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Measuring the Relationship between Stellar Scintillation and Altitude: A Simple Discovery-based Observational Exercise used in College Level Non-major Astronomy Classes

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Abstract

A simple naked eye observational exercise is outlined that teaches non-major astronomy students basic observational and critical thinking skills but does not require complex equipment or extensive knowledge of the night sky. Students measure the relationship between stellar scintillation and the altitude of a set of stars. Successful observations provide a correlation that can reveal the fundamental cause of stellar scintillation. Altitude is measured using an outstretched fist (~9°), while stellar scintillation is measured using a 4-point subjective scale. Seven classes (300 students) have been evaluated and survey results of 72 students suggest the exercise is effective in teaching the intended population. Teaching techniques are outlined that may remediate misconceptions or challenge more advanced classes.

1. STELLAR SCINTILLATION

1.1. Introduction

Before starlight reaches a terrestrial observer it must pass through Earth's atmosphere. Cells of air at different temperatures and hence densities are formed in the atmosphere as air masses mix turbulently. The variation in densities between these cells causes the starlight to refract, and as these cells move in front of the star, the point-like stellar image appears to rapidly and randomly change brightness, color, and position. Since the apparent size of the star is much smaller than the apparent size of these atmospheric cells, the stellar image is affected more systemically than an apparently larger object like a planet. This visual phenomenon is called stellar scintillation or twinkling. A naked-eye planet such as Jupiter has an angular area larger than the average atmospheric cell. Therefore, more than one cell affects the planetary image at the same time. The appearance of the planet is the result of a time average of many cell's scintillation effects and the planet appears to have a more constant brightness.

The optical path length through the atmosphere determines how many cells the starlight will encounter and thus how much scintillation will occur. Therefore, stars at higher altitudes (lower zenith angles) should display less scintillation, while maximum scintillation will occur closest to the horizon. Local sources of atmospheric turbulence and heat produced by such things as terrain; nearby heat sources and meteorology can also change the amount of scintillation observed on a particular night or from a specific location.

Stellar scintillation is an important parameter in astronomical research since the greater the scintillation the poorer the resolution from an optical instrument. Therefore, astronomers seek the best locations and times for minimum scintillation and thus maximum optical resolution. This is commonly referred to as the quality of atmospheric seeing and is one of the reasons that remote island mountains are some of the best locations for large aperture research telescopes. Online computer models that forecast atmospheric seeing have been developed in order to assist in astronomical observations (Environment Canada 2012).

1.2. A Brief History of Stellar Scintillation

Those instructors who choose to include this exercise in their classes may benefit from a brief outline of the intellectual process that led to our current understanding of the phenomenon, something not easily found in most introductory textbooks. Nonetheless, the reader could skip this section without loss in continuity.

The history of stellar scintillation studies includes some of the greatest figures in Western science. The major hypotheses regarding the causation of the phenomenon can be divided into three camps; (1) those who believed scintillation is a phenomenon of vision, (2) those who thought scintillation was due to physical properties of the stars themselves, or (3) those who correctly saw it as caused by Earth's atmosphere. It is interesting to note that the student's own self-developed hypotheses fell into these three categories as well.

Aristotle in his *De Caelo* believed that vision was an outward phenomenon where the eye sent out "visual rays" (Stock 1930). According to Aristotle, the extra distance needed to travel past the planets to the stars caused these rays to become "weak and wavering," thus producing stellar scintillation. Some historians believe that Tycho Brahe may have been the first to suggest a possible atmospheric connection (Coulman 1985). Galileo Galilei and Johannes Kepler appeared to have believed the stars twinkle due to their own variability (Heilbron 2010). As the successful completion of this project should illustrate, the relationship between the amount of scintillation and the altitude of the star clearly points to an atmospheric origin. Thus, those students who are successful at this project can be told that they may, at least in this regard, be more clever than Aristotle or Galileo.

Robert Hooke may have been the first to outline the true origins of scintillation when in his *Micrographia* he wrote, "I find much reason to think, that the true cause of all these Phænomena is from the inflection, or multiplicate refraction of those Rays of light within the body of the Atmosphere." (Hooke 1665) Hooke then went on to suggest the origin on these "multiplicate" refractions was "that the parts of the Air are some of them more condens'd, others more rarified, either by the differing heat, or differing pressure it sustains, or by the somewhat heterogeneous vapours interspers'd through it."

Sir Isaac Newton also correctly connected the atmosphere to stellar scintillation. In his *Opticks*, Newton stated that twinkling was caused by "confusion of the Rays which arises from the Tremors of the Atmosphere." Newton then went on to predict modern-day mountaintop observatories by adding, "The only Remedy is a most serene and quiet Air, such as may perhaps be found on the tops of the highest Mountains above the grosser Clouds." (Newton 1730).

One of the first physical theories of stellar scintillation came from Lord Rayleigh (Rayleigh 1893). Today, the study of stellar scintillation is highly integrated into astronomical research as astronomers seek out the best possible observing conditions. Without sending a telescope beyond the turbulent atmosphere, astronomers and engineers have resorted to computer-controlled adaptive optics systems, which attempt to monitor and then correct for the wave front distortions caused by scintillation.

2. THE EXERCISE

2.1. Outline and Motivations

One of the challenges of introductory astronomy classes for non-majors is attempting to incorporate observational exercises into the syllabus that do not require an extensive learning curve. This exercise was developed to give novice non-major astronomy students a simple but rewarding observational project that is both real world and instructive. Real data are collected with all its biases and real world issues and thus is filled with pedagogical potential. The serendipitous nature of actually observing nature is one of the foundations of scientific discovery. This project attempts to give the students the opportunity to witness the benefits and excitement of chance discovery.

The project was also fashioned to discourage students from looking up the answer on the Internet or in the library and instead promotes a sense of self-discovery through observation and critical thinking. Therefore, no literature references are required for the final paper.

2.2. Procedure

The project is introduced in the first lecture, when full attendance is almost guarantied. A detailed outline of the project is contained in the syllabus, and a PowerPoint presentation is used to further illustrate the concept and the procedures. For safety and comfort reasons, students are encouraged to work in pairs. An “anti-procrastination” device is also included in the project and outlined in the instruction sheet. Leaving the project’s data collection to the last minute will certainly ensure a solid week of cloudy weather. This is something research astronomers face when provided with telescope-time and therefore provides a tangible connection to the real world of professional astronomy.

Students observe at least five different stars on three different nights. Students are to observe stars through a broad altitude range especially those closest to the zenith and the horizon. The altitude of the star is measured by using their outstretched fist where one fist-width is equal to about 9°. People with small hands normally have shorter arms and vice versa, therefore, the angular width of the fist is surprisingly consistent as long as the viewing distance and configuration of the fist is kept as constant as possible. The thumb should be placed on top of the index finger of the fist, and not in the palm. Students must estimate the location of the astronomical horizon and thus where to start their fist measurements. This altitude measurement technique is illustrated in the PowerPoint presentation, during subsequent lectures, and in laboratory exercises.

Scintillation values are determined from a four point subjective scale where “0” is reserved for stars that exhibit no apparent scintillation and “3” is applied to those that display the maximum scintillation observed on a given night. Students are also encouraged to record other parameters such as air temperature, wind speed, cloud cover, and sky brightness (light pollution and presence of the Moon). Over the time of the project some potentially interesting observations have occurred relating stellar scintillation and the presence of cumulus clouds, wind, and local terrain.

Students often ask if they must observe the same stars on each night or identify the individual stars they observe. This is not necessary but is not discouraged since carefully reducing experimental variables to a minimum is often good scientific practice and identification of individual stars may help them identify planets and thus provide extra learning opportunities for the student. The location and appearance of naked-eye planets is discussed in the lectures. Students are warned to be on the lookout for such objects, which can appear as outliers in their graphs.

The star’s altitude and scintillation is then graphed, and a correlation is found either through the application of a spreadsheet trend-line or through a visual estimation.

2.3. Results and Assessment

The exercise has now been offered in seven classes for a total of 300 students. A detailed survey was administered to the two most recent classes in the fall of 2012 and spring 2013. The survey was given on the final due date of the assignment. These two classes had a total of 85 students with 73 students taking the survey. The results of this survey appear in Table 1.

In a sample of students taken from the first year of the project 93% completed the assignment (40/43), but only 65% of those students who completed the assignment observed the correct correlation and 15% of those students deduced the correct causation. The completion rate has improved to 95% as measured from the last two classes the project was offered (81/85). In this more recent sample, an 11% improvement was observed in the number of students who successfully observed a negative correlation between stellar scintillation and altitude (76% of students surveyed), and in the same sample an improvement of 61% was seen in the number of students who deduced the correct cause of scintillation (76%).

Much of this improvement may be due to one change made in the pedagogical logistics implemented after the first year of the project’s inception. It appears that many significant errors can be easily identified and remedied if

Table 1. Survey results from two classes of a total of 72 respondents. The survey was presented in the fall of 2012 (37 responded out of 41 students) and spring of 2013 (35 out of 44 students). Questions 9 through 12 were inadvertently deleted from the second survey and so the sample size for these questions was 37.

No.	Response to question	%
1	Appeared to know the difference between cause and correlation	97
2	Claimed to have found that twinkle decreases with increased altitude	76
3	Claimed to have found that twinkle increased with increased altitude	4
4	Claimed to have found no correlation between twinkle and altitude	20
5	Believed their results showed that twinkle was caused by the atmosphere	76
6	Believed their results showed the star itself, caused twinkle.	15
7	Believed their results showed that twinkle was caused by vision	3
8	Had inconclusive results or could not tell what their results showed	5
9	Knew what caused twinkle before starting the class	5
10	Had never noticed that stars twinkle before taking the class	24
11	Had their observations in the project suggest why the stars twinkled	76
12	Found out why stars twinkle by doing their own reading	35
13	Had no difficulty understanding the project and its concepts	70
14	Claimed to have difficulty making graphs on a computer	30
15	Initially measured stellar brightness not twinkle	17
16	Enjoyed the project and did the entire project including coming up with a reason for why stars twinkle	57
17	Found the project interesting but put in only enough work to get the job done so they could concentrate on more important things—like their major.	41
18	Found the project unenjoyable, too difficult or intimidating	3
19	Were uncomfortable going out at night.	10

the students are asked to submit a preliminary report at least four weeks before the final draft is due. Only their graphs and data were submitted, and 20% of the project's final grade is attached to this early submission. It should be noted that about 10% of those students who handed in a final draft do not submit a first draft, thus failing to benefit from this evaluation.

From the survey of the most recent semester, eight of the ten students (80%) who measured an incorrect correlation between altitude and scintillation reported having difficulty with the assignment while only 40% of those who correctly recorded a negative correlation reported having difficulty with the project. The most common error uncovered in the first draft and subsequently supported by the survey results appeared to be students mistakenly measuring the star's brightness rather than its scintillation. (See Table 1.) In the sample of students surveyed, those who observed no correlation between altitude and scintillation (9/37 24%) or a positive correlation (1/37 3%) were 38% more likely to have initially measured stellar brightness rather than scintillation in comparison to those students who successfully measured a negative correlation. This error in understanding was often revealed in their first drafts as an uncorrelated relationship in their graphs. Almost a quarter of the students surveyed had never before observed the twinkling of stars. (See Table 1.) However, the survey suggests that this was not the reason the students mistakenly measured stellar brightness. None of the students who made this error were amongst those who had reported never witnessing the phenomenon of stellar scintillation before taking the class. Motivation did not appear to be the reason either. Motivation was not correlated with incorrect measurements since the percentage of students who reported moderate to low motivation (response numbers 17 and 18 in Table 1) were the same in the group that successfully measured the appropriate correlation. Therefore, further analysis may be needed to uncover the underlying cause of this misunderstanding.

Another issue found in the first draft (but not tested in the survey) was the students neglecting to measure stars near the zenith and horizon and thus confining their data to a relatively narrow band of altitude in the middle of the sky. As in much of experimental science, it is at the extremes of the independent variable that can cause correlation to become most apparent. Again, this is easily diagnosed through a quick examination of their preliminary graphs.

Students with any of these deficiencies were encouraged to do at least one more night's observing before the final due date. Rapid evaluation of the student's first draft was crucial since clear sky opportunities are limited.

Difficulties producing graphs on a computer was also a commonly reported issue (10/37 or 27%) and was easily identified in the first draft. Students with limited experience with spreadsheet software were encouraged to graph their results by hand. A short review of graphing techniques, such as visually fitting a trend-line, was done in the middle of the semester.

The survey suggests that the assignment was effective in leading a majority of the students (76%) to conclude that stellar scintillation is caused by the earth's atmosphere. Only 5% of the surveyed students claiming prior knowledge of the cause of scintillation which suggests that the project is effective in teaching the cause of scintillation. The results also suggest that the project was appropriate for the level of the class since only a handful did not complete the project and only 3% (one student) found the project "enjoyable, too difficult or intimidating."

2.4. More Advanced Exercises

The project may be augmented to suit the abilities and ambitions of the students. The theoretical trigonometric relationship between the amount of scintillation and the altitude of the star could be derived by those students with more advanced mathematical skills. The relationship is found by deriving the equation for the starlight path-length through the earth's atmosphere. A simple cosine relationship can be deduced from the angle produced by the altitude of the star a, and the triangle formed with the points defined by the observer, the center of the earth of radius r, and the top of a scale atmosphere of height H. Also, extra credit may be awarded to those students who could infer and then articulate why planets do not appear to scintillate as much as stars.

To challenge the student's critical thinking abilities, the class also could be presented with a real-world, flawed hypothesis as to the cause of scintillation. In a strange case of ancient notions resurfacing, a paper published in *Nature* (Hartridege and Weale 1949) suggested the perception of scintillation was caused by the stellar image moving over local variations in the retinal receptors. Students could be asked to review the paper and then comment on the hypothesis with respect to their own observations. Care would need to be taken so as not to bias the students with regard to the instructor's opinion regarding the validity of this paper.

3. CONCLUSION

Observing the relationship between altitude and stellar scintillation appears to provide a simple and effective exercise for non-major astronomy students. The project attempts to instruct the students in basic observational/ measurement skills, graph making and interpretation, and critical thinking skills. Evaluation of four years of implementation has suggested that such a project can be an effective technique in providing discovery-based learning in non-major astronomy students. The project has room for expansion for more advanced students and to include more critical thinking opportunities. Anecdotal evidence gleaned from informal discussions with the students also appears to reveal one other advantage to the project: Many students felt it was fun and surprising.

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