From Real-Life Astrophysics Research Questions to Olympiad Problems

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Outline

- Background about the Olympiad
- Motivation for this project
- Problem I: Virgo's Magnetic Noise
- Problem II: The Reionization of the Universe
- Problems III and IV: Transiting Exoplanets and Eclipsing Binary Systems
- Conclusion

Background About The Olympiad

IOAA (International Olympiad on Astronomy and Astrophysics)

- Annual global competition for high school students, founded in 2007
- Focuses on theoretical, data analysis, and observational astronomy problems
- Aims to promote astronomy education and cross-cultural scientific exchange
- 57 participating countries in 2024

IOAA-Jr (International Olympiad on Astronomy and Astrophysics – Junior)

- Newer initiative for younger students (middle school level), started in 2022 in Romania
- Provides early exposure to astronomy and scientific thinking
- Includes a mix of practical and theoretical challenges tailored to age level
- 19 participating countries in 2024

Each country has its own selection process

Challenges in Romania

- No official astronomy classes in the national curriculum for middle and high school
- A few NGOs and astronomy clubs offer extracurricular lessons
- Limited access to study materials (mainly outdated textbooks and past Olympiad problems)
- Despite this, growing student interest and increasing participation in the Astronomy Olympiad since its inception in 2007

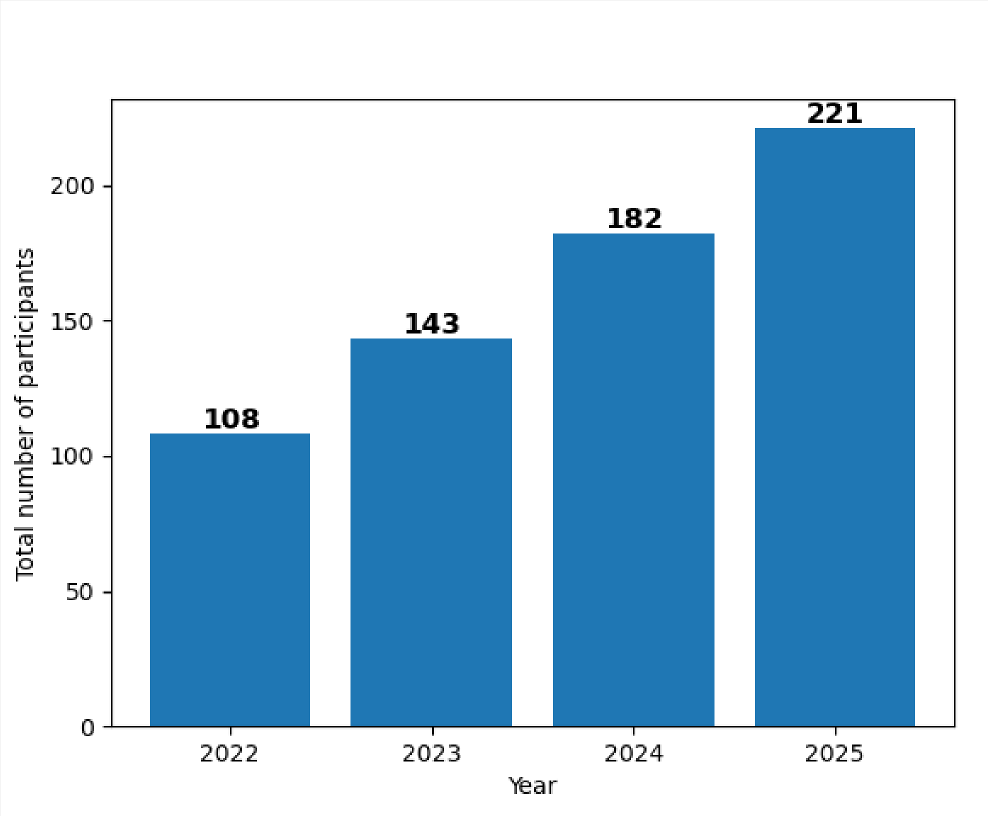

Figure 1. The evolution of the number of participants in the National Olympiad of Astronomy and Astrophysics in Romania.

Motivation

- Olympiad exams offer a unique opportunity to introduce current research topics
- Ensures that outreach reaches motivated students
- Encourages scientific curiosity through real-world, relevant contexts
- Aligns problem difficulty with students' existing math and physics skills
- Helps bridge the gap caused by limited access to up-to-date astronomy resources

Problem I: Virgo’s Magnetic Noise

- Problem inspired by research stay at Virgo gravitational wave detector
- Part of Data Analysis task at the National Olympiad in 2023
- Introduces the importance of environmental noise characterization before an observing run, with focus on magnetic noise [1]
- Students analyse the response of the detector to magnetic line injections

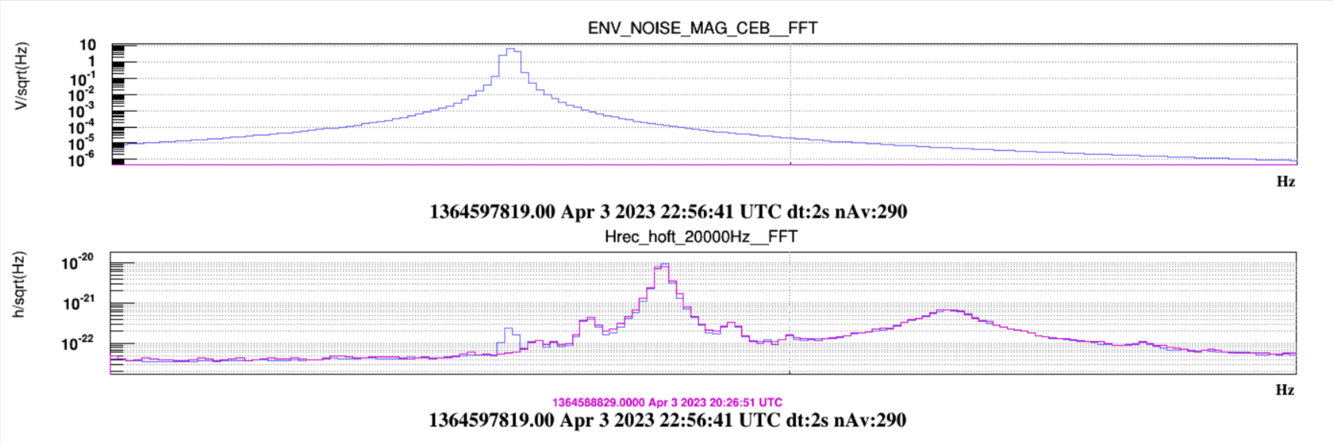

Figure 2. Example of a line injection (in blue) compared to the background signal outside of injection time (in pink). The line appears in the magnetometer channel (top) and in the interferometer's main channels: Hrec (middle) and DARM (bottom) at the same frequency.

Virgo's Magnetic Noise – Summary

- Data from 20 injections at logarithmically spaced frequencies
- Coupling function (CF) formula between magnetometers (X) and interferometer (Y)

$$CF(f)=\sqrt{\frac{Y_{inj}^2-Y_{bkg}^2}{X_{inj}^2-X_{bkg}^2}} \quad (1)$$

$$CF_{ul}(f)=\frac{Y_{bkg}}{\sqrt{X_{inj}^2-X_{bkg}^2}} \quad (2)$$

- Criteria between measurable couplings and upper limits
- Tasked with calculating these couplings and upper limits, and plotting the results

$f(Hz)$	$X_{inj}\,(nT)$	$X_{bkg}\,(nT)$	$Y_{inj}(m)$ $\times 10^{-18}$	$Y_{bkg}(m)$ $\times 10^{-18}$	$\frac{X_{inj}}{X_{bkg}}$	$\frac{Y_{inj}}{Y_{bkg}}$	$CF(f)\left(\frac{m}{T}\right)$ $\times 10^{-11}$	$CF_{ul}(f)\left(\frac{m}{T}\right)$ $\times 10^{-11}$
10.00	363.40	0.02	1278.46	1266.61	18170	1.01	-	348.54
12.74	431.91	0.04	322.67	104.27	10797	3.09	70.70	-
16.24	451.09	0.07	173.33	26.03	6444	6.66	38.00	-
20.69	435.11	0.17	97.30	43.46	2559	2.24	20.00	-
26.37	396.32	0.33	67.85	51.99	1200	1.30	-	13.12
33.60	357.63	0.06	22.37	1.79	5960	12.50	6.23	-
42.81	343.03	0.03	16.44	0.50	11434	32.88	4.79	-
54.56	328.85	0.02	4.17	0.58	16442	7.19	1.26	-
69.52	295.71	0.15	5.11	0.22	1971	23.23	1.73	-
88.59	234.26	0.03	1.42	0.18	7808	7.89	0.60	-
112.88	179.06	0.05	0.56	0.15	3581	3.73	0.30	-
143.84	134.47	0.02	0.31	0.16	6723	1.94	-	0.12
183.30	102.81	0.01	0.15	0.12	10281	1.25	-	0.12
233.57	79.91	0.01	0.14	0.17	7991	0.82	-	0.21
297.63	62.94	0.01	0.15	0.15	6294	1.00	-	0.24
379.27	49.84	0.01	0.15	0.11	4984	1.36	-	0.22
483.29	39.15	0.01	0.30	0.28	3915	1.07	-	0.72
615.85	29.85	0.01	0.12	0.12	2985	1.00	-	0.40
784.76	21.44	0.01	0.12	0.11	2144	1.09	-	0.51
1000	13.62	0.01	0.16	0.13	1362	1.23	-	0.95

Table 1. The table provided served as the initial dataset for students' analyses. Cells highlighted in red were left blank for students to complete as part of the exercise.

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Virgo’s Magnetic Noise

Skills Tested:

- Understanding a logarithmic scale and how a power dependency looks like in this scale
- Fitting a dataset using the least squares method
- Determining the slope of the fitted

Scientific Concepts:

- Noise sources in gravitational wave
- Noise injection campaigns and the equipment used
- The formula for coupling function and its upper limit

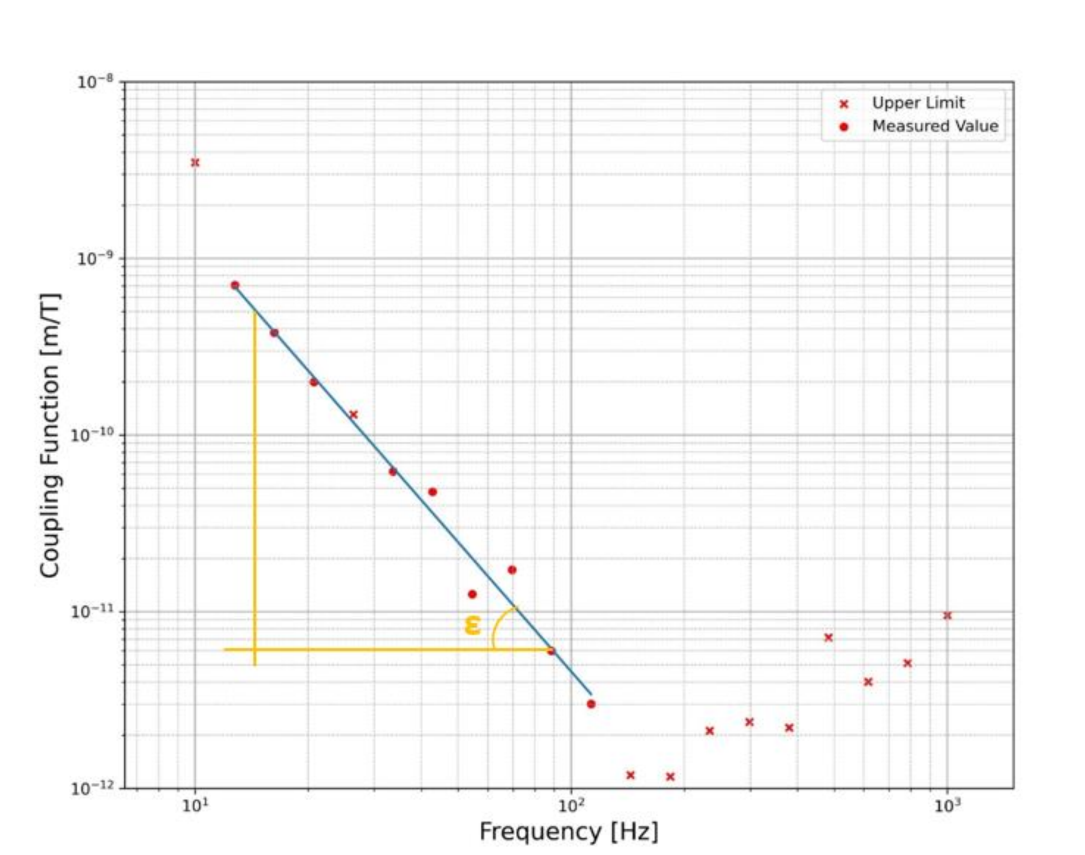
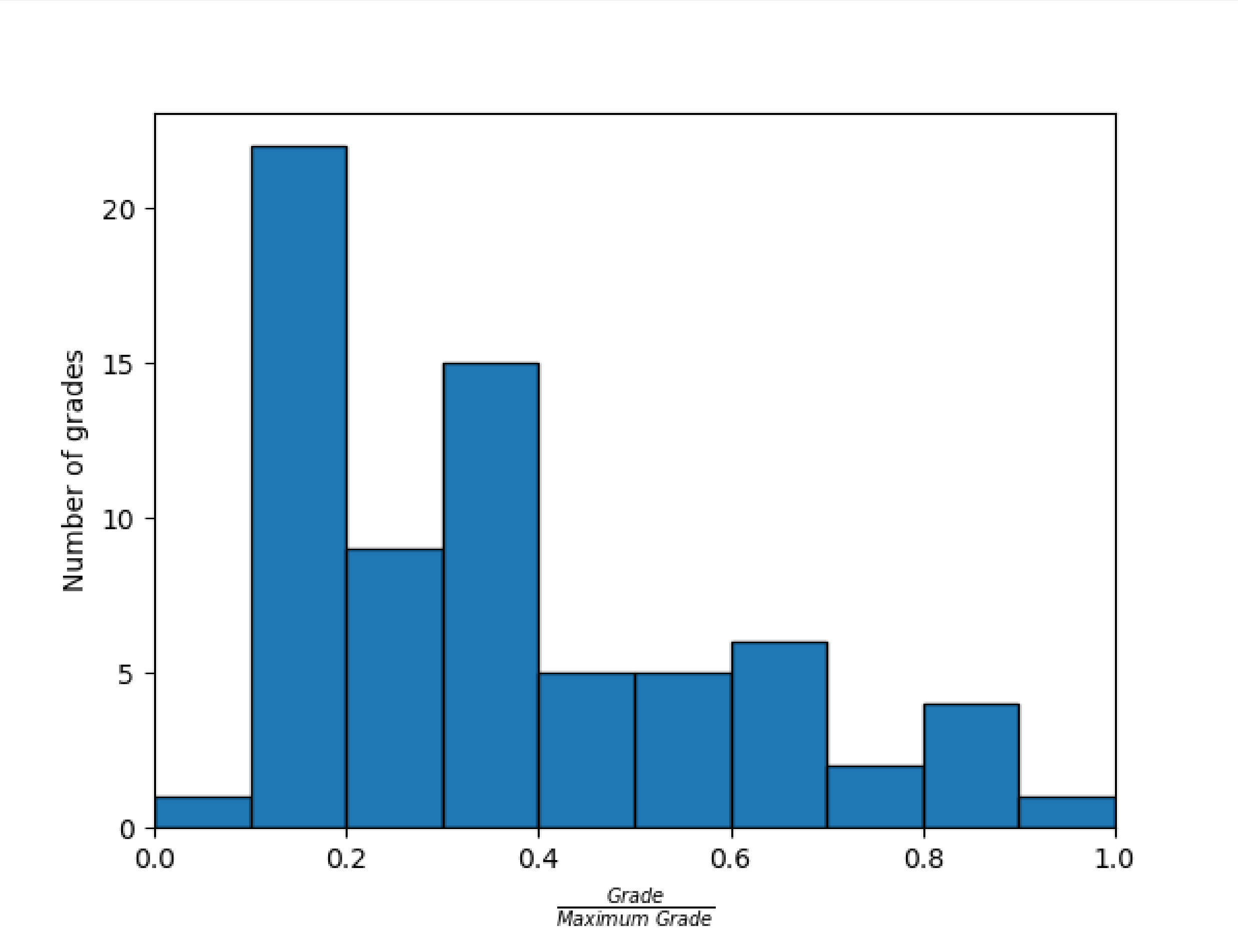


Figure 3. The final graphic result of the exercise.

Virgo’s Magnetic Noise – Student Performance

Figure 4. Grade distribution for this problem.



Problem II: The Reionization of the Universe

- Problem inspired by my summer research project at IPAC, Caltech in 2016
- Adapted for use in the National team selection process in 2017
- Introduces students to the hypothesis that galaxies with strong oxygen emission lines were major contributors to reionization [2]
- Focuses on galaxies from the COSMOS field [3]

The Reionization of the Universe – Provided Data

- The coordinates (RA and DEC) of 5 galaxies in the COSMOS field and the ACS image of the field (Figure 5)
- Galaxy spectra from a spectrograph with a 5550–9450 Å wavelength range (Figure 6)
- Close ups of the [O II] and [O III] emission lines for each spectrum (Figure 6)

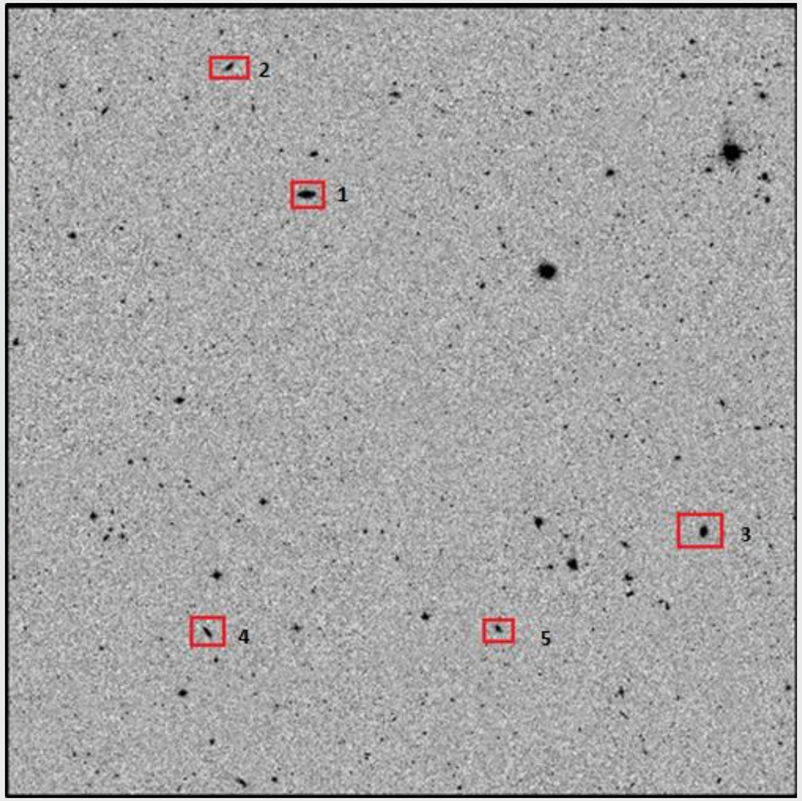


Figure 5. The ACS image of the galaxies of interest[4]. Based on their equatorial coordinates, students were tasked to identify the galaxies in the red boxes (unmarked in the exam question).

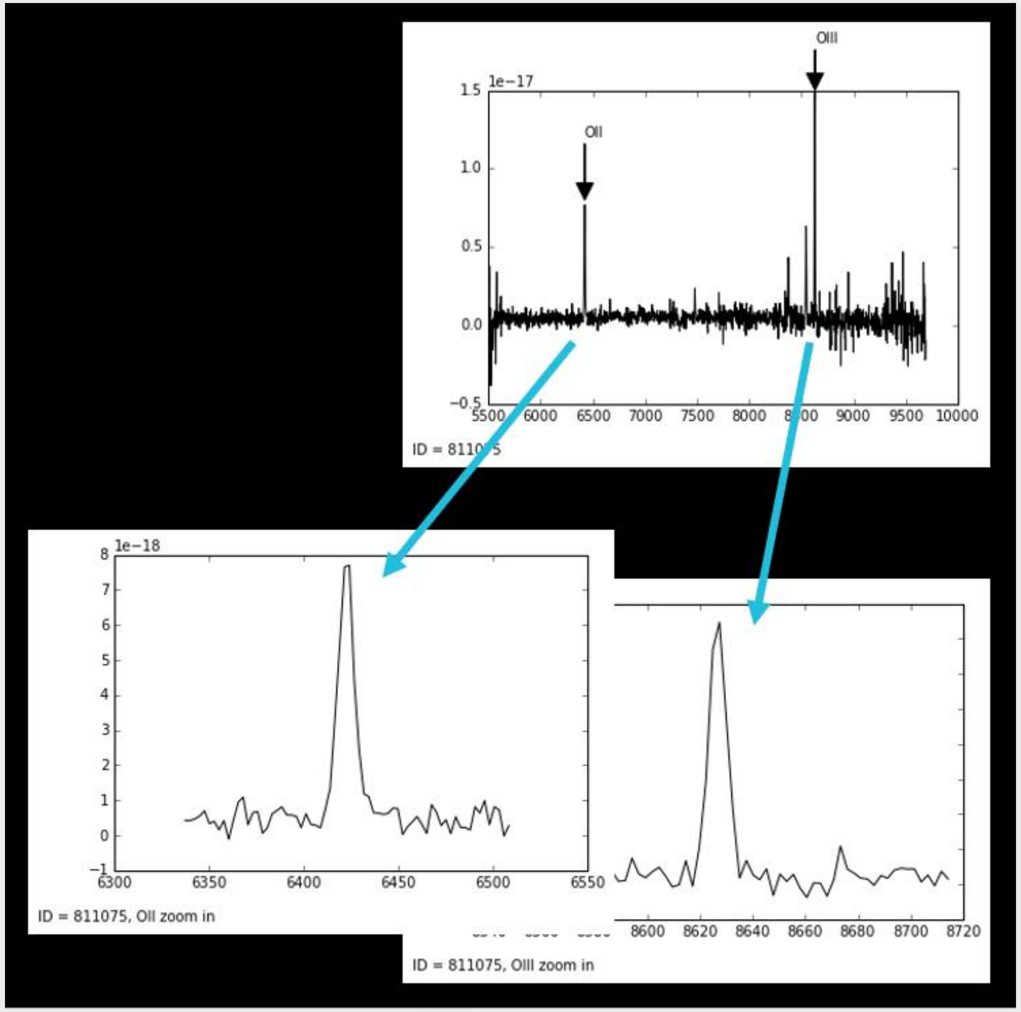


Figure 6. One of the five galaxy spectra used by the students (top), together with the zoom-ins on the oxygen lines (bottom).

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The Reionization of the Universe - Tasks

- Calculate redshift intervals to determine the visibility of both [O III] and [O II] emission lines in this spectrograph;
- Identify the 5 galaxies of interest on the ACS image based on their celestial coordinates (Figure 5);
- Estimate cosmological redshifts from the real spectral data;
- Measure the continuum and emission line fluxes using basic approximation techniques (Figure 7);
- Compute the f_OIII/f_OII flux ratios and rank the galaxies according to these values.

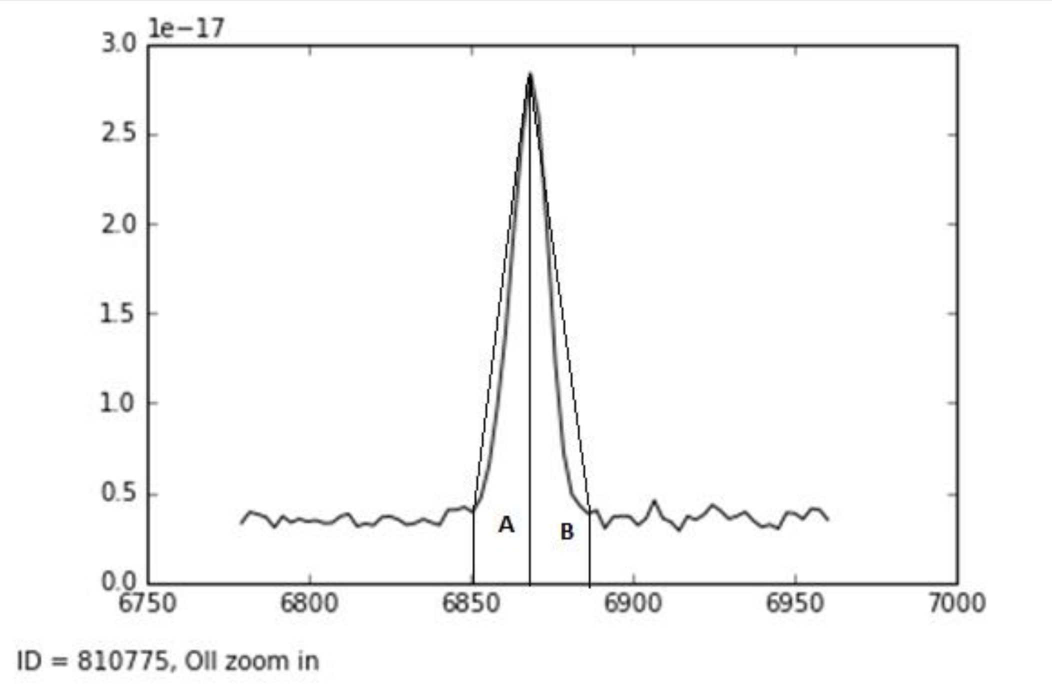

Figure 7. Example of the approximation used to calculate the area under the emission line.

The Reionization of the Universe

Skills Tested:

- Performing an astronomical image search to identify objects based on known coordinates, using a reference point with given celestial coordinates;
- Understanding and calculating cosmological redshift using spectra and spectral lines;
- Recognizing that the intensity of an emission line corresponds to the area under the spectral curve and estimating this area using a trapezoidal approximation;
- Keeping the correct number of significant figures.

Scientific Concepts:

- That galaxies with high [O III]/[O II] emission line ratios are likely to emit large quantities of ionizing UV photons;
- The significance of the COSMOS field as a well-studied multi-frequency region for galaxy evolution research;
- The importance of background subtraction in extracting reliable physical quantities from astronomical data.

Problems III and IV: Transiting Exoplanets and Eclipsing Binary Systems

- Use citizen science lightcurves from Zooniverse.org:
  - For exoplantes transits – Planet Hunters Tess[5-7] https://www.zooniverse.org/projects/nora-dot-eisner/planet-hunters-tess
  - For eclipsing binary star systems – Eclipsing Binary Patrol [8,9] https://www.zooniverse.org/projects/vbkostov/eclipsing-binary-patrol

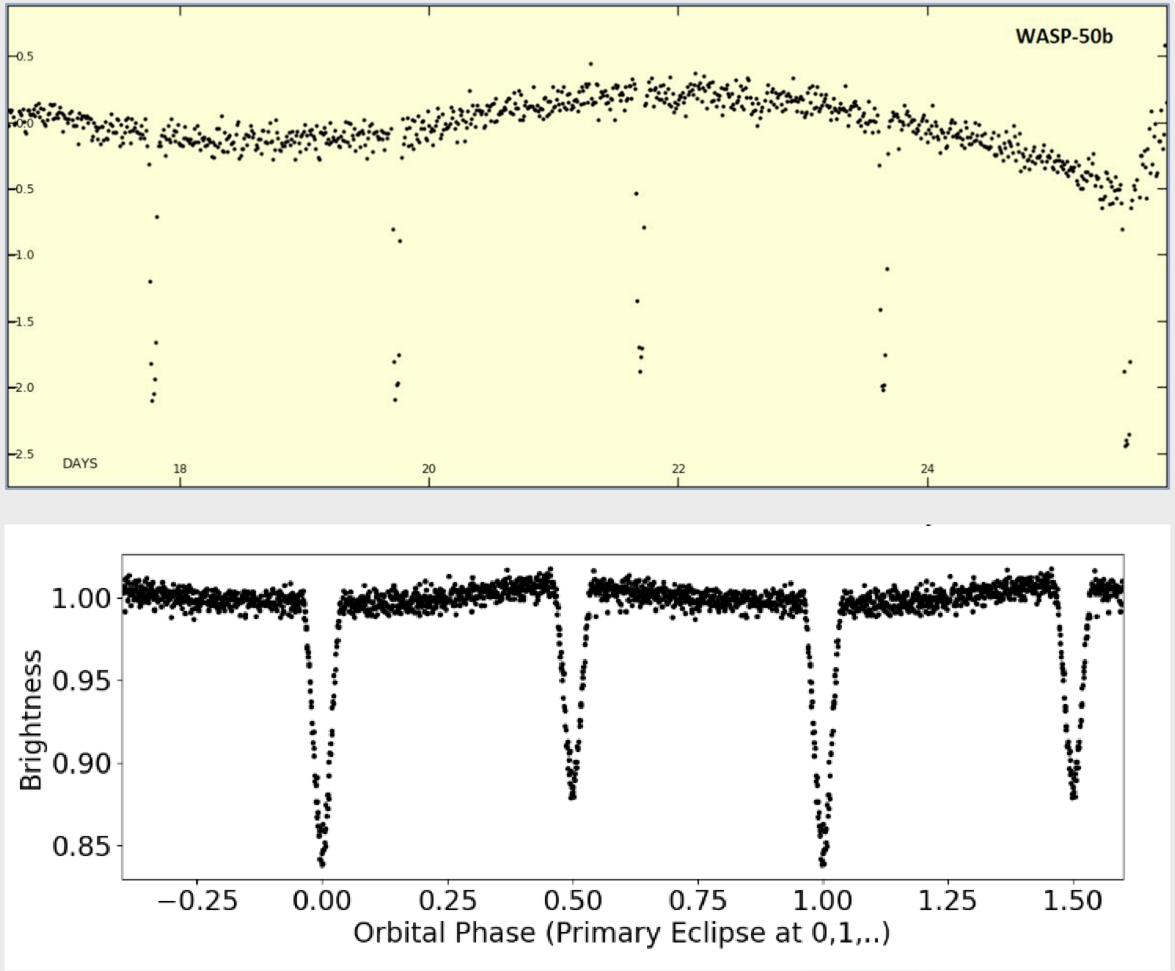

Figure 8. Top: transiting exoplanet lightcurve from TESS project. Bottom: Phase wrapping lightcurve from Eclipsing Binary Patrol Project.

Problems III and IV: Transiting Exoplanets and Eclipsing Binary Systems

Skills Tested:

- Understanding lightcurve shapes, based on physical reasoning involving orbital mechanics, planetary and star radii, and orbital periods;
- Extracting measurable quantities: Ability to determine values like the orbital period and planet/star radius ratio (Rp/Rs) or star1/star2 ratio (Rs1/Rs2) from lightcurve data;
- Error estimation from repeated measurements.

Scientific Concepts:

- How citizen science contributes to state-of-the-art research;
- Current status of the exoplanet detection field;
- How to calculate an orbital phase curve from a lightcurve of an eclipsing binary star system.

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Conclusion

- Olympiad problems can be outreach tools
- Introduce modern workflows and ideas
- Real scientific data use in exam settings
- Encourage high school students to pursue scientific careers

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Thank you for your time!
Questions?