, my volunteer group makes the trip an enjoyable experience by using free time for sports, games, ice cream stops, and more.

Activity #6

Activity Type:	Athletics
Name of Activity (type of sport, name of club, etc):	Varsity Tennis and Soccer
Your Role/Leadership Roles:	Captain of the Varsity Tennis team
How many years have you participated in this activity?	4
Explain the time commitment to this activity:	2 hour practices each day, about 2-3 matches of 2-4 hours per week.
Awards won/accomplishments related to this activity	All-League player each year for tennis. Qualified for All-Section tournament as a junior through success in the Conference tournament.
Anything else you would like to share about this activity? (75 words maximum)	I have played both these sports since my early childhood. When I selected "4 years" of participation above, I was only including high school sports.

Activity #7

Activity Type:	STEM-related Club
Name of Activity (type of sport, name of club, etc):	MathWorks Math Modeling Challenge
Your Role/Leadership Roles:	As a member of the first group of students to participate in this challenge in my school, I helped to form and spread the word about this club so that students from my school continue to take part in this activity.
How many years have you participated in this activity?	1
Explain the time commitment to this activity:	14 consecutive hours of work for the actual competition. Last year's preparation was limited due to our last-minute registration, but we will likely spend 50-100 hours preparing next year.
Awards won/accomplishments related to this activity	We were recognized among the top 20% of submissions nationally.
Anything else you would like to share about this activity? (75 words maximum)	The question last year was to analyze past trends and predict how the popularity of different drugs will fluctuate in the next ten years, with a focus on vaping. The submission which was evaluated was a ~20 page paper communicating our conclusions.

Summer Activities

What did you do in the last 3 summers? Tell us about any jobs, activities, research, travel, etc. (Maximum 200 words)

I kicked-off my last three summers with a powerful volunteer trip for the Appalachia Service Project. After that unbeatable start, significant portions of my summers were filled with scientific research: I looked into journal articles that interested me two summers ago, I worked with Pennsylvania State University professor Dr. James Kasting to address the faint young Sun problem last year, and I worked with Dr. Tansu Daylan and Dr. Max Günther (members of Dr. Sara Seager's exoplanet atmosphere group) at the MIT Kavli Institute to recharacterize previously known exoplanets using TESS data this summer. Last summer, I was able to do most of the work remotely, so I also traveled to India to visit family. This year, I spent six weeks working on campus at MIT. During my time in Cambridge, I presented a poster at the first TESS Science Conference, helped in the preparation of two journal articles, discovered the YouTube channel PBS Space Time and watched most of their videos, and explored the city (especially the ice cream shops!). I returned home in time for my school's soccer tryouts each year.

SCIENCE COMPETITIONS AND PROGRAMS

Have you participated in any of the following?

Select all that apply.

Science fair at the local or regional level

Science training program or summer institute

Share information about your participation in science training programs and/or summer institutes in Task 6.

AWARDS

List special recognitions, awards, honors and scholarships from both school and community, if any.

Include national or international honors received during your high school career not previously listed in the activities section above. (250 words maximum)

- Salutatorian of YHS Class of 2020
- Yale Book Award(2019)

Received this award for "Outstanding Personal Character and Intellectual Promise," as determined by a panel of teachers.

- Member of National Honor Society (NHS)
- National Merit Scholarship Commended Student

INTERESTS

What single accomplishment are you most proud of and why? OR, Tell us about any challenges you have overcome.

(100 words maximum)

I am most proud to be involved in the publication of two scientific journals articles as a high school student. It is especially satisfying because my contributions to their creation are significant, both in terms of research and writing. Many science majors do not have published works until late in their undergraduate years, or even later. I am incredibly grateful to have had the opportunity to achieve this milestone in high school, and to contribute to the awe-inspiring scientific community.

Share a fun fact that we might otherwise not know about you.

(75 words maximum)

Considering I spend much of my time trying to better understand reality, I have a surprising love for the forms of entertainment which are the furthest from it! I love fantasy books, such as the Kingkiller Chronicle and the Stormlight Archive, and superhero movies, including all the ones in the Marvel Cinematic Universe and The Dark Knight Trilogy.

Test Scores (optional)

Created: 09/27/2019 • Last updated: 10/02/2019

Sharing your standardized test scores is optional. If you choose not to share your test scores, this decision will not be held against you. If you would like to share your scores, enter them in this task, then upload evidence that supports your scores in the next task. Superscoring is permitted.

SAT Scores

	Score	Test Date (MM/DD/YYYY)
Composite	1560	12/01/2018
Section Score: Evidence-based Reading and Writing	770	12/01/2018
Section Score: Math	790	12/01/2018
Cross-Test: Analysis in Science	40	12/01/2018
Cross-Test: Analysis in History/Social Studies	40	12/01/2018
Test Score: Reading	40	12/01/2018
Test Score: Writing and Language	37	12/01/2018
Test Score: Math	39.5	12/01/2018

SAT II

(Science, Math, Engineering, and Technology tests only) List top 4 only

	Subject	Score	Test Date (MM/DD/YYYY)
SAT II Test #1	Biology (M)	800	06/03/2017
SAT II Test #2	Physics	800	06/01/2019
SAT II Test #3	Math II	800	06/01/2019
SAT II Test #4			

ACT Scores

List highest score in each category on any date.

	Score	Test Date (MM/DD/YYYY)
English		
Reading		
Math		
Science		
Composite		

Advanced Placement Course Test Scores

(Science, Math, Engineering, and Technology tests first) List top 8 only.

	Subject	Score	Test Date (MM/DD/YYYY)
AP Test #1	Statistics	5	05/16/2019
AP Test #2	United States History	5	05/10/2019
AP Test #3			
AP Test #4			
AP Test #5			
AP Test #6			
AP Test #7			
AP Test #8			

International Baccalaureate Course Test Scores

(Science, Math, Engineering, and Technology tests first) List top 8 only.

	Subject	Score	Test Date (MM/DD/YYYY)
IB Test #1			
IB Test #2			
IB Test #3			
IB Test #4			
IB Test #5			
IB Test #6			
IB Test #7			
IB Test #8			

US Territories: Other Tests

For students attending accredited overseas secondary schools only. If you do not attend school in the US and take different tests than those listed above, please report the test names and your scores here.

Do not write in this box if you live in the US and/or took the tests listed above.

(No response)

You will need to upload proof of the test scores you have mentioned above in Task 10 (next task).

Please merge your various test score documents into one PDF document for the upload. We ask that you remove extraneous pages about how to interpret scores. Should you need assistance, email sts@societyforscience.org.

CollegeBoard **SAT**

SAT Score Report

Test Date: **Dec. 01, 2018**
Registration Number: **0070276128**
Gender: **MALE**
Date of Birth: **Apr. 16, 2002**
Test Center Number: **33006**
CB Student ID: **100421519**
High School Code: **336085**
High School Name: **Yorktown High School**

Rohan Subramani
433 Rutledge Dr
Yorktown Heights, NY 10598 - 5011

Your Total Score

1560 | *400–1600*

99th
Nationally Representative Sample Percentile

99th
SAT User Percentile

Essay Scores

6 | *2 to 8*
Reading

4 | *2 to 8*
Analysis

6 | *2 to 8*
Writing

Section Scores

770 | *200–800*
Your Evidence-Based Reading and Writing Score

99th Nationally Representative Sample Percentile
99th SAT User Percentile

You've met the benchmark!

790 | *200–800*
Your Math Score

99th Nationally Representative Sample Percentile
99th SAT User Percentile

You've met the benchmark!

Test Scores

40 | *10–40*
Reading

37 | *10–40*
Writing and Language

39.5 | *10–40*
Math

Cross-Test Scores | *10–40*

40
Analysis in History/Social Studies

40
Analysis in Science

Subscores | *1–15*

15
Command of Evidence

15
Words in Context

15
Expression of Ideas

13
Standard English Conventions

15
Heart of Algebra

15
Problem Solving and Data Analysis

14
Passport to Advanced Math

Am I on Track for College?

Look for the green, yellow, or red symbols next to your section scores. They let you know if your scores are at or above the benchmark scores. Benchmarks show college readiness. If you see green, you're on track to be ready for college when you graduate.

If you score below the benchmark, you can use the feedback and tips in your report to get back on track.

Benchmark scores:

Evidence-Based Reading and Writing: 480
Math: 530

How Do My Scores Compare?

A percentile shows how you scored, compared to other students. It's a number between 1 and 99 and represents the percentage of students whose scores are equal to or below yours.

For example, if your Math percentile is 57, that means 57% of test takers have Math scores equal to or below yours.

The Nationally Representative Sample Percentile compares your score to the scores of typical U.S. students.

SAT® User Percentile compares your score to the scores of students who typically take the test.

How Can I Improve?

To see which skills are your strongest and what you can do to boost your college readiness, go to your full report online and look for Skills Insight™.

What Are Score Ranges?

Test scores are single snapshots in time—if you took the SAT once a week for a month, your scores would vary.

That's why score ranges are better representations of your true ability. They show how much your score can change with repeated testing, even if your skill level remains the same.

Colleges know this, and they get score ranges along with scores so they can consider scores in context.

Your online score report shows your score ranges.

CollegeBoard SAT

SAT Subject Tests
Score Report

Test Date: **June 03, 2017**
Registration Number: **0056464515**
Gender: **MALE**
Date of Birth: **Apr. 16, 2002**
Test Center Number: **33006**
CB Student ID: **100421519**
High School Code: **336085**
High School Name: **Yorktown High School**

Rohan Subramani
433 Rutledge Dr
Yorktown Heights, NY 10598 - 5011

Biology-M

800 | *200 to 800*

95th Percentile

How Do My Scores Compare?

A percentile shows how you scored, compared to other students. It's a number between 1 and 99 and represents the percentage of students whose scores are below yours.

For example, if your Biology Test score is 500 and the national percentile for 500 is 47, you did better than 47% of all high school students who took this test.

Keep in mind that different groups of students take different SAT Subject Tests™, so you can't compare percentiles of different tests.

What Are Score Ranges?

Test scores are single snapshots in time—if you took the test once a week for a month, your scores would vary.

That's why score ranges are better representations of your true ability. They show how much your score can change with repeated testing, even if your skill level remains the same.

Usually your scores fall in a range of roughly 30–40 points above or below your true ability. There must be a difference of at least 60 points between your score and another student's to say that one of you performed better than the other. Colleges know this, and they get score ranges along with scores so they can consider scores in context.

Your online score report at sat.org/scorereport shows your score range for each test you took.

Should I Take the Test Again?

Each Subject Test measures your knowledge of a particular subject. If you continue to study the subject and take the test again, your new score should reflect your increased knowledge.

You can also register for other Subject Tests, or the SAT, at collegeboard.org/mysat.

CollegeBoard SAT

SAT Subject Tests
Score Report

Test Date: **June 01, 2019**
Registration Number: **0073617054**
Gender: **MALE**
Date of Birth: **Apr. 16, 2002**
Test Center Number: **33006**
CB Student ID: **100421519**
High School Code: **336085**
High School Name: **Yorktown High School**

Rohan Subramani
433 Rutledge Dr
Yorktown Heights, NY 10598 - 5011

Math Level 2

800 | *200 to 800*

79th Percentile

Physics

800 | *200 to 800*

87th Percentile

How Do My Scores Compare?

A percentile shows how you scored, compared to other students. It's a number between 1 and 99 and represents the percentage of students whose scores are below yours.

For example, if your Biology Test score is 500 and the national percentile for 500 is 47, you did better than 47% of all high school students who took this test.

Keep in mind that different groups of students take different SAT Subject Tests™, so you can't compare percentiles of different tests.

What Are Score Ranges?

Test scores are single snapshots in time—if you took the test once a week for a month, your scores would vary.

That's why score ranges are better representations of your true ability. They show how much your score can change with repeated testing, even if your skill level remains the same.

Usually your scores fall in a range of roughly 30–40 points above or below your true ability. There must be a difference of at least 60 points between your score and another student's to say that one of you performed better than the other. Colleges know this, and they get score ranges along with scores so they can consider scores in context.

Your online score report at sat.org/scorereport shows your score range for each test you took.

Should I Take the Test Again?

Each Subject Test measures your knowledge of a particular subject. If you continue to study the subject and take the test again, your new score should reflect your increased knowledge.

You can also register for other Subject Tests, or the SAT, at collegeboard.org/mysat.

SAT Summary of Scores

	Date	Dec. 01, 2018					
	Grade	11					
	SAT						
	Total	1560					
	Evidence-Based Reading and Writing	770					
	Math	790					
Essay	Reading	6					
Essay	Analysis	4					
Essay	Writing	6					
	Old SAT						
	Critical Reading						
	Mathematics						
	Writing						

SAT Subject Test Scores

	Date	June 01, 2019	June 03, 2017				
	Grade	11	9				
	Subject Test						
		Math Level 2	Biology-M				
	Test Score	800	800				
Language Subscores	Reading						
Language Subscores	Listening						
Language Subscores	Usage						
	Subject Test						
		Physics					
	Test Score	800					
	Subject Test						
	Test Score						

* Scores from the SAT Subject Test in Mathematics aren't comparable to Math section, test, and related subscores on the SAT.
*Not all SAT Subject Tests have subscores.

How Do I Send My Scores to Colleges?

This student score report is for your use only.

Most colleges require you to have the College Board send them official score reports. They don't accept copies of student score reports, online score reports, or score report labels on transcripts.

Can I Choose Which Scores to Send?

With Score Choice™, you decide which scores you send to colleges. Choose by test date for the SAT and individual test for SAT Subject Tests. Just make sure you follow each college's stated score-use policy.

What's Next?

Go to sat.org/scorereport and choose your next steps:

Student Score Report

AP® CollegeBoard

Report Date: 10/21/19

Rohan Subramani
433 Rutledge Dr
Yorktown Heights, NY 10598

AP Number: 77323295

School: 336085 - YORKTOWN HIGH SCHOOL

Year taken	Name of exam	Score
2019	Statistics	5
2019	United States History	5

Beyond the Project

Created: 09/26/2019 • Last updated: 11/13/2019

Information collected in this section is confidential and will not be shared with evaluators or judges. The Society will use this information for general record keeping, and to contact your parents/guardians, teachers, principals, etc. in the event you are named a Scholar or Finalist.

STUDENT INFORMATION

Your Contact Information

Your Cell Phone Number (optional)	(No response)
Your Home Phone Number	914-302-2528
Your preferred email address for long term contact:	rohan.subramani@yorktown.org

Your Address

Do you live in the United States or in a US territory?	Yes
Street Address	433 Rutledge Dr.
Street Address 2 (optional)	(No response)
City	Yorktown
State	NY
Zip Code	10598
Name of County	Westchester

Date of Birth (MM/DD/YYYY) 04/16/2002

Are you Hispanic or Latino? No

Regardless of your answer to the prior question, please indicate how you identify yourself (select all that apply). Asian or Asian American

T-shirt Size M

Explain your ability to speak, read, or write languages other than English (optional)

5.5 years learning to speak, read, and write Spanish.

Your Name for Public Materials

Please tell us how you would like your name to appear in public materials relating to the Regeneron Science Talent Search (official bio if selected as a finalist, press releases, etc). We collected your legal name in Task 1, but understand that you might prefer a different variation of your name to be used for public materials.

First Name for Public Materials	Rohan
Middle Name for Public Materials (optional)	(No response)
Last Name for Public Materials	Subramani

FAMILY INFORMATION

Do you have any siblings? (optional)	(No response)
Are any of your relatives former top 40 finalists or former top 300 semifinalists/scholars/honors group in the Science Talent Search (under Regeneron, Intel or Westinghouse sponsorship?)	No

Tell us more about Parent/Guardian #1:

Name	Shoba Viswanathan
Email Address	shobaviswanathan@yahoo.com
Do you share a primary mailing address with this Parent/Guardian?	Yes
Marital Status in Relation to Parent/Guardian #2 named below (optional)	Married

Tell us more about Parent/Guardian #2 (optional):

Name	Mahadevan Subramani
Email Address	msubramani@yahoo.com
Do you share a primary mailing address with this Parent/Guardian?	Yes
Parent/Guardian #2's State	NY
Parent/Guardian #2's Zip Code	10598
Marital Status in Relation to Parent/Guardian #1 (name is above)	Married

SCHOOL INFORMATION

Please provide additional information about your high school principal, and the teacher most closely associated with your application.

The teacher listed here will receive prizes if you are named a finalist.

Principal First Name	Joseph
Principal Last Name	DeGennaro
Principal Email Address	jdegennaro@yorktown.org
Teacher (at your HS) First Name	Rachel
Teacher (at your HS) Last Name	McNelis
Teacher (at your HS) Email Address	rmcnelis@yorktown.org

High School Newspaper

Please complete this section if your school has a newspaper or newsletter. We will notify this source if you are named a scholar or finalist so that your school community can celebrate this achievement.

Name of High School Newspaper	The Voice
Email Contact at High School Newspaper	cjohns@yorktown.org

PROJECT INFORMATION

Mentor Information

In a previous task, you shared the name(s) of your scientific mentors for your STS project. Please provide their contact information:

**if the names are not appearing correctly, please leave the mentor names blank, reference Task 4 and enter the contact information for the mentor(s) you listed in slots 1, 2, and/or 3.

Mentor/Supervisor Name 1	Tansu Daylan
Phone Number of Mentor/Supervising Adult 1	617-902-8724
Email Address of Mentor/Supervising Adult 1	tdaylan@mit.edu
Mentor/Supervisor Name 2	Maximilian Günther
Phone Number of Mentor/Supervising Adult 2	(No response)
Email Address of Mentor/Supervising Adult 2	maxgue@mit.edu
Mentor/Supervisor Name 3	
Phone Number of Mentor/Supervising Adult 3	(No response)
Email Address of Mentor/Supervising Adult 3	msubramani@yahoo.com

Do you have any patents related to your STS research?

Select all that apply

I do not have, nor do I plan to apply for any patents related to my research.

Do you have any patents unrelated to your STS research?

Select all that apply

I do not have, nor do I plan to apply for any patents related to my research.

Who has been the most positive influence on your scientific endeavors?

We will send a letter to this person to tell them that you chose them and to thank them for encouraging and assisting you.

Most Influential Person Prefix (Dr., Ms., etc.)	Mrs.
Most Influential Person First Name	Rachel
Most Influential Person Last Name	McNelis
Most Influential Person Address	2727 Crompond Road
Most Influential Person Address 2	(No response)
Most Influential Person City	Yorktown Heights
Most Influential Person Country	United States
Most Influential Person State	NY
Most Influential Person County Name	NY
Most Influential Person Zip Code	10598
Most Influential Person E-mail Address	rmcnelis@yorktown.org
How do you know this person? (maximum 75 words)	She is my Science Research teacher.

Do you intend to major in a STEM-related field in college? Yes