NOTE: answers in **RED** have clarifications at the bottom of the page!

Your name(s): ____________________

# Astronomy — 2018 — Answer key

All questions are 1 point each unless marked otherwise

## Station A

Folder #: ______ Porg Question: (2) A11 Subscore: ______ /31

| | | | | |
|---|---|---|---|---|
| A1. Betelgeuse | A6. SN 1987A | A11. DEM L241 | A16. D | A21. RCW 103 |
| A2. B | A7. C | A12. A | A17. B | A22. 24,000* s |
| A3. A | A8. A | A13. B | A18. D | A23. 0.7* $s^{-1}$ |
| A4. A | A9. (2) 0.20* pc | A14. 300-11000 eV | A19. A | A24. 17,000* $\gamma$ |
| A5. (2) 40000* × | A10. (3) 42* ° | A15. 1* $e^-$ | A20. B | A25. Norma |

## Station B

Folder #: ______ Porg Question: (2) B9 Subscore: ______ /33

| | | | | |
|---|---|---|---|---|
| B1. D | B7. BD-or-DB | B10. C | B16. C | B22. M |
| B2. 25* | B8. E | B11. 5* % | B17. C | B23. O |
| B3. B | B9. D | B12. 85* % | B18. (2) DH-or-HD | B24. M |
| B4. B | | B13. (2) 0.016* | B19. B | B25. K |
| B5. (2) 30* % | | B14. A | B20. C | B26. (1) A (1) F |
| B6. (2) H He | | B15. 15* | B21. C | |

ORDER MUST BE RIGHT! (B6)

ORDER NOT IMPORTANT (B26)

## Station C

Folder #: ______ Porg Question: (2) C14 Subscore: ______ /31

| | | | | |
|---|---|---|---|---|
| C1. 46* | C6. 42* | C11. B | C16. B | C21. A |
| C2. 44* | C7. D | C12. A | C17. A | C22. D |
| C3. 42* | C8. D | C13. (2) C | C18. D | C23. A |
| C4. 42* | C9. A | C14. C | C19. A | C24. C |
| C5. 44* | C10. O | C15. A | C20. B | C25. (2) L (2) T |

ORDER NOT IMPORTANT (C25)

## Station D

Folder #: ______ Porg Question: (2) D20 Subscore: ______ /49

| | | | |
|---|---|---|---|
| D1. (1) B | D6. (2) -1.57* | D12. (2) 250* $R_\odot$ | D17. (2) $6.9\times10^{6}$* K |
| D2. (2) 27* Mpc | D7. (2) 9270* K | D13. (3\|1) 110* $M_\odot$ | D18. (1\|1) 0.42* nm |
| D3. (3) $6.6\times10^{4}$* km/s | D8. (1) A | D14. (2) -10.92* mag | D19. (2) $6.3\times10^{4}$* pc |
| D4. (3\|1) 970* Mpc | D9. (2) $4.5\times10^{14}$* Hz | D15. (2\|1) 0.10* mag | D20. (3\|1) $7.0\times10^{29}$* W |
| D5. (3\|1) $4.0\times10^{1}$* | D10. (3) 2.0* | D16. (3\|1) $3.0\times10^{-5}$* | D21. (3\|1) $2.3\times10^{29}$* W |
| | D11. (1) B | | D22. (1) A |

## Scoring Notes

Responses with an asterisk (*) must be **exactly** what is on answer key. Use of scientific notation optional. See test for why.

A1. Spelling counts. Also accept $\alpha$ Orionis or $\alpha$ Ori.

A14. Accept any number in listed range.

D4. Accept 190 for 1 pt

D5. Accept 41 for 1 pt

D13. Accept 0.26 for 1 pt

D15. Accept 14.16 for 1 pt

D16. Accept $1.3\times10^{-2}$ for 1 pt

D18. Also accept 500 for 1 pt

D20. Accept $5.2\times10^{28}$ for 1 pt

D21. Accept $1.1\times10^{17}$ for 1 pt

Tiebreakers: Station A subscore, station D subscore, station B subscore, first missed question in station D

# Station A

# Images and identification

## Instructions

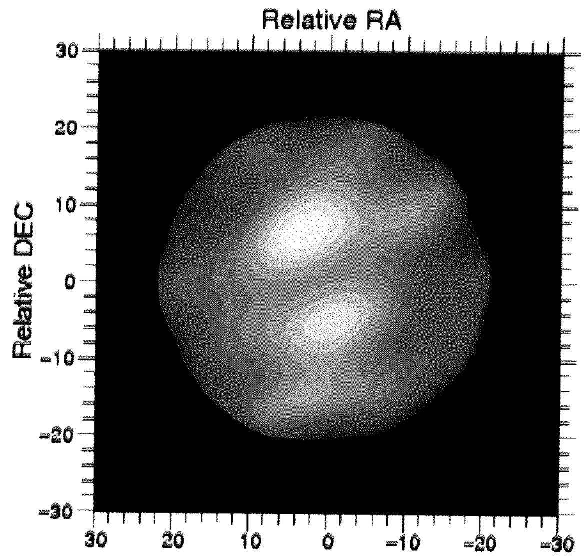
Answer the questions about the images listed in this section. Use your scratch paper for any math you do—**DO NOT WRITE ON THE TEST!** If you need more paper, raise your hand and one of the volunteers will (quickly!) bring some.

Unless otherwise noted, all questions at this station are worth one (1) point.

Hi, I'm a porg! I'm hiding somewhere in this station. Look for me, and write the question number on your answer sheet for two points!

Questions A1-A5 use the following image, that of a resolved stellar disk

A1. The image at right is of the first star (besides the Sun) to be seen as anything other than a point source. Which DSO on the official rule sheet is the target of this observation? (**Spelling counts!** Don't you dare write the name of that Michael Keaton movie.)




A2. The outer rim of the star appears dimmer than the central part. What is the name for this effect?

A. Edge fade
B. Limb darkening
C. Michelson–Pease cooling
D. Sight-line illusion

A3. The image was taken using an interferometer. What is that?

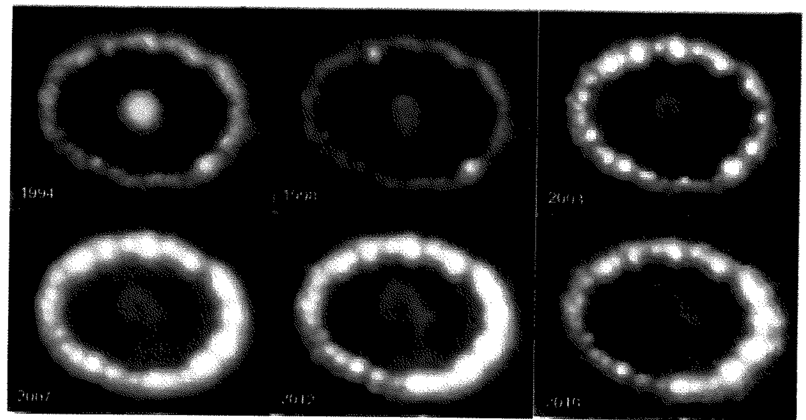
A. A collection of small telescopes that act as one larger one
B. A grate placed across a telescope to modify the photons as they pass
C. A concentric ring of mirrors designed to cause small deflections to incoming light
D. An array of tube-like channels, each with a square cross-section

A4. The Gaia mission is expected to greatly increase the measurement accuracy of what property of the star in the image?

A. Parallax
B. Color index
C. Apparent magnitude
D. Variability profile

A5. **(2 pts)** As you can see in the image, the angular diameter of the star is 45 milliarcseconds. How many times closer would the star have to be for it to appear the same size as the Sun, whose angular diameter is 30 arcminutes? Give your answer **to one significant figure**.

## Questions A6-A10 use the following image




A6. Which DSO on the official rule sheet is the target of this time sequence of Hubble images?

A7. Which of the following true statements about the object at right was the **most surprising** to astronomers?

A. Neutrinos from the supernova were detected at Earth
B. It was the closest visible supernova since the invention of the telescope
C. The progenitor star was a blue supergiant, not a red supergiant
D. Gamma-ray detections proved that supernovae are powered by radioactive decay

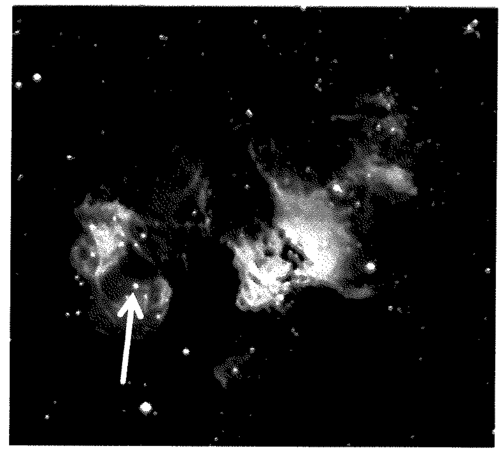
A8. What is the source of the ring that can be seen brightening from 1994 (first image) to 2012 (fifth image), and is beginning to fade in 2016 (sixth image)?

A. Circumstellar material being heated by a strong shock
B. Ejecta clumps from the progenitor star
C. A nearby molecular cloud absorbing energy from the supernova
D. Companion stars being activated by the neutrino pulse

A9. **(2 pts)** The longer axis of the ring has a radius of 0.808 arcseconds. If the object is 51,400 parsecs from Earth, what is the physical radius of the ring in parsecs? Give your answer **to two significant figures**.

A10. **(3 pts)** The shorter axis of the ring has a radius of 0.600 arcseconds. Assuming the ring is actually circular, what is the inclination angle of the ring to observers on Earth (that is, how many degrees has the ring been tilted from a face-on view)? Give your answer in degrees, **to two significant figures**. (*Hint*: draw a picture.) (*Second hint*: draw it from the side.)

## Questions A11-A15 use the following image of a supernova remnant



A11. Which DSO on the official rule sheet is shown in the image?

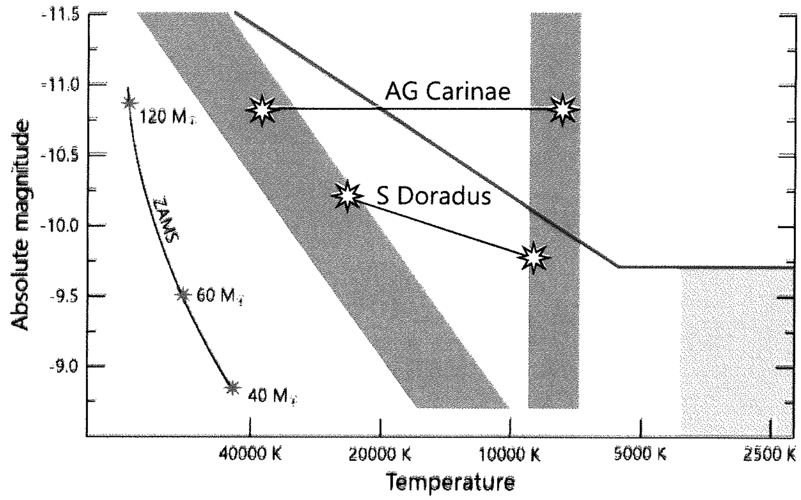
A12. What is special about the object?
   A. The progenitor star had a companion star, and it is located inside the supernova remnant
   B. The supernova remnant shows signs of interaction with a nearby OB association
   C. There is an X-ray point source in the supernova remnant, but it is off-center
   D. The progenitor star of the supernova was less than 8 solar masses

A13. Seward et al. (2012) specifically checked whether the compact X-ray source in the image (indicated by an arrow) was an active galactic nucleus in order to rule out what possibility?
   A. The X-ray source is a neutron star with unusually weak magnetic fields
   B. The X-ray source is a background object, aligned by chance in the plane of the sky
   C. The X-ray source is a supermassive black hole
   D. The X-ray source is a foreground microquasar passing in front of the supernova remnant

A14. In the image, magenta is used for *Chandra* ACIS data. In units of electron volts, what is the energy of a photon that might have been collected by this instrument?

A15. The white filaments around the magenta are optical emission from SII, which is a species of ionized sulfur. How many electrons are these atoms missing? (*Hint*: your answer had better be an integer.)

Questions A16-A20 use the following image, which shows a temperature-magnitude diagram with several features marked.




A16. Two specific stars are shown in the diagram (AG Carinae and S Doradus), both of which are members of what unusual group?

A. Gamma-ray binary systems
B. Yellow hypergiants
C. Cataclysmic variables
D. Luminous blue variables

A17. The green area in the bottom right corner of the plot contains stars of what variety?

A. Cepheid variables
B. Red supergiants
C. Yellow hypergiants
D. S Doradus variables

A18. The thick red line running top-left to bottom-right, then flattening out at ~5000 K is an empirical demarcation above which astronomers see very few stars. What is this line called?

A. Payne–Cannon sequence
B. Hertzsprung–Russell maximum
C. Hubble–Sandage luminosity
D. Humphreys–Davidson limit

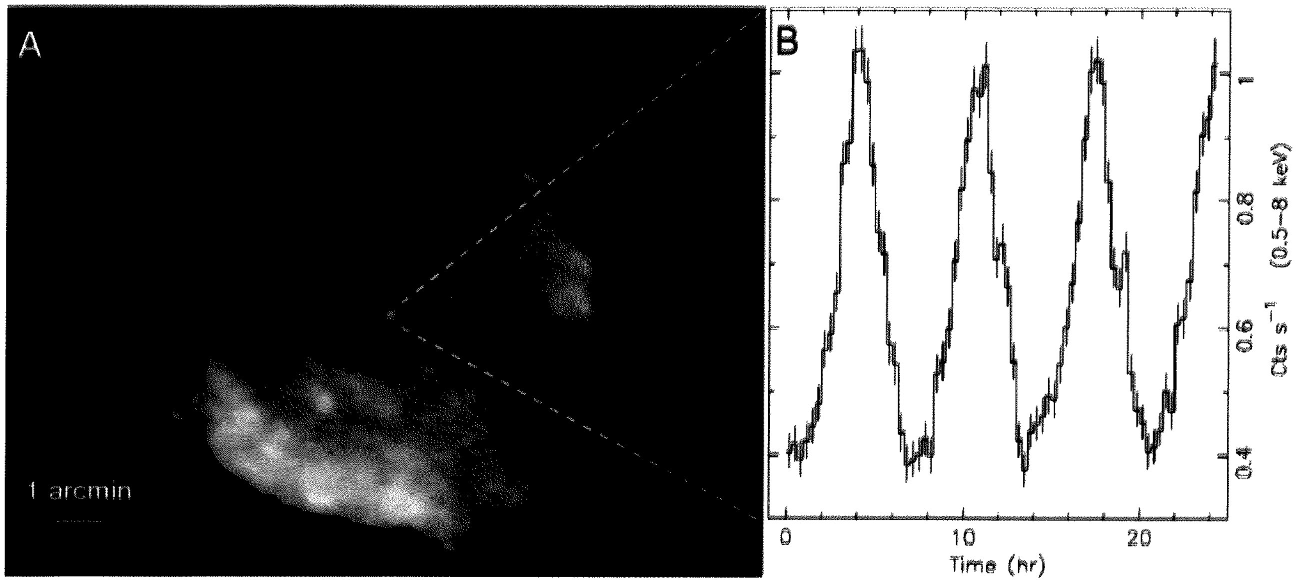
A19. The reason few stars are expected above this line is that they are so luminous they blow off their outer layers, reducing the luminosity needed to counteract their gravitational force. What is another name for this effect?

A. Eddington limit
B. Bondi–Hoyle luminosity
C. Saha recombination threshold
D. Schwarzschild radius

A20. During an outburst AG Carinae moves to the right on the plot, maintaining a constant absolute magnitude. However, its magnitude in visible light decreases. Why is this?

A. The expelled shells of stellar material block some of light from the star
B. A lower temperature means more light at visible wavelengths
C. A circumstellar disk causes a partial eclipse
D. Its photosphere expands so there is more area emitting light

Questions A21-A25 use the following image, taken from De Luca et al. (2006)



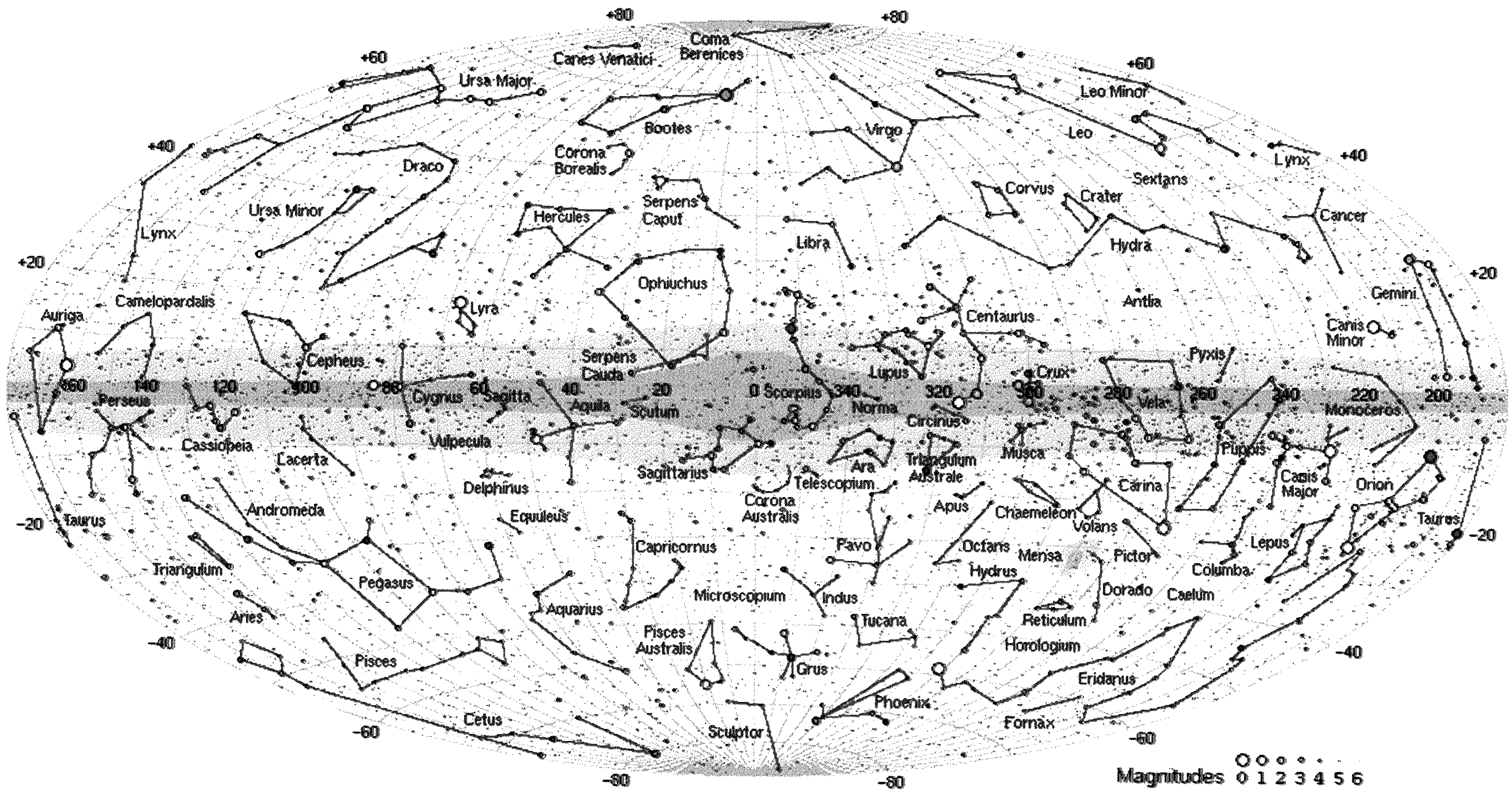

A21. Which DSO from the official rule sheet is the target of the telescope observation in the left-hand image?

A22. The central object of this image shows clear periodicity. What is the period of this object, in seconds? Round your answer **to the nearest thousand**.

A23. What is the average amplitude of the luminosity curve? Round your answer **to the nearest 0.1 counts per second**.

A24. How many photons are detected from the central object over one period? Round your answer **to the nearest thousand**. (The $\gamma$ on your answer sheet means "photons". There wasn't enough space for me to write out the word.)

A25. The galactic coordinates of this object are b = 332.4°, l = -0.4°. Using the map on the opposite page, in which constellation is this object located? **Spelling counts**; I've given you the words!


+80
+80
Coma Berenices
Canes Venatici
+60
+60
Ursa Major
Leo Minor
Bootes
Virgo
Leo
+40
+40
Corona Borealis
Draco
Lynx
Sextans
Corvus
Crater
Serpens Caput
Ursa Minor
Hercules
Cancer
Lynx
Libra
Hydra
+20
+20
Ophiuchus
Camelopardalis
Antlia
Gemini
Auriga
Lyra
Centaurus
Canis Minor
Cepheus
Serpens Cauda
Pyxis
Lupus
Crux
360
140
120
100
80
Cygnus
60
Sagitta
40
20
0
Scorpius
340
320
300
280
Vela
260
240
220
200
Perseus
Aquila
Scutum
Norma
Monoceros
Circinus
Cassiopeia
Vulpecula
Lacerta
Musca
Puppis
Triangulum Australe
Sagittarius
Ara
Carina
Canis Major
Orion
Delphinus
Telescopium
-20
-20
Taurus
Andromeda
Corona Australis
Apus
Chaemeleon
Taurus
Equuleus
Volans
Capricornus
Pavo
Octans
Mensa
Pictor
Lepus
Triangulum
Hydrus
Columba
Pegasus
Microscopium
Indus
Dorado
Caelum
Aquarius
Aries
Tucana
Reticulum
Pisces Australis
-40
-40
Horologium
Pisces
Grus
Eridanus
Cetus
Phoenix
Fornax
-60
-60
Sculptor
-80
-80
Magnitudes 0 1 2 3 4 5 6

# Station B

# Stellar evolution

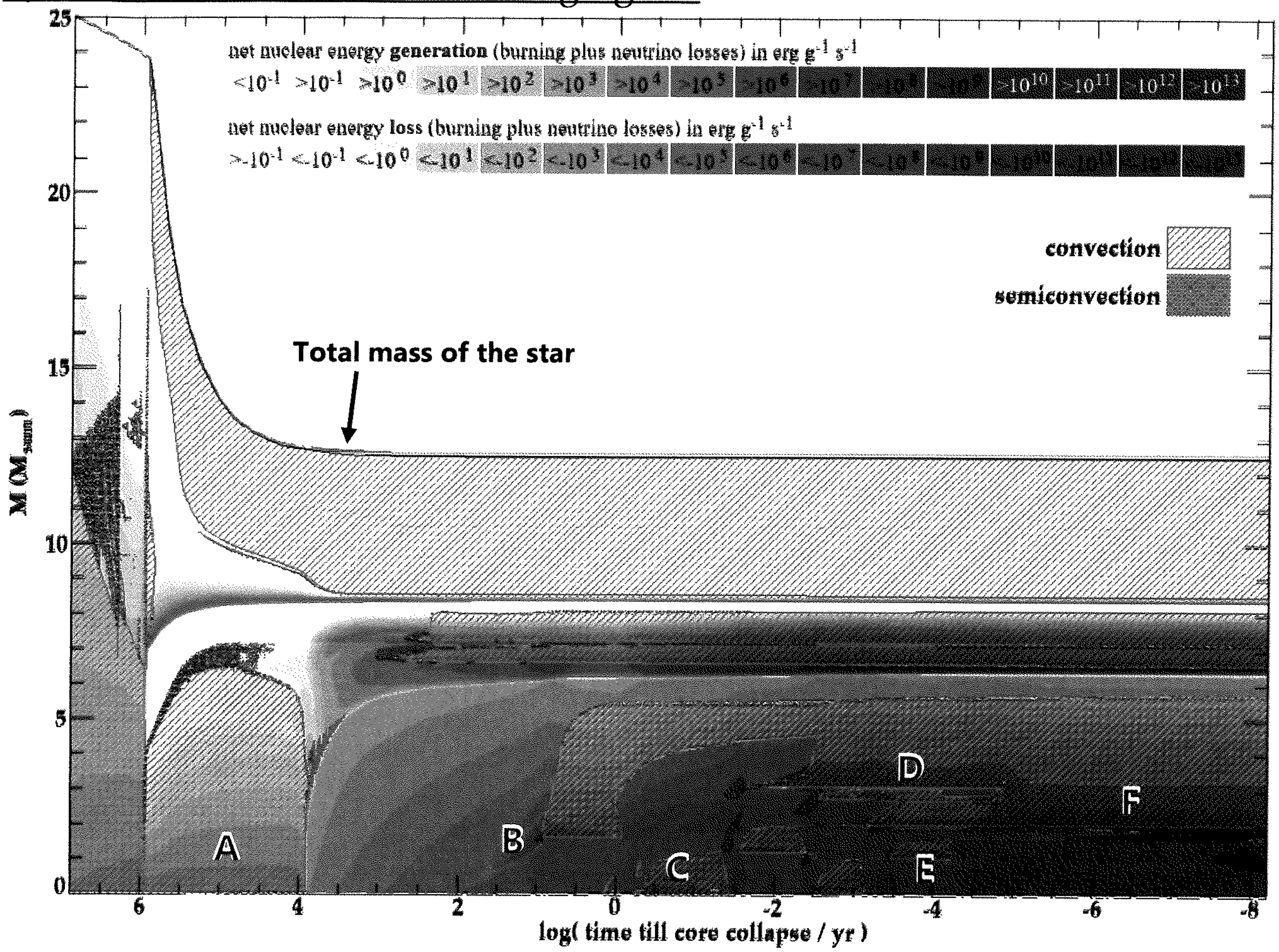
## Instructions

Answer the questions about the images listed in this section. Use your scratch paper for any math you do—**DO NOT WRITE ON THE TEST!** If you need more paper, raise your hand and one of the volunteers will (quickly!) bring some.

Unless otherwise noted, all questions at this station are worth one (1) point.

Hi, I'm a porg! I'm hiding somewhere in this station. Look for me, and write the question number on your answer sheet for two points!

## Questions B1-B9 use the following figure:




B1. The figure above (and the one two pages from now) are examples of what kind of chart used in astronomy and astrophysics?

A. Burning rate representation
B. Burbidge plot
C. Hertzsprung–Russell diagram
D. Kippenhahn diagram

B2. The figure above shows the entire life (except for the last few milliseconds) of a massive star. What is the mass of the star at birth, in units of the solar mass? Give your answer **to the nearest whole number**.

B3. What is the lifetime of the star shown above?

A. 100,000,000 years
B. 10,000,000 years
C. 1,000,000 years
D. 0.000 1 years
E. 0.000 001 years
F. 0.000 000 01 years

B4. By the end of the star's life, it has lost fully half its initial mass. Why is this?

A. Difference in mass between fusion reactants and products
B. Stellar wind blowing off the outer layers of the star
C. Increased fusion rate due to smaller energy-producing volume
D. A change in how energy is transported in the outer layers of the star

B5. **(2 pts)** At x = 3 on the figure, what fraction of the star's mass is transporting energy via convection (as opposed to radiation)? Give your answer **to the nearest ten percent**.

B6. **(2 pts)** At x = 6 on the figure, the star switches from burning ________ to burning ________ at its core. Write the **chemical symbols** for the appropriate elements on your answer sheet. **Order matters!**

B7. On the bottom of the diagram you can find the letters A-F. Which letter(s) is/are next to regions where carbon is the primary fusion fuel? If there is more than one correct answer, you must give all of them for credit.

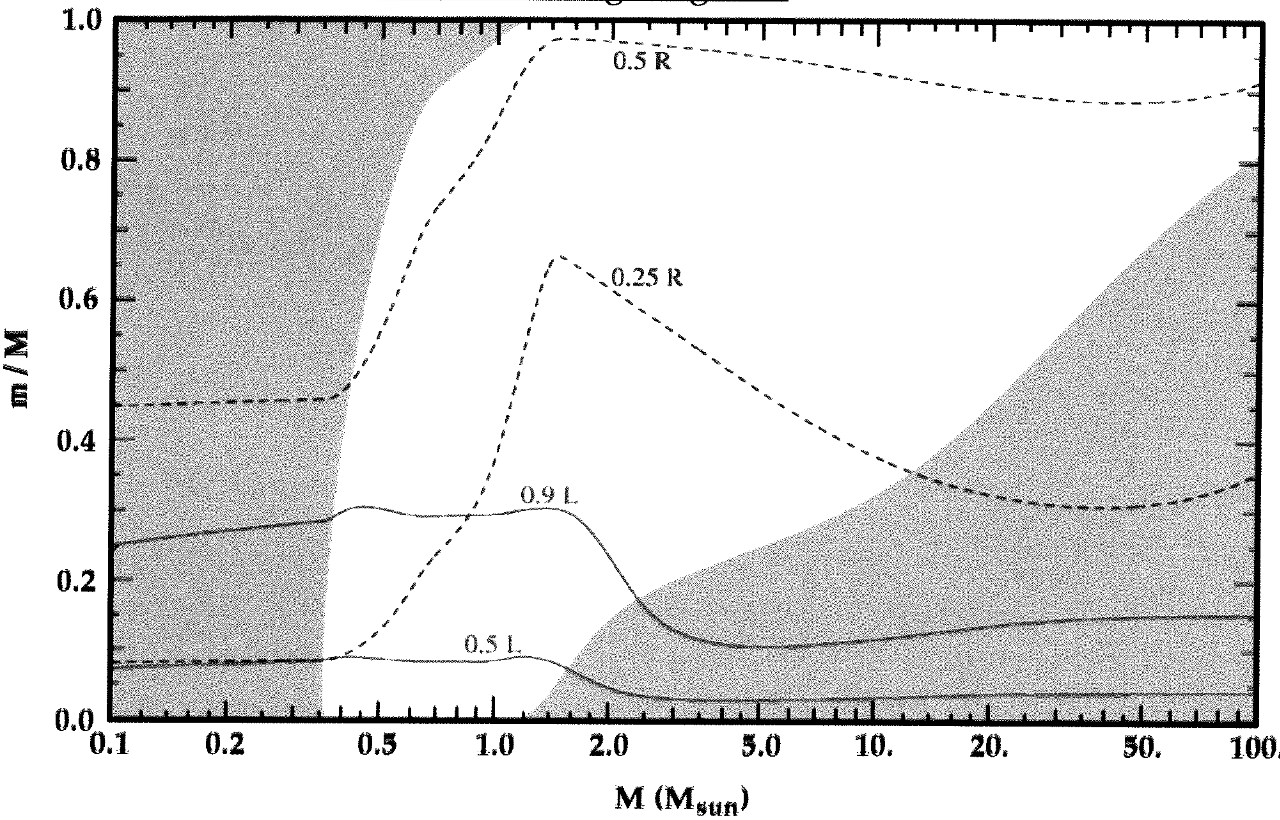
B8. On the bottom of the diagram you can find the letters A-F. Which letter(s) is/are close to regions where silicon is being burned to iron ash? If there is more than one correct answer, you must give all of them for credit.

B9. This star makes no blue loops during its evolution. When it collapses in a supernova, which of the following is closest to the temperature of its surface?

A. 30,000 K
B. 10,000 K
C. 7,000 K
D. 3,000 K

As you can guess from your answer sheet, there are more questions on the next page. Turn it over already; time's wasting!

Questions B10-B15 use the following diagram:




The gray shaded regions of this diagram show where energy is being transported via convection (as opposed to radiation). The blue dashed lines trace 25% and 50% of the star's radius. The solid red lines show the mass enclosing 50% and 90% of the total stellar energy production.

B10. According to this diagram, what mass separates stars that are entirely convective from stars with a radiative region?

A. 0.24 $M_\odot$
B. 0.30 $M_\odot$
C. 0.34 $M_\odot$
D. 0.40 $M_\odot$

B11. How much of the Sun's mass is convective? Give your answer **to the nearest five percent**.

B12. For a star the mass of the Sun, how much of its mass lies beneath a radius of 0.5 $R_\odot$? Give your answer **to the nearest five percent**.

B13. **(2 pts)** A star of 0.3 $M_\odot$ produces 50% of its energy in what fraction of its volume? Give your answer **to two significant figures**.

B14. Which fusion process is the primary energy source of stars whose mass is greater than about 1.25 $M_\odot$, causing their cores to change from radiative to convective?

A. CNO cycle
B. Triple alpha process
C. p-p chain
D. Helium capture

B15. Which **whole number** makes this sentence true? "The inner ____ solar masses of a 100 $M_\odot$ star are responsible for 90% of its energy production."

B16. O-type stars are characterized by intense radiation and strong stellar winds. These two can combine to excavate a (roughly) spherical cavity around the star. What is this cavity called?

A. Emission bubble
B. Line-driven nebula
C. Strömgren sphere
D. Ionization region

B17. B-type main sequence stars have both lower luminosity and weaker stellar winds. The cavity mentioned in question B16 is smaller or non-existent. What is one consequence of this?

A. Their supernovae are of Type I rather than Type II
B. The stars are difficult to observe from Earth until they collapse and become supernovae
C. Their supernova remnants often show interaction with their environments
D. They are generally unable to fuse all the way to iron at their cores

B18. **(2 pts)** Which two properties of stars in the following list are equivalent to each other?

A. Mass
B. Radius
C. Temperature
D. Luminosity
E. Metallicity
F. Mass loss rate
G. Multiplicity
H. Absolute magnitude

B19. Which of the following is **not** a color traditionally used to describe stars?

A. Blue
B. Green
C. Yellow
D. Orange
E. Red
F. White

B20. In which of the following locations would you expect to find the largest fraction of O-type stars?

A. Elliptical galaxies
B. The central bulge of spiral galaxies
C. The arms of spiral galaxies
D. Globular clusters

B21. The mass-lifetime relation for stars says that their lifetime $T$ is proportional to their mass $M$ to some power, namely $T \propto M^{-2.5}$. If the Sun's lifetime is 10 billion years, which of these is closest the expected lifetime of an 8 solar mass B-type star?

A. 80,000,000,000 years
B. 1,000,000,000 years
C. 50,000,000 years
D. 8,000,000 years

For questions B22-B26, select one (or more) of the Harvard spectral classifications of stars.

B22. Which spectral classification is the most numerous in the Milky Way?

B23. Which spectral classification contains the hottest stars?

B24. Which spectral classification contains the least massive stars?

B25. Into which spectral classification does HR 5171-A (on the official rule sheet) fall?

B26. **(2 pts, 1 each)** Which spectral classifications are associated with the color white?

# Station C

# Extreme stars & stellar deaths

### Instructions

Answer the questions about the images listed in this section. Use your scratch paper for any math you do—**DO NOT WRITE ON THE TEST!** If you need more paper, raise your hand and one of the volunteers will (quickly!) bring some.

Unless otherwise noted, all questions at this station are worth one (1) point.

Hi, I'm a porg! I'm hiding somewhere in this station. Look for me, and write the question number on your answer sheet for two points!

Questions C1-C9 use the following table on how energy is distributed in supernovae. Numbers don't add precisely to 100% because of rounding.

C1-C6. Both Type II and Type Ia supernovae release $10^{44}$ Joules in kinetic energy of their ejecta. Use this information to determine how much energy is produced in each type of supernova and each channel, in units of Joules. On your answer sheet, **write the exponent**, not the number! (If one answer is $10^3$ J, write 3; don't write $10^3$ or 1000.) Round all answers **to the nearest whole number**.

| | Type II | | Type Ia | |
|---|---|---|---|---|
| **Neutrinos** | 99% | (C1) | 1% | (C4) |
| **Kinetic energy** | 1% | (C2) | 99% | (C5) |
| **Radioactivity** | 0.01% | (C3) | 1% | (C6) |

C7. Radioactivity is the power source for what aspect of supernovae?
- A. Supernova remnant
- B. Neutron star/black hole formation
- C. Gravitational unbinding
- D. Supernova light curve

C8. Kinetic energy is the power source for what aspect of supernovae?
- A. Initial gravitational collapse
- B. Neutron star/black hole angular momentum
- C. Supernova light curve
- D. Supernova remnant

C9. Wolf–Rayet stars are associated with Type Ib and Type Ic supernovae. How is energy distributed in Type Ib/c supernovae?
- A. Close to Type II, because they have the same mechanism for collapse
- B. Close to Type Ia, because they are the same Type of supernova
- C. Close to both, since Wolf–Rayet stars have a wide range of properties
- D. Close to neither, since Wolf–Rayet stars do not undergo core collapse

C10. The eclipsing X-ray binary M33 X-7 was localized in 2003 to a single star with a mass of 25-35 $M_\odot$. Into which spectral classification would this star have fallen at birth?

C11. Since M33 X-7 is eclipsing, the mass ratio between the massive star (visible in optical) and its companion (visible in X-rays) was determined to be 11. This information makes it highly likely the companion star is what kind of compact object?
- A. Neutron star
- B. Stellar-mass black hole
- C. Intermediate mass black hole
- D. White dwarf

C12. If a different inclination angle is assumed, the mass of the compact companion could be 1.4-2.0 $M_\odot$, meaning the companion is more likely to be what kind of compact object?
- A. Neutron star
- B. Stellar-mass black hole
- C. Intermediate mass black hole
- D. White dwarf

C13. **(2 pts)** Assuming a distance of 795 kiloparsecs, which of these is closest to the distance modulus of the X-ray binary system?
- A. 34.1
- B. 29.5
- C. 24.3
- D. 19.8
- E. 17.7
- F. 14.4

C14. Type II supernovae are distinguished from Type I supernovae according to what criterion?

A. The detection of a binary companion to the progenitor star
B. The mass at birth of the progenitor star
C. The presence of hydrogen in the supernova spectra
D. The measured luminosity of the supernova at peak brightness

C15. The neutrinos from all kinds of supernovae are produced by interactions involving which of the four fundamental forces?

A. Weak nuclear force
B. Strong nuclear force
C. Gravitational force
D. Electromagnetic force

C16. Conservation of momentum is typically invoked to explain which of the following features associated with supernovae?

A. Asymmetric supernova remnants
B. Neutron star kick velocity
C. Circumstellar matter distribution
D. Line widths in spectra

C17. Assuming a white dwarf (WD), neutron star (NS), and black hole (BH) all have equal mass, rank them in order from smallest radius to largest.

A. BH < NS < WD
B. BH < WD < NS
C. NS < BH < WD
D. NS < WD < BH
E. WD < BH < NS
F. WD < NS < BH

C18. What provides the support that keeps neutron stars from (further) gravitational collapse?

A. Casimir force
B. Electromagnetic repulsion
C. Thermal pressure
D. Nucleon degeneracy pressure

C19. Which of the following criteria is used to identify Wolf–Rayet stars?

A. Strong emission lines of highly ionized nitrogen, carbon, or oxygen
B. Broad emission lines associated with extremely high surface temperatures
C. Massive circumstellar nebulas with super-Solar helium enrichment
D. Strong hydrogen absorption features consistent with dense environments

C20. Wolf–Rayet stars are typically considered to be massive stars transitioning either to or away from what other class of observed massive star?

A. Cepheid variable
B. Luminous blue variable
C. Yellow hypergiant
D. Red supergiants

C21. The spectra of Wolf–Rayet stars always show enhanced abundances of nitrogen, carbon, and/or oxygen relative to the Sun (note the additional qualifiers in that one answer choice in question C19 before you assume any connection to this question). Why is this?

A. Strong convection that dredges fusion products to the surface
B. Broad emission lines associated with extremely high surface temperatures
C. Massive circumstellar nebulas with super-Solar helium enrichment
D. Strong hydrogen absorption features consistent with dense environments

C22. Research suggests that the mass range of stars that can undergo a Wolf–Rayet phase extends higher in lower metallicity environments. What does metallicity mean here?

A. Lanthanide and actinide seeding by previous supernovae
B. Amount of iron and silicon available
C. Ratio of lithium and sodium to carbon, nitrogen, and oxygen
D. Fraction of elements heavier than helium present

C23. The most luminous Wolf–Rayet stars show lines from which additional element in their spectra, which is typically missing from their fainter ("only" $10^5$ $L_\odot$ instead of $10^6$) cousins?

| | | |
|---|---|---|
| A. Hydrogen | C. Lithium | E. Silicon |
| B. Helium | D. Neon | F. Iron |

C24. Wolf–Rayet stars' strong stellar winds most directly affect which property of those stars?

| | |
|---|---|
| A. Linear momentum | C. Angular momentum |
| B. Core temperature | D. Magnetic field |

This question is long. Don't even *read* further unless you've already attempted everything else at this station.

C25. **(4 pts, 2 each)** The cores of stars are kept at roughly constant temperature because many nuclear reaction rates depend sensitively on temperature: $R \propto T^p$ for some power $p$. The power $p$ can be expressed as a function (shown at right) of $\tau$, which itself depends on several other quantities: the atomic numbers $Z$ of the two fusion reactants $A$ and $B$, their reduced mass $\mu_{\text{red}}$ in atomic mass units, and the current temperature $T$ at which the reaction is occurring.

$$p = \frac{\tau - 2}{3}$$

$$\tau = 42.5\left[Z_A^2 Z_B^2 \mu_{\text{red}} \left(\frac{10^6\,\text{K}}{T}\right)\right]^{1/3}$$

$$\mu_{\text{red}} = \frac{m_A m_B}{m_A + m_B}$$

For the p-p chain, both reactants are hydrogen. In the CNO cycle the rate-limiting reaction involves hydrogen and oxygen. Consider a 40 $M_\odot$ star with a core temperature of $3.89\times10^7$ K.

Find the temperature dependences $p$ for the p-p chain and the CNO cycle for this star. Choose the **closest** options from the following list; **order does not matter** on your answer sheet.

| | | | | |
|---|---|---|---|---|
| A. -17 | F. -1.0 | K. 1.5 | P. 6.8 | U. 21 |
| B. -11 | G. -0.50 | L. 2.5 | Q. 8.8 | V. 25 |
| C. -6.8 | H. 0.0 | M. 3.2 | R. 11 | W. 30 |
| D. -4.1 | I. 0.50 | N. 4.1 | S. 14 | X. 35 |
| E. -2.5 | J. 1.0 | O. 5.3 | T. 17 | Y. 41 |

# Station D

# Mathy questions

## Instructions

Answer the questions about the images listed in this section. Use your scratch paper for any math you do—**DO NOT WRITE ON THE TEST!** If you need more paper, raise your hand and one of the volunteers will (quickly!) bring some.

Point values for each question are given after the question number.

When questions rely on previous answers, use the rounded numbers you put on your answer sheet instead of the exact values you calculated. (For example, if you rounded 3.14159 to 3.142 on your answer sheet, use 3.142 and not 3.14159 on the next question.)

Hi, I'm a porg! I'm hiding somewhere in this station. Look for me, and write the question number on your answer sheet for two points!

## Questions D1-D5 are about Hubble's Law

D1. **(1 pt)** Hubble's constant is traditionally written with units of km/s/Mpc. Which of the following units has the same physical dimensionality?

A. $m^{-2}$
B. Hz
C. kg-m/s
D. J

D2. **(2 pts)** According to the analysis of the Planck group, the value of the Hubble constant in the nearby Universe is $H_0$ = 67.8 km/s/Mpc. A dwarf galaxy was recently discovered with a recessional velocity of 1803 km/s. How far is the galaxy, in megaparsecs? Give your answer **to two significant figures**.

D3. **(3 pts)** The Universe starts to deviate from Hubble's Law at a *redshift* of approximately 0.22. What is the recessional velocity associated with this redshift, in kilometers per second? Give your answer **to two significant figures**.

D4. **(3 pts)** Assume a value of 67.8 km/s/Mpc for the Hubble constant. How far away is an object with a redshift of 0.22? Give your answer in units of megaparsecs, **to two significant figures**. You will need your answer to question D3. If you did not get an answer to D3, or if you do not trust your answer, you may use a value of 13,000 km/s for one (1) point.

D5. **(3 pts)** What is the distance modulus of a supernova observed at a redshift of 0.22? Give your answer **to two significant figures**. You will need your answer to question D4. If you did not get an answer, or if you used the one-point option, use a distance of 1.5 gigaparsecs for one (1) point.

## Questions D6-D11 are about black bodies and thermal radiation

The *spectral index* of a measurement of black body radiation at two frequencies can be written using the formula at right. (The frequencies used here were blue light at 650 THz and red light at some other frequency.) In the formula, $\alpha$ is the spectral index and $T$ is the temperature (in Kelvins) of the object.

$$\alpha = \frac{\ln\left(\dfrac{e^{\frac{21600}{T}} - 1}{e^{\frac{31200}{T}} - 1}\right) + 1.1032}{0.36772}$$

D6. **(2 pts)** What is the spectral index of the Sun, whose surface temperature is 5780 K? Give your answer **to the nearest hundredth**.

D7. **(2 pts)** What is the temperature, in Kelvins, of a star whose spectral index is exactly zero? Give your answer **to three significant figures**. (*Hint*: don't try to solve this analytically.)

D8. **(1 pt)** In which spectral class would the star mentioned in D7 fall?

D9. **(2 pts)** The denominator of the fraction is actually $\ln(\nu_1/\nu_2)$, where $\nu_1 = 650$ THz is the frequency of the blue light. What is $\nu_2$, the frequency of the red light used? Give your answer, in units of Hertz, **to two significant figures**.

D10. **(3 pts)** As the temperature of the star gets very large (that is, as $T$ approaches infinity), what value does $\alpha$ approach? Give your answer **to two significant figures**.

D11. **(1 pt)** The above definition of spectral index assumes that the measured spectrum is what kind of function (specifically, a function of the wavelength of detected light)?

A. Gaussian

B. Power law

C. Thermal

D. Polynomial

Questions D12-D16 are about a hypergiant star in the Milky Way.

D12. **(2 pts)** The temperature of this hypergiant is measured to be 13,700 K. Based on distance measurements, its luminosity is found to be 2,000,000 times that of the Sun (I *did* say it was a hypergiant). What is the radius of this exceptional star? Give your answer in units of the solar radius $R_\odot$, **to two significant figures**. (The surface temperature of the Sun is 5780 K.)

D13. **(3 pts)** The surface gravity of the star can be measured from absorption lines in its spectrum. Astronomers determine that the surface gravity of the star is 0.501 $m/s^2$. What is the mass of the star, in units of the solar mass $M_\odot$, **to two significant figures**? You will need your answer to question D12. If you did not get an answer, or if you do not trust it, you may use a radius of 12 $R_\odot$ for one (1) point.

D14. **(2 pts)** The absolute magnitude of the Sun is 4.83. Using the luminosity mentioned in question D12, calculate the absolute magnitude of the hypergiant star. Give your answer **to the nearest hundredth**.

D15. **(2 pts)** Parallax measurements of the hypergiant show that it is located 1,600 parsecs from Earth. At this distance, what should the apparent magnitude of the star be? Give your answer **to the nearest hundredth**. You will need your answer to question D14. If you did not get an answer, or if you do not trust it, you may use an absolute magnitude of 3.14 for one (1) point.

D16. **(3 pts)** The apparent magnitude you calculated in question D15 would make this hypergiant one of the brightest stars in the night sky. Instead, its apparent visual magnitude is just 11.40, much too faint to see with the naked eye. What fraction of the visible light from the star is **not** absorbed by interstellar dust and makes it to Earth? Give your answer **to two significant figures**. You will need your answer to question D15. If you did not get an answer, or if you used the one-point option, use an apparent magnitude of 6.72 for one (1) point.

<u>Questions D17-D22 are about a distant neutron star.</u>

D17. **(2 pts)** Using an X-ray telescope, astronomers find that the spectrum of this neutron star is well-fitted by a black body with a temperature given by $k_B T = 0.595$ keV. In this equation, $k_B$ is the Boltzmann constant. What is the temperature $T$ of the neutron star in Kelvins? Give your answer **<u>to two significant figures</u>**.

D18. **(1 pt)** At what wavelength of light does the neutron star's spectrum peak? Use the version of Wien's Law based on wavelength, not on frequency, which is given at right. The constant is $b = 2.898\times10^6$ nm-K. Give your answer in units of nanometers, **<u>to two significant figures</u>**. You will need the temperature found in question D17. If you did not get an answer to D17, or if you do not trust your answer, you may use a temperature of 5780 K for one (1) point.*

$$\lambda_{max} = \frac{b}{T}$$

D19. **(2 pts)** The neutron star is located in a galaxy with a distance modulus of 19.0. How far away is the galaxy (and therefore the neutron star)? Give your answer in units of parsecs, **<u>to two significant figures</u>**.

D20. **(3 pts)** The X-ray flux from this neutron star is measured to be $1.48\times10^{-14}$ W/m$^2$. Using the distance found in question D19, what is the X-ray luminosity $L_X$ of the neutron star in units of Watts? Give your answer **<u>to two significant figures</u>**. If you did not get an answer to D19, or if you do not trust your answer, you may use a distance of 17,200 parsecs for one (1) point.

D21. **(3 pts)** Assume that the neutron star's radius is 12 km. What is the black-body luminosity associated with the neutron star's radius and temperature? For comparison, the Sun's temperature is 5780 K, its radius is 696,000 km, and its luminosity is $3.83\times10^{26}$ W. Give your answer, in units of Watts, **<u>to two significant figures</u>**. You will need the temperature found in question D17. If you did not get an answer to D17, or if you do not trust your answer, you may use a temperature of 5780 K for one (1) point.

D22. **(1 pt)** Compute the ratio of the observed X-ray luminosity and the expected (bolometric) black-body luminosity. What conclusion can you draw from this ratio?

A. The neutron star's X-ray emission is generated by spindown, and isn't thermal in origin
B. Most of the neutron star's energy is emitted in wavelengths other than X-ray
C. The neutron star is embedded in an undetected supernova remnant
D. Background objects contributed additional X-ray flux to the observations

* Yes, this question is only worth one point anyway. I'm trying to make sure you earn *some* points. Complain to Kim Gervase if this bothers you.