Science Olympiad
Dick Smith Memorial Invitational
December 2, 2023

Astronomy C

Directions:

- Each team will be given **50 minutes** to complete the test.
- There are four sections: **§A** (General Knowledge), **§B** (Deep-Sky Objects), and **§C** (Calculations).
- For significant figures, **use 3 or more in your answers** unless otherwise specified.
- Tiebreakers, in order: §C, §C1, §C2, §B, §A1, . . . , §A21.
- Best of luck! And may the odds be ever in your favor.

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Feedback? **Test Code**: *2024DSM-AstronomyC-Escape*

Section A: General Knowledge

Use the images in Image Set A to answer the following questions. Unless otherwise specified, each question or sub-question is worth two (2) points, for a total of 50 points.

The following six (6) questions refer to the H-R diagram (or color-magnitude diagram) of a star cluster shown in Image A1. For each question, identify all of the positions in the H-R diagram that correspond to the following descriptions. Each may have multiple answers; list all of them. Write "None" if none of the labeled positions apply.

1. A main-sequence star
2. A red giant or red supergiant star
3. A horizontal branch star
4. A brown dwarf
5. A remnant of a star after its death
6. A star at the main sequence turnoff point

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7. What is the main difference between H I and H II regions with regard to the property of its main constituent?
8. The onset of what process in the stellar interior marks the transition of a protostar into a main-sequence star?
9. What is the primary process of energy generation in brown dwarfs?
10. What kind of objects are created when protostars eject material through jets and those jets interact with the surrounding material?
11. What element in the atmosphere of T Tauri stars gets destroyed as they become main-sequence stars?
12. Briefly explain why T Tauri stars cannot be classified/discovered by their light curves.
13. What type of T Tauri star is accompanied by an almost non-existent disk?
14. Identify a property of molecular clouds that cause them to be undetectable through visible light.
15. Emission processes from what molecule is the main way of detecting molecular clouds?
16. Protostars and pre-main sequence stars often exhibit an "infrared excess," meaning more energy is being emitted at infrared wavelengths than would be expected for a blackbody. What is the most typical cause of this infrared excess?
    A. Carbon in their atmospheres
    B. An undetected cool stellar companion
    C. A nebula produced by mass loss
    D. A circumstellar disk with dust
17. How are the dust grains of debris disks primarily formed?
    A. They are the dust grains of the original protostar-surrounding clump that were not not accreted by planetesimals
    B. Collisions between small bodies left over from planet formation, like comets and asteroids
    C. Dust grains ejected by nearby stars and supernovae come close to the star and are trapped by its gravitational influence
    D. None of the above; debris disks are made of gas rather than dust
18. [3 pts] Which of the following are currently thought to be processes involved in planet formation? (Select all that apply)
    A. Scattering of planets via their gravitational interactions
    B. Accretion of small dust particles into larger rocky objects
    C. Planetary migration to inward orbits (closer to the star)
    D. Ignition of hydrogen fusion within planet cores

The following three (3) questions are about the direct imaging method.

Image A2 displays idealized spectra of the Sun and Earth as viewed by an external observer of the Solar System. The Earth is at its maximum angular separation from the Sun. The gray shaded area indicates the range of visible light.

19. [4 pts] The Earth's spectrum in the diagram is composed of two humps.
    (a) What causes the hump at shorter wavelengths?
    (b) What causes the hump at longer wavelengths?

20. [6 pts] The *contrast* between a star and a planet is defined as the ratio between the planet brightness and star brightness at a certain wavelength, and is particularly important in direct imaging.
    (a) Estimate the contrast at the Earth's visible wavelength peak at 0.5 μm to the nearest order of magnitude (i.e. give your answer as 10^p, where p is an integer).
    (b) Estimate the contrast at the Earth's mid-infrared peak at around 10 μm to the nearest order of magnitude.
    (c) Assuming it were possible, would you expect directly imaging the Earth to be easier in visible wavelengths or mid-infrared wavelengths? Use your answers from parts (a) and (b) to justify your answer.

21. [3 pts] If the Earth were placed in orbit around a different star, and *assuming the spectrum of the Earth remained completely the same*, what spectral class star would result in a larger contrast?[1]
    A. O9Ib
    B. F4V
    C. M0V
    D. A3II

[1] This question was removed from scoring due to a wording error. It has now been fixed.

Section B: Deep-Sky Objects

Use the images in Image Set B to answer the following questions. Unless otherwise specified, each question is worth two (2) points, for a total of 60 points.

1. [1 pt] Identify the DSO represented by the graph in Image B15.
2. What is similar about the planetary system in Image B15 as Image B11?[2]
3. What is the orbital period of the DSO from Image B15 according to the graph?
4. What exoplanet detection method does the graph in Image B15 represent?
5. [3 pts] What is one advantage of this exoplanet detection method?
6. Which of the following best describes the DSO from Image B3?
   - A. A star with changing luminosity and a peculiar lack of metals in its upper atmosphere
   - B. A pre-main sequence undergoing gravitational contraction
   - C. A bright patch of nebulosity formed when jets of ionized gas collide with nearby clouds of gas and dust
   - D. A dwarf Cepheid surrounded by a protoplanetary disk
7. What is the source of the variability for the DSO in Image B3?
8. [1 pt] Identify the DSO in Image B2.
9. Which of the following compounds was not detected in the atmosphere of the object from Image B2?
   - A. Carbon dioxide
   - B. Sulfur dioxide
   - C. Nitrous oxide
   - D. They were all detected in its atmosphere
10. What ingredient necessary for life on Earth was detected on the DSO in Image B5?
11. [1 pt] Identify the DSO in Image B1.
12. What is thought to be the cause of the dark ring in the middle of Image B1?
13. [3 pts] Name one other piece of evidence for the source of the dark ring in Image B1.
14. Name another DSO which is the same type of object as the DSO in Image B1.
15. Which planetary formation theory would be supported by significant evidence if a gas giant were discovered within the planetary system around Image B11?
    - A. Core accretion
    - B. Hydrostatic equilibrium
    - C. Disk instability
    - D. Triple alpha process

[2] This question was removed from scoring due to ambiguity.

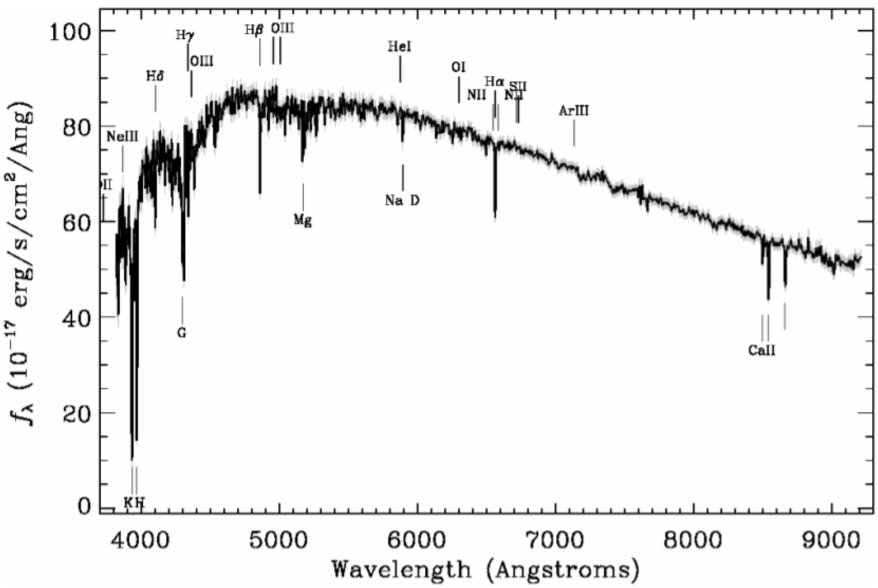
16. Which of the following is not true about the planetary system in Image B11?
    - A. The host star emits more UV radiation than our Sun
    - B. There are several planets within the habitable zone
    - C. At least one of the planets is tidally locked towards the host star
    - D. The atmosphere around most of the planets are likely nitrogen-dominated
17. [1 pt] Identify the DSO in Image B13.
18. What exoplanet detection method does the graph in Image B13 represent?
19. [1 pt] Identify the DSO in Image B4.
20. What is the closest object to Earth that is most similar to the object in Image B4?
21. Which image number corresponds to a DSO from the same region as the DSO from Image B4?
22. Which image number corresponds to the brown dwarf DSO closest to Earth?
23. What wavelength was this image taken in?
24. What type of star does V830 Tau B orbit?
25. Which of the following is true about the star orbited by V830 Tau B?
    - A. It is a fully convective star that follows the Hayashi track
    - B. It is a type of extrinsic variable star with quasi-periodic changes to its luminosity
    - C. It belongs to a class of stars that are especially likely to host extraterrestrial life systems because they are abundant and stable on the main sequence for a long time
    - D. Both A and B are correct
26. An object from the Carina Nebula can be found in which image?
27. What is the evolutionary stage of this object from the Carina Nebula?
28. Which of the following is true about this object from the Carina Nebula?
    - A. It will eject its outer layers into a planetary nebula and become a white dwarf
    - B. It is a triple star system of O-class stars that are short-lived with high UV radiation
    - C. It is surrounded by a small cloud of ionized hydrogen thought to have been ejected by the object itself
    - D. It is an isolated, dark nebulae found within an H II region where star formation occurs
29. Which image number corresponds to an exoplanet that will spiral towards and eventually merge with its host star?
30. What is the name for this process?
31. [3 pts] Rank the following images from smallest to largest by mass: Image B9, B10, B12, B14.

Section C: Calculations

Points are shown for each question or sub-question, for a total of 60 points.

1. [2 pts] If the parallax of a star is detected to be 0.01 arcseconds, what is the distance to the star in light years?

The following three (3) questions refer to the spectrum of a certain star shown below.



2. [2 pts] Estimate the effective temperature of the star in kelvins.

3. [3 pts] If this star has an absolute visual magnitude of 4.8 and an apparent visual magnitude of 10.8, what is its distance to Earth in parsecs?

4. [2 pts] This star most likely a member of which Harvard spectral type (i.e. O, B, A, F, G, K, M)?

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5. [3 pts] The planet J1407b is thought to have an incredibly giant ring system with a diameter of 1.2 au[3]. If these rings were instead placed around Saturn, and viewed when Saturn is closest to Earth (an Earth-Saturn distance of 8.0 au), what would be the angular diameter of the rings, as seen from Earth, in arcseconds? *(Hint: You should get an answer wider than the angular diameter of the Moon, which is "only" about 1800 arcseconds across.)*

6. [3 pts] "Circumbinary" planets exist that orbit two stars instead of just one (i.e. like Tatooine from Star Wars).

   If a planet is discovered orbiting two stars named star A and star B, with the stars having masses of $M_A = 3.0\,M_\odot$ and $M_B = 5.0\,M_\odot$, and the planet's orbit has a semi-major axis of 21 au, what is the period of its orbit in Earth years? Assume that the planet has negligible mass and orbits far enough away that we can approximate it as orbiting one star with an effective mass of $M_A + M_B$.

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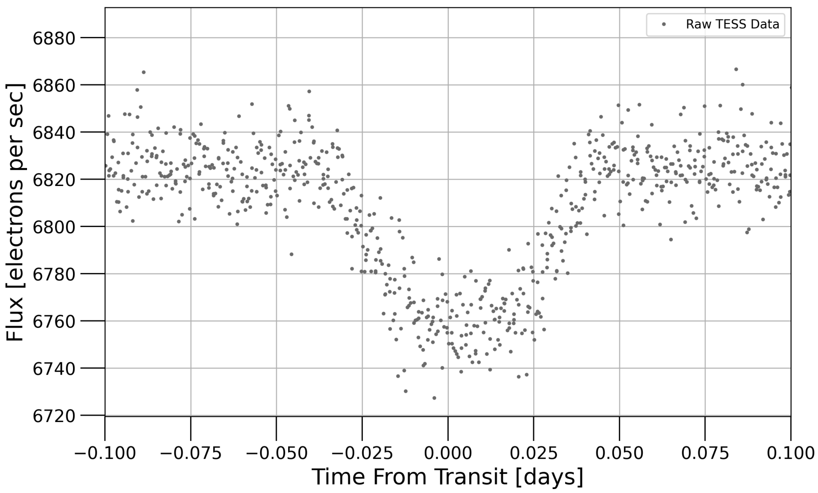
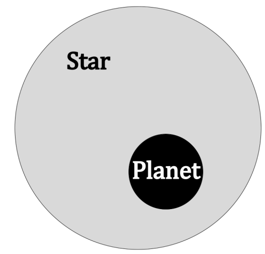
[3] Yes, they may be wider than the distance between the Earth and Sun!

The following five (5) questions are about the transit method.

You think you've discovered a new planet! Your initial evidence is composed of transit measurements shown below on the left. Using this, we will characterize your planet.





7. [3 pts] The host star of the planet has a luminosity of $2.00\,\mathrm{L}_\odot$ and a temperature of $6100\,\mathrm{K}$. Determine its radius in solar radii.

8. [15 pts] We can estimate the radius of a transiting planet using the light curve of its host star. The phase-folded light curve for your planet is shown above on the left.[4]

   (a) [7 pts] First, estimate the following quantities to three significant figures:
   (Note: Do not worry about being super precise as answers will be accepted within a range.)

      i. [1 pt] The average flux outside of transit, F_0, in electrons/sec

      ii. [1 pt] The average flux during transit, F_{transit}, in electrons/sec (excluding the beginning/end of transit during which the flux is increasing/decreasing)

      iii. [2 pts] The transit depth, which is the (absolute value of) the fractional change in flux during the transit, $\Delta F = (F_0 - F_{\text{transit}})/F_0$. Give your answer as a decimal, not a percentage

      iv. [3 pts] The corresponding increase in apparent magnitude during the transit

   (b) [3 pts] Assume that both the star and planet are far enough away that they are effectively at the same distance. When the disk of the planet as seen from Earth is entirely in front of the disk of the star during transit, as shown in the image above on the right, determine a formula for the fraction of the star's area the planet blocks from our view, in terms of the radii of the star (R_s) and planet (R_p). *(Note: Do not include this formula in your answer.)* Then use your formula to calculate this fraction for a transiting planet with a radius 1/16 that of its star. *(Hint: pretend that the star and planet are two-dimensional objects rather than three-dimensional ones.)*

   (c) [2 pts] If we additionally assume that the star has uniform brightness across its disk, then what fraction of the star's flux that we would normally receive at Earth is blocked during transit (i.e. ΔF)? Again, compute ΔF for a planet with a radius 1/16 that of its star.

   (d) [3 pts] Using the transit depth you determined in part (a.iii) and the stellar radius you determined previously, compute the radius of the planet shown in the transit light curve, in units of Earth radii. *(Hint:* $1\,\mathrm{R}_\oplus = 6.38 \times 10^6\,\mathrm{m}, 1\,\mathrm{R}_\odot = 6.96 \times 10^8\,\mathrm{m}$.*)*

[4] The units of electrons/sec are due to the way light detection works in CCDs, which are commonly used in telescopes.

9. [1 pt] Is the planet radius you derived in the previous question consistent with what you might expect for a planet? If not, what other kind of object might it be?

10. [2 pts] Next, you want to determine the mass of the planet. Provide one reason why the mass may be useful for understanding the planet.

11. [3 pts] Unfortunately, it is (usually) not possible to determine the mass of a planet from a transit light curve alone. Name a method astronomers commonly use to measure an exoplanet's mass, and briefly describe how it works.

The following six (6) questions are about finding planetary equilibrium temperatures and habitable zones.

The equilibrium temperature of a planet is defined as the effective blackbody temperature at which a planet must radiate such that it outputs thermal energy at the same rate it receives thermal energy. We can derive the equilibrium temperature using the equation $S(1-\alpha)/4 = \sigma T_{\mathrm{eq}}^4$, where:

- S is the flux from the host star at the planet's position (in $\mathrm{W\,m^{-2}}$);
- α is the Bond albedo of the planet, the percentage of incident stellar radiation (as a decimal) that it reflects rather than absorbs (dimensionless);
- σ is the Stefan-Boltzmann constant, $5.670 \times 10^{-8}\,\mathrm{W\,m^{-2}\,K^{-4}}$;
- and T_{eq} is the planetary equilibrium temperature (in K).

The expression on the left side represents the rate at which light energy from the host star is absorbed by the planet, while the expression on the right side corresponds to the blackbody emission from the planet.

12. [6 pts] You've discovered a hot Jupiter exoplanet orbiting a $1.0\,\mathrm{L_\odot}$ star at a mean orbital radius of $0.050\,\mathrm{au}$. Assume that it has an albedo of 0.5.
    (a) [3 pts] S at some distance d from a star can be calculated via the inverse-square law for light, $S = L/(4\pi d^2)$, where L is the stellar luminosity. Determine the value of S for this planet in $\mathrm{W\,m^{-2}}$.
    (b) [3 pts] Using your answer from part (a), determine the equilibrium temperature for the planet in kelvins.[5]

13. [3 pts] If we were to make the (poor) decision to push the Earth from its current orbital radius to a new orbital radius sixteen times as large, what would the ratio between its new equilibrium temperature and its original equilibrium temperature be? Answer as a decimal.

14. [3 pts] Planetary equilibrium temperature is a useful concept, but is *not* necessarily equal to the actual surface temperature of a planet. Name an effect that may cause the surface temperature to be different.

[5] Your answer should make it obvious why we call this a "hot" Jupiter!

Though the definition of planetary equilibrium temperature has its flaws, one way it is useful is to estimate the habitable zone around a star, i.e. the range of distances at which liquid water can exist on the surface of a planet. If we assume that the atmospheric pressure is 1 atm, then water is liquid between 273 K and 373 K. We can then estimate the habitable zone by assuming the surface temperature equals the planetary equilibrium temperature (again, not a perfect assumption) and then determining the corresponding distances.

15. [3 pts] For the Sun, assuming that the albedo of all planets is 0, the inner and outer limits of the habitable zone are currently at 0.56 au and 1.04 au. The Sun has not remained the same brightness during its time on the main sequence, so let's consider how the habitable zone in the solar system changes over time. If the Sun becomes 25.0 % brighter than it is now, what would be the new inner and outer limits of the habitable zone?

16. [3 pts] Give one reason why the habitable zone, when defined as "the region where surface liquid water can exist," is not necessarily the region around a star that can support life. You do not need to explain your answer in detail; simply naming a reason is sufficient.

17. [3 pts] Since planets on eccentric orbits have distances to their host star that change over time, they may or may not always remain in the habitable zone. For a certain star, let the inner limit of the habitable zone be at 3 au and the outer limit be at 6 au. Calculate the maximum value of the eccentricity for which a planet can remain within the habitable zone at all points during its orbit.

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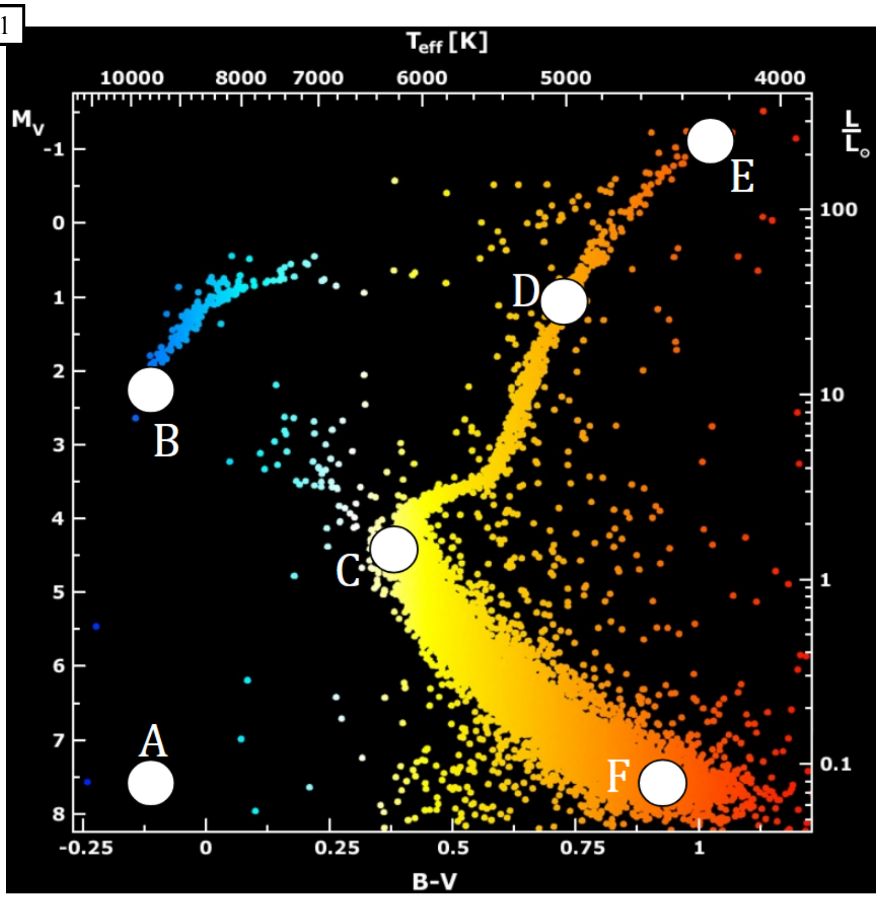
Astronomy C Image Sheet

Directions:

- Do not open until the test begins.

Image Set A

1



2

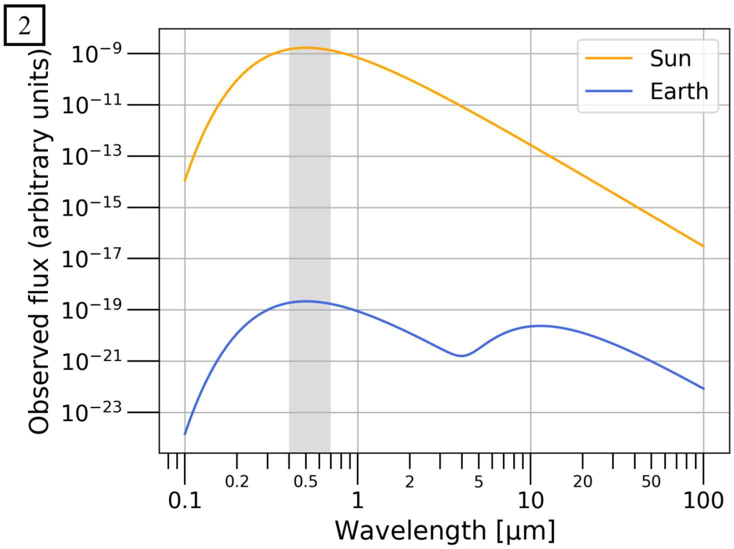
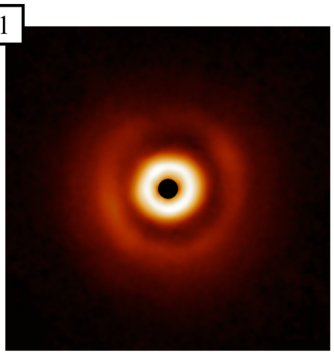


Image Set B (1/2)

1



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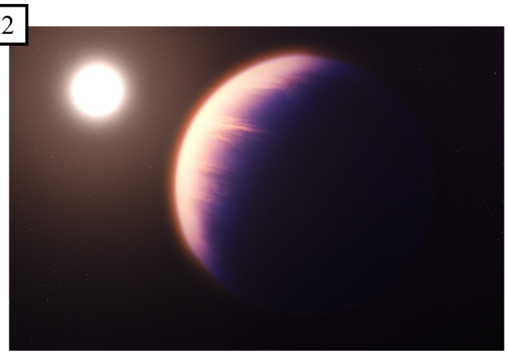
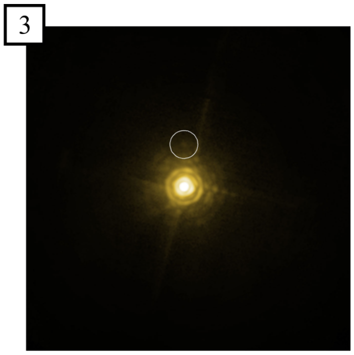
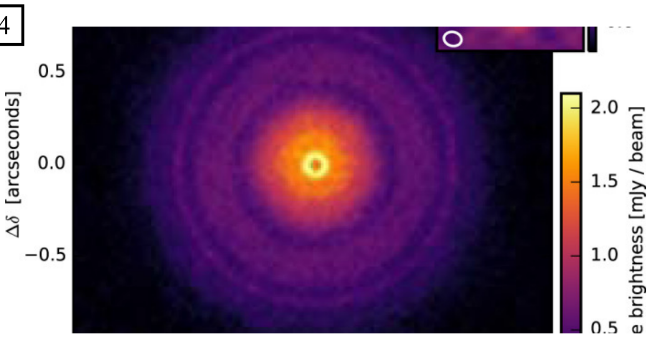


3



4



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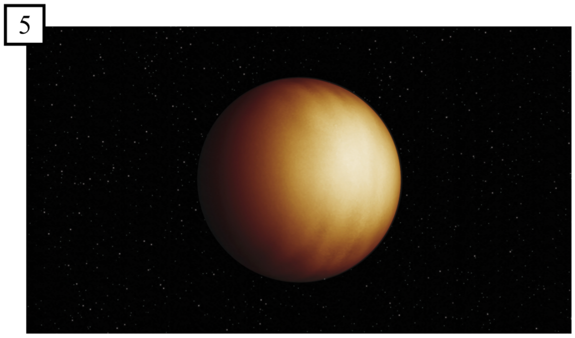

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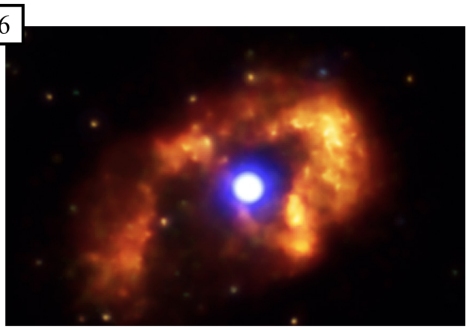

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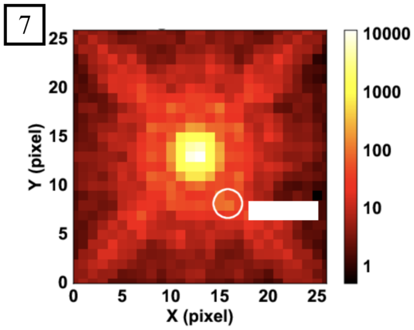

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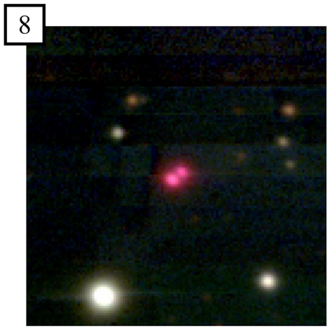
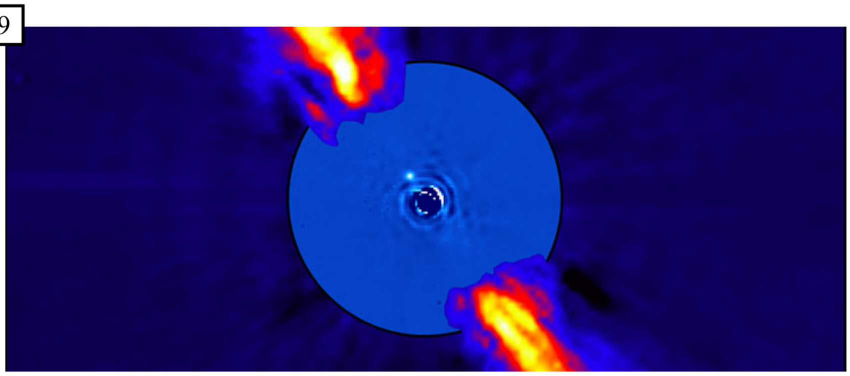


9



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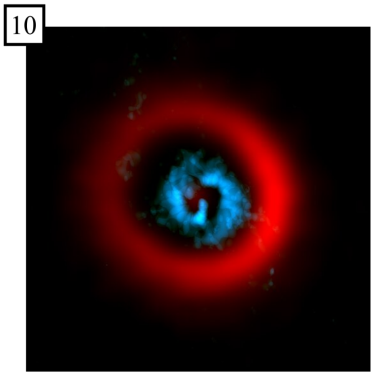
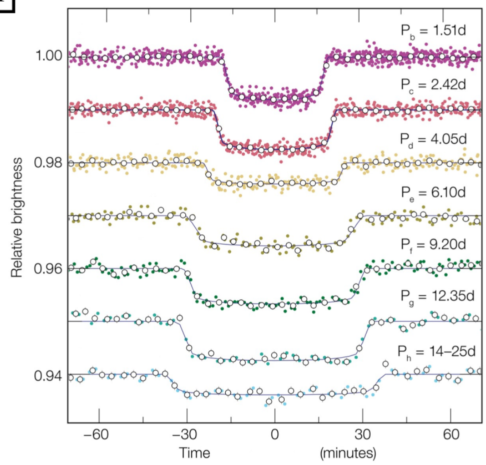
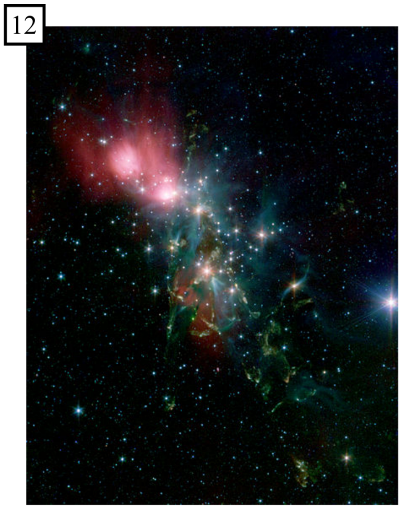


Image Set B (2/2)

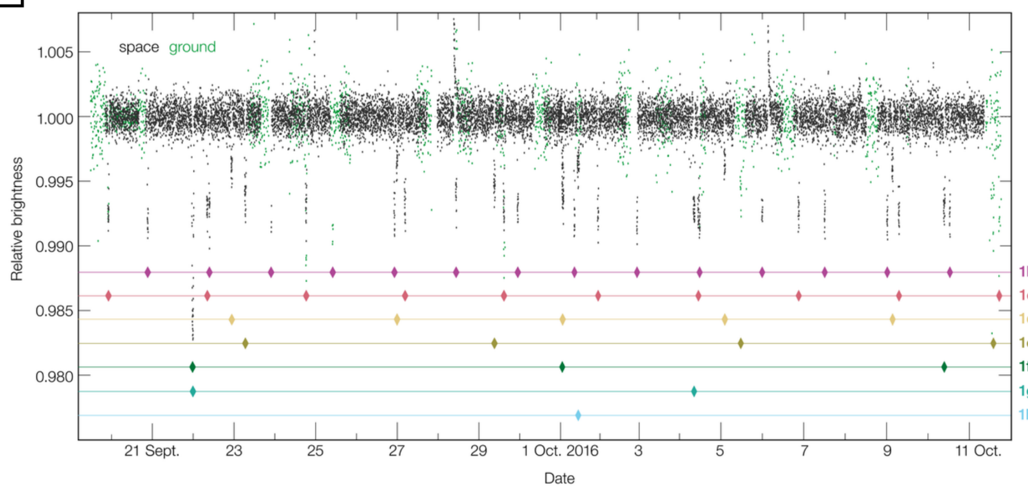
11



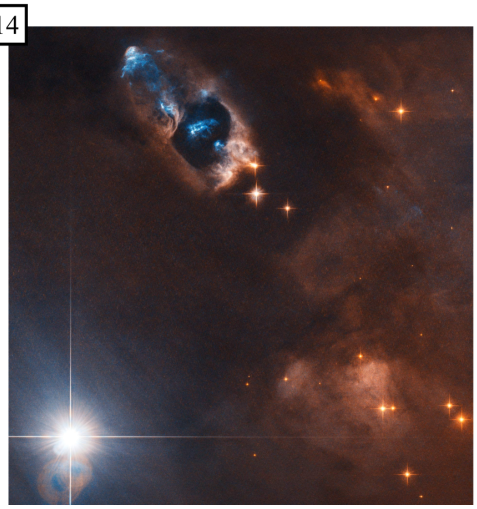
12



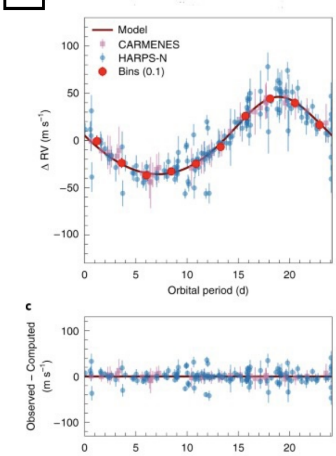
13



14



15



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Astronomy C Answer Key

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Section A (50 points)

1. C, F
2. D, E
3. B
4. None
5. A
6. C
7. H I consists of un-ionized gas while H II consists of ionized gas
8. Fusion of hydrogen into helium
9. Gravitational contraction
10. Herbig-Haro objects
11. Lithium
12. Too erratic/unpredictable
13. Weak
14. Extremely cold and dark and shrouded in dust
15. Carbon monoxide
16. D
17. B
18. [3 pts] ABC
19. (a) Reflection of solar radiation
    (b) Thermal emission
20. (a) 10^{-10}
    (b) Accept 10^{-7} or 10^{-8}
    (c) Mid-infrared; contrast is larger in the mid-infrared meaning Earth is less "drowned-out" by the Sun's light. "Contrast is larger" is accepted regardless of the correctness of parts (a) and (b) (i.e. if they had a contrast larger in visible than in infrared and answered visible with the justification of higher contrast, points are awarded).
21. [3 pts] C[1]

[1] This question was removed from scoring due to a wording error. It has now been fixed.

Section B (60 points)

1. [1 pt] V 1298 Tau b
2. They both exhibit resonance[2]
3. 24 days
4. Radial velocity method
5. [3 pts] Provides minimum mass estimate. Better at detecting planets around low-mass stars which are the most common in the universe and more likely to have rocky planets. Potentially can detect a planet's eccentricity and orbital inclination.
6. (HR 8799) A star with changing luminosity and a peculiar lack of metals in its upper atmosphere
7. Non-radial pulsations
8. [1 pt] WASP-39b
9. Nitrous oxide
10. (WASP-18b) Water in the atmosphere. Partial credit [1 pt] for carbon monoxide
11. [1 pt] HD 169142
12. Protoplanet. Partial credit [1 pt] for identifying it as a protoplanetary disk or that the dark ring is an "annular gap"
13. [3 pts] Full credit for spiral-patterned wakes, the object detected follows Keplerian motion, or SO_2/SO/CO detected at the position of the planet. No credit for identifying "carbon", methanol, hydrogen cyanide, or carbon monosulfide. Additionally, no credit for carbon monoxide in the disk itself.
14. AB Aurigae (Image B10 also accepted)
15. (TRAPPIST-1) Disk instability
16. The atmosphere around most of the planets are likely nitrogen-dominated

[2] This question was removed from scoring due to ambiguity.

17. [1 pt] TRAPPIST-1
18. Exoplanet transit detection method
19. [1 pt] TW Hydrae b
20. Neptune or Uranus (or Sun)
21. Image B7 (2M 1207)
22. Image B8 (Luhman 16). Partial credit [1 pt] for correctly naming Luhmann 16 without the correct image number.
23. Full credit for visible light or specifying the measured wavelength in the range of 400 to 700 nanometers.
24. Full credit for T Tauri star or M- or K-type star.
25. Both A and B are correct
26. Image B6
27. Luminous Blue Variable. Partial credit [1 pt] for "hypergiant", "blue supergiant", "O- class supergiant" but no credit for "blue giant".
28. It is surrounded by a small cloud of ionized hydrogen thought to have been ejected by the object itself
29. Image B5 (WASP-18b)
30. Tidal deceleration
31. [3 pts] Image B14 (HH7-11), Image B9 (Beta Pictoris), Image B10 (AB Aurigae), Image B12 (NGC 1333). Partial credit [1 pt] for one in the correct spot and [2 pts] for two in the correct spot.

Section C (60 points)

1. [2 pts] 326 ly
2. [2 pts] 5800 K [5000, 6500]
3. [3 pts] 158 pc [141, 176]
4. [2 pts] G (also accept F)
5. [3 pts] $3.09 \times 10^{4\prime\prime}$ [3.07×10^4, 3.11×10^4]
6. [3 pts] 34.0 yr [33.0, 35.0]
7. [3 pts] 1.27 $R_\odot$ [1.26, 1.28]
8. (a) i. [1 pt] 6830 electrons/s [6820, 6835]
      ii. [1 pt] 6760 electrons/s [6750, 6770]
      iii. [2 pts] 0.0104 [0.00739, 0.0126]
      iv. [3 pts] 0.0111 [0.00799, 0.0136]
   (b) [3 pts] 0.00391 [0.0039, 0.0040]
   (c) [2 pts] 0.00391 [0.0039, 0.0040]
   (d) [3 pts] 14.1 $R_\oplus$ [11.0, 16.0] (No points if stellar radius was incorrect)
9. [1 pt] Yes. If their planet radius was incorrect and outside the expected range of planet radii (about 0.3 $R_\oplus$ lower limit to an upper limit somewhere between 25 $R_\oplus$ and 73 $R_\oplus$), but they correctly identified a different kind of object it could be based on their radius (e.g. asteroid, brown dwarf, M dwarf) then still award points.
10. [2 pts] Potential answers may include: density/determining composition; verify identity as a planet; or identify which population of exoplanets it belongs to. Answers about gravitational influences on other things such as other planets or the host star were accepted with full or partial credit (based on the depth of the answer), as those could be used to make predictions about the radial velocity curve or transit timing variations. "How the planet formed" is also allowed since that comes from the exoplanet population. Surface gravity is also acceptable with full points.
11. [3 pts] Accept naming any of the following [1 pt], with appropriate descriptions [2 pts]:
    - Radial velocity
    - Timing variations (transit, pulsar, or variable star)
    - Direct imaging
    - Astrometry
    - Phase curve based methods (ellipsoidal variations, relativistic beaming)
    - Gravitational microlensing
    - Transmission spectroscopy/scale height measurement

12. (a) [3 pts] $5.4 \times 10^5\,\mathrm{W\,m^{-2}}$ [5.2×10^5, 5.6×10^5]

    (b) [3 pts] $1.03 \times 10^3\,\mathrm{K}$ [1020, 1070]

13. [3 pts] 0.25 (exact)

14. [3 pts] Accept any of the following:

    - Greenhouse effect, atmosphere, clouds, aerosols, and etc.
    - Internal heating
    - Tidal heating

    Also accept answers alluding to causes of non-uniform temperature across the surface (i.e. day/night cycle, shallower angle of light incidence near poles, heat may not be perfectly redistributed across the surface)

15. [3 pts] 0.63 au to 1.16 au [[0.61, 0.65], [1.14, 1.18]]

16. [3 pts] Possible responses include:

    - Alternative biochemistries (i.e. no dependence on water)
    - Volatile or hostile environment (e.g. flares, lack of an atmosphere, too much high-energy radiation, wrong pH, etc.)
    - Lack of other processes or nutrients necessary for life
    - Water might never have been accumulated on the planet
    - Subsurface oceans/deep biospheres/chemosynthesis (e.g. water can exist below the surface; hydrothermal vents powered by heat from tidal heating or radioactive decay in ocean might support life)
    - Other reasonable answers

17. [3 pts] 0.333 [0.33, 0.34]