Science Olympiad
National Tournament
May 25, 2024

Reach for the Stars – Division B

Directions:

- This exam consists of **7 questions** worth **190 points** in total. There is no penalty for wrong answers.
- You are allowed to bring in **two 8.5"×11" sheets of paper** with information on both sides.
- The use of calculators or AI tools (e.g. ChatGPT) is expressly forbidden.
- In the event of a tie, placement will be determined by cumulative score on the following questions, in order: **Q1, Q7, Q6, Q4, Q2, Q3, Q5**.
- This exam will be posted online after the competition at https://chandra.si.edu/edu/ and https://www.universeunplugged.org/series/nso-webinars.
- Above all else, just believe!

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Question 1: Means of Identification, Please [40 pts.]

For each object given below, identify the letter on the star map that best matches its location, and the corresponding image number(s) on the ***first page*** of the Image Sheet.

Letters and images may be used **once, more than once, or not at all**. If multiple images depict the same object, list **all images** that do so. If an object is not depicted, either in the star map, image sheet, or both, answer **"None"**.

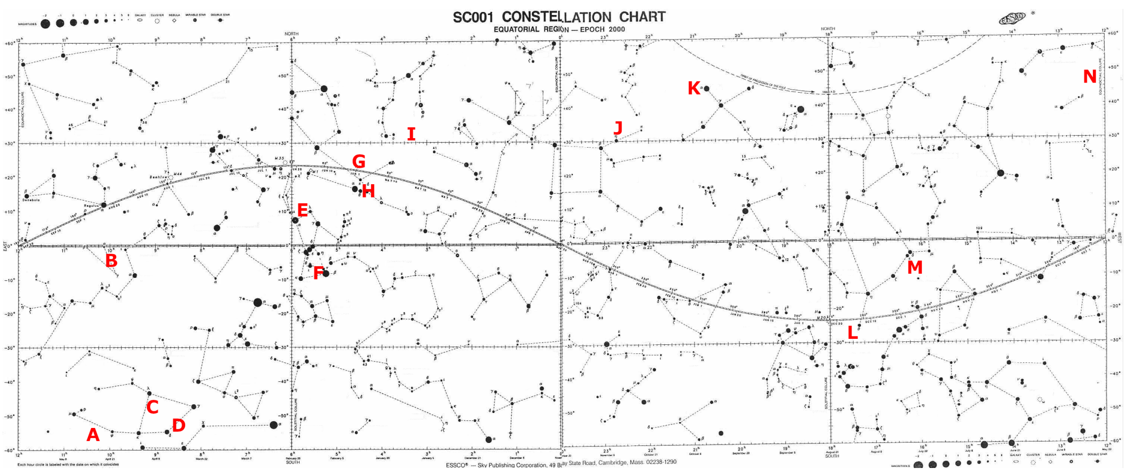

Figure 1: Star Map from +60° to -60° Dec

a. [2 pts] 30 Doradus

b. [2 pts] Baby Boom Galaxy

c. [2 pts] Barnard 68

d. [2 pts] FU Orionis

e. [2 pts] HD 100546

f. [2 pts] HD 141569

g. [2 pts] HD 95086

h. [2 pts] HH 46/47

i. [2 pts] HL Tauri

j. [2 pts] HOPS 383

k. [2 pts] J122051+491255

l. [2 pts] L1527

m. [2 pts] Messier 42

n. [2 pts] NGC 1333

o. [2 pts] NGC 1555

p. [2 pts] NGC 3324

q. [2 pts] RCW 38

r. [2 pts] Stephan's Quintet

s. [2 pts] T Tauri

t. [2 pts] V1057 Cygni

Question 2: Digging in Deep (Sky) [20 pts.]

For each of the questions below, refer to ***both pages*** of the Image Sheet.

a. [1 pt] What type of object is depicted in Image 10?

b. [1 pt] What is the sequence of letters in Image 30 that best correspond to T Tauri's evolution?

c. [1 pt] Image 4 depicts the formation of what type of object?

d. [1 pt] What is the primary result of the current galactic merging event in Stephan's Quintet?

e. [1 pt] Image 3 depicts what two major components of its protostellar system?

f. [1 pt] What causes the green coloration seen in galaxies like J122051+491255?

g. [1 pt] What wavelength regime does Image 15 subdivide?

h. [1 pt] What are the two major star-formation-related features visible in Image 18?

i. [1 pt] What might the x-ray outbursts of HOPS 383 indicate about the content of rocky bodies in our own early Solar System?

j. [1 pt] What do the disk subdivisions in the object in Image 7 indicate about the disk itself?

k. [1 pt] What is indicated by the spots of bright pink light in Image 6?

l. [1 pt] The Baby Boom Galaxy is notable for what astronomical record?

m. [1 pt] What is the likely identity of the bright source marked with a black "X" in Image 2?

n. [1 pt] What feature is visible in Image 14 that is not visible in other images of this object?

o. [1 pt] Which image depicts the behavior of V1057 Cygni?

p. [1 pt] What major structure is resolved by the contour grading seen in Image 16?

q. [1 pt] What does the structure in Image 8 reveal about the star formation process?

r. [1 pt] Which two images depict the behavior of FU Orionis over the short and long timescales?

s. [1 pt] Image 1 depicts what two major components of its protostellar system?

t. [1 pt] What important pre-stellar threshold must be crossed before Barnard 68 can begin to undergo star formation?

Question 3: It's Elementary [18 pts.]

When a large dust or molecular cloud begins to collapse and form stars, astronomers can study the characteristics of the spectra of stars that form within it. One such spectrum is given below:

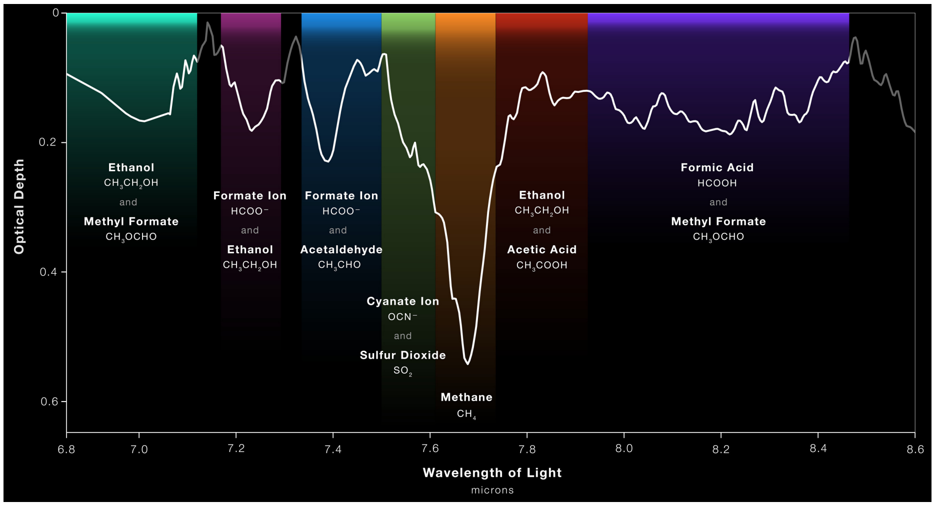

Figure 2: Spectrum of the region around a single protostar in this same star-forming region

a. [1 pt] What do the labels in Figure 2 correspond to physically within the collapsing cloud?

b. [1 pt] What primary chemical characteristic do these labels (with one exception) share?

c. [2 pts] Which chemical species is most abundant? At what wavelength does it fall?

The collapsing cloud represented by this spectrum is being studied primarily to increase understanding of the star formation process.

d. [1 pt] What wavelength range was this spectrum composed within? *Hint: Think general wavelength regimes, like x-ray, ultraviolet, etc.*

e. [1 pt] What benefit do observations in this range provide for obtaining a spectrum like this?

f. [2 pts] How would you expect this spectrum to change if the same observation were re-created in visible light? Which chemical species would then dominate? *Hint: You can think of this like being able to creating a "spectrum" with your naked eye*

Question 3: Continued

Most of the compounds depicted in this spectrum are heavy, and not typically produced in abundance within the cores of stars themselves. This spectrum is thought to have been taken 50 million years into the star formation process.

g. [3 pts] Describe the approximate process by which complex, heavy molecules such as these are thought to form. Why do they only begin showing strong spectral signatures at this point in the cloud collapse process? *Hint: Think about the stages of collapse and what parameters (temperature, density, etc.) delineate them.*

h. [4 pts] Describe, with brief explanation, the likely structure of this system at the following milestones in time:
   (i) 100 million years
   (ii) 1 billion years

i. [3 pts] Based on the above information, identify the following:
   (i) Which object this spectrum depicts
   (ii) Which telescope produced this spectrum
   (iii) Relative age (older, younger) of this star-forming region

Question 4: An Occasional Flare-Up [24 pts.]

As protostars form from the process of cloud collapse, they will irregularly undergo events of extreme brightening. Two such examples are given below for two different protostars over similar timeframe:

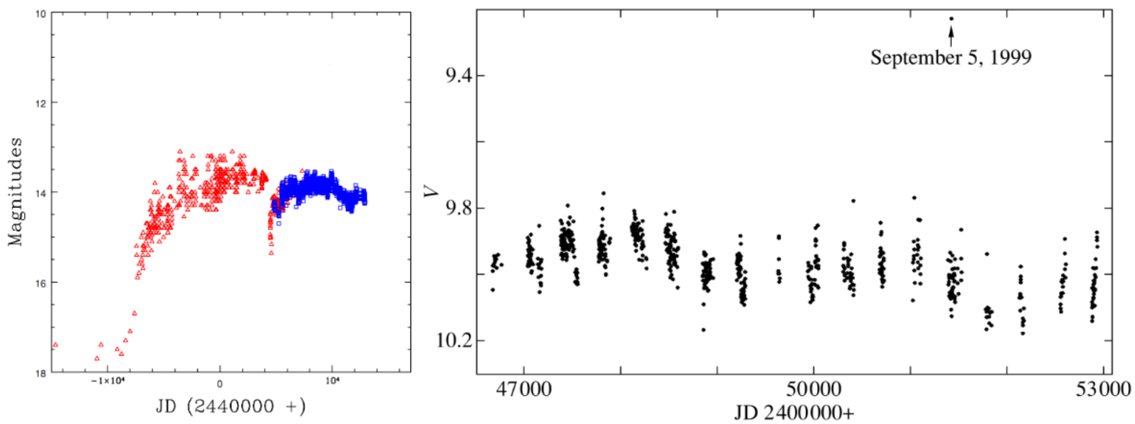

Figure 3: V-band apparent magnitude light curves for *Atreides (Left)* and *Chani (Right)*

a. [1 pt] Which protostar, *Atreides* or *Chani*, appeared brighter on average over its observation?

b. [2 pts] What type of protostar is *Atreides* most likely to be? What type is *Chani*?

c. [2 pts] Assuming each protostar had the same *absolute magnitude* before their brightening events, which star is closer to the Earth?

You may assume for the following questions that both protostars saw their respective brightening events occur under *isothermal* conditions.

d. [1 pt] What does the term "isothermal" indicate about these brightening events?

e. [4 pts] What was the visual magnitude change seen in *Atreides*? In *Chani*?

f. [4 pts] How many times more **luminous** did *Atreides* and *Chani* become over the course of their brightening events? You may leave your answer in exponential form. *Hint: The change in apparent magnitude and change in absolute magnitude is by the same* ***factor****.*

g. [2 pts] Does a brightening event like these correspond to a **contraction** or **expansion** of the protostar? *Hint: Expansion/contraction represent changes in a star's* ***radius****.*

h. [4 pts] Which protostar saw the greater change in this respect, and by what factor was this change greater? You may leave your answer in exponential form.

i. [4 pts] We have made several assumptions about both *Atreides* and *Chani*, which we used to draw our conclusions above. Name four potential inaccuracies with our assumptions that may have influenced our conclusions.

Question 5: A Cloud Hanging Over [18 pts.]

When studying dark molecular clouds, it is sometimes possible to fine-tune observations to isolate the density distribution of certain molecular species in the cloud, as given below:

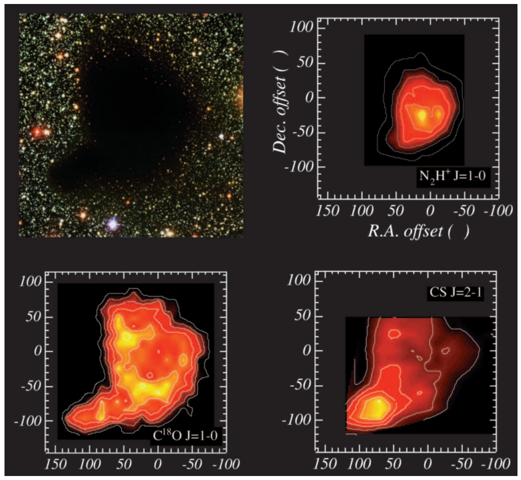

Figure 4: An optical image of a molecular cloud, alongside three other images isolating the densities of three molecular species at normalized scale (axes in arcseconds)

a. [1 pt] What is the name of the object depicted in this figure?

b. [2 pts] What is the approximate area of the sky obscured by this cloud, in square arcseconds?

c. [2 pts] Which chemical species is most broadly-distributed throughout the area of the cloud?

d. [3 pts] What are the approximate coordinates of the point of densest organic molecule concentration, in arcseconds offset?

For each of the three molecular species distribution plots, there is a label, “J=”. This is in reference to the rotational energy transition that took place to emit the photons obtained for the creation of that plot. Thus each plot shows the "rotational energy distribution" of one molecule.

e. [3 pts] Describe the mechanism by which transitions like this might occur from a base state. How does this relate to the environment within and around the molecular cloud? (*Hint: You can think of this as being similar to the electron transitions that produce emission spectra.)*

f. [3 pts] The top-left inset to this figure shows the molecular cloud in an optical image, while the remaining three are isolated to show particular molecular species. Why is the optical image darkened within the cloud, while the others are colorful in the same region?

g. [4 pts] This set of images depicts various maps of density within the cloud. What force do these pockets of density exert on their surroundings and what second force are they balanced by? How would a fifth image of this second force end up looking?

Question 6: Putting Your Ideas Into Motion [30 pts.]

Although the Sun is the only star in our Solar System, many stars are thought to have companions. In this question, we'll explore a sliver of the physics that underlies multi-star systems.

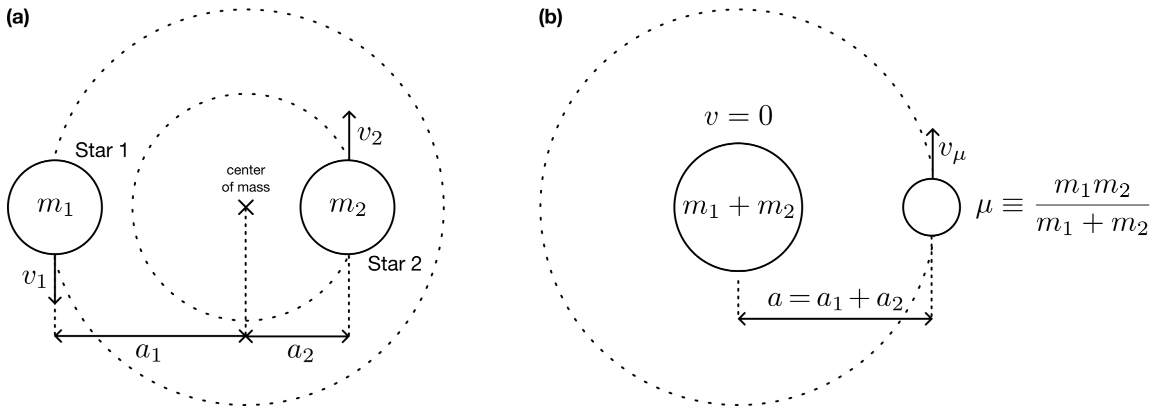

Figure 5: (a) Two stars of masses m_1 and m_2 in circular orbits around their center of mass; (b) equivalent "reduced-mass" system to the system in (a).

a. [3 pts] Based on the distance that each star is from the center of mass in Fig. 5(a), which one is more massive? Which one has a larger velocity? How do you know?

b. [3 pts] Your friend is trying to calculate the period of the system shown in Fig. 5(a) and doesn't know whether they should plug in a_1 or a_2 as the semimajor axis in Kepler's Third Law:

$$P_1 = \sqrt{\frac{a_1^3}{m_1 + m_2}} \text{ or } P_2 = \sqrt{\frac{a_2^3}{m_1 + m_2}}$$

Should they use a_1, a_2, or something else entirely as the semimajor axis in Kepler's Third Law? Does it even make physical sense for the stars to have different periods? Explain.

Scientists often simplify two-body systems using "reduced-mass" systems. Instead of worrying about the motion of two objects, we only consider the relative motion of one object around another, and we transform the masses of the objects so the energy, period, etc. of the orbit stay the same. For the system shown in Fig. 5(a), this corresponds to an object of mass $\mu = m_1 m_2/(m_1 + m_2)$ orbiting at a distance $a = a_1 + a_2$ around a stationary object of mass $m_1 + m_2$, as shown in Fig. 5(b).

c. [2 pts] Show that the gravitational force between the two stars in the "real" system in Fig. 5(a) is the same as the one in the "reduced-mass" system in Fig. 5(b).

d. [4 pts] Calculate the velocity of the object of mass μ in its orbit in the "reduced-mass" system in Fig. 5(b). Express your answer in terms of m_1, m_2, a, and physical constants, like G. *Hint: equate the centripetal force, $\mu v^2/a$, with the gravitational force from the previous part.*

Question 6: Continued

e. [5 pts] Calculate the kinetic energy (KE) and gravitational potential energy (GPE) associated with the "reduced-mass" system in Fig. 5(b). Add them together to find the total mechanical energy of the system. Is the total mechanical energy positive, negative, or zero? Express your answers in terms of m_1, m_2, a, and physical constants, like G.

You may have noticed that in the previous part, KE $= -\frac{1}{2}$GPE. This is a result of the *virial theorem*, which states that for gravitational attraction in a closed, stable system at equilibrium, the time-averaged kinetic energy equals half of the time-averaged negative gravitational potential energy.

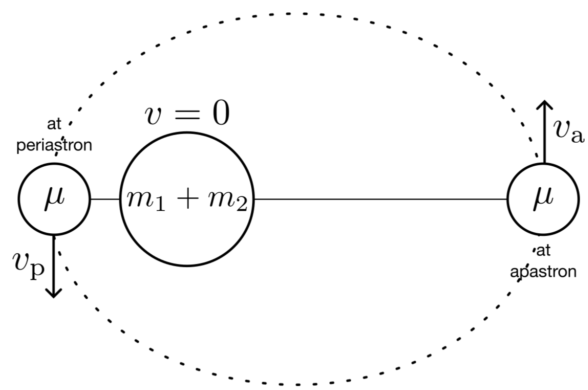

Figure 6: Position of object of mass μ at periastron and apastron during an elliptical orbit in a "reduced-mass" system.

f. [6 pts] Suppose that the orbit was an ellipse, as shown in Fig. 6. Sketch curves that describe the total mechanical energy, kinetic energy, and gravitational potential energy for the system as a function of time. On the horizontal axis, mark the positions that correspond to periastron and apastron. Does the virial theorem apply at every point in the orbit? Explain.

Let's apply some of these concepts to one of the DSOs on this year's rules. In 2017, researchers examined a group of five young stars in the Kleinmann-Low Nebula, near the center of the Orion Nebula complex. At first, all of the stars were orbiting each other, but over time, two of them moved much closer together. This resulted in the other three stars being ejected from the system.

g. [3 pts] How might two stars moving closer together result in three other stars being ejected? Frame your answer in terms of kinetic energy and gravitational potential energy.

h. [2 pts] It is valid to apply the virial theorem to our system of five stars? Explain.

i. [2 pts] Throughout this question, we have assumed that the force of gravity is proportional to $1/r^2$. Suppose that in an alternate universe, the force of gravity was instead proportional to $1/r^3$. Which, if any, of Kepler's Laws would remain true? Explain.

Question 7: Your Mission, Should You Accept It [40 pts.]

You are the Principal Investigator for a high-energy astrophysics research team at Goddard Space Flight Center. Today, you read the following as part of a news article:

> *"As of May 2024, the Chandra X-Ray Observatory, NASA's flagship mission for x-ray astrophysics research, is expected to receive large reductions to its operational budget for Fiscal Year 2025 and beyond. This is most likely the beginning of the mission draw-down process, bringing Chandra to a minimal-operations capacity with significantly reduced science time."*

This is concerning: just yesterday, your team finally isolated the regions of high x-ray activity in HOPS 383, an object of intense study in high-energy astrophysics. This was done by analyzing data you obtained from Chandra, producing the plot below:

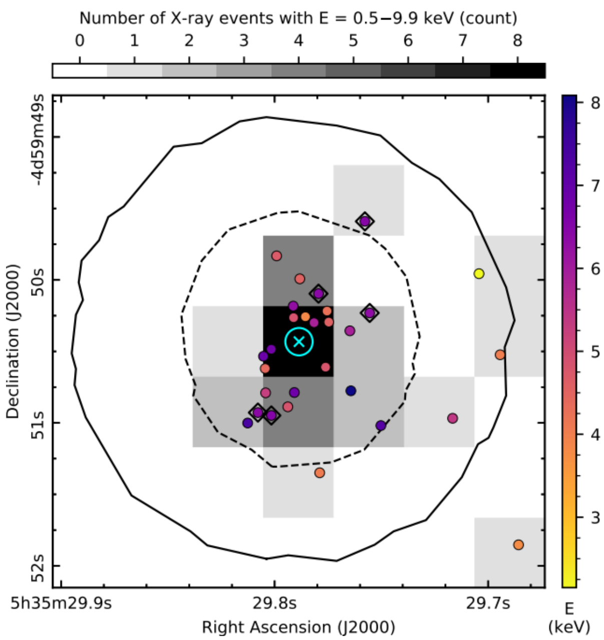

Figure 7: X-ray events detected by Chandra in HOPS 383

Recognizing the importance of continuing x-ray astrophysics research and the potential for a gap to develop in the field, you set out to design a proposal for a new space-based x-ray astrophysics observatory. In particular, you want your mission to be capable of continuing your work on **transient x-ray events in protostellar regions**, such as HOPS 383.

Using your knowledge of existing missions, as well as the science of protostellar evolution and high-energy astronomy, your job is to:

a. [4 pts] Define your overall **Mission Goal** – In a sentence, what should your observatory be capable of doing?

b. [8 pts] Identify **four key Science Requirements** driving your mission's overall design, namely:
   (i) Observational wavelength regime and detectable **targets** of observation
   (ii) Timeframe of detectable **events** (*Hint: Can your mission see quickly-occurring events? Slow ones? Static ones?*)
   (iii) Resolvable **targets** of observation
   (iv) Observable **regions** of the sky

c. [8 pts] Identify **one key Engineering Requirement** for each of the above **Science Requirements**, namely:
   (i) Wavelength capacity (*Hint: This is a length or energy range*)
   (ii) Exposure duration (*Hint: This is a duration of time*)
   (iii) Exposure resolution (*Hint: This is a length limit*)
   (iv) Field of regard (*Hint: This is an area limit*)

   (*Hint: Engineering requirements are driven by science requirements – they are your way of ensuring the **design** of the mission will meet the **needs of the scientists** who will use it*)

d. [14 pts] Based on the goal and requirements you identified above, design the observatory that will fulfill them! Here you have full freedom of imagination, so long as you meet **all Science and Engineering Requirements you specified above**. You may consider:
   (i) Orbital Configuration
   (ii) Onboard Instruments (the "science payload")
   (iii) Power & Electronics
   (iv) Communication & Data Handling
   (v) Anything else you find relevant, fascinating, cool, etc.

   You may focus your attention on any or all of these areas, but none is explicitly necessary – your design will primarily be graded on its **feasibility** and the degree to which it meets the **Science and Engineering Requirements** you specified.

e. [6 pts] Bonus points for **creativity**! This is a loose category, and could encompass novel approaches to old ideas, a fun mission name or patch, a sketch of the observatory, non-requirements-based capabilities, or anything else to help it stand out and draw attention. Remember: NASA is funding your mission, and NASA's money comes from the general public, so make your mission something people would want to support, whether or not they are scientists themselves. Have fun, get creative, and enjoy making something brand new!