CONSTRUCTION OF A HERTZSPRUNG-RUSSELL DIAGRAM

Introduction: The spectral classification of stars began in the mid-19th century with two major efforts. One was to obtain a large sampling of low-resolution spectra, while the other was to image the spectra of a select number of stars to a high degree of resolution. At the same time, laboratory work made it abundantly clear that there was a relationship between the bright emission lines being produced under controlled laboratory experiments and with the absorption spectra of the stars being imaged. Astronomers speculated about the key to understanding the variety of lines which filled these spectrograms. Various classification schemes were proposed, but it was not until the early years of the 20th century, with the development of quantum theory, that it became clear that the distribution and intensity of the lines were mainly a function of the temperature of the stars being observed. The electrons of the various atoms making up the chemical components of a star were able to change their orbital positions in relationship to the temperature of the star. The Harvard classification system was eventually perfected by Annie Jump Cannon and Edward Charles Pickering. It consisted of O, B, A, F, G, K, and M stars, taken from the more orderly attempts of earlier classification schemes, but now arranged into a temperature sequence from hottest to coolest.

Concurrent with the investigation of stellar spectra were efforts to determine the distances (parallaxes) to the stars. The first successful measurements was achieved by the German, Friedrich Wilhelm Bessel, in 1838 with the faint star 61 Cygni. Knowing the distance to a star and its apparent magnitude as observed from Earth, allowed astronomers to calculate mathematically (using the Distance Modulus $M = m + 5 - 5\log r$) the star's absolute magnitude (M) or its apparent brightness from a standardized distance of 10 parsecs or 32.6 light years from the sun.

The absolute magnitudes (parallaxes) and the temperatures (spectral classification) of the stars could now be determined with some precision, but was there a relationship connecting these two parameters, or did all luminosities fit randomly into all temperature ranges? The problem was solved by two astronomers between 1910 and 1913, an American, Henry Norris Russell (1877-1957) and a Dane, Ejnar Hertzsprung (1873-1967). Together they constructed with much less accurate data than is available today, a two-dimensional representation of the stars (absolute magnitude vs. spectral type). This Hertzsprung-Russell diagram would in future years be expanded into a working model of stellar evolution whereby the life histories of stars and star clusters could be determined with confidence.

Purpose: Your task will be to create and analyze an H-R diagram constructed from two different groupings of stars: the brightest stars in the sky, many of which are easily seen from a city environment and some of the closest stars to our sun. Several stars, including the sun, can be found in both groupings.

Materials Needed: Graph paper (1/4-inch squares), ruler, lead pencil, colored pencils, preferably a blue, yellow, and red pencil for plotting points.

Procedure: Create the framework for your H-R diagram by plotting spectral types along the X-axis and absolute magnitudes (M) along the Y-axis. Make sure that both axes are properly labeled and that your graph is titled.

<u>Follow these instructions</u>:

1. Data for your Hertzsprung-Russell diagram can be found in the brightest and nearest star tables found with this lab.
2. Spectral types will be plotted along the horizonal x-axis. Start with O_6 stars at the origin and continue to M_8 in increments for each square as follows: O_{4}, $_{6}$, $_{8}$, B_{0}, $_{2}$, $_{4}$, $_{6}$, $_{8}$, A_{0}, $_{2}$, $_{4}$, $_{6}$, $_{8}$, F_{0}, $_{2}$, $_{4}$, etc., to M_8
3. Plot absolute magnitude along the vertical y-axis. Start at the origin with an absolute magnitude of +18 and continue upward in increments of one magnitude per square until an absolute magnitude of -9 is reached.
4. Use a <u>BLUE</u> pencil to color star plots of spectral types 0_6-A_9.
5. Use a <u>YELLOW</u> pencil to color star plots of spectral types F_0-G_9.
6. Use a <u>RED</u> pencil to color star plots of spectral types K_0-M_9.
7. Stars contained in the <u>BRIGHTEST</u> Stars Table should have a short <u>VERTICAL</u> line segment drawn through them.
8. Stars of the <u>NEAREST</u> Stars Table should have a short <u>HORIZONTAL</u> line segment drawn through them.
9. A few stars can be found in both tables. These are indicated with a double asterisk in the "Thirty Brightest Stars Table." These stars should appear on your graph as small dots with crosses through them. Label these stars with their name on your graph.
10. In the NEAREST star table, you will notice a "wd" in front of several spectral types. These stars are white dwarfs. Plot the spectral type as if they were a zero (wdA = A_0).
11. The data in the BRIGHTEST star table that have a double asterisk are a compilation of the brightnesses if the system has multiple components.
12. One star, Aldebaran, in the BRIGHTEST star table has a "v" next to the absolute magnitude to indicate that it is a variable star.
13. Create a key by showing in tabular form what the colors and line segments represent on your graph. Your graphing grade will be determined by its accuracy (60%), neatness (20%), and labeling (20%).
14. After completion of your Hertzsprung-Russell diagram, answer the questions found at the end of this exercise.
15. <u>Note</u>: If a star's absolute magnitude is -2.5, the plot occurs above the -2 <u>position</u> on your H-R Diagram, but if the absolute magnitude is positive, like +4.3, the plot would occur below the line that indicates +4.

THIRTY OF THE BRIGHTEST STARS

From the Hipparcos Star Catalog
Mark these stars with a vertical line segment.

Star	Rank	Name	MAGNITUDE apparent m	absolute M	DISTANCE light years	Spectral Type **w/o luminosity**
**Sun			-26.7	+4.8	8.3 light min.	G_2
**Alpha CMa	(1)	Sirius	-1.46	+1.43	8.6	A_1
Alpha Car	(2)	Canopus	-0.73	-5.64	310	F_0
**Alpha Cen	(3)	**Rigil Kentaurus**	-0.29	+4.06	4.39	G_2*/K_1
Alpha Boo	(4)	Arcturus	-0.05	-0.31	37	K_2
Alpha Lyr	(5)	Vega	+0.03	+0.58	25	A_0
Alpha Aur	(6)	Capella	+0.07	-0.49	42	G_0*/G_5
Beta Ori	(7)	Rigel	+0.15	-6.72	770	B_8
**Alpha CMi	(8)	Procyon	+0.36	+2.64	11	F_5
Alpha Eri	(9)	Achernar	+0.45	-2.77	144	B_3
Alpha Ori	(10)	Betelgeuse	+0.55var	-5.05	430	M_2
Beta Cen	(11)	Hadar	+0.61	-5.42	530	B_1
**Alpha Aql	(12)	Altair	+0.77	+2.20	16.77	A_7
Alpha Tau	(14)	Aldebaran	+ 0.86v	- 0.64v	65	K_5
Alpha Sco	(15)	Antares	+0.95	-5.39	600	M_1*/B_4
Alpha Vir	(16)	Spica	+0.97	-3.56	260	B_1*/B_2
Beta Gem	(17)	Pollux	+1.14	+1.07	34	K_0
Alpha PsA	(18)	Fomalhaut	+1.15	+1.72	25	A_3
Alpha Cyg	(19)	Deneb	+1.24	-8.74	3000	A_2
Alpha Leo	(21)	Regulus	+1.36	-0.52	78	B_7
Epsilon CMa	(22)	Adhara	+1.50	-4.10	430	B_2
Alpha Gem	(23)	Castor	+1.58	+0.59	52	A_1*/A_2
Gamma Ori	(26)	Bellatrix	+1.64	-2.72	240	B_2
Alpha UMa	(34)	Dubhe	+1.79	-1.09	124	K_0*/F_0
Delta CMa	(36)	Wezen	+1.83	-6.87	1800	F_8
Alpha UMi	(48)	Polaris	+1.99v	-3.63v	430	F_7
Alpha And	(54)	Alpheratz	+2.07	-0.30	97	B_9
Kappa Ori	(56)	Saiph	+2.07	-4.65	720	$B_{0.5}$
Beta UMi	(57)	Kochab	+2.07	-0.87	127	K_4
Beta Leo	(62)	Denebola	+2.14	+1.92	36	A_3

Key: M = absolute magnitude, m = apparent magnitude, and r is the distance to the star measured in parsecs (1 pc = 3.2616 ly).

Where * = binary or multiple star system in which the component with the asterisk contributes most of the light of the system. Plot only the star with the asterisk.

** = stars that are both bright and near.

THIRTY OF THE NEAREST STARS

From the Hipparcos Star Catalog*
Mark these stars with a horizontal line segment.

Star Name		MAGNITUDE apparent m	absolute M	DISTANCE light years	Spectral Type
Sun		-26.7	+4.8	8.3 light min.	G_2
Alpha Cen	C **Proxima**	+11.01	+15.45	4.22	M_5
	B	+1.35	+5.70	4.39	K_0
	A **brightest**	-0.01	+4.34	4.39	G_2
Barnard's star		+9.54	+13.24	5.94	M_5
Wolf 359		+13.5	+16.5	7.5	M_8
Lalande 21185		+7.5	+10.7	8.1	M_2
Sirius	A **brightest**	-1.44	+1.45	8.60	A_1
	B	+8.7	+11.6	8.6	wdA
UV Ceti	A	+12.5	+15.3	8.8	M_6
	B	+13.0	+15.8	8.8	M_6
Ross 154		+10.6	+13.3	9.5	M_5
Epsilon Eridani		+3.72	+6.18	9.69	K_2
61 Cygni	A	+5.20	+7.49	11.36	K_5
Alpha CMi	**Procyon A**	+0.36	+2.64	11.41	F_5
	B	+10.7	+13.0	11.41	wdF
61 Cygni	B	+6.05	+8.33	11.43	K_7
Epsilon Indi		+4.69	+6.89	11.83	K_5
Tau Ceti		+3.49	+5.68	11.89	G_8
Lacaille 8760		+7.4	+9.5	12.4	M_1
Kapteyn's star		+8.86	+10.89	12.77	M_0
Kruger 60	A	+9.59	+11.58	13.07	M_4
	B	+11.3	+13.4	13.07	M_5
Van Maanen's star		+12.37	+14.15	14.37	wdG
40 Eridani	A	+4.43	+5.92	16.45	K_1
	B	+9.5	+11.1	16.45	wdA
	C	+11.2	+12.8	16.45	M_4
70 Ophiuchi	A	+4.03	+5.50	16.59	K_0
	B	+6.0	+7.5	16.59	K_5
Altair		+0.76	+2.20	16.77	A_7

Key: where M = absolute magnitude, m = apparent magnitude, and r is the distance to the star measured in parsecs (1 pc = 3.2616 ly).
* Visual and absolute magnitudes taken to the hundredth decimal place are from the Hipparcos Star Catalog..

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MAKING SENSE OF THE HERTZSPRUNG-RUSSELL DIAGRAM

Instructions: Answer the following questions about the Hertzsprung-Russell Diagram. You can refer back to the completed graph, noting the representations given by the symbols or working with the two tables which contain information about the 30 nearest and the 30 brightest stars in the sky. **Your answers go at the top of each numbered problem.**

1. ____________________, ____________________ Most of the stars which are near to the Earth (stars with horizonal bars on the graph) are of HIGH/LOW luminosity and HIGH/LOW temperature.

2. ____________________, ____________________ Most of the stars which appear bright in the sky (stars with vertical bars) actually have HIGH/LOW luminosities and HIGH/LOW temperatures. Do you recognize any of the names in the "Thirty of the Brightest Stars" table?

   Statement: The stars on your H-R diagram appear to congregate in three different groupings which are called luminosity classifications.

3. **Main Sequence:** ____________________, __________________ A propeller-shaped band of stars moves from the upper left to the lower right on your H-R diagram. It is known as the main sequence. The location of the sun along this curve sits near the __________, demonstrating why we call the sun an ___________ star.

4. ____________________, __________________ All of stars along the main sequence are powering themselves just like the sun by converting __________ into __________ through thermonuclear fusion.

5. ____________________, __________________ The stars along the upper left of the main sequence are millions of times more __________ than the stars along the lower right of the main sequence. The most common category among main sequence stars is the O, B, A, F, G, K, M classification. Pick only one and enter it in the second space.

6. ____________________, ____________________ The rate at which a star consumes its fuel is directly related to the __________ of that star, and therefore, the position of that star along the main sequence. Luminosity will not be accepted, but it is directly related to the correct word. Stars in the upper left corner of the main sequence have greater compression in their cores and higher core temperatures, causing these blue supergiants to burn hydrogen at a much FASTER/SLOWER pace. Just the opposite is true for the cool, red main sequence stars.

7. ____________________, ____________________ High mass stars found in the upper left of the H-R diagram's main sequence have LONG/SHORT lives, while low mass stars found along the main sequence along the bottom right have LONG/SHORT lives.

8. **Giants:** ____________________ Stars which are generally positioned to the upper right of the H-R diagram are extremely luminous, but according to their spectral characteristics (temperatures), they are very __________.

9. ____________________, ______________________________ Since the energy emitted per unit area is a function of temperature, and the temperatures of these stars are cool, in size they must be extremely __________ in order to compensate for their lower surface luminosities. These stars are known as __________ (two words).

10. ____________________, ____________________, ____________________ The cores of such stars have run out of the basic element that normally powers them, __________, and they have made thermonuclear adjustments to keep themselves from collapsing. The cores of solar mass stars are probably not undergoing thermonuclear fusion, but hydrogen burning still continues in a thin shell which surrounds them. The more massive stars in this group are burning helium or even heavier elements in their cores. Because of their hotter interiors, they are producing energy MORE/LESS rapidly, and this has caused the outer layers of the star to EXPAND/CONTRACT in size.

11. **Dwarfs:** ____________________, ____________________ In an opposite sense, there appears to be several stars on your Hertzsprung-Russell diagram (lower left) which are, with respect to temperature, very __________, but are not very bright. The matter present in these stars is inert, nonreacting helium or carbon-oxygen, leftover material from the cores and shells of stars that were at one time undergoing thermonuclear fusion. Because these stars are radiating a great deal of energy per unit area, but are not very luminous, their sizes must be very __________.

12. ______________________________ Stars with high surface temperatures, but low luminosities are called __________ stars (two words).

13. ____________________ From main sequence to red giant to white dwarf suggests a sequence of __________ from core hydrogen burning to other types of fusion processes, and eventually death.

14. Predict why the population densities, the number of stars in the various luminosity classifications, are lower than the number of stars found in the same spectral classifications along the main sequence.

    Red Giants (cool, but big): ____

    White Dwarfs (hot, but faint): ____

15. Mark areas of the main sequence, red giant, and white dwarf regions of your H-R diagram.

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16. **The Hertzsprung-Russell diagram is a powerful tool for calculating the distances to stars when their parallax angles are too small to measure**. A star is photographed in a nearby galaxy, and it is determined to have an apparent magnitude of +14.55. When a spectrogram is obtained, it is found to be a main sequence star similar to Kappa Orionis (absolute magnitude = -4.65) which you plotted on your graph. Use the distance modulus, to find how far away the galaxy is from us.

$M = m + 5 - 5 \log r$ **Distance Modulus**

solving for r

M = absolute magnitude (consult brightest star table)
m = apparent magnitude (given in problem)
r = distance in parsecs (pc), the variable to be solved

$M - m - 5 = -5 \log r$

$$\frac{M - m - 5}{-5} = \log r$$

$$\text{antilog } \frac{M - m - 5}{-5} = \text{antilog } (\log r)$$

The log of a number is the exponent to which 10 must be raised.
The antilog is the number created when 10 is raised to the "x" power = 10^x.

$$10^x = 10^{\frac{M - m - 5}{-5}} = r$$

Show all work for problem 16 here.

17. A star with an apparent magnitude of +15.78 has a parallax of 282.85 mas. Predict its location on the Hertzsprung-Russell diagram. Below, first make a qualitative prediction in ink, then complete the mathematical calculations below.

What is your hunch? ____

Was your hunch correct? ______________

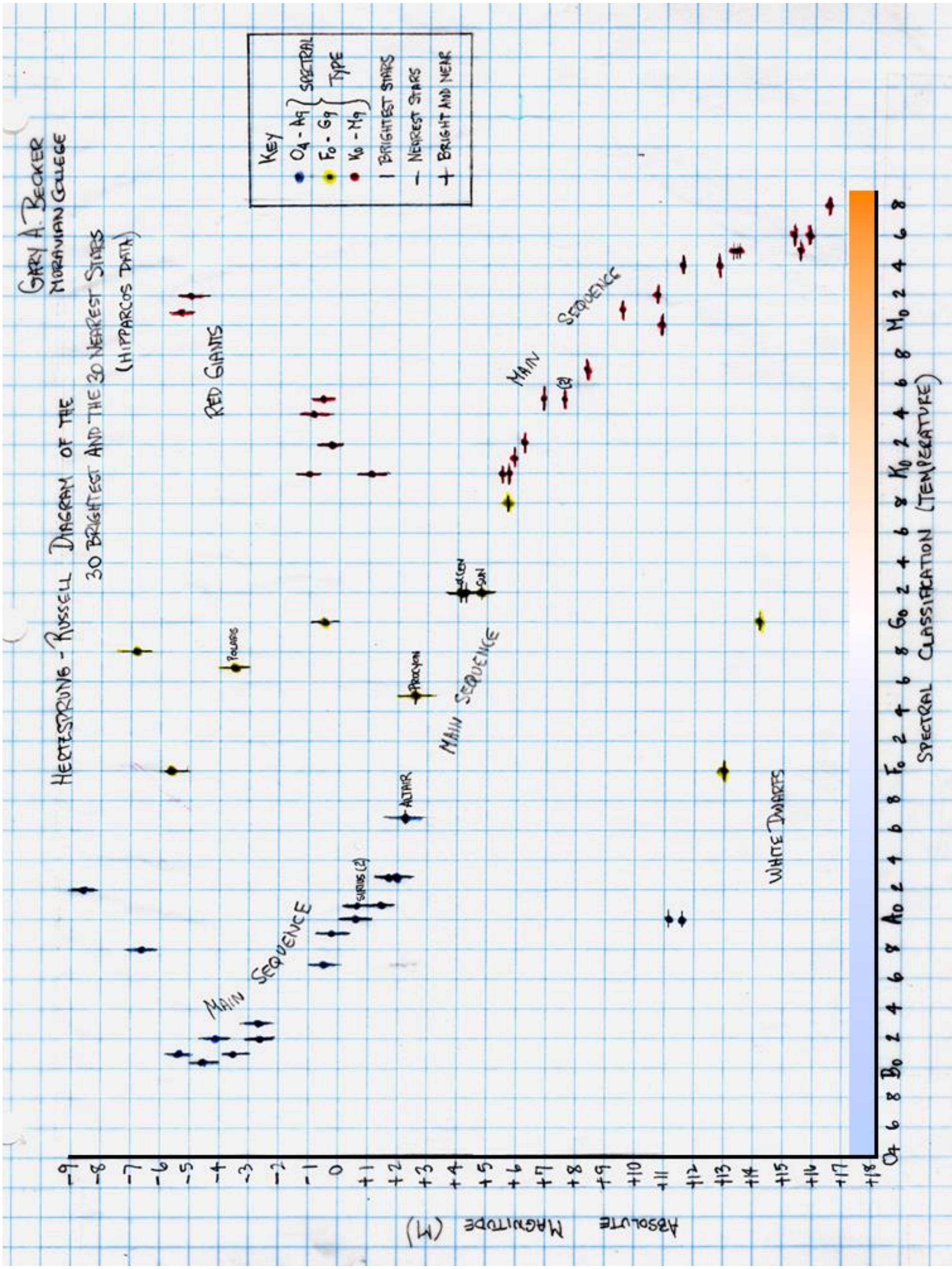
18. Quantify your answer to question 17 mathematically and state one precise location on the H-R diagram where this star could be located and then proceed to the last two questions on the sheet.

<u>Compute the distance to the star</u>: $d_{pc} = \frac{1}{P''}$

<u>Use the Distance Modulus to calculate the absolute magnitude of the star</u>:
$M = m + 5 - 5 \log r$

19. _________________________ If this star had a spectral classification of F_6, its luminosity classification would make it (a) an __________.

20. _________________________ If this star had a luminosity classification of M_8, its luminosity classification would make it (a) an __________.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Hertzsprung-Russell Diagram of the
30 Brightest and the 30 Nearest Stars
(Hipparcos Data)
Key
O4 - A9
F0 - G9
K0 - M9
Spectral Type
| Brightest Stars
— Nearest Stars
+ Bright and Near
Red Giants
Main Sequence
Main Sequence
Main Sequence
White Dwarfs
Polaris
Procyon
Altair
Sirius (2)
Sun
Absolute Magnitude (M)
Spectral Classification (Temperature)