Station A

Images & objects

Instructions

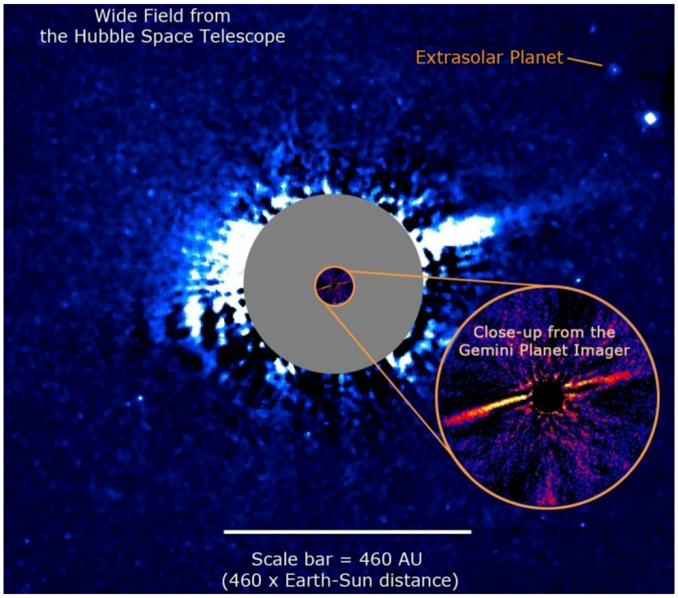
Use the images provided to answer the questions. For all questions about parts of the electromagnetic spectrum, choose from the following list:

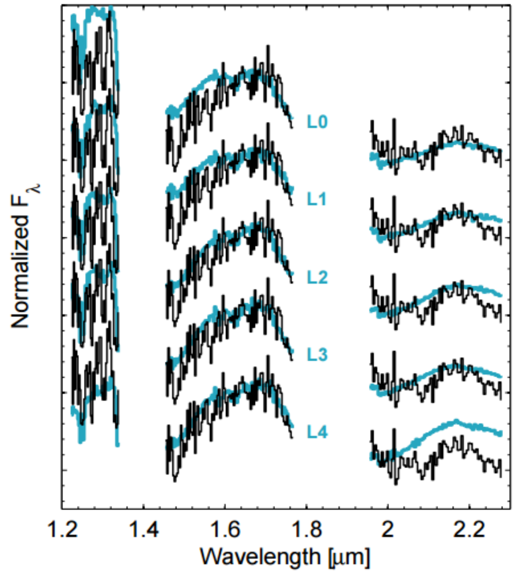
Infrared, Radio, Sub-millimeter, Ultraviolet, Visible, X-ray

All questions at this station are worth one (1) point.

Push if needed. It won't do anything, but it might make you feel better.

Questions A1–A5 use the pictures below, both regarding the same exoplanet.





A1. Which method of detection was used to observe the planet, shown in the top left image?

A. Transit timing variation
B. Direct imaging
C. Gravitational microlensing
D. Radial velocity variation

A2. The planet is currently 650 AU away from its parent star. Why is this noteworthy?

A. It is unusual for hot Jupiters to be discovered so close to their star
B. It is the largest planet ever detected with direct imaging
C. Current models of planetary disk evolution cannot explain its wide separation
D. Planets at that distance should be mostly rocky, but it is a gas giant

A3. The image at right is the SED of the exoplanet, compared against five templates. What quantity is measured on the vertical axis?

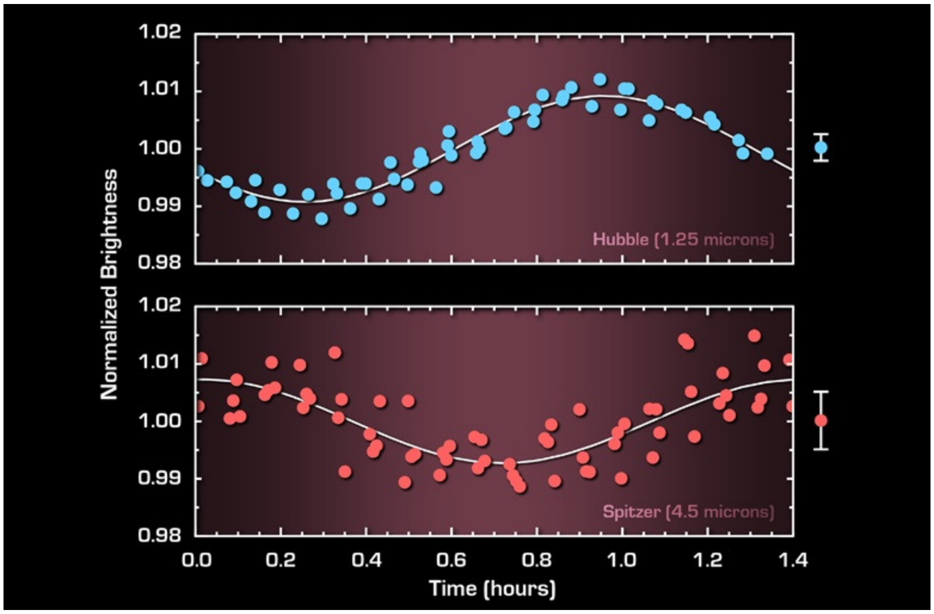
A. Flux per unit wavelength
B. Opacity at a given wavelength
C. First derivative of magnitude
D. Average wavelength per photon

A4. In which part of the electromagnetic spectrum was the SED above measured?

A. Visible light
B. Near infrared
C. Mid infrared
D. Far infrared

A5. Which deep sky object is described by the two images above?

Questions A6–A9 use the following image.



A6. Which part of the electromagnetic spectrum was used for the observations shown above?

A7. Which deep sky object is the subject of the above data?

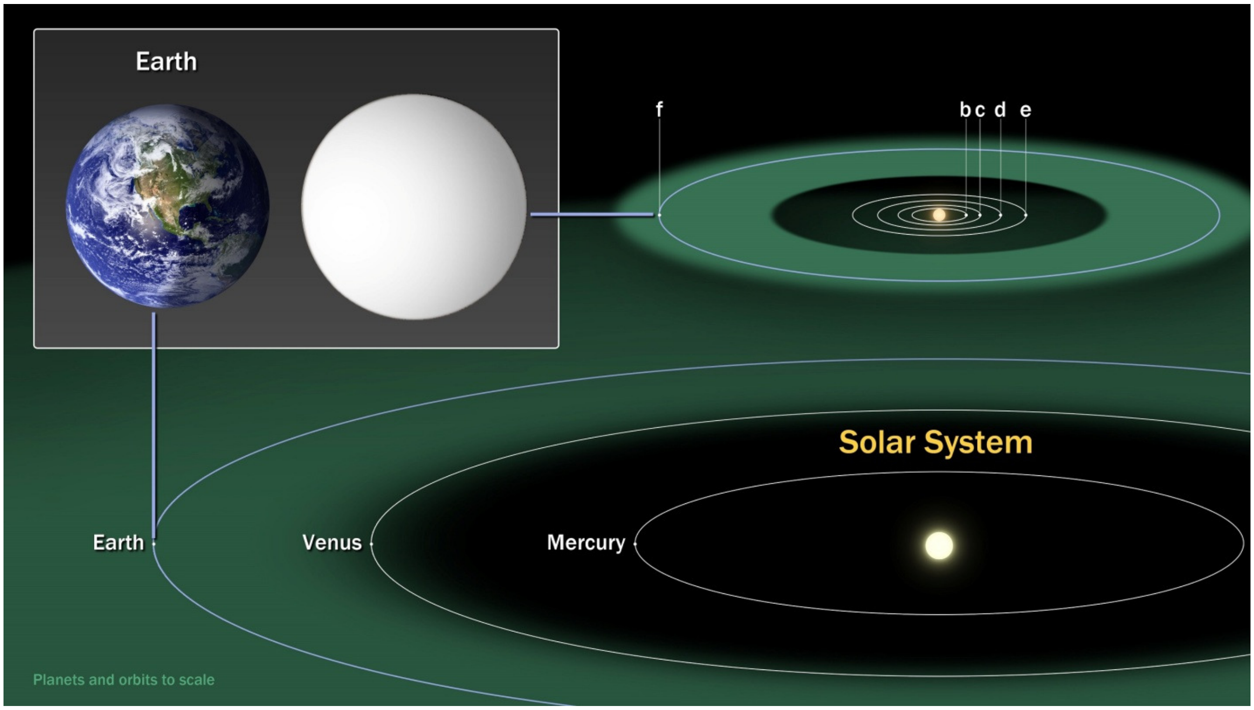
A8. Which feature of the plot is most noteworthy?

A. The curves are out of phase with each other
B. The scatter of the bottom points is larger than that of the top points
C. The period of the oscillation is less than two hours
D. The amplitudes of the two curves are almost identical

A9. According to the models of Buenzli et al. (2012), the above curves are evidence for what?

A. Evaporation of a planet's atmosphere due to the parent star
B. Different atmospheric conditions at different altitudes
C. Coronal mass ejections from a brown dwarf
D. Differentiation of the planet's core and mantle

Questions A10–A14 involve the figure below



A10. Given its location and size, planet "f" in the upper planetary system is most likely to be which variety of exoplanet?

A. Ice giant
B. Super-Earth
C. Hot Jupiter
D. Brown dwarf

A11. What is the name of the green annulus around both stars?

A. Planetary disk
B. Instability strip
C. Goldilocks zone
D. Snow line

A12. Both star systems are drawn to scale. Why is the green annulus around the upper star smaller than the one around the Sun?

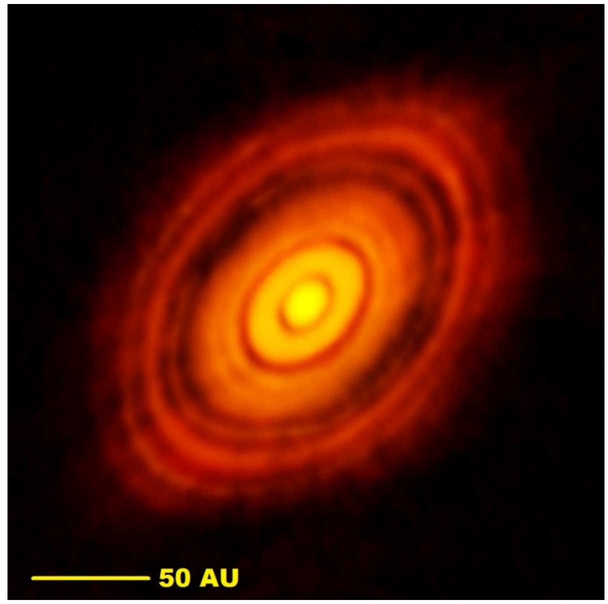
A. Because the other star's Oort cloud is much closer to the star
B. Because stellar winds have blown away the material beyond the green ring's edge
C. Because the other star is older than the Sun
D. Because the other star is less luminous than the Sun

A13. Assume that planet "f" above has an orbital radius *exactly* the same as Mercury's (you can see this isn't quite true, but since I'm writing the test I get to say that). If the other star's mass is **smaller** than the Sun's, how does planet "f"'s orbital period compare to Mercury's?

A. It is shorter than Mercury's
B. It is the same as Mercury's
C. It is longer than Mercury's
D. More information is needed to answer

A14. Which deep sky object is illustrated in the image above?

Questions A15–A19 involve the figure below



A15. Which deep sky object is pictured at right?

A16. The observations were performed by the ALMA telescope, and used which part of the electromagnetic spectrum?

A17. Which feature of the image is of greatest scientific interest?

A. The lack of a central object
B. The elliptical shape of the object
C. The size of the object
D. The well-defined gaps in emission

A18. The disk in the image has an estimated mass of 0.1 $M_\odot$. About how many Jupiter masses (M_J) is this?

A. 1 M_J
B. 10 M_J
C. 100 M_J
D. 1000 M_J

A19. The object in the image has an elliptical shape. Is the object actually elliptical or not, and why?

A. Elliptical, due to interaction with a nearby stellar companion
B. Elliptical, due to its relatively young evolutionary stage
C. Not elliptical; only appears elliptical due to the telescope's optics system
D. Not elliptical; only appears elliptical due to an inclined viewing angle

Questions A20–A24 involve the image below

A20. Which deep sky object is the subject of the long-exposure photograph at right?

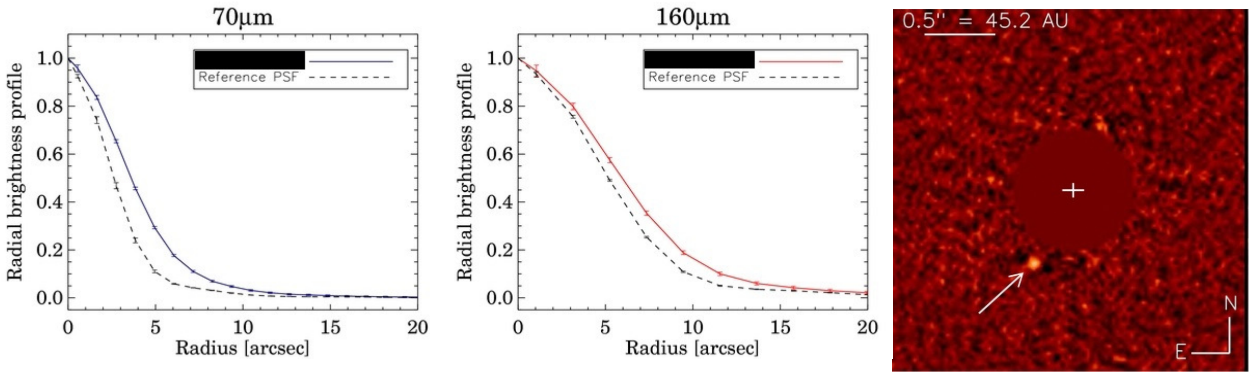
A21. The red-colored region is best described as a/an
   A. H I (“H one”) region
   B. H II (“H two”) region
   C. Absorption nebula
   D. Radio-bright nebula

A22. High-resolution images of this object show well over a hundred star systems in which early stage of formation?
   A. T Tauri variable star
   B. Bok globule
   C. Herbig-Haro object
   D. Protoplanetary disk

A23. According to current models, the diffuse emission shown in the image has a lifetime of a few hundred thousand years. Which process limits the lifetime of the pictured object?
   A. Photoevaporation
   B. Gravitational collapse
   C. Dark flow
   D. Planetesimal accretion

A24. Shortly after the process in question A23 finishes, what will remain in the area viewed in the photograph?
   A. Globular cluster
   B. Debris disk
   C. Planetary nebula
   D. Open cluster

Questions A25–A29 involve the following figures



A25. The left and middle plots show brightness as a function of separation from a star. What part of the electromagnetic spectrum was used for those measurements?

A. Visible light
B. Near infrared
C. Mid infrared
D. Far infrared

A26. The image on the right shows an infrared image of an exoplanet orbiting its parent star at a separation of 56 AU. How does this orbit compare to the extended emission plotted in the left two figures?

A. The orbit is much smaller than the extended emission
B. The orbit is somewhat smaller
C. The orbit is roughly the same size
D. The orbit is somewhat larger
E. The orbit is much larger

A27. The dashed lines in the two plots show the “Reference PSF” at two wavelengths. What does the acronym “PSF” stand for?

A28. The exoplanet appears in the right hand image as a point with much smaller size than the “Reference PSF” curves in the left two plots. What is the **primary** reason for this difference?

A. The atmosphere was drier on the night the right-hand image was taken
B. The wavelength of light used for the right-hand image is shorter
C. The instrument used for the right-hand image has much better optics
D. The instrument used for the right-hand image operates at a higher altitude

A29. Which deep sky object is the subject of all three images above?

Station B

Stellar evolution & planet formation

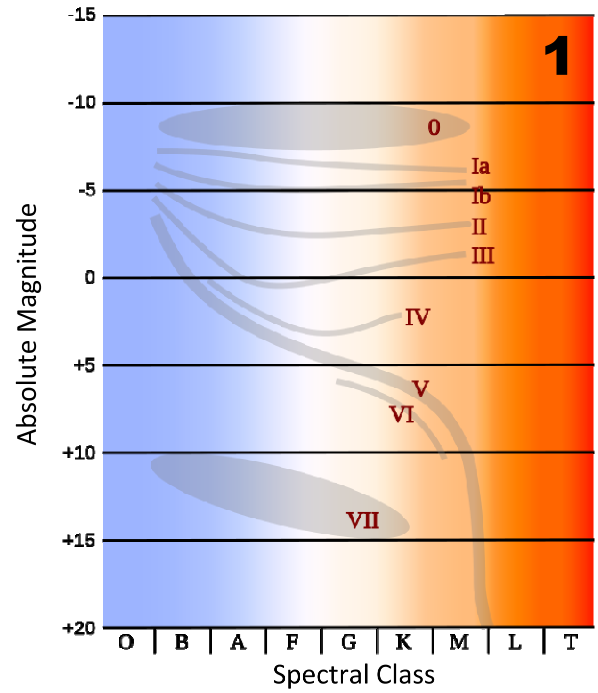
Instructions

Answer the questions on your response sheet.

Unless specified otherwise, all questions are worth one (1) point.

Push if needed. It won't do anything, but it might make you feel better.

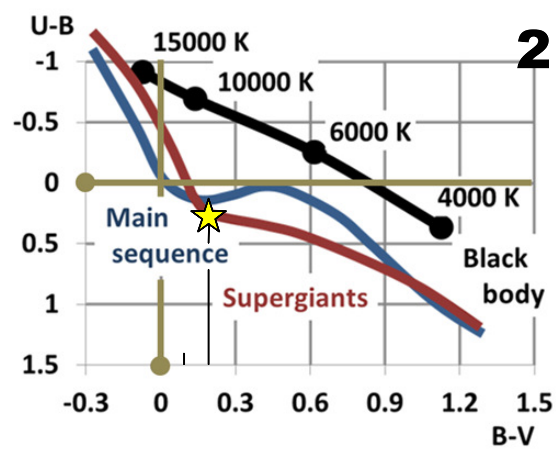
Questions B1–B15 involve the four figures on this page and the next.



B1. What is one name for figures like Figure 1, which plots magnitude vs. spectral class?
  A. Kippenhahn diagram
  B. Two-color diagram
  C. Saha plot
  D. Hertzsprung-Russell diagram

B2. In Figure 1, what population of stars is traced out by curve V?

B3. What feature in/of stellar spectra is used to place stars in spectral classes?
  A. Spectral lines
  B. Chemical makeup
  C. Brightness
  D. Opacity



B4. The feature mentioned in question B3 is closely (but not entirely) related to what property of stars?
  A. Distance
  B. Size
  C. Mass
  D. Temperature

B5. In Figure 1, stars of spectral class M could be in luminosity classes 0, I, II, III, or V. What is used to distinguish the different groups of stars?
  A. Emission profile
  B. Line widths
  C. Infrared excess
  D. Multiplicity

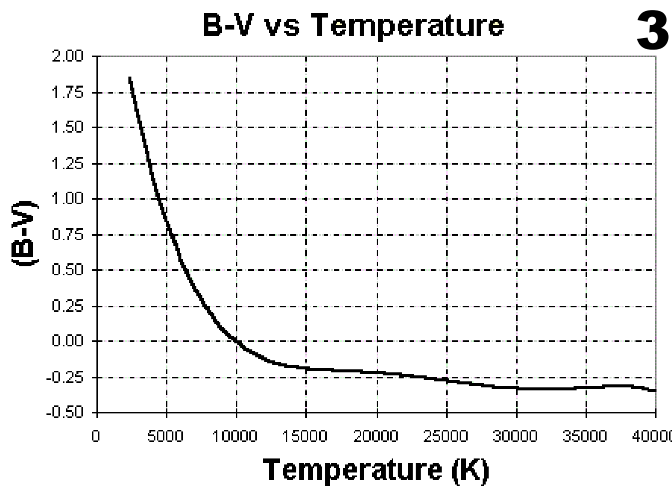
B6. The brown lines in Figure 2 divide the coordinate space into quadrants. The blue curve in Figure 4 would be plotted in which of those quadrants?
  A. Top left
  B. Top right
  C. Bottom left
  D. Bottom right

B7. Interstellar dust between Earth and a star causes *reddening*, a change in a star's light compared to its real spectrum. In which direction on Figure 2 would reddening move the observed colors of a star?
  A. Up
  B. Up and left
  C. Left
  D. Down and left
  E. Down
  F. Down and right
  G. Right
  H. Up and right

B8. In Figure 2 the yellow star marks a hypothetical supergiant. Based on Figure 3, what is the surface temperature of this star? Give your answer in Kelvin, **<u>to the nearest thousand</u>**.

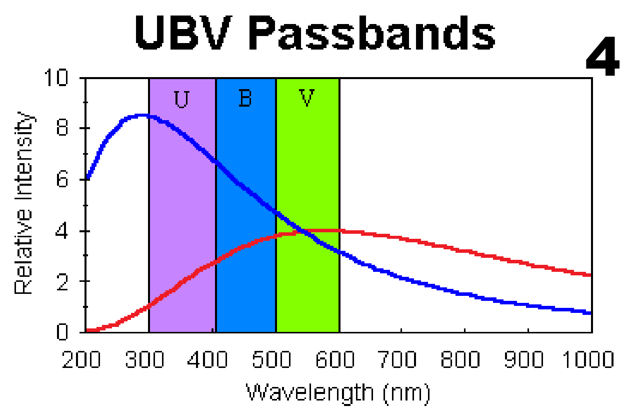
B9. In Figure 4, which curve shows the spectrum of the hotter star, and why?

A. The red curve, because it peaks in the visible part of the spectrum.
B. The red curve, because the area under it is larger than under the blue.
C. The blue curve, because it peaks at a shorter wavelength.
D. The blue curve, because its spectrum is steeper in the B band.



B10. Based on Figure 3, what color would a 10,000 K star appear to be?

A. Red
B. Blue
C. Green
D. White



B11. Above 10,000 K, stars release a plurality of their energy in which part of the electro-magnetic spectrum?

A. Infrared
B. Visible
C. Ultraviolet
D. X-ray

B12. In question B4, I wrote that spectral class doesn't *exactly* match up to temperature. Why doesn't it?

A. Large stars have lower electron densities at their photospheres.
B. Supergiant stars have a higher temperature than giant or dwarf stars.
C. Stars on the main sequence are more likely to have companion stars.
D. Sharknadoes.

B13. **(2 pts)** In Figure 4, the blue curve peaks at 300 nm and the red curve peaks at 580 nm. The star represented by the blue curve is how many times hotter or cooler than the star represented by the red curve? Give your answer **to two significant figures**, and circle "H" (for hotter) or "C" (for cooler) on your answer sheet.

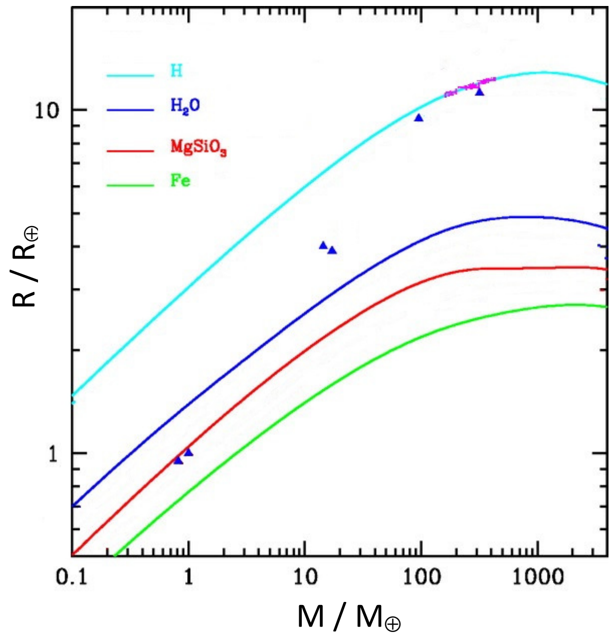
B14. In Figure 1, which group(s) of stars contain(s) the stars with the largest radius?

B15. In Figure 1, which group(s) of stars contain(s) the stars with the smallest radius?

Questions B16–B19 involve the figure to the right.

The lines represent expected planet sizes & masses for a variety of different compositions. From top to bottom they are (cyan) pure hydrogen, (blue) pure ice/water, (red) pure enstatite, and (green) pure iron.

The six blue triangles on the plot are the location of six planets in our Solar System.



B16. Which curve represents planets with the highest density?

A. Cyan
B. Blue
C. Red
D. Green

B17. **(2 pts, 1 each)** Which two Solar System planets are represented by the two triangles near the center of the figure?

B18. Planets above which curve are likely to have gaseous envelopes on top of a rocky core?

A. Cyan
B. Blue
C. Red
D. Green

B19. Planets above the cyan curve are most likely to be which kind of exoplanet?

A. Hot Jupiters
B. Mini-Neptunes
C. Super-Earths
D. Ice giants

B20. What is the name for the process in which heavier elements in a forming terrestrial protoplanet settle downwards, forming a dense core underneath a lighter mantle/crust?

A. Aggregation
B. Sedimentation
C. Differentiation
D. Condensation

B21. Which conserved quantity must be lost in order for a collapsing cloud of gas and dust to turn into a star and planetary system?

A. Linear momentum
B. Mass
C. Charge
D. Angular momentum

B22. What instability is responsible for the initial collapse of a nebula into a protostar, or a clump of gas and dust in a protoplanetary disk into planetesimals?

A. Magnetorotational instability
B. Kelvin-Helmholtz instability
C. Richtmyer-Meshkov instability
D. Jeans instability

B23. Which term refers to the fraction of energy hitting a surface that gets reflected away from the surface rather than absorbed?

A. Hill ratio
B. Albedo
C. Radiance
D. Cooper coefficient

B24. In a protoplanetary disk, gas orbiting the star is partially supported by thermal pressure. What does this support do to the gas's orbital velocity compared against solid objects (e.g. planetesimals) that do not receive such support?

A. The gas's orbital velocity is lower than the planetesimals'.
B. The support does not affect orbital velocity in any way.
C. The gas's orbital velocity is the same, but is shifted to an inclined orbit instead.
D. The gas's orbital velocity is greater than the planetesimals'.

B25. In astronomy, people often discuss "metals" in stars or nebulae. To what does this term refer?

A. Molecular compounds sharing electrons in a free-flowing sea rather than forming bonds
B. Elements in the lanthanide and actinide series
C. Elements heavier than helium
D. Dust particles primarily composed of silicates

B26. What distinguishes large gas giant planets from brown dwarf stars?

A. The ability to fuse deuterium into helium
B. The ability to support satellites in orbit
C. The presence/absence of a protoplanetary disk
D. The presence/absence of Herbig-Haro objects during their formation

B27. Protoplanetary disks are commonly detected as an excess at what EM wavelengths?

A. Radio
B. Microwave
C. Infrared
D. Ultraviolet

B28. Which of the following methods of detecting planets is fundamentally non-repeatable?

A. Direct imaging
B. Radial velocity variation
C. Gravtiational microlensing
D. Transit timing variation

B29. Many multiple-planet systems feature pairs of planets whose orbital periods form ratios like 1:2, or 2:3, or 3:5. What is the name for this occurrence?

A. Forced oscillation
B. Resonance
C. Orbital anomaly
D. Coincidence

<u>Station C</u>

Numerical questions

Instructions

Answer the questions on your answer sheet. Use scratch paper for your work—**DO NOT WRITE ON THE TEST**. If you need more paper, raise your hand and one of the volunteers (quickly!) will bring some.

The point values for each question are given in parentheses after the question number.

When questions rely on previous answers, use the rounded numbers you put on your answer sheet rather than the exact values you calculated.

Push if needed. It won't do anything, but it might make you feel better.

Questions C1 and C2 are about an exosolar sytem.

C1. **(2 pts)** The parallax of a distant planetary system is measured to be 34.2 milliseconds of arc. What is the distance to this planet, in parsecs? Give your answer **to two significant figures**.

C2. **(2 pts)** A directly imaged planet orbits the parent star at a separation of 13 arcseconds. At the distance you found in question C1, what is the physical separation, in AU, between the planet and the star? Give your answer **to two significant figures**. If you did not get an answer to question C1, you may use a distance of 100 parsecs for one (1) point.

Questions C3–C6 are about a distant star.

C3. **(3 pts)** A distant star on the main sequence is measured to have an apparent magnitude of 7.4. Models of stars that temperature suggest that its absolute magnitude is -5.1. How distant is the star, in parsecs? Give your answer **to two significant figures**.

C4. **(2 pts)** What is the distance modulus of the star in question C3? If you did not get an answer to question C3, you may use a distance of 100 parsecs for one (1) point. Give your answer **to two significant figures**.

C5. **(2 pts)** The absolute magnitude of the Sun is 4.8; how many times more luminous than the Sun is the star? If the star is less luminous than the Sun, give a number less than 1; e.g., 0.5 means the star is half as luminous. Give your answer **to two significant figures**.

C6. **(2 pts)** The temperature of the star is measured to be 39,000 K (for comparison, the Sun's temperature is "only" 5800 K). Using your answer to question C5, what is the ratio of the star's radius to that of the Sun? If the star is smaller, give a number less than 1, and give your answer **to two significant figures**. If you did not get an answer to question C5, you may use a ratio of 140 for one (1) point.

Questions C7–C12 are about a transiting exoplanet. Assume the system is perfectly coplanar as viewed from Earth.

C7. **(4 pts)** The orbital period of the exoplanet is 1230 minutes (about 85% of a day), and the transits last for 75 minutes. What is the ratio of the parent star's radius to the planet's orbital radius? Give your answer **to two significant figures**.

C8. **(2 pts)** The relative drop in flux during the transit is 3.35×10^{-4}. What is the ratio of the planet's radius to that of the star? Give your answer **to three significant figures**.

C9. **(3 pts)** The mass of the star is 0.91 $M_{\odot}$. At what distance from the star does the planet orbit, in AU? You may assume the planet's mass is much less than the star's. Give your answer **to two significant figures**.

C10. **(2 pts)** The amount of energy the Earth receives from the Sun is 1366 Watts/m^2, called the *solar irradiance*. If the star's luminosity is 0.46 $L_{\odot}$, use your answer to question C9 to determine the energy flux received by the planet. If you did not get an answer to C9, you may use 0.11 AU for one (1) point. Give your answer **to two significant figures**.

C11. **(2 pts)** The star's radius is 0.82 $R_{\odot}$ (where $R_{\odot} = 6.96 \times 10^8$ m). What is the total energy falling on the planet, in units of Watts? You will need answers from previous questions; there is no 1 point option here. Give your answer **to two significant figures**.

C12. **(4 pts)** Assume that the planet's surface reflects 30% of the light that hits it, and that it is in thermal balance (i.e. energy in = energy out). What is the temperature of the planet's surface in Kelvin? You will need answers from previous questions; there is no 1 point option here. Give your answer to **two significant figures**.