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RESOURCES & ACTIVITIES

Adapting Betelgeuse's Dimming Event to A High School Level Astronomy Exercise

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Abstract

This article outlines the process of designing a problem for Astronomy Olympiad at high-school level, based on a recent curious astrophysical event. Betelgeuse, one of the brightest star in the night sky and a supernova candidate, started dimming in October 2019 and reached a record minimum magnitude in February 2020. This extraordinary event piqued curiosity in professional astronomers, amateur astronomers as well as mass media. The problem presented here, tries to build a quantitative model of the event for the students, based on just high school physics. This problem included three models viz., a stellar pulsation model, an exoplanet transit model and a mass loss event model. The students were asked to calculate few physical quantities or parameters to deduce the most suitable model. The entire process of problem design including constraints involved, alternative approaches explored and discarded and the final draft is laid out. It is hoped that this discussion will serve as a guiding light to fellow problem designers and question setters.

Keywords: Betelgeuse Dimming; High School; Problem Design; Olympiad

1 Introduction

It is widely acknowledged that most of the members of the society are fascinated about the celestial bodies and phenomena. People like looking at the night sky and those who have internet access readily consume astronomy related e-content like videos or simulation applets. Science sections of newspapers are always keen to publish stories and pictures of astronomical discoveries. This natural interest of students in astronomy is what has prompted International Astronomical Union (IAU) to set up an Office of Astronomy for Education (OAE). One of the mandates of OAE is to leverage the students' interest in astronomy to increase their engagement with other Science, Technology, Engineering and Mathematics (STEM) subjects. Salimpour et al. (2020) shows that in Organisation for Economic Co-operation and Development (OECD) countries as well as in China and South Africa, astronomy is included in the school curriculum. In context of India, astronomy content forms only a tiny fraction of the whole school curriculum (CIET, NCERT (2022), CBSE Research & Development Unit (2021)). Anecdotal evidence as gathered from discussions with various International Olympiad on Astronomy and Astrophysics (IOAA) team leaders of many countries reveal similar conclusions about missing/minor component of astronomy syllabus in school curricula. Further, the primary focus of the astronomy content in school curriculum (wherever it is present) is factual information about the solar system and other observable phenomena. There is not much effort to convey physics behind these celestial phenomena and hardly any scope for quantitative analysis. Thus, many astronomy educators are looking for external prompts (e.g. activities, projects, problem sets etc.) which can help connect students' factual knowledge about celestial bodies to these skills required for understanding modern astrophysics.

Olympiads are competitions at the high school level (grades 10-12) which test students' competency in quantitative analysis and conceptual clarity. There are different Olympiads focused on different curricular subjects. Like many other countries, India too registers teams of students to participate in different Olympiads such as International Physics Olympiad (IPhO), International Chemistry Olympiad (IChO), International Biology Olympiad (IBO), International Mathematical Olympiad (IMO) etc. In the subject domain of Astronomy, India sends a team each year to participate in International Olympiad on Astronomy and Astrophysics (IOAA). A national level selection process, involving multiple stages of selection tests, is organised each year to select the Indian team for this competition. This article discusses one question which was included in Indian Olympiad Qualifier in Astronomy (IOQA) part II examination held in February 2021.

In October 2019, astronomers were intrigued by unusual dimming of the star Betelgeuse in the constellation of Orion. This dimming was reported widely in different media channels and there was a lot of excitement around it in amateur astronomy community, which translated into a curiosity about this event among everyone who had even a faintest interest in Astronomy. There were different physical models proposed to explain this dimming and some of the models included some exotic scenarios as shown in section 2 which generated further media attention. We noticed that most of the outreach related to this event only explained the models qualitatively and hardly any numerical estimates were discussed. The authors of this article took it upon themselves to design a problem for IOQA, which can convey excitement around this rare celestial event to high school students, by allowing them to investigate validity of some of the models by applying high school level physics.

We demonstrate that core scientific ideas behind real world astronomical phenomena and complex research problems can be presented to school students in a simplified form accessible at their pedagogic level. The simplified models used may differ in detail from the actual models used by the researchers (e.g. assuming the star to be non-rotating or using volume density of dust rather than column density), but they are still useful in conveying the broad picture of how modelling is a useful tool in scientific research and how fine tuning process in modelling works. The students can get a feel of how some of the models lead to totally absurd situations that researchers may rule them out based on even crude, simplified calculations. The purpose of this article is to explain the process of resource generation to encourage other educators to explore these kind of examples in the school science classrooms.

In Section 2, we do a brief recap of the Betelgeuse dimming event from astrophysical perspective. In section 3, we discuss the examination structure, marking strategy, design principles, constraints and the actual problem statement. We also briefly discuss alternative problem formations considered and discarded. Lastly, in Section 4 we will discuss learning for the future from this exercise.

2 The Extraordinary Dimming of Betelgeuse

Betelgeuse is one of the nearest red super giant star to the solar system. Its proximity has made Betelgeuse one of the best observed late type massive star. Betelgeuse has the largest angular diameter after the Sun. Both the light curve and the photometry of the star indicate appearance of intermittent bright spots associated with irregular variability in the star's luminosity and temperature (Dolan et al., 2016). It has also been observed that the star has a shell of circumstellar material and it ejects mass at rate of $\approx 3 \times 10^{-6}$ $M_{\odot}$/yr (Kervella et al., 2016), (Dolan et al., 2016). Betelgeuse is a candidate for a core-collapse Type II supernova. What makes this star interesting is it can undergo a supernova explosion anytime. For over past 180 years, the semi-regular variability of Betelgeuse has been documented using the photometric data. It is hence classified as a semi-regular variable with a period of ≈ 2335 days. The radial velocity data also shows semi-regular variability over a similar period (Chatys et al., 2019) (Dupree et al., 2020).

In November 2019, observers across the globe reported a drop in the visible band magnitude of Betelgeuse. By February 2020, magnitude drop was over 1 magnitude and Betelgeuse became the dimmest observed in recorded history. This drop was noticed even in the amateur astronomer circles and speculations aroused regarding a possible supernova event.

Despite the speculations in amateur circles of a possible supernova event, the scientific consensus settled on two theories viz., 1) convection of stellar material near the surface (convective cells) could lead to decrease in temperature and hence the V band magnitude and 2) the star must have undergone mass loss and the ejected mass could have condensed, leading to the obscuring of the light from the star.

Comparison of observations using Spectro-Polarimetric High-contrast Exoplanet REsearch (SPHERE) and Very Large Telescope Interferometer (VLTI) on 29 Dec 2019 and earlier observations of Betelgeuse revealed that there was a dimming in the southern hemisphere of the star which resulted in change in apparent shape (Levesque and Massey, 2020). This was attributed to formation of dust clouds in the stellar atmosphere. With the help of sub-millimeter and polarization studies Dupree et al. (2020) suggested that there was no significant decrease in T_{eff} as compared to the decrease in brightness. If the convection of stellar material near the surface caused temporary low apparent T_{eff}, other signature like strong titanium-oxide bands in the stellar spectra would have been visible and the decrease in T_{eff} would have been substantial. However, this is not the case of Betelgeuse, since there was no significant drop in T_{eff} (Levesque and Massey, 2020) and hence could not be considered as the primary reason.

This brings us to the second possible explanation of formation of dust due to mass loss from the star. Such dimming has been observed in other similar stars in the Milky Way and nearby satellite galaxies. Literature also suggests that the time scales of dimming agrees with mass loss and dust formation in red super giants. The mass expelled by the star condensed and formed large dust grains of the order of microns. This causes the V band magnitude to decrease and also justifies why there is no significant change in T_{eff}. In the exercise below, we used the dust formation model and simplified it so that students can visualise the geometry and more or less get to work with a model based on latest research.

3 Design of the Problem

The exercise designed is guided exploration of three specific models that might explain the extraordinary dimming of Betelgeuse. Question comprises of a light curve (plot), which the students were supposed to read and interpret. The three possible scenarios were then presented as 3 sub-questions, wherein the students calculate various parameters or quantities and infer if the presented scenario is physically possible. The light curve data was taken from American Association of Variable Star Observers (AAVSO) International Database (https://www.aavso.org).

3.1 Indian Olympiad Qualifier in Astronomy (IOQA)

Indian Olympiad Qualifier (IOQ) is a national olympiad program conducted by the Government of India. The aim of this program is to promote excellence in science and mathematics among class 10 to 12 students (age $\sim$ 15 to 18 years) of the Indian educational system. The IOQ is a voluntary extra-curricular competition. This program leads to training and selection of the Indian team which represents India in the International Olympiads.

The Indian Olympiad Qualifier in Astronomy (IOQA) examination comprises of two parts. IOQA part I is a multiple choice question paper while IOQA part II is a descriptive paper. IOQA part I is used as a qualifying examination for IOQA part II and has no role in selection to the international olympiads and hence will not be discussed here. The question discussed in this manuscript was a part of IOQA part II for the year 2021. The 2021 IOQA part II consisted of 5 questions for a total of 80 marks, and the question under consideration here consisted of 3 subparts worth 8, 9 and 7 marks each. The questions for IOQA part II are designed with the understanding that the students will have none to a very limited exposure to astronomy and astrophysics.

Since the examination in question is an external optional examination specifically related to astronomy, it is natural to expect that the participants will possess basic knowledge of the subject either through their school curriculum or extra readings out of their interest in the subject. These concepts includes amateur level topics like phases of moon, eclipses, some bright constellations, distances to planets and nearest stars and order of magnitude values for masses of stars, speeds of planets etc.

The problems are designed to understand the thought process of the student rather than concentrating on only the final answers. Hence, sometimes Fermi type (open-ended) questions are also included in the paper. Such open ended questions are very crucial to check student understanding, their process and logic for making assumptions and logical thinking. The paper also consists of some guided questions as the one in discussion in this manuscript, which introduces students to previously unknown concepts and test their skills of comprehension of such concepts in the exam setup. As it will be evident in later sections, the solutions to such questions are purely based on high school physics.

Calculus is introduced in the final year of high school, whereas many of the participating students are from lower grades. It should thus be noted here that most of the students appearing for this competition may not be familiar with calculus and hence a mandatory non-calculus based solution has to be present for any given question. A calculus based solution is also completely acceptable and the student is given due credit. The grading/evaluation system is made keeping in mind the principle mentioned above. The process leading to the solution is considered more important than the final answer itself. Students are asked to write their assumptions and necessary justifications clearly in the answer sheets.

Another grading principle followed is the rule that same mistake should not be penalised twice in the same solution. For example if a student makes a numerical / transcription error in the early part of solution a small penalty is given in that step for carelessness. After that it is assumed that further solution will diverge from the original due to this mistake and no further penalty is imposed. It is expected that student comprehends the feasibility of the obtained value in the answer, for example if obtained value for speed of an object exceeds that of speed of light, then the student is expected to acknowledge the problem. Reading values from graphs, visual fit to the plots, approximate plots of the functions are also tested.

3.2 Guiding principles of the design process

Before introducing the final statement of the exercise as it appeared in the examination, we briefly list the considerations which went into the final statement.

Design constraints

- As mentioned in the introduction the participants lack formal training in astrophysics. Hence the question text must include detailed explanation of necessary concepts.
- The introduction of any new concept should be done in such a way that it can be cognitively processed by most of the students in a time-limited and stressful environment of high stakes examination. This may lead to simplified / formulastic boiling down of new concepts, but it can't be helped.
- As many of the participants may not be familiar with calculus the problem assumes that the star is perfectly spherical with uniform density and it expands uniformly. Further in model C of the problem, density of the ejected gasses is assumed to be uniform in the whole ejecta.
- Students at this level are not familiar with pseudo forces. Further, in model C the tip of the ejecta is attached to the stars' surface. To keep the calculations within the reach of students, we must specify that the star is a non-rotating one.
- Modelling stellar expansion is a non-trivial exercise. However, at high school level the best approach can be to imagine the expansion comprising of large number of small steps, where during each step the star remains in quasi-equilibrium and hence can still be expected to behave like a black body.
- Betelgeuse is only a semi-regular variable. Further, students may not even have read about variability of Betelgeuse before. Thus, in the dataset, it may be safer to explicitly point them towards the starting point of particular event that we are interested in.
- To simplify the question further, we ask the students to calculate the average density of the cone instead of column density which might make the problem even more complex. Obviously, at the level of this examination, students are not expected to be familiar with concept of opacity. Hence, we do not introduce opacity in the question.

Skills and concepts to be tested

- Understanding of Kepler's Laws of planetary motion.
- Ideal Black body and Stefan-Boltzmann law.
- Small angle approximations and trigonometry.
- Visuo-spatial ability.
- Visual fitting of a best fit to a large dataset on a scatter plot. Judicious determination of statistical outliers.
- Reading of graph.

3.3 The question text and solution

Preamble

Betelgeuse, a red supergiant star, in the constellation of Orion, is known as an irregular variable star. Its magnitude varies between +0.3 to +1.0 from time to time. However, last year astronomers were surprised to observe an unexpected dimming of Betelgeuse. We may assume this event started from 12 October 2019.

Notes

- The relation between magnitude of the star and light flux received from it is given by :

$$m_1 - m_2 = -2.5\, log_{10}\left(\frac{F_1}{F_2}\right)$$

  where m_1 and m_2 are magnitudes measured in two different observations and F_1 and F_2 are corresponding light fluxes.
- Mass of Betelgeuse: $M_B = 2.1 \times 10^{31}$ kg
- Distance of Betelgeuse from the Earth: $d_B = 200$ pc
- Typical radius of Betelgeuse: $R_1 = 6.17 \times 10^{11}$ m
- Mass of Earth: $M_\oplus = 5.972 \times 10^{24}$ kg

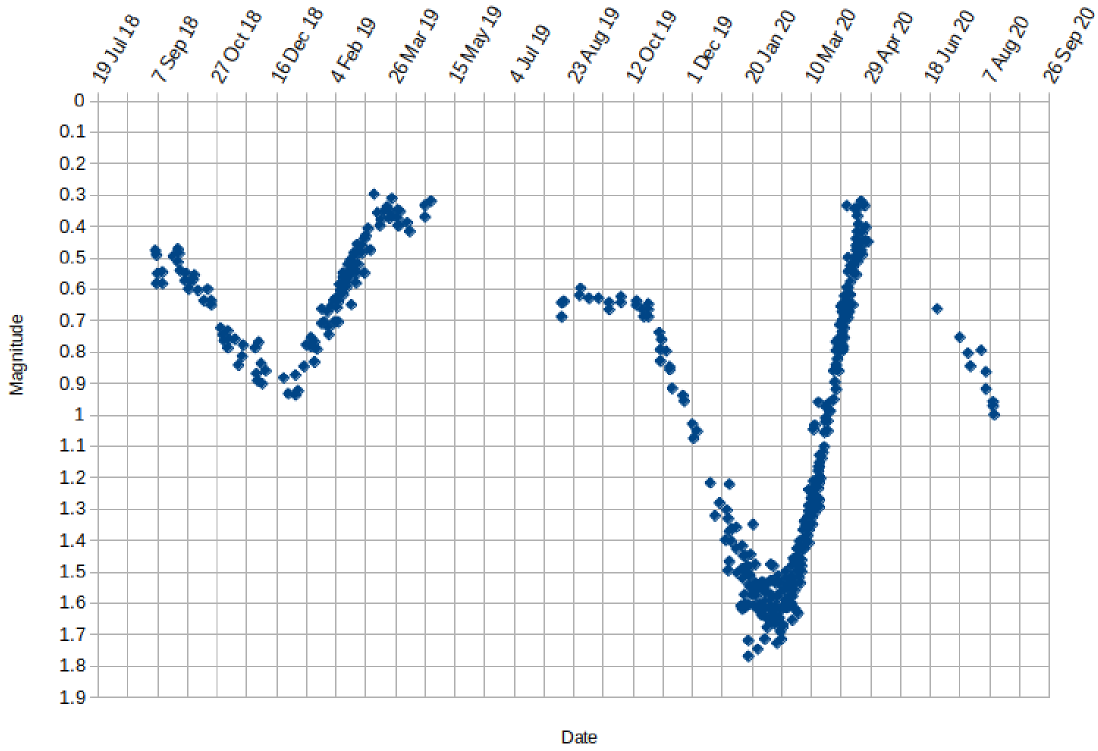

Figure 1. The V band magnitudes are observations from the AAVSO International Database (https://www.aavso.org)

Figure 1 shows a plot of the observed magnitude vs time (light-curve) of Betelgeuse.

Model A - Expanding star

One of the proposed model for this dimming was that the whole star suddenly started expanding and hence cooled down. Let us assume that the star is still acting as perfect black body at each stage of expansion (and subsequent contraction). By other measurements, we know that the star's effective temperature at the start of expansion was $T_1 = 3500\,\mathrm{K}$ and the effective temperature at the most expanded state is $T_2 = 2625\,\mathrm{K}$. Find the average velocity of the expansion of gas.

Solution

When the star is in the most expanded state the radius is large, temperature is low and the magnitude is minimum. On the other hand, when it is contracted the radius is small, temperature is high and the magnitude is maximum.
Here we will consider only the period starting from 12 October 2019, when the magnitude is maximum till 14 February 2020, when the magnitude is minimum.
The magnitude is maximum on 12 Oct 2019: $m_x = 0.65$
The magnitude is minimum on 14 Feb 2020: $m_c = 1.60$
This gives the time period from the most contracted state to most expanded state to be:

$$t_{cx} = 125 \text{ days} = 1.08 \times 10^{7}\,\mathrm{s}$$

Now, for radius, temperature and magnitude we have,

	Start of expansion	Fully expanded state
Radius	$R_1 = 6.17 \times 10^{11}\,\mathrm{m}$	$R_2 = ?$
Temperature	$T_1 = 3500\,\mathrm{K}$	$T_2 = 2625\,\mathrm{K}$
Magnitude	$m_1 = 0.65$	$m_2 = 1.60$

$$m_1 - m_2 = -2.5\, log_{10}\left(\frac{F_1}{F_2}\right)$$

$$\frac{F_1}{F_2} = 2.399$$

$$F = \frac{4\pi R^2 \sigma T^4}{4\pi D^2}$$

Here, D is the distance to Betelgeuse.

$$\therefore \frac{R_1}{R_2} = \sqrt{\frac{F_1}{F_2}} \times \frac{T_2^2}{T_1^2}$$

$$\frac{R_1}{R_2} = 0.871$$

$$\boxed{R_2 = 7.08 \times 10^{11}\,\mathrm{m}}$$

Therefore, change in the Radius

$$R_2 - R_1 = 9.1 \times 10^{10}\,\mathrm{m}$$

and the velocity of expansion v_{exp} is:

$$v_{exp} = \frac{\text{Change in radius}}{t_{cx}}$$

$$\boxed{v_{exp} = 8.4\,\mathrm{km\,s^{-1}}}$$

Considerations in the solution

- Students have to make judicious choice of the date when the star was faintest. As the box grid in the graph has size of about 24 days, a fairly large range (±10 days) of dates were accepted.
- Similarly, box grid size on the vertical axis is 0.1 magnitude. Consequently, the magnitudes of the star during the event and at the time when the star was the faintest were accepted

within a range of ±0.05 each.

Model B - Exo-planet around star

Some other astronomers proposed that the said dimming is caused due to the transit of a giant exoplanet with radius 'r' orbiting Betelgeuse. Argue if such a scenario is possible for an edge-on circular orbit of the exoplanet with orbital radius 'a'.

Solution

Transit time from first contact to centre of the eclipse and flux ratio are [from solution of model A]

$$t = 1.08 \times 10^7\,\text{s}$$
$$\text{Flux ratio} = 2.399$$

Let P be the period of the orbit and a be the orbital radius then,

$$P^2 = \frac{4\pi^2}{GM_B} a^3$$

The angle travelled in time t be θ;

$$\therefore \frac{\theta}{2\pi} = \frac{t}{P} \Rightarrow \theta = \frac{2\pi t}{P}$$

Distance travelled in apparent view = $r + R_B = a \sin\theta$

$$\theta = t\sqrt{\frac{GM_B}{a^3}} = \sin^{-1}(r + R_B)$$

If θ is small,

$$t\sqrt{\frac{GM_B}{a^3}} = r + R_B$$
$$\sqrt{a^3} = \frac{4.04 \times 10^{17}}{(r + R_B)} < \frac{4.04 \times 10^{17}}{R_B}$$
$$a < 7541\,\text{km}$$
$$\therefore a \ll R_B$$

This is physically impossible as the orbital distance of a planet cannot be less than the stellar radius.
There are other ways to rule out exoplanet as the cause of this intensity dip, by arguing that exoplanet radius needed for such a major dip would be too high and hence nonphysical for a planet. All such alternate approaches would be deemed acceptable.

Model C - Simplified plume model

A popular model to explain this dimming states that this event started with a large plume of hot material getting ejected from the star's surface. This material cooled down after ejection and became opaque to block light from a part of the star. As this dense cloud expanded, it kept blocking more and more part of the star dimming it further. However, as this expansion lowered the density of the cloud, the cloud's opaqueness started reducing after a few weeks and the star started brightening again.
Here we will consider a simpler version of this model. We assume that this material ejection happened in a narrow cone in very short timescale from a single point on the non-rotating stellar surface. The total mass of the ejected material was approximately equal to mass of the earth and the axis of the cone was exactly along our line of sight. Let us assume that at each instant during the expansion the density of material is constant throughout the cone and the vertex of the cone is still attached to the stellar surface.
We assume that the star starts brightening again when the average density inside the cone falls to $5 \times 10^{-14}\,\text{kg m}^{-3}$. Find the time averaged velocity of particles, which form the front of the expanding cone.

Solution

Volume V of the cone, at its flux minima, is:

$$V = \frac{\text{Mass}}{\text{Density}} = \frac{5.972 \times 10^{24}}{5 \times 10^{-14}} \approx 1.2 \times 10^{38}\,\text{m}^3$$

Let r be base of the cone and h be the height. Now as per the solution in model A, flux ratio from the start of emission to attainment of critical density is 2.399. As the flux reduction is happening due to circular disk of base obscuring part of the star,

$$\frac{F_1}{F_2} = \frac{R_B^2}{(R_B^2 - r^2)}$$
$$\therefore r^2 = \frac{R_B^2(F_1/F_2 - 1)}{F_1/F_2}$$

The volume of the cone is given by,

$$V = \pi \times r^2 \times \frac{h}{3}$$
$$V = \frac{\pi}{3} \times \left(\frac{R_B^2(F_1/F_2 - 1)}{F_1/F_2}\right) \times h$$
$$\therefore h = vt = \frac{1.2 \times 10^{38}}{2.32 \times 10^{23}} = 5.1 \times 10^{14}\,\text{m}$$
$$\therefore h = 5.1 \times 10^{14}\,\text{m}$$
$$\therefore v = \frac{h}{t} = \frac{5.1 \times 10^{14}}{1.08 \times 10^7}$$
$$\boxed{v \approx 48\,000\,\text{km s}^{-1}}$$

3.4 Alternative, unusable problem formulations

It will be dishonest to claim that the final problem design was achieved through a linear development process. Several other ideas were tried, but deemed unfeasible. Some of those used more realistic models but could not be solved without more involved physics / mathematics. Some of the ideas were prone to misinterpretation by students. We list some of these ideas here to further highlight the constraints on problem designing.

- Model B - Exoplanet in non-circular orbit:
  It would be more realistic to think of exoplanet model with a highly eccentric elliptical orbit. That would also explain why we didn't see any such event in past two centuries. However, the Indian high school curriculum doesn't deal with mathematical expressions for parameters of elliptical orbits. Thus, this model went beyond the scope of the test.
- Model B - Exoplanet in an inclined orbit:
  Edge-on orbit is just a special case, which is realised rarely in the real observations. Inclined orbits are much more common. However, angle of inclination for any exoplanets is notoriously difficult to determine. We wished the students to experience how viability of different models is decided by actual researchers. Thus, we felt that inserting some random inclination angle as a given constant will be against that spirit.
- Model C - Ejecta in shape of a disk:
  In this case, it was proposed that the ejecta may have been spewn out for a short period of 5 days in a shape of disk. The length of this time period of ejection was supposed to help calculate the thickness of the disk. The disk may be assumed to be perpendicular to the line of sight. As the disk would move away from the surface of Betelgeuse, it also would expand in radius, resulting in a decrease in its density. However, the model was deemed to be too unrealistic. The period of ejection was inconsistent with the lightcurve. It is evident from the light curve that, before the minima, intensity decreases slowly. However, in this model, the decrease in

intensity would be faster than the increase.
- Model C - Ejecta taking shape of hemispherical shell only covering the southern hemisphere:
In this iteration, we tried that ejecta would be in form of a hemispherical shell covering only the southern hemisphere of the star. This was tried to introduce the VLT observations of Betelgeuse in the mix. In this model we assumed that the thickness of the shell remained the same, as it travelled away from the star. However, this meant that all particles in the shell travelled with exactly same radial velocity throughout the expansion. This would be so far removed from the reality that we feared that it might confuse the students.
- Model C - Ejecta in shape of a truncated cone:
The final problem specifies that the ejecta is spread in shape of a cone. In one iteration, we considered a truncated cone instead of a full cone. However, the added extra calculations was not yielding any significant additional educational benefit. Hence this model was dropped.

4 Discussion

Experience from past IOQA evaluations suggest few of the below mentioned stumbling blocks students might face -

- It can be anticipated that some students may fail to realize the importance of fitting a smooth curve to the data and end up considering outliers in their calculations.
- Some students who might be familiar with the with calculus may use it to solve the question.
- Since students are familiar with ideal gases and that stars are gas balls, it is possible that they consider star as a ball of ideal gas while solving for Model A.

A detailed analysis of students responses will be an article in itself and the authors see it as future work.

5 Summary

In this article we have tried to demonstrate design process of a challenging high school level question based on the current astrophysical research. The question, although based on unfamiliar context, remains cognitively accessible to the students. The failed iterations of the design process serve the purpose of alerting other problem designers of the pitfalls.

6 Declarations

6.1 List of abbreviations

- AAVSO - American Association of Variable Star Observers.
- HBCSE - Homi Bhabha Centre for Science Education.
- IAU - International Astronomical Union.
- IBO - International Biology Olympiad.
- IChO - International Chemistry Olympiad.
- IMO - International Mathematical Olympiad.
- IOAA - International Olympiad on Astronomy and Astrophysics.
- IOQA - Indian Olympiad Qualifier in Astronomy.
- IPhO - International Physics Olympiad.
- MCQ - Multiple Choice Question.
- OAE - Office of Astronomy for Education.
- OECD - Organisation for Economic Co-operation and Development.
- SPHERE - Spectro-Polarimetric High-contrast Exoplanet Research.
- STEM - Science, Technology, Engineering and Mathematics.
- VLT - Very Large Telescope.
- VLTI - Very Large Telescope Interferometer.

6.2 Ethical Approval

The approval from ethics board is not applicable as the article does not use any individual responses or statistics.

6.3 Consent for publication

Not Applicable.

6.4 Competing Interests

The authors declare that they have no competing interests.

6.5 Funding

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6.6 Author's Contributions

The problem was originally conceptualised by author 4. Authors 1 and 2 had significant inputs in its development process. Authors 1, 2 and 3 wrote the original draft. Author 4 played the role of supervisor and reviewer/editor of the draft.

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