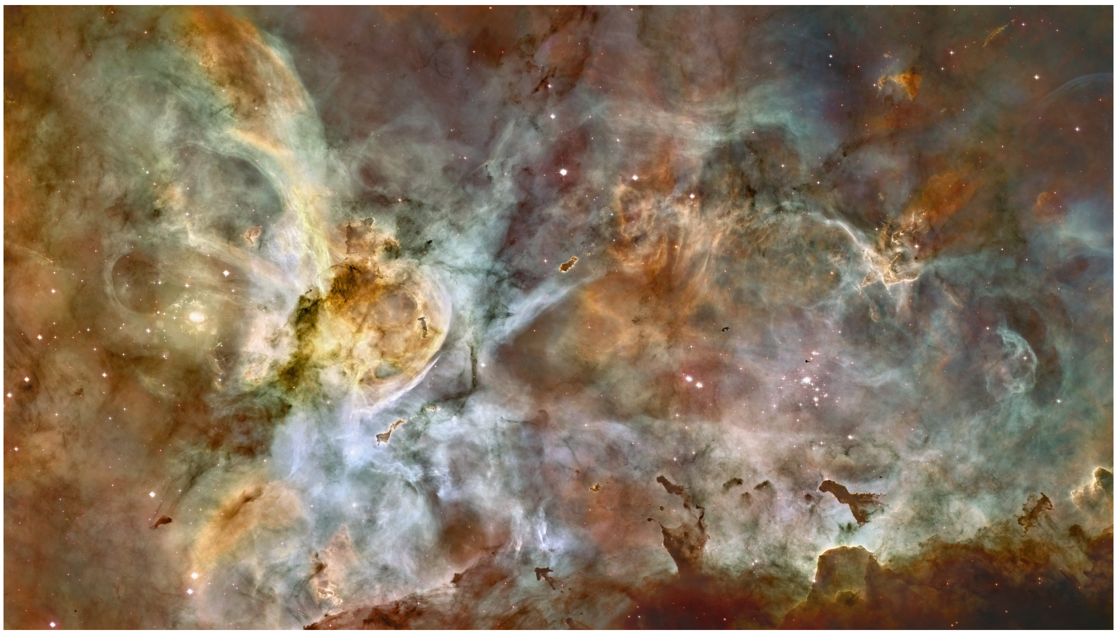
Science Olympiad
Solon Invitational
February 3, 2024

Astronomy C



Directions:

- Each team will be given **50 minutes** to complete the test.
- There are three sections: **§A** (Qualitative), **§B** (Deep-Sky Objects), and **§C** (Quantitative).
- For significant figures, **use 3 or more in your answers** unless otherwise specified.
- The use of AI tools (i.e. ChatGPT) are expressly forbidden.
- Tiebreakers, in order: §A-II, §B, §C, §A-III, §A1, . . . , §A10.
- Best of luck! And may the odds be ever in your favor.

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Feedback? **Test Code**: *2024Solon-AstronomyC-Evolution*

Section A: Qualitative

In this section, you will answer general, qualitative questions about astronomy. This section contains three subsections for a total of 75 points.

A-I: True/False

There are 10 questions in this subsection. Each question is worth one point.

1. Earth is a star.
2. The order of spectral types from hottest to coolest is OBAFGKM.
3. Absorption lines are generated by spontaneous emission of hot gas.
4. White stars are hotter than blue stars.
5. A star with a magnitude of -2 is a thousand times brighter than a star with a magnitude of 3.
6. Protoplanetary disks are composed of 99% gas and only 1% dust.
7. Most stars emit most of their radiant energy in the visible wavelength.
8. Stars on the Henyey track are fully convective.
9. The radial velocity method is primarily sensitive to the detection of exoplanets with orbits that are nearly edge-on from our line of sight.
10. Herbig Ae/Be stars are typically more massive than T Tauri stars.

A-II: Multiple Choice

There are 20 questions in this subsection. Each question is worth two points.

11. In which wavelength is a star formation region most likely to be detected?
    A. Infrared
    B. Visible
    C. UV
    D. X-ray

12. What type of object are shock waves caused by young stars ejecting high-speed ionized jets that interact with the surrounding interstellar medium?
    A. Cosmic rays
    B. Active galactic nuclei
    C. Herbig Haro objects
    D. Neutrinos

13. Which specific characteristic of molecular clouds is essential for initiating the process of star formation?
    A. High metallicity promoting efficient cooling
    B. Rapid expansion due to shock waves
    C. Low density allowing for easy gravitational collapse
    D. Elevated ionization levels from nearby supernovae

14. Which of the following processes contribute specifically to ionization in H II regions?
    A. The collision of neutral hydrogen atoms leading to ionization, driven by gravitational collapse.
    B. Magnetic fields influence H I regions to transition to H II.
    C. X-ray radiation from the accretion of young stars triggers ionization of neutral hydrogen.
    D. The absorption of ultraviolet radiation from hot stars, causing ionization and the formation of H II regions.

15. In the context of molecular clouds and star formation, what role do magnetic fields play, especially in relation to the density structure of the cloud?
    A. Magnetic fields have no significant impact on the density structure of molecular clouds.
    B. Magnetic fields promote even compression of the cloud, facilitating the formation of isolated protostars.
    C. Magnetic fields hinder gravitational collapse, preventing the formation of stars within molecular clouds.
    D. Magnetic fields induce turbulence and can lead to the formation of dense filaments, influencing the fragmentation process during star formation.

16. Which of the following is NOT true about Herbig Haro objects?
    A. They are by-products of star formation activity.
    B. They have dominant Hydrogen Balmer emission lines in their spectra.
    C. They are highly ionized objects.
    D. They are most detectable in the ultraviolet wavelength.

17. Why are T Tauri stars larger than main sequence stars of the same spectral class?
    A. They have not finished core collapsing so their radius is larger.
    B. They have a higher temperature.
    C. The energy from core collapse increases their radius.
    D. Strong X-ray emission counteracts the slow contraction phase.

18. What is the primary source of luminosity for a T Tauri star?
    - A. Continuous process of hydrogen burning
    - B. Continuous process of helium burning
    - C. Stochastic process of deuterium burning
    - D. Stochastic process of accretion

19. What distinguishes Mini-Neptunes from Super-Earths among exoplanet classifications?
    - A. Mini-Neptunes have thicker atmospheres than Super-Earths.
    - B. Super-Earths are gas giants, while Mini-Neptunes are predominantly rocky.
    - C. Mini-Neptunes have masses closer to that of Earth than Super-Earths.
    - D. Super-Earths are exclusively found in binary star systems.

20. What aspect of the proton-proton chain reaction produces energy in stars?
    - A. The conversion of protons into neutrons releases energy.
    - B. Mass defect results in the conversion of mass into energy, as described by $E = mc^2$.
    - C. Fusion reactions increase the gravitational potential energy of the star.
    - D. Neutrinos escaping from the star create energy through their interactions.

21. How does the luminosity of a star change during the asymptotic giant branch (AGB) phase of its evolution?
    - A. Luminosity increases due to helium burning in the core.
    - B. Luminosity decreases as the star exhausts its nuclear fuel.
    - C. Luminosity remains constant through the AGB phase.
    - D. Luminosity fluctuates unpredictably during this stage.

22. A pre-main sequence star with a mass of 0.9 solar masses will experience what before reaching hydrostatic equilibrium?
    - A. Rightwards motion on the HR diagram corresponding to a decrease in temperature as the core becomes fully convective
    - B. Leftwards motion on the HR diagram corresponding to an increase in temperature as the core becomes fully radiative
    - C. Upwards motion on the HR diagram corresponding to an increase in luminosity as the core becomes fully radiative
    - D. Downwards motion on the HR diagram corresponding to a decrease in luminosity as the star sheds its outer envelope

23. How can we distinguish a 200 Myr old, 0.1 $M_\odot$ star from a brown dwarf?
    A. By detecting exoplanets in orbit around the object
    B. By detecting deuterium in the object's spectra
    C. By detecting an absence of lithium in the object's spectra
    D. It is not possible to distinguish the two this early in its lifespan

24. During which stage of stellar evolution does a star experience helium burning in its core, leading to the formation of heavier elements?
    A. Protostar phase
    B. Main sequence stage
    C. Red giant phase
    D. Supernova stage

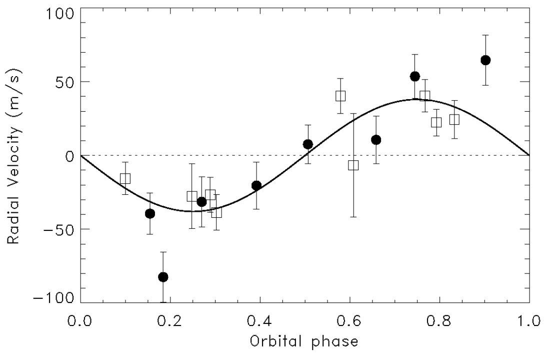
25. What role do transitional debris disks play in the study of planetary system evolution?
    A. They are debris disks located in the transitional zone between the inner and outer planets.
    B. Transitional debris disks fall into orbit from outside the system to produce comets.
    C. These disks are remnants of ancient planetary collisions in a solar system.
    D. They provide insights into the early stages of planet formation and the clearing of material in a developing system.

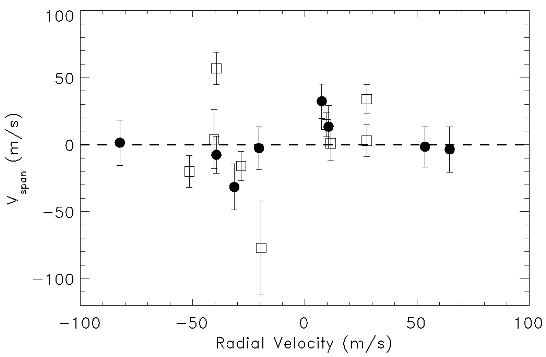
26. Which of the following characteristics is the most direct factor in classifying exoplanets and understanding their potential habitability?
    A. Eccentricity of the exoplanet's orbit
    B. Size and composition of the exoplanet
    C. Intensity of the host star's magnetic field
    D. Temperature fluctuations on the exoplanet's surface

27. Which of the following processes plays a crucial role in determining the chemical composition of a protoplanetary disk and subsequently influences the elemental makeup of planets?
    A. Radiative transfer in the interstellar medium
    B. The Kelvin-Helmholtz mechanism in protostars
    C. Disk accretion and the infall of gas and dust
    D. Magnetic reconnection in circumstellar regions

28. Which of the following are low-mass stars in a state of variability with temperatures between 2000 K and 5000 K and luminosities below 0.1 solar luminosities?
    A. T Tauri stars
    B. Herbig Ae/Be stars
    C. Brown dwarfs
    D. Subdwarf stars

29. The graph below represents example data of radial velocity measurements. This data is of WASP-39b obtained from SOPHIE and CORALIE spectrographs (which are ground-based) with a superimposed best-fit model RV curve.





Which of the following explain why the center-of-mass velocities are often subtracted from the original spectrograph data when interpreting radial velocity measurements for an exoplanet?

A. To account for the motion of the host star and create a reference frame centered on the exoplanet.

B. To enhance the overall radial velocity of the system for clearer visualization in the plot.

C. To correct for errors in the spectrograph measurements caused by changes in atmospheric conditions.

D. To adjust the data for variations in the exoplanet's luminosity, ensuring accurate radial velocity measurements.

30. When interpreting a radial velocity diagram in the context of exoplanet detection, what information can we deduce from the observed velocity variations of a star?

A. The amplitude of the radial velocity curve provides insights into the exoplanet's size and mass.

B. The shape of the curve indicates the eccentricity of the exoplanet's orbit.

C. The fundamental period of the variations reveals the star's rotation rate.

D. The spectral lines during the transit reveal information about the star's luminosity.

A-III: JS9!

For this subsection, use the JS9 imaging software on the provided computer to answer the questions. There are 10 questions in this subsection and points are shown for each question, for a total of 25 points.

Setup Instructions

- Go to chandra.cfa.harvard.edu/js9
- Select the button on the right with the text `[The Unofficial Chandra Archive Search Page]`. A pop-up should appear.
- In the `[Object Name]` box, enter "`Proxima`" and select `[Search]`.

31. [1 pt] How many observations are listed?

32. [2 pts] What is the declination of this object? Is it visible from Solon, Ohio through a telescope? *(Hint: Solon, Ohio is located at* 41.39° *N,* 81.44° *W.)*

In the table of observations (you may need to scroll down in the pop-up window to see it), find the row with `ObsID 12360` and the `Title` column. Load the data by dragging the link there and dropping it onto the JS9 window.

To adequately see the object, make sure that `[Scale > log]` is selected; you may also need to adjust the contrast and bias by holding down left click in the JS9 window and moving up/down and left/right, respectively.

33. [3 pts] In one or two sentences, describe the character of the emission that you see.

34. [2 pts] What is the name of this object?

35. [2 pts] What instrument and grating was used for this observation?

Set a circular region and move it to encompass the brightest point. It will be used for the next two questions.

36. [3 pts] Do an energy spectrum by using `[Analysis > Energy Spectrum]` and describe the results in one or two sentences.

37. [3 pts] Perform a light curve on the observation with `[Analysis > Light Curve]`. (Be sure to use the light curve routine listed under "`Server-side Analysis`".) In one or two sentences, describe the results.

38. [3 pts] Does the light curve show any statistically significant variability or not?

39. [3 pts] Why is it unusual for an object like this to have X-ray emission at all?

40. [3 pts] Why is this emission significant for the study of exoplanets?

Section B: Deep-Sky Objects

Use the Image Sheet to answer the following questions about this year's objects of interest. This section contains a total of 75 points.

1. HH 7-11 are a set of five Herbig-Haro objects shown in Image 1.
   (a) [1.5 pts] Name the young star that formed them.
   (b) [1.5 pts] What nebula does HH 7-11 reside in?
   (c) [3 pts] Identify the image depicting this nebula and the telescope that produced it.
2. Image 2 is a CHARIS image taken in 2020.
   (a) [2 pts] Name the objects located behind the white circle and in the green circle.
   (b) [3 pts] Identify the type of objects they are.
   (c) [3 pts] Which planetary formation theory most appropriately applies to this system?
3. 2M1207A is a brown dwarf with the first directly imaged exoplanet, 2M1207 b.
   (a) [2 pts] Which image can you find them in?
   (b) [2 pts] Image 10 shows normalized light curves for the two objects and best fitted sinusoids in blue with a period of 10.7 hours. What does F125W and F160W refer to?
   (c) [2 pts] What does the period correspond to?

   To find the sinusoids with the best fit, astronomers determined the posterior (i.e. after considering the data) probability distributions for amplitude and periods using a Markov Chain Monte Carlo (MCMC) approach. The ones generated using the F125W light curves can be seen in Image 11.

   (d) [3 pts] Describe the general shape of the two univariate (period/amplitude only) distributions.
   (e) [3 pts] How would this influence the error reported for the period and the amplitude?
4. Image 3 is a composite image—consisting of J-, H-, and Ks-band images—taken by the Keck telescope.
   (a) [1 pt] Name the object in the center of the image.
   (b) [2 pts] Which image depicts its light curve?
   (c) [2 pts] Identify the objects by the labeled letters (A, B, and C).
   (d) [2 pts] What method was used to detect the objects in the previous question?
5. WASP-18b is a high-mass, ultra-hot Jupiter orbiting very close to its host star. This causes the planet to be tidally locked. Image 12 shows the dayside planet-to-star flux ratio spectrum of WASP-18b.
   (a) [1 pt] What does it mean for a planet to be tidally locked?
   (b) [2 pts] What part of the electromagnetic spectrum are the red data points of Image 12 in?
   (c) [2 pts] What telescope imaged the data points in black?
   (d) [3 pts] Describe the physical process occurring in the inset light curves around time ± 1 hour.
   (e) [2 pts] Which inset light curve has the highest noise?
   (f) [3 pts] The light curve fits are shown with a black line. Why are they slightly curved downwards when time is less than -1 hour and greater than 1 hour? *(Helpful hint: This connects to part (a).*)*

* *(Unhelpful hint: A key term (one word) has the anagram "metro train".)*

6. The image on the cover of the exam is a massive panoramic image taken by Hubble and CTIO.
   (a) [1 pt] What object does it depict?
   (b) [2 pts] How far is it located from Earth in light-years?
   (c) [1 pt] Image 9 depicts an object located within the the object in part (a). Identify what type it is.
   (d) [3 pts] What process causes the edges of the object in part (c) to glow?

7. V1298 Tau is a young star with a compact and complex system of four planets.
   (a) [2 pts] What method of exoplanet detection was used to discover them?

   Image 13 depicts the full K2 light curve of V1298 Tau before (above) and after (bottom) subtracting the stellar variability model.†

   (b) [3 pts] Identify the two planets with the shortest semi-major axis and their mean-motion resonance. Your answer should be two colors out of the four in Image 13 (i.e. blue, yellow, green, and red) that each correspond to a planet and a ratio (e.g. 17:11).
   (c) [1 pt] Which planet has the largest radius? Your answer should be a color from Image 13.
   (d) [2 pts] The stellar variability is associated with the rotation of the host star. At least how many modes of oscillation are needed to model this behavior?
   (e) [2 pts] Image 14 shows a zoomed in, phase-folded light curve for one planet. What phenomenon causes the flux near time zero to be curved rather than flat?

   The placement of V1298 Tau b and e, giant planets in close orbits, suggests that they formed far from their host star and migrated inwards. Through the next five questions, we will follow along the investigation by Turrini et al. (2023).

   The current theory for the formation of gas giants, *core accretion*, first requires the growth of a large solid core. As it grows, a thin atmosphere accumulates forming a hydrostatic envelope. Once a critical mass ($\sim 10\,M_\oplus$) is reached, then gas in its envelope begins to flows onto its core causing further growth which continues until there is no more gas to accrete.

   (f) [3 pts] Explain why this first formation step (underlined) implies gas giants form at large orbital radii. *(Hint: Snow lines and gravity.)*
   (g) [3 pts] What two forces are in imbalance once the critical mass is exceeded? Compare their strengths.
   (h) [1 pt] One possible way the gas giant's supply of gas runs out is through it clearing a gap in the protoplanetary disk along its orbit. What other T Tauri star, in the object list, has visible gaps in its disk, which is viewed face-on from Earth?

   Due to the young age of the system, the migration must have been occured extremely rapidly. Turrini et al. suggests the current system formed by "convergent migration and resonant trapping, i.e. that the planets were trapped in a sequence of mean motion resonances while migrating inwards due to disk-planet interactions." However, the current system is very close to, but is not in a resonant configuration. This suggests some mechanism was able to break the resonance lock.

   (i) [3 pts] Suppose there was a Jupiter-mass planet with a long ($a \sim 4 - 8\,\mathrm{au}$), highly eccentric orbit. Describe how this planet could break the resonance lock. *(Hint: What does eccentricity measure?)*
   (j) [2 pts] Give one possible reason why this planet isn't seen in the K2 light curve (Image 13).

†In the associated paper, David et al. (2019), a Gaussian process model is used, which is a very powerful and flexible nonlinear regression technique. Check out this Distill article to learn about it!

Section C: Quantitative

In this section, you will be asked to perform calculations and provide numerical answers, as well as answer follow up questions that test your understanding. Please box your final answer! Work will not be graded. This section contains a total of 50 points.

Conversions and constants you may find helpful:

$1\,\text{au} = 1.496 \times 10^{11}\,\text{m}$
$1\,\text{ly} = 9.461 \times 10^{15}\,\text{m}$
$1\,\text{pc} = 3.086 \times 10^{16}\,\text{m}$
$1\,\text{M}_\odot = 1.989 \times 10^{30}\,\text{kg}$ (Solar Mass)
$1\,\text{M}_♃ = 1.898 \times 10^{27}\,\text{kg}$ (Jupiter Mass)
$1\,\text{M}_\oplus = 5.972 \times 10^{24}\,\text{kg}$ (Earth Mass)
$1\,\text{R}_\odot = 6.957 \times 10^{8}\,\text{m}$ (Solar Radius)
$1\,\text{R}_\oplus = 6.371 \times 10^{6}\,\text{m}$ (Earth Radius)
$G = 6.674 \times 10^{-11}\,\text{N}\,\text{m}^2\,\text{kg}^{-2}$
$b = 2.898 \times 10^{-3}\,\text{m}\,\text{K}$
$\sigma = 5.670 \times 10^{-8}\,\text{W}\,\text{m}^{-2}\,\text{K}^{-4}$
$M_\odot = 4.74$

Peekaboo! Matilda, a precocious child, is fascinated with astronomy and wishes to discover an exoplanet. She receives a telescope from Miss H and begins observing a star that she dubs Agatha.

1. [2 pts] Agatha has a parallax of 7.24 mas. At what distance d is it located (in parsecs)?
2. [2 pts] Matilda determines the apparent magnitude to be +9.15. What is its absolute magnitude?
3. [3 pts] The effective temperature of Agatha is 8280 K. Calculate its radius $R_\star$ (in $\text{R}_\odot$).
4. [3 pts] Matilda confirms that Agatha is a main sequence star. Using the mass-luminosity relationship for main sequence stars, $L \propto M^{3.5}$, determine the mass of Agatha (in $\text{M}_\odot$).

One night, Matilda has a dream about Agatha. Floating in the air on a hot air balloon, she finds herself on a gas giant orbiting Agatha. She charts the sky and runs into fantastical beasts zipping through the planet's atmosphere. Most importantly, she determines the planet's circumference is 483 000 km and its orbit period is 56.4 years. She wakes up from her long dream and makes some calculations. (If you were unable to determine either the radius or mass of the star in Questions 3 or 4, you may substitute values of $1\,\text{R}_\odot$ and $0.5\,\text{M}_\odot$. Do not substitute only one value.)

5. [2 pts] Estimate the transit depth δ for the gas giant.
6. [4 pts] For simplicity, Matilda assumes the planet follows a circular orbit that is viewed edge-on. She also assumes $d \gg a \gg R_\star \gg R_\text{p}$, where a and R_p are the planet's semi-major axis and radius, respectively. If she were to observe a transit, estimate the transit duration (in hours). Note that the transit duration is the time between first and fourth contact. (If you were unable to determine the radius of the star in Question 3, you may substitute a value of $1\,\text{R}_\odot$.)
7. [4 pts] Using the values found in the last two questions, plot the transit light curve she expects to see. Indicate the transit depth and the time between each of the four contacts (in hours). Assume there is no limb darkening and that the flux changes linearly.
8. [3 pts] Ultimately, the likelihood of Matilda detecting the gas giant with the transit method depends on the orientation of the orbital plane relative to her. It can be shown that the geometric transit probability can be approximated as $R_\star/a$. This equation suggests that transits are most probable for what type of planetary systems?

Due to the low likelihood of the orbit plane aligning and the long orbit period of the planet, Matilda isn't able to detect it and decides to search for a planet at a different star.

Alien Woes

You are an alien astronomer trying to detect an exoplanet around the Sun. In this question, we'll investigate the challenges with detecting the largest and brightest planet in the Solar System, Jupiter.

The most direct method of detection is, well, direct imaging. The two key parameters that make it difficult are the distance you are from the Solar System and the contrast ratio between the Sun and Jupiter. Let's be generous and suppose you live on Proxima Centauri b, the closest exoplanet to the Solar System, which is located 4.2 light years from the Solar System.

9. [2 pts] Knowing that Jupiter orbits at a distance of 5.2 au from the Sun, what is their angular separation (in arcseconds) when viewed from Proxima Centauri b?

10. [2 pts] The majority of the light from Jupiter comes from reflected sunlight. Compute the (bolometric) luminosity of Jupiter (in $L_\odot$), which has a radius of 71 500 km, if it reflects 70 % of the sunlight casted onto it.

As can be seen by the values you calculated, it will be extremely difficult for you to detect Jupiter directly as both the angular separation and contrast ratio are low. However, there is one way you could improve the contrast ratio: observe in the infrared. Image 18[‡] shows the spectral energy distribution (SED) of the Sun and a few planets.

11. [2 pts] Notice that the SED is a log-log graph. Why wouldn't a linear or semi-log graph be well suited to representing this data?

12. [2 pts] There are two peaks in the SED for all of the planets. Explain what each peak corresponds to.

13. [2 pts] Use Wien's law to estimate the effective surface temperature of Mars (in °C).

14. [2 pts] Over the range of wavelengths depicted, which wavelength gives the best contrast ratio? Determine this contrast ratio to the nearest magnitude.

(Question set continues on next page.)

[‡]Carole A. Haswell, *Transiting Exoplanets*, 22

Alien Woes cont.

With this information, you draft and submit a proposal to build a space-based telescope that can observe the Solar System at the wavelength determined in the previous question. The review board of the National Alien Space Administration (NASA) brings up some issues that were not addressed in your proposal.

15. [4 pts] Infrared telescopes are a challenging engineering problem due to the many sources of noise affecting their measurements. The board would like (1) an explanation of the primary source of noise and (2) two methods that could be employed to mitigate it. *(Hint: JWST suffers from the same challenges.)*

16. [3 pts] The choice of wavelength is a multifaceted issue and should not be solely based on its contrast ratio. The board would like the proposal to identify an advantage of observing at $20\,\mu\text{m}$ over the wavelength in the original proposal.

You submit your revised proposal and after ten months the review board gets back to you. "Direct imaging seems like a complete hassle. And (more importantly) building the telescope is too expensive. Try again." Determined to be the first to detect Jupiter, you consider applying the radial velocity method. For simplicity, let's assume Jupiter orbits in a perfect circle and it takes 11.9 years for it to complete one revolution.

17. [2 pts] How fast does Jupiter orbit (in $\text{km}\,\text{s}^{-1}$)?

18. [2 pts] If the Sun has a mass of $1000\,\text{M}_{♃}$, how much would the Sun wobble (in $\text{m}\,\text{s}^{-1}$)?

19. [2 pts] The value found in the previous question is the "best" case in observing the Sun. Why?

20. [2 pts] Spectral resolution is defined as $R = \lambda/\Delta\lambda$ where $\Delta\lambda$ is the smallest difference in wavelengths that can be distinguished at a wavelength of λ. Scientists on Proxima Centauri b have developed high-resolving-power spectrographs with a spectral resolution of $R \sim 150\,000$. Would it be possible to resolve the wobble of the Sun with two measurements? Justify your answer by finding the minimum velocity that can be resolved (in meter/s).

This investigation gives you a lot to think about. You don't feel like writing another proposal so you stash your findings away and leave it for another day.