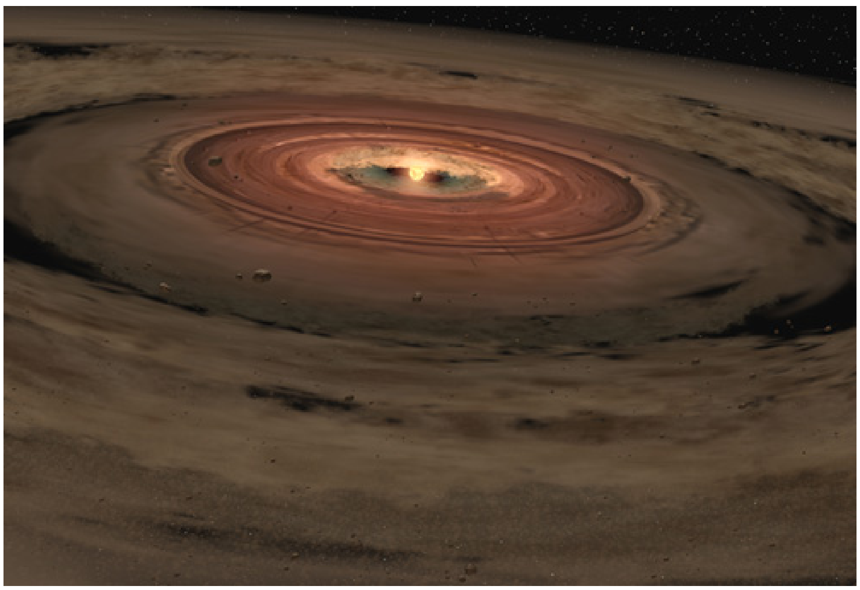
Science Olympiad
Annotated
Astronomy C Division Event
Sample Exam

Stellar Evolution: Star and Planet Formation

2014-2015



Team Number: ______________

Team Name: ______________________________________

Example Instructions:

1) Please turn in all materials at the end of the event.

2) Do not forget to put your team name and team number at the top of all answer pages.

3) Write all answers on the answer pages. Any marks elsewhere will not be scored.

4) Do not worry about significant figures. Use at least 2 or 3 in your answers, regardless of how many are in the question.

5) Note, the answer key for a real exam would include ranges of acceptable answers. Use ±10% (give or take a few %) when checking yours against the key.

6) Please do not access the internet during the event. If you do so, your team will be disqualified.

7) This test was downloaded from: `www.aavso.org/science-olympiad-2015`.

8) Good luck! And may the stars be with you!

Guidelines:

Hello, supervisor! Thank you for lending your time to put together an Astronomy event. The entire Science Olympiad organization relies on the hard work of volunteers like you (and I), and it is great that you are helping Science Olympiad continue to foster extracurricular secondary education in the sciences.

Though the backbone of the Astronomy event is the same, focusing on stellar evolution using a mixture of image analysis, qualitative reasoning, and quantitative physics, the specific topic has changed to star formation and exoplanets. Pay attention to the bold lettering on the rules sheet, as this shows the new information for this year.

To review the rules, first, the event parameters have remained the same. Teams are allowed to bring in either 2 binders, 2 laptops/tablets, or 1 binder and one laptop/tablet. Please check during the event that there is no internet access being used by the teams. How specifically to do so is at your discretion, but checking that the wireless is turned off (easy to do by sight on both PC and Mac) is the simplest way. Additionally, be sure to note that many teams may download webpages and open them in a browser - this is fine, simply check the URL to see that it leads to their hard drive.

The rules are split into 3 sections, as before: a) general topics, b) physics topics, and c) objects (and planetary systems for this year). Section (a) of the rules focuses on the impact of stellar evolution on planet formation, using traditional astronomical methods (spectra, blackbody radiation, Hertzsprung-Russell diagram, etc.) to diagnose young stars, such as T Tauri stars, their formation environment (clouds in the interstellar medium), and potential exoplanets forming around them. Section (b) is related to the physics of these planetary systems, where students use non-calculus Keplerian physics to understand how to obtain distances to and the orbits of exoplanetary systems. Specifically, both the radial velocity and transit method of diagnosing exoplanet orbits will be focused on. Section (c) then looks at specific objects- young stars (e.g. FU Origins), systems with exoplanets (CoRoT-2), exoplanets themselves (HD 209458b), brown dwarfs (Gliese 229B), star formation regions (M20). Students should be able to identify and know basic information about these objects, specifically why they are important in the context of the event and their knowledge from Sections (a) and (b).

The test itself here is also split into 3 sections, which do not map directly onto the rules themselves. Section (a) is a basic qualitative section, focusing on Sections (a) and (c) of the rules. Hence, it is about understanding the foundation of the event, specifically how stellar evolution works and knowing concepts and objects outlined in the rules. Section (b) is the physics section, which here focuses on exoplanet detection. Essentially, given the same information as a real astronomer has about a given system, students are asked to calculate properties of the exoplanetary system, e.g. the semi-major axis from the planet to the star or the radius and/or mass of the exoplanet. Section (c) combines material from Sections (a), (b), and (c) together for students to make inferences about the habitability of exoplanets and understand the context of exoplanetary systems with respect to stellar evolution and our own Solar System.

Resources may be found at http://soinc.org/astronomy_c, http://www.aavso.org/science-olympiad-2015, **and** http://chandra.harvard.edu/edu/olympiad.html.

Section A: Use Image/Illustration Set A to answer Questions 1-19. This section focuses on qualitative understanding of stellar evolution, specifically relating to star formation and planets.
This section is effectively split into two parts, with Questions 1-4 covering Section (a) of the rules, and the remainder covering Section (c) using parts of Section (a) as a backbone. Note how questions on specific types of objects and those in Section (c) are split into their own question for easy referral to by students when collaborating. Additionally, if there are many choices for an answer, they are delimited in the question itself for clarity.

1. A schematic of a T-Tauri star is shown in Image A1.
   (a) Which point (A-F) marks the location of the disk surrounding the protostar?
   (b) Which point (A-F) displays the bipolar outflow that may form Herbig-Haro objects?
   (c) Which point (A-F) shows the strongly variable hot spots on the protostar?
2. A color-magnitude diagram for a sample of brown dwarfs is shown in Image A2. The x-axis shows the J-K color index, while the y-axis displays J-band magnitude. The different colors represent different brown dwarf spectral types.
   (a) Which lettered region (A-D) corresponds approximately to a spectral type L2 brown dwarf?
   (b) Which lettered region (A-D) corresponds approximately to a spectral type T6 brown dwarf?
   (c) Which lettered region (A-D) corresponds approximately to the brown dwarf L-T type transition?
3. The spectrum of a star with a circumstellar disk is shown in Image A3.
   (a) Which line (red or blue) represents the blackbody spectrum of the star itself?
   (b) Which point (A-C) shows where the disk emission dominates over that of the star?
   (c) This point is at much longer wavelengths than the peak emission from the star. Why is this?
4. Light curves from a variety of objects are shown in Images A4-A8.
   (a) Which light curve is from a star with a transiting exoplanet in orbit around it?
   (b) Which light curve is from a T Tauri star?
   (c) Which light curve is from an FU Orionis star?
   (d) Which light curve is from a variable brown dwarf?
   (e) Which light curve is from a Herbig Ae/Be star?

   The following questions (5-19) correspond to Images A9-A24.
5. Which two images show star formation regions?
6. TW Hydrae is the closest T Tauri star to the solar system.
   (a) Which image shows TW Hydrae?
   (b) What surrounds TW Hydrae in the image?

7. WISE 1049-5319 harbors the closest brown dwarf to Earth.
   (a) Which image shows this system?
   (b) How many brown dwarfs are in this system?
8. Which one of the following images shows an object with a debris disk?
   (a) A15
   (b) A20
   (c) A10
   (d) A17
9. Which image shows LP 944-20?
10. One of the images displays a star that is bright in X-Rays and has a planet in a close-in orbit.
    (a) Which image shows this star?
    (b) What is the name of this star?
11. FU Orionis is a prototype of a class of variable stars with its namesake.
    (a) Which image shows FU Orionis?
    (b) What distinguishes this type of object from normal T Tauri stars?
12. Beta Pictoris is a nearby star with a circumstellar disk.
    (a) Which image shows this object?
    (b) Beta Pictoris has a planet, Beta Pictoris b, in orbit around it. Is the distance from Beta Pictoris to Beta Pictoris b greater or less than the distance from the Sun to Neptune?
13. The 2M 1207 system was discovered in 2004.
    (a) Which image shows this object?
    (b) What two types of objects comprise this system?
14. HR 8799 is a star with both a debris disk and planets in its system.
    (a) Which image shows this object?
    (b) Which method was used to detect the orbital motion of its planets?
15. Gliese 229B is a brown dwarf orbiting a star, Gliese 229.
    (a) Which image shows this object?
    (b) What type of variable star is Gliese 229?
16. Image A21 shows a simulated atmospheric temperature map of HD 209458b.
    (a) What longitude and latitude is the substellar point located on this map?
    (b) Why is the hottest point not located directly at the substellar point?

17. Image A22 shows an observed atmospheric temperature map of an exoplanet.
    (a) Which exoplanet is this?
    (b) Does this object have a hotter or colder substellar point than HD 209458b?
18. Image A23 shows a transmission spectrum of an exoplanet. The black points show observations, with the lines indicating models for different atmospheric compositions.
    (a) Which exoplanet is this?
    (b) What is indicated by the misfit between the data points and expectation?
19. Image A24 shows the brightness map of an exoplanet.
    (a) Which exoplanet is this?
    (b) What is a possible implication of the brightest point on this planet being on the opposite side of the planet than expected?

Section B: Use Image/Illustration Set B to answer Questions 20-25. This section discusses radial velocity and transit methods, working through the advantages of each, and concluding with calculations of planet properties using these methods. This section is also split into two parts, with Questions 20-23 covering qualitative aspects of exoplanet detection with Questions 24 and 25 focusing on quantitative problem solving. Question 24 focuses on radial velocity detection of exoplanet mass (taking students step-by-step to the calculation), while Question 25 focuses on transit detection of radius, again taking students step-by-step to the final answer (and asking a follow-up question).

20. Which of the following planet properties is best constrained via the transit method?
    (a) Mass
    (b) Atmospheric Composition
    (c) Density
    (d) Radius

21. Which of the following planet properties is best constrained via the radial velocity method?
    (a) Mass
    (b) Atmospheric Composition
    (c) Density
    (d) Radius

22. How can an observer obtain the effective temperature of a planet via the transit method?

23. When using the radial velocity method, is an observer measuring the maximum or minimum mass of a planet? Why?

24. Image B1 shows the radial velocity curve of host Star A, around which Planet B orbits. Star A has the same mass, radius, and luminosity as the sun. Assume that the system has no inclination and Planet B has 0 eccentricity (a circular orbit).
    (a) What is the distance from Star A to Planet B, in AU, assuming Planet B has a mass much less than that of Star A?
    (b) What is the velocity of Planet B in its orbit around Star A, in km/s?
    (c) What is the mass of Planet B, in Jupiter masses?
    (d) Planet B has a radius of 0.8 Jupiter radii. What is the density of Planet B, in g/cm^3?

25. Image B2 shows the light curve of Star C, displaying transits due to Planet D. Star C is a K1 star with a mass of 0.80 Solar Masses and radius of 0.79 Solar Radii. The orbital period of Planet D is 2.22 days. Assume that the system has no inclination and Planet D has 0 eccentricity.
    (a) Which point (A-E) shows the Primary Eclipse, when Planet D blocks light from Star C?

(b) Which point (A-E) shows the Secondary Eclipse, when Star C blocks light from Planet D?

(c) What is the transit depth of the Primary Eclipse, in terms of the % of normal (non-eclipse) system flux?

(d) What is the radius of Planet D, in Jupiter radii?

(e) What is the total duration of the Primary Eclipse, in seconds?

Section C: Use Image/Illustration Set C to answer Questions 26-29. This section focuses on the mathematics of stars & planetary systems.

This section is for the astrophysical "jack of all trades," and is nominally the hardest, hence why it is the last to appear on the exam. Question 26 goes step-by-step through a habitability calculation: knowing some basic information about an exoplanetary system, can the student say something about whether water might be present on its surface in liquid form? Question 27 is an astrophysical question, looking at stellar spectra and qualitatively explaining their differences. Question 28 is a combined astrophysical and planet question, including both calculating a distance to a star and then using that distance to compare the brightness of a planet and its host star. Question 29 is a question using a graph to compare the properties of planets in the Kepler-11 planetary system, seeing which ones have densities unlike and similar to our own Earth, for purposes of comparative planetology.

26. Image C1 shows the blackbody spectrum of Star E, which is a main-sequence star with a parallax of 0.1" and radius of 0.480 Solar Radii. Planet F orbits Star E, has the same mass and radius as Earth, and lies at a distance of 0.176 AU from Star E.

    (a) What is the distance to Star E, in parsecs?

    (b) What is the effective temperature of Star E, in Kelvin?

    (c) What is the Spectral Type of Star E?

    (d) What is the equilibrium temperature of Planet F, in Kelvin, assuming it has 0 albedo?

    (e) Is Planet F potentially habitable? Use the phase diagram for water in Image C2 to aid your response. Assume that habitability only requires the existence of liquid water on the surface of a planet, and that Planet F has the same atmospheric surface pressure as Earth.

    (f) Your response for Part (d) did not include the greenhouse effect. Would the greenhouse effect be stronger or weaker for Planet F than for Earth? Why?

27. Images C3, C4, and C5 show spectra from 3 different main-sequence stars.

    (a) Which image corresponds to the star with the highest luminosity?

    (b) Which image corresponds to the star with the lowest effective temperature?

    (c) Which image corresponds to a spectral type F5 star?

28. Star G is a M2V star at a distance of 50 parsec. Planet H orbits Star G at a distance of 0.01 AU, and has a radius equal to that of Jupiter.

    (a) What is the apparent visual magnitude of Star G?

    (b) Assuming that Planet H has 0 albedo, how many times brighter is Star G than Planet H?

29. A plot of planet Radius (in Earth Radii) vs. Mass (in Earth Masses) for the Kepler-11 system is shown in Image C6, with the Solar System planets over-plotted as triangles and a sample of transiting exoplanets plotted as squares. Lines of constant density for a given composition are also shown.

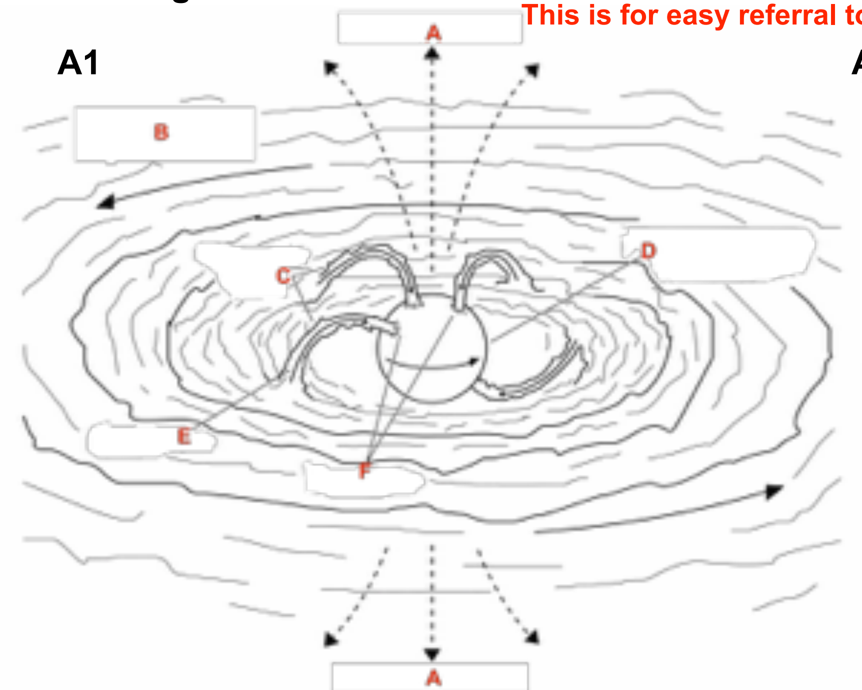
(a) Which planet orbiting Kepler-11a has the highest density (b-f)?

(b) What is the density of Kepler-11c, in g/cm^3?

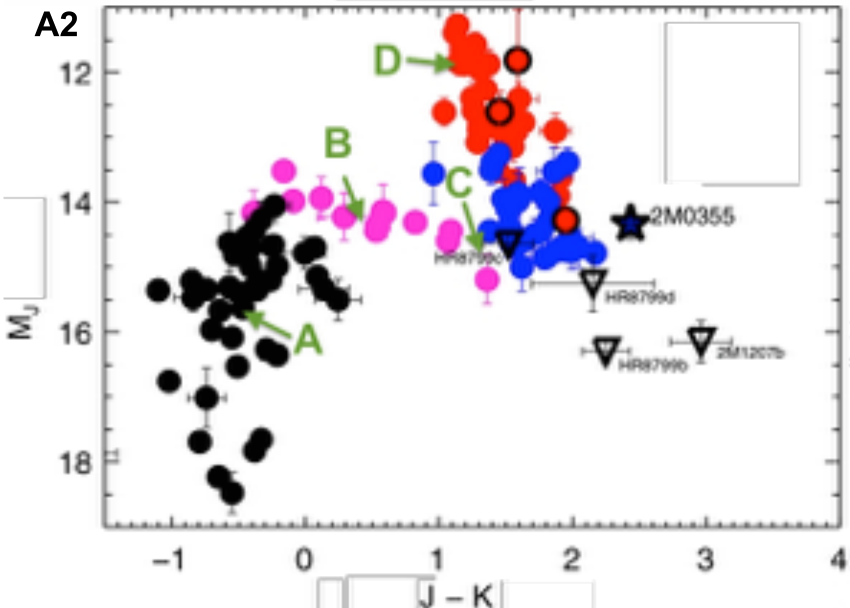
(c) Kepler-11g is a recently discovered member of the system, with a yet-undetermined density. Its semi-major axis is 0.46 AU, and it has an orbital period around Kepler-11a of 118.4 days. What is the mass of Kepler-11a, in Solar Masses, assuming the mass of Kepler-11g is much smaller than Kepler-11a?

Image/Illustration Set A: Note how the images are numbered by Section and number within Section. This is for easy referral to images in the test, to minimize confusion.

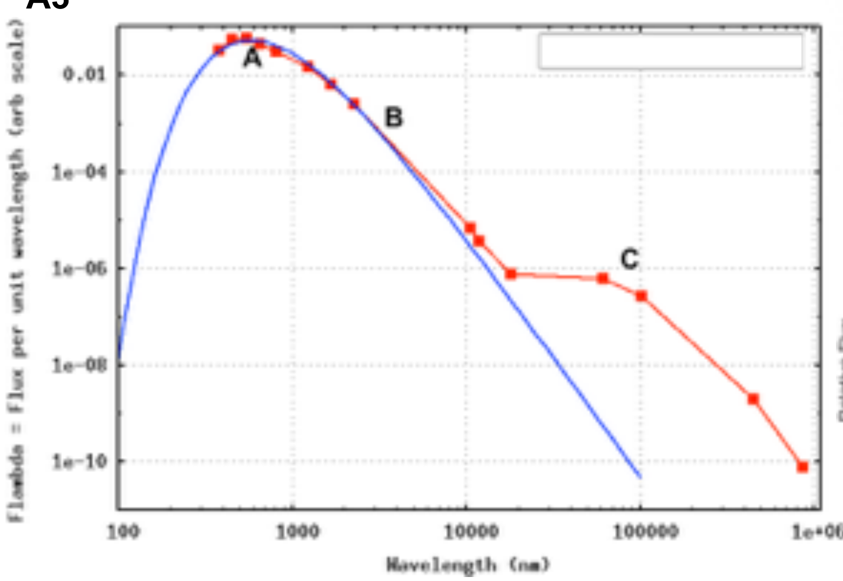
A1



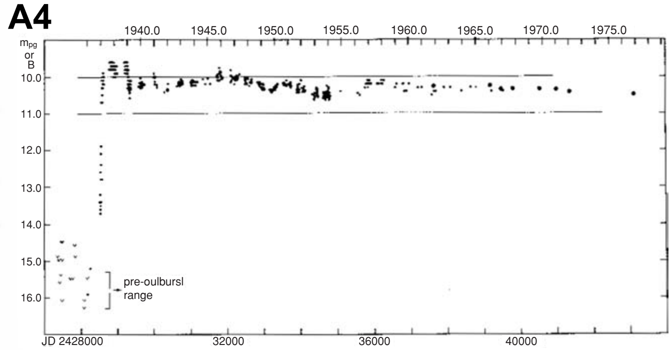
A2



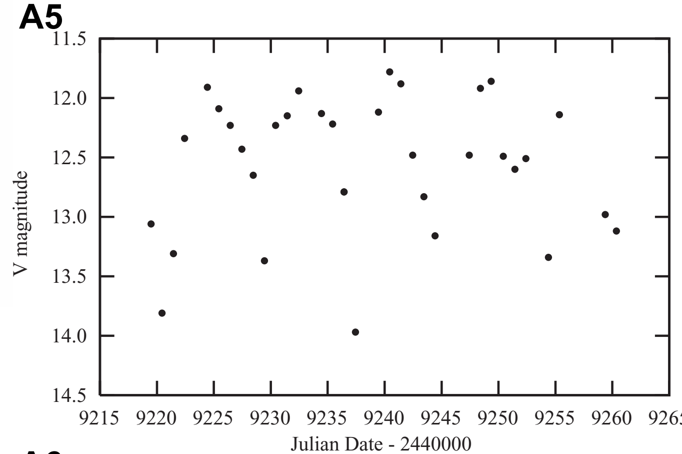
A3



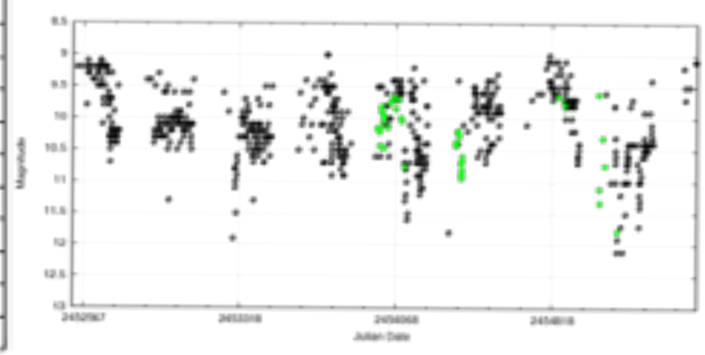
A4



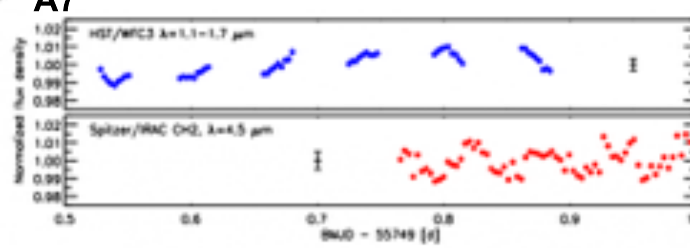
A5



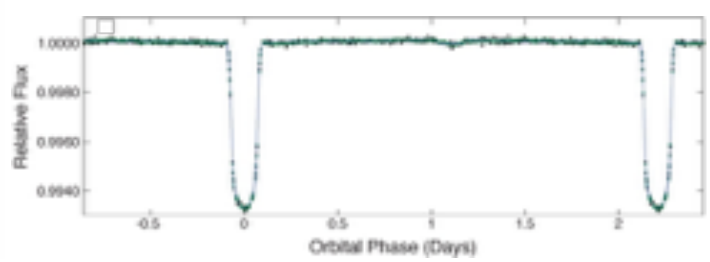
A6



A7

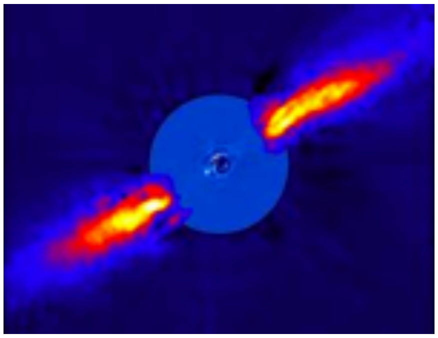


A8



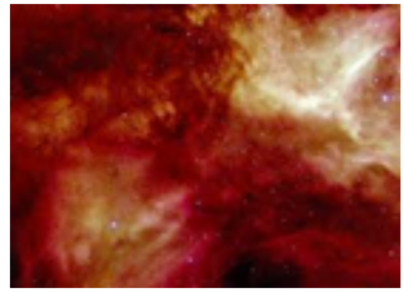
Image/Illustration Set A: Separated light curves/diagrams (last page) from DSO images (this page) to help students.

A9

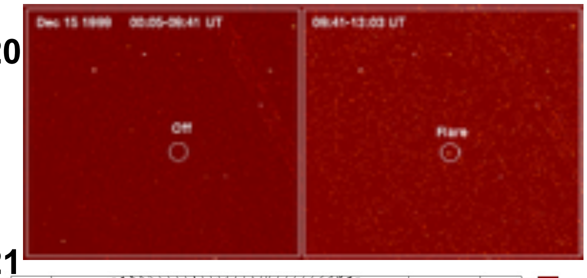


A14

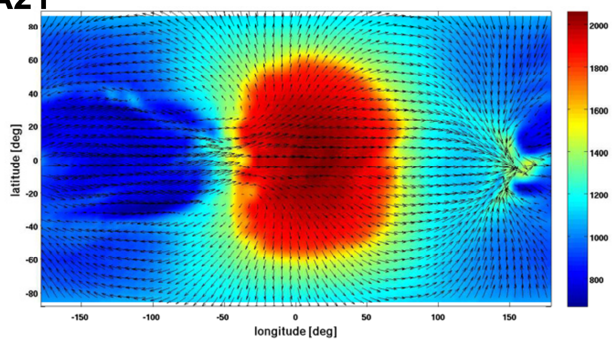
A19



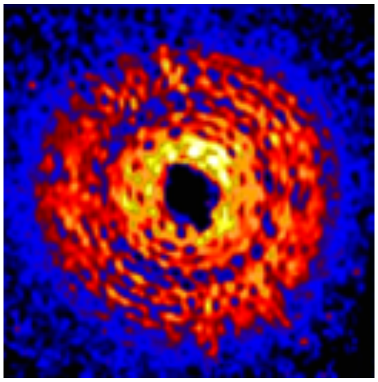
A20



A21

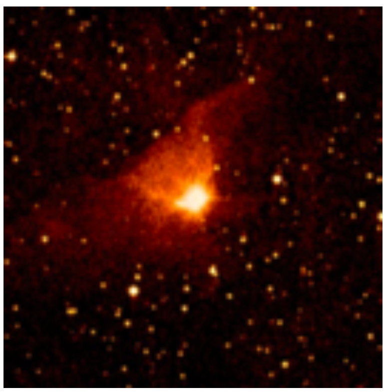


A10

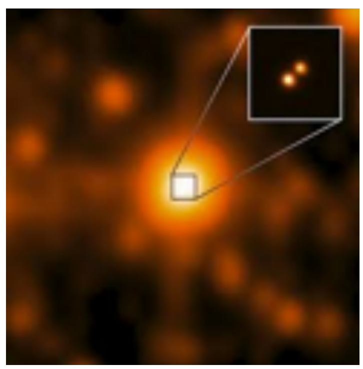


A15

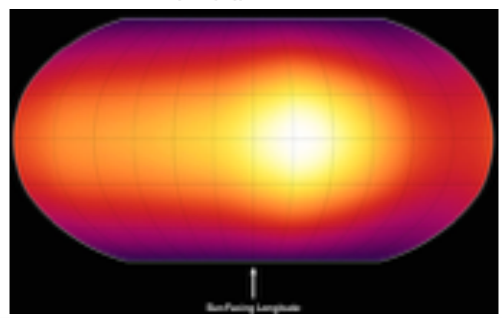
A11



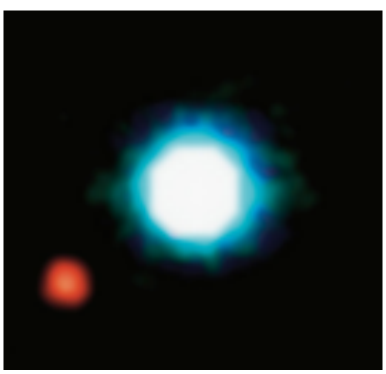
A16



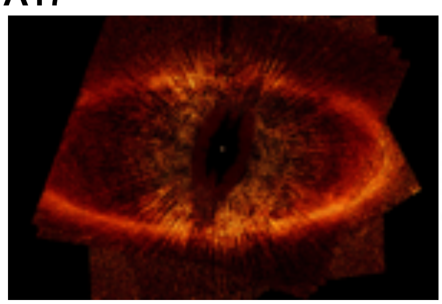
A22



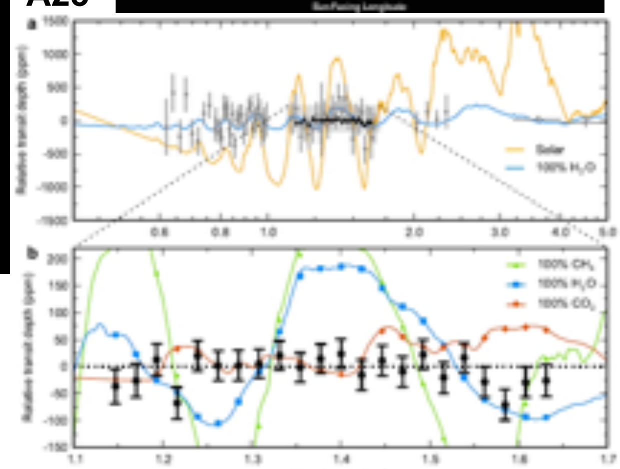
A12



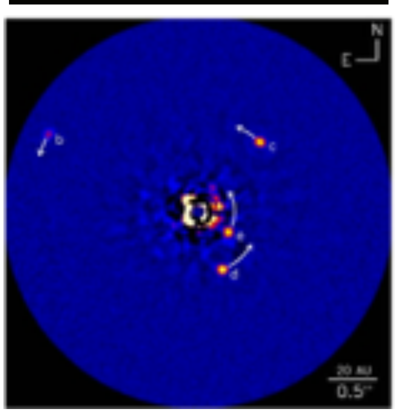
A17



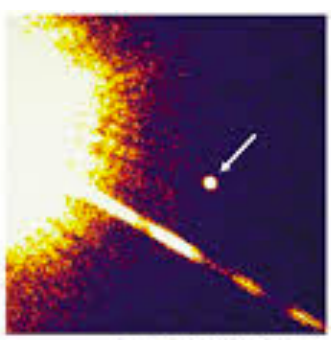
A23



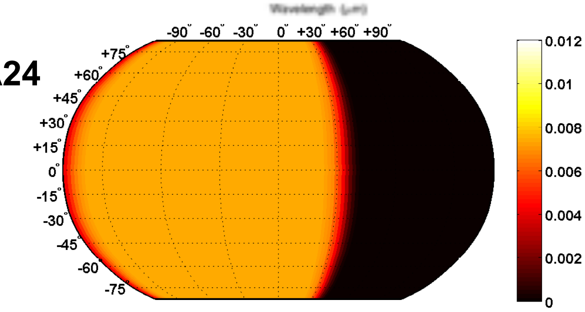
A13



A18

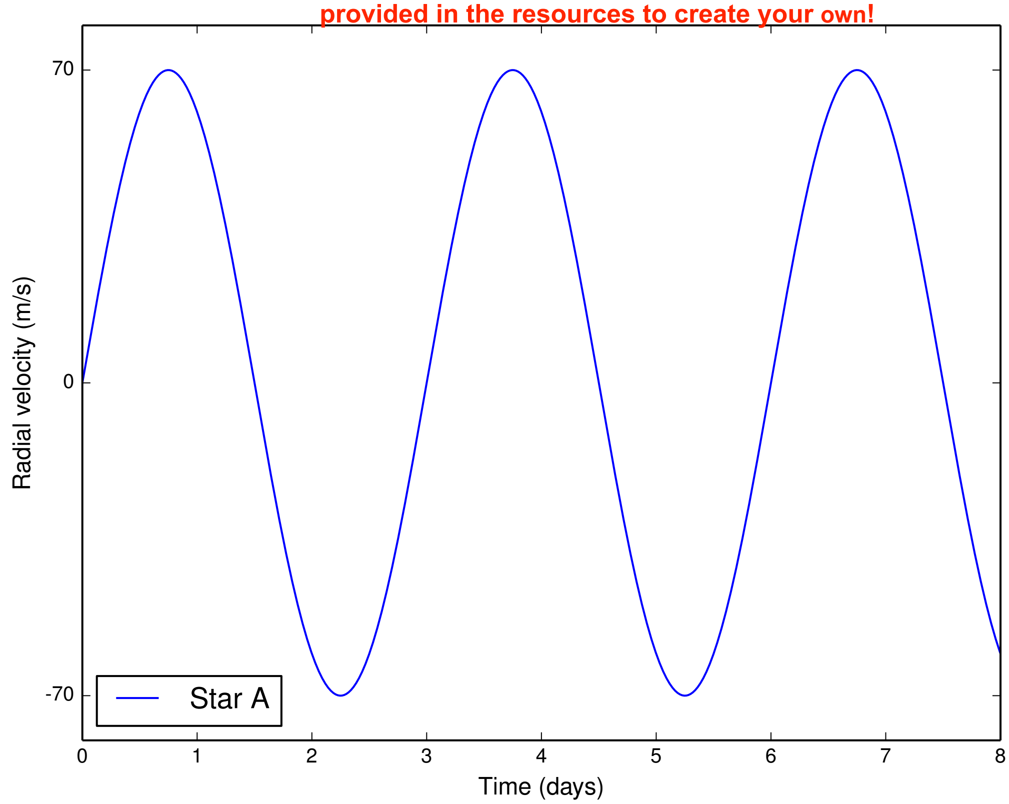


A24

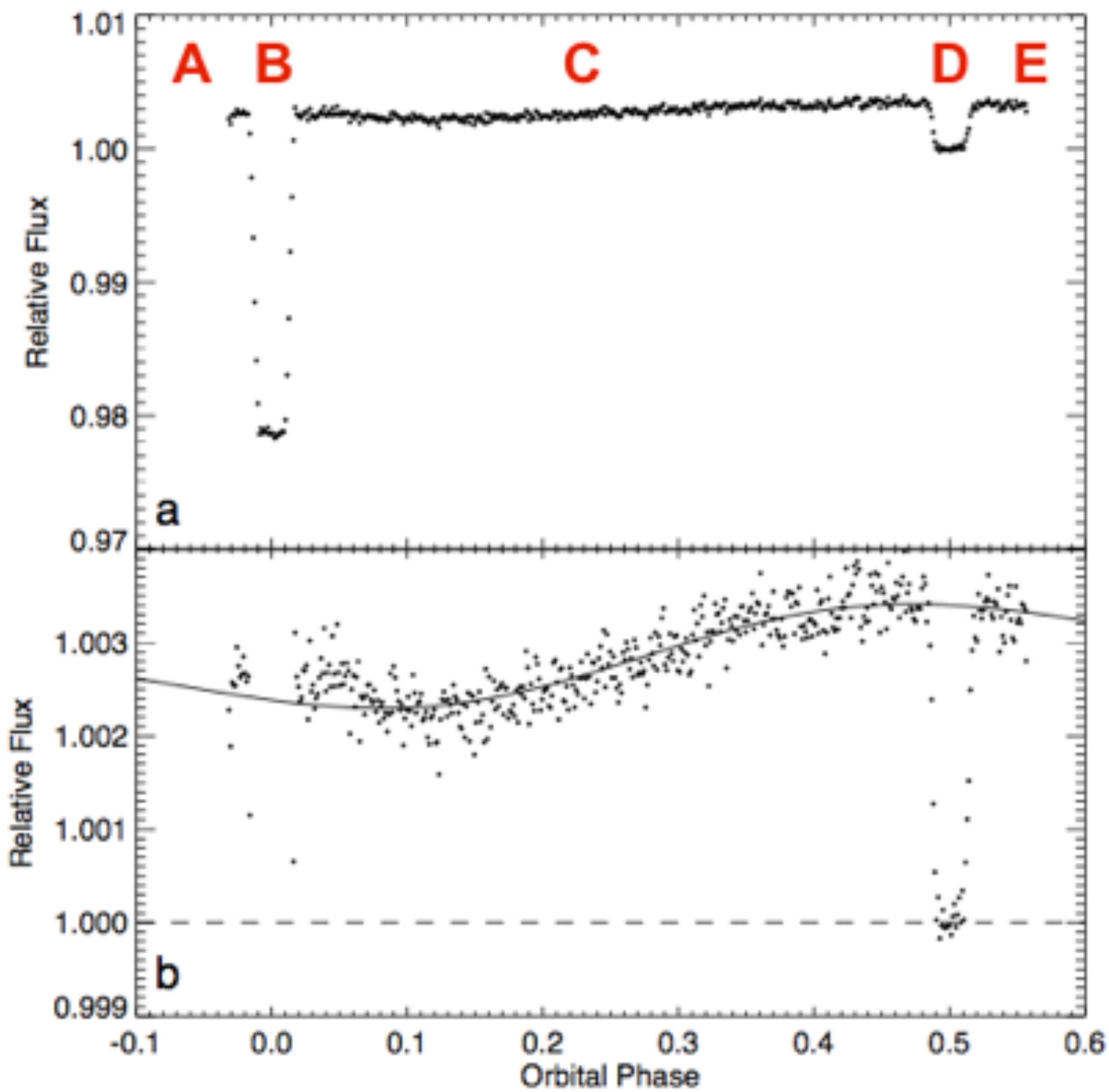


Image/Illustration Set B: Similarly to how I created Image B1 myself, you can use the radial velocity applet provided in the resources to create your own!

B1

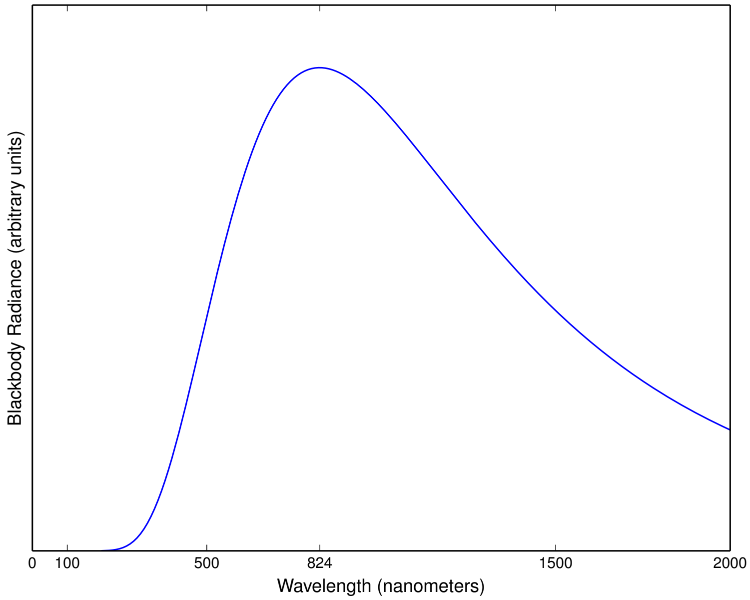


B2

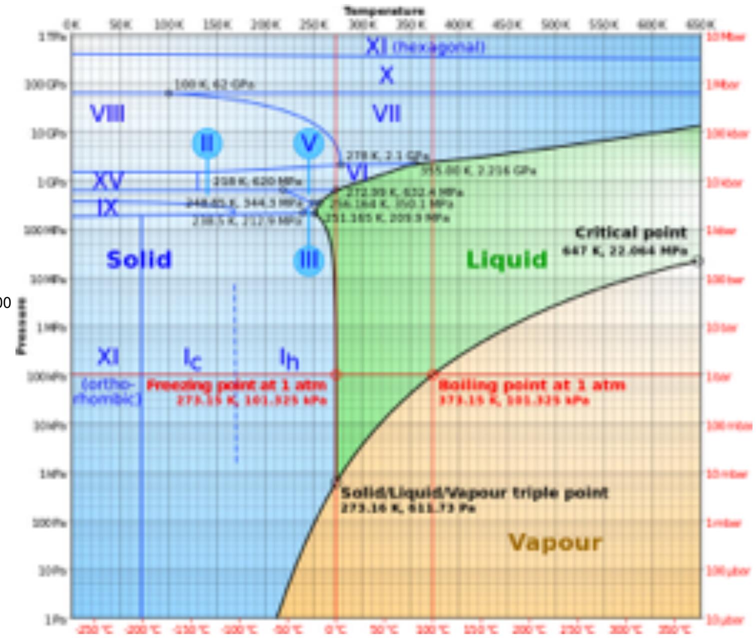


Image/Illustration Set C:

C1



C2

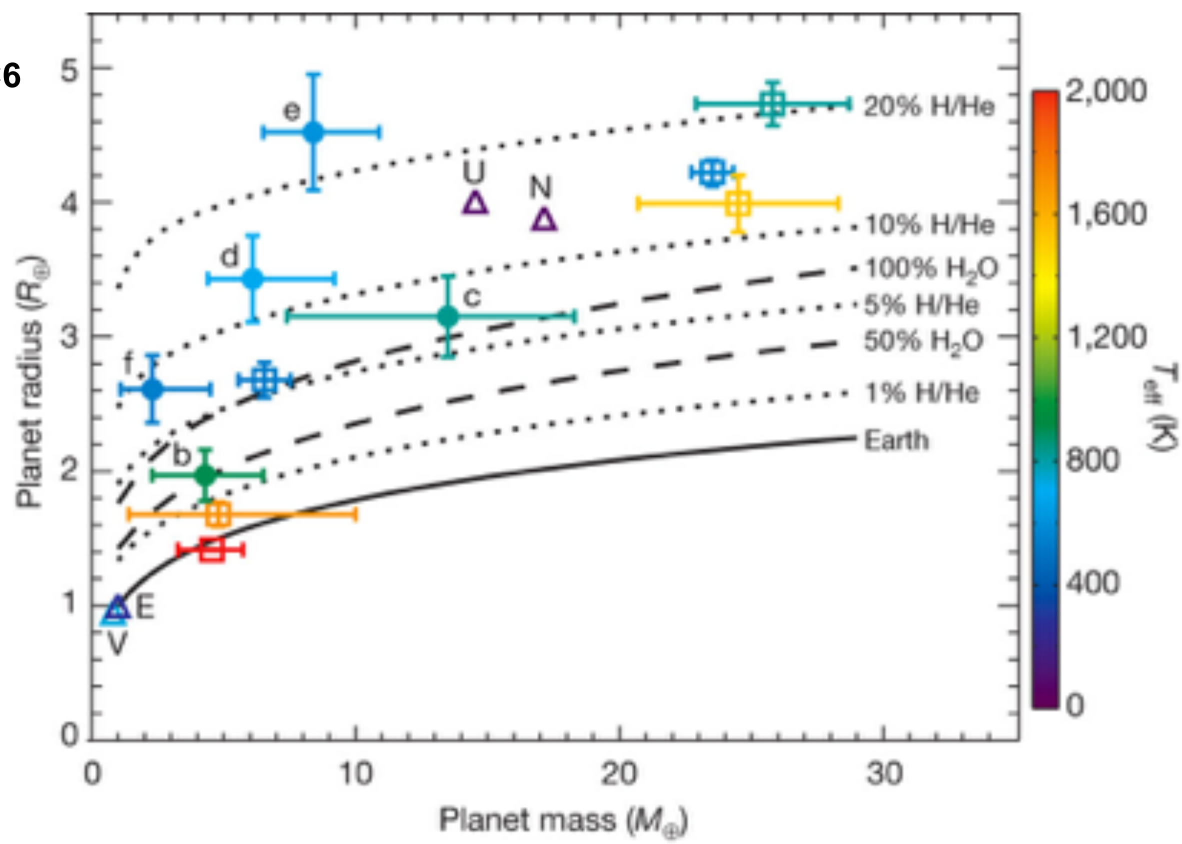


C3

C4

C5

C6



Team name: KEY Team number: KEY

Answer Page: Section A

1. (a) B
   (b) A
   (c) F
2. (a) D
   (b) A
   (c) C
3. (a) Blue
   (b) C
   (c) Dust in disk re-radiates in Infrared
4. (a) A8
   (b) A5
   (c) A4
   (d) A7
   (e) A6
5. A15, A19
6. (a) A10
   (b) Protoplanetary Disk
7. (a) A16
   (b) Two
8. D, A17
9. A20
10. (a) A14
    (b) CoRoT-2
11. (a) A11
    (b) Strong outbursts
12. (a) A9
    (b) Less
13. (a) A12
    (b) Brown Dwarf, Planet
14. (a) A13
    (b) Direct imaging
15. (a) A18
    (b) Flare star (eruptive variable)
16. (a) $0°, 0°$
    (b) Winds moving hot air eastward
17. (a) HD 189733b
    (b) Colder
18. (a) GJ 1214b
    (b) It has clouds/haze in its atmosphere
19. (a) Kepler-7b
    (b) It has clouds in the bright region

Scoring: Choose a point value for all questions beforehand. At the National level, each question (in this test, sub-question) is worth 1 point, for ease of grading given that we have $\sim$ 1 hour to get all of our tests in after the day of competition is over. However, if you are supervising in the morning, there is much more flexibility in terms of grading. Hence, please take into account the time you are supervising and how many teams there are to grade, along with how much help you have, when choosing a markscheme and deciding how to evaluate exams. For example, too many short-answer questions would be problematic if you were testing in the afternoon, as great care must be taken to ensure that all questions are graded evenly and fairly.

Team name: KEY Team number: KEY

Answer Page: Section B

20. D
21. A
22. Secondary Eclipse depth
23. Minimum mass, because one needs to account of the (unknown) inclination of the system.
24. (a) 0.041 AU
    (b) 149 km/s
    (c) 0.495 Jupiter Masses
    (d) 1.20 g/cm^3
25. (a) B
    (b) D
    (c) 2.49 %
    (d) 1.21 Jupiter Radii
    (e) 7240 Seconds

Ensure that there is enough space for students with large handwriting to write responses on the answer sheets, and make sure to taking the test yourself for any inconsistencies in numbering or errors in the answer key. Also, it is nominally a good idea to have teams write their team number and name on each page of the answer sheets, so that if there is a mix-up when the tests are handed in it is still possible to salvage misplaced sheets.

Be clear to indicate the units you want a quantitative answer in, both on the answer sheet and in the question itself.

Team name: KEY Team number: KEY

Answer Page: Section C

26. (a) 10 Parsec
    (b) 3520 Kelvin
    (c) M2
    (d) 280 Kelvin
    (e) Yes, it is habitable, at 1 atm surface temperature needs to be between 273 and 373 Kelvin
    (f) Weaker, more Infrared radiation incident than for Earth so more absorption of incoming radiation
27. (a) C4
    (b) C5
    (c) C3
28. (a) 13.9
    (b) 1770
29. (a) B
    (b) 2.38 g/cm^3
    (c) 0.926 Solar Masses

Be clear to indicate the units you want a quantitative answer in, both on the answer sheet and in the question itself.

Team name: ______________________________ Team number: ____________

Answer Page: Section A

1. (a) ____________________
   (b) ____________________
   (c) ____________________
2. (a) ____________________
   (b) ____________________
   (c) ____________________
3. (a) ____________________
   (b) ____________________
   (c) ____________________
4. (a) ____________________
   (b) ____________________
   (c) ____________________
   (d) ____________________
   (e) ____________________
5. ____________________
6. (a) ____________________
   (b) ____________________
7. (a) ____________________
   (b) ____________________
8. ____________________
9. ____________________
10. (a) ____________________
    (b) ____________________
11. (a) ____________________
    (b) ____________________
12. (a) ____________________
    (b) ____________________
13. (a) ____________________
    (b) ____________________
14. (a) ____________________
    (b) ____________________
15. (a) ____________________
    (b) ____________________
16. (a) ____________________
    (b) ____________________
17. (a) ____________________
    (b) ____________________
18. (a) ____________________
    (b) ____________________
19. (a) ____________________
    (b) ____________________

Ensure that there is enough space for students with large handwriting to write responses on the answer sheets, and make sure to taking the test yourself for any inconsistencies in numbering or errors in the answer key. Also, it is nominally a good idea to have teams write their team number and name on each page of the answer sheets, so that if there is a mix-up when the tests are handed in it is still possible to salvage misplaced sheets.

Team name: ______________________ Team number: __________

Answer Page: Section B

20. ______________________

21. ______________________

22. ______________________

23. ______________________

24. (a) ______________________ AU
    (b) ______________________ km/s
    (c) ______________________ Jupiter Masses
    (d) ______________________ g/cm^3

25. (a) ______________________
    (b) ______________________
    (c) ______________________ %
    (d) ______________________ Jupiter Radii
    (e) ______________________ Seconds

Be clear to indicate the units you want a quantitative answer in, both on the answer sheet and in the question itself.

Team name: ______________________ Team number: __________

Answer Page: Section C

26. (a) ______________________ Parsec
    (b) ______________________ Kelvin
    (c) ______________________
    (d) ______________________ Kelvin
    (e) ______________________
    (f) ______________________

27. (a) ______________________
    (b) ______________________
    (c) ______________________

28. (a) ______________________
    (b) ______________________

29. (a) ______________________
    (b) ______________________ g/cm^3
    (c) ______________________ Solar Masses

Be clear to indicate the units you want a quantitative answer in, both on the answer sheet and in the question itself.