(Jk-digital)

DETERMINING THE CIRCUMSTELLAR HABITABLE ZONES OF FIVE STARS.

An in-depth analysis of one method to determining the circumstellar habitable zone of different stars.

Physics IA – May 2016

1. **Research Question**

When faced with the task of doing a laboratory report on whatever pleased my mind, I immediately jumped to astrophysics, a strand of the vast physics spectrum for which I have a fond interest. I absolutely love the abstractness involved in its theories and in its observations. It seems as if the more you delve into the topic, the more breadth it gains. However, I also wanted to do something which I felt was of interest to a broader public. It was at this time that I figured that the search for exoplanets which could be habitable by humans is a growing field in which people are gaining more interest, especially after recent findings that Mars could be housing life and running water. I therefore decided to do my Internal Assessment on the Circumstellar Habitable Zones, and I tried to calculate the aptly named "Goldilocks zone" of nearby stars which are within reasonable reach of Earth, giving insight to possible habitable planets close to home.

My hypothesis for the findings of the study are that higher class stars will have a CHZ further from its surface, however the range of every CHZ will remain relatively constant throughout all-star classes.

2. **Selection of stars**

I decided to choose five stars for analysis, two stars which are within 10 lightyears from Earth and three stars which are between 10 and 20 lightyears from Earth.

3. **Luminosity of a star**

The luminosity of a star is defined as the total amount of energy emitted by a star, galaxy or other astronomical energy per unit time. It is related to the brightness and magnitude of a star, which will be discussed later.

4. **Calculating the luminosity of a star**

To calculate the luminosity of the star, the Stefan-Boltzmann Law is used (Option D.1). This law works under the assumption that a star is a black body, which is defined as an object which is perfectly opaque and is non-reflecting. Although this is an ideal assumption, it is reasonable with stars as their emission far outweighs the light they reflect.

Under this assumption, the equation to calculate the luminosity of a star is:

$$L = \sigma A T^4$$

Where; *L* is the luminosity of the star (W)

σ **is the Stefan-Boltzmann constant** (5.67×10^{-8} W m^{-2} K^{-4})

***A* is the area of the star** (m^2)

***T* is the temperature** (K)

5. **Going further from the syllabus**

Although calculating luminosities of a star is not simple, it is not what the focus of this IA is. The luminosity of a star is closely related to the apparent magnitude of a star, one of the essential factors of calculating the Circumstellar Habitable Zone for stars.

6. **Circumstellar Habitable Zones**

The Circumstellar Habitable Zone (CHZ for short), is a concept first introduced to the realm of Astrophysics in 1953 by scientist Hubertus Strughold. In principle, a CHZ is considered to be a zone around a star where planets can – under the correct circumstances – host liquid water, which according to Earth scientists is a necessity for life as we know it to exist.

7. **Determining the CHZ of a star**

The method for determining the CHZ of a star in this IA was derived from planetary biology (Morris). In this method, there are two stages to determining the CHZ of a star. The first stage is estimating the host star's absolute luminosity which is dependent on its apparent visual magnitude. This is done in three steps;

1) Determining the absolute visual magnitude based on the apparent visual magnitude of the host star
   - The formula for calculating the absolute visual magnitude of a star is:

$$M_v = m_v - 5\log\left(\frac{d}{10}\right)$$

Where; M_v is the absolute magnitude of the star

m_v is the apparent magnitude of the star (its visual spectrum)

d is the distance from earth to the star in parsecs

2) Calculating the bolometric magnitude of the host star
   - The bolometric magnitude is the magnitude of the star's luminosity including wavelengths outside of the visible spectrum. This is done by the formula:

$$M_{bol} = M_v + BC$$

Where; M_{bol} is the bolometric magnitude of the star
M_v is the absolute magnitude of the star
BC is the bolometric correction constant*

* The bolometric correction constant is a predetermined constant. The constants I am using are generalized from Habets and Heintz (1981) given below:

Spectral Class	Bolometric Correction constant
B	-2.0
A	-0.3
F	-0.15
G	-0.4
K	-0.8
M	-2.0

3) Calculating the absolute luminosity of the host star

- The absolute luminosity of the host star is the luminosity in relation to the luminosity of our sun. The formula is:

$$\frac{L_{star}}{L_{sun}} = 10^{\left[\frac{M_{bol\,star} - M_{bol\,sun}}{-2.5}\right]}$$

Where; $\frac{L_{star}}{L_{sun}}$ is the absolute luminosity of the star relative to our sun's

$M_{bol\,star}$ is the bolometric magnitude of the star in question

$M_{bol\,sun}$ is the bolometric magnitude of our sun*

2.5 is a constant value used for relating stellar luminosities, called Pogson's Ratio

* The bolometric magnitude of our sun is 4.72

The second stage is approximating the radii of the boundaries of the CHZ. The formulas used for this are:

$$r_i = \sqrt{\frac{L_{star}}{1.1}}$$

$$r_o = \sqrt{\frac{L_{star}}{0.53}}$$

Where; r_i and r_o are the radii of the inner and outer rim of the CHZ respectively

L_{star} is the absolute luminosity of the star in question

1.1 and 0.53 are constants representing stellar flux at the inner radius and outer radius of the CHZ respectively (based on Kasting et al. (1993); Whitmire et al. (1996))

8. Astronomical distances

In this report, the distances used are parsecs and AU (astronomical units). For reference, one parsec is the distance at which one astronomical unit subtends an angle of one arc-second. The term “parsec” originates from the **par**allel angle of one **sec**ond. A parsec distance is shown in diagram below, where; *E* is Earth, *S* is the Sun, and *D* is the distance of a parsec from the sun (Heron).

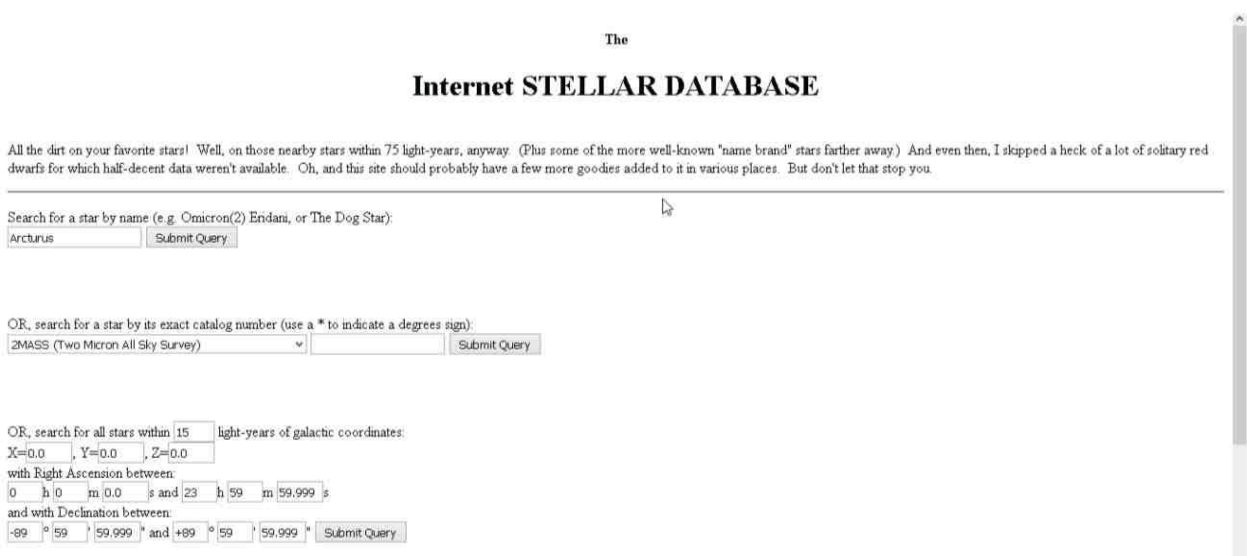
The second and final distance unit is the Astronomical Unit (AU), which is defined as the mean distance between the Sun and the Earth. A parsec is approximately 206 265 AU.

Also for reference, the CHZ of our Sun is between 0.95 and 1.37 (Kasting et al.)

9. Online database collection

Some data used in this report is collected from the Stellar Database (W, Roger)

The website looks like this:



An example of the data found is below:

Arcturus

Find all stars within 15 light-years

Proper names: Arcturus, Alpha Boötis, 16 Boötis, Alpha Bootis, 16 Bootis
Catalog numbers:
Gliese (Gl) 541, Henry Draper (HD) 124897, Bonner Durchmusterung (BD) +19°2777, Luyten Half-Second (LHS) 48, Hipparcos Input Catalog (HIC) 69673, Smithsonian Astrophysical Observatory (SAO) 100944, Fifth Fundamental Catalogue (FK5) 526, Hoffleit Bright Star (HR) 5340, New Suspected Variable (NSV) 6603
Heavy element abundance: 34% of Sol
Standard error in heavy element abundance: 7%
Source for heavy element abundance: Strobel [Fe/H] Determinations
Arity: singular
Points of interest:
Arcturus is a classic example of a Red Giant; a light- to middle-weight star that has passed the end of its main sequence lifetime and is in a transitional period of bloating up and cooling off. The total amount of time a star can remain in the red giant stage is on the order of a couple million years, which is not nearly enough time for life as we know it to engage in any serious evolution (if Arcturus has any life-bearing planets at all).

Right Ascension and Declination: 14h15m39.677s, +19°10'56.71" (epoch 2000.0)
Distance from Sol: 36.71 light-years (11.25 parsecs)
Standard error in distance: 0.826%
Source for distance: Hipparcos
Celestial (X,Y,Z) coordinates in ly: -28.77, -19.35, 12.06
Galactic (X,Y,Z) coordinates in ly: 12.98, 3.517, 34.16
Proper motion: 2.281 arcsec/yr (208.8° from north)
Radial Velocity: -5 km/sec
Source for proper motion and radial velocity: Gliese
Galactic (U,V,W) velocity components in km/s: 25.69, -119.0, -2.878

What do all these fields mean?

Spectral class: K2pe
Luminosity Class: III

From this data, the apparent visual magnitude of the selected stars was found.

The SIMBAD Astronomical Database is a database formed by the University of Strasbourg (Wenger et al.). From this database, the parsec distances of stars were found.

CDS Portal Simbad VizieR Aladin X-Match Other Help

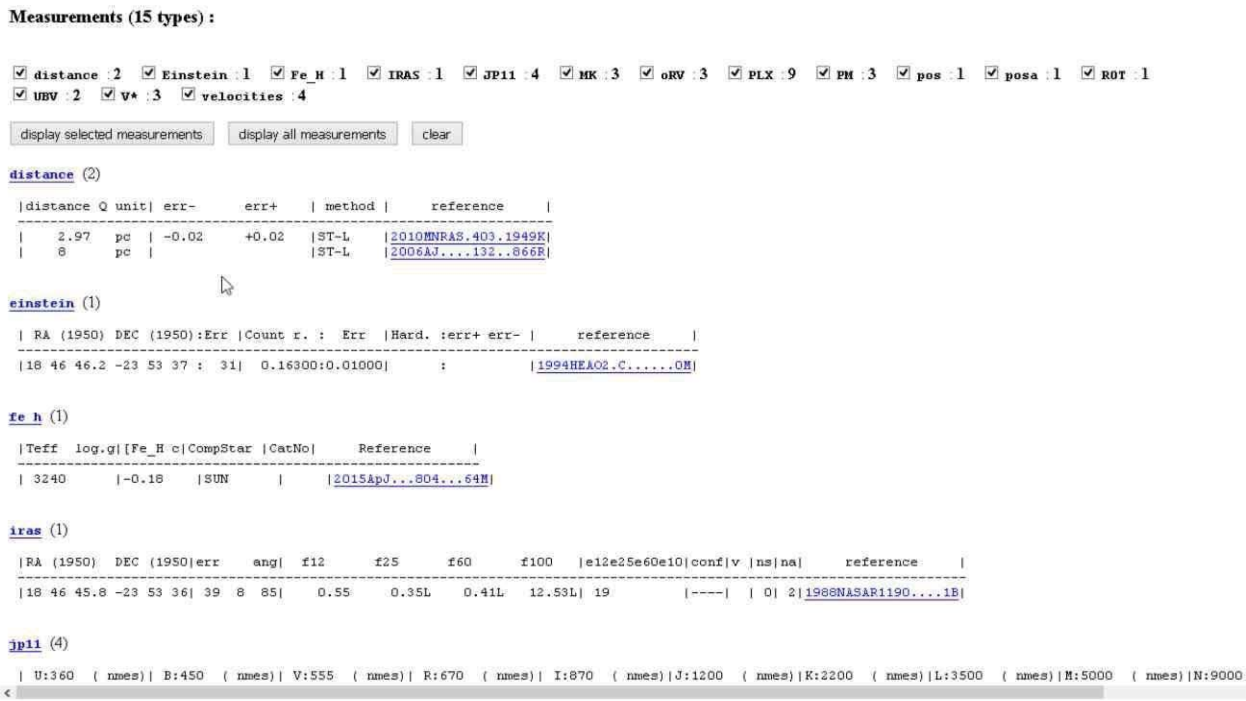
SIMBAD Astronomical Database

Queries	*Documentation*	*Information*
basic search	User's guide	Presentation
by identifier		
by coordinates		Acknowledgment
by criteria	Query by urls	
reference query	Nomenclature Dictionary	
scripts	Object types	
TAP queries	List of journals	SimWatch
	Measurement description	
options	Spectral type coding	Release:
	User annotations documentation	SIMBAD4 1.3 - Sept-2015
Display all user annotations		Release history

Content
The SIMBAD astronomical database provides basic data, cross-identifications, bibliography and measurements for astronomical objects outside the solar system.
SIMBAD can be queried by object name, coordinates and various criteria. Lists of objects and scripts can be submitted.
Links to some other on-line services are also provided.

Statistics	
Simbad contains on *2015.10.30*	
7,998,745	objects
22,331,006	identifiers
309,592	bibliographic references
12,224,927	citations of objects in papers

From the front page, a basic search is conducted using the name of a star, and the following data is presented:



Measurements (15 types) :

☑ distance :2 ☑ Einstein :1 ☑ Fe_H :1 ☑ IRAS :1 ☑ JP11 :4 ☑ MK :3 ☑ oRV :3 ☑ PLX :9 ☑ PM :3 ☑ pos :1 ☑ posa :1 ☑ ROT :1
☑ UBV :2 ☑ V* :3 ☑ velocities :4

display selected measurements | display all measurements | clear

distance (2)

```
|distance Q unit| err-      err+    | method |      reference       |
-----------------------------------------------------------------------
|    2.97    pc  | -0.02     +0.02   |ST-L    |2010MNRAS.403.1949K|
|    8       pc  |                   |ST-L    |2006AJ....132..866R|
```

einstein (1)

```
| RA (1950) DEC (1950):Err |Count r. :  Err  |Hard. :err+ err- |      reference      |
--------------------------------------------------------------------------------------
|18 46 46.2 -23 53 37 :  31|  0.16300:0.01000|       :          |1994HEAO2.C......0M|
```

fe h (1)

```
|Teff  log.g|[Fe_H c|CompStar |CatNo|      Reference      |
----------------------------------------------------------
| 3240      |-0.18   |SUN      |     |2015ApJ...804...64M|
```

iras (1)

```
|RA (1950)  DEC (1950|err    ang|  f12      f25      f60      f100   |e12e25e60e10|conf|v |ns|na|      reference      |
---------------------------------------------------------------------------------------------------------------------
|18 46 45.8 -23 53 36| 39  8  85|   0.55     0.35L    0.41L   12.53L| 19          |----|  | 0| 2|1988NASAR1190....1B|
```

jp11 (4)

```
| U:360  ( nmes)| B:450  ( nmes)| V:555  ( nmes)| R:670  ( nmes)| I:870  ( nmes)|J:1200  ( nmes)|K:2200  ( nmes)|L:3500  ( nmes)|M:5000  ( nmes)|N:9000
```

From here the parsec distances of each specified star were collected including their uncertainties (if available).

10. Data Collected

From the stellar databases, the following information was collected:

Star Name	Stellar Classification	Apparent Visual Magnitude (m_v)	Distance from earth (Parsecs)
Tau Ceti	G	+3.500	3.647
Groombridge 1618	K	+6.600	4.873 +/- 0.019
Wolf 359	M	+13.45	2.391
Ross 154	M	+11.00	2.97 +/- 0.02
EP Eridani	K	+6.040	3.218 +/- 0.008

11. Stage one, estimating the host star's absolute luminosity

a. Step one (determining absolute visual magnitude)

From above, the formula for determining the absolute visual magnitude is:

$$M_v = m_v - 5\log\left(\frac{d}{10}\right)$$

Although the calculations were done in an excel document, an example calculation is provided below (using Groombridge 1618).

$$M_v = m_v - 5\log\left(\frac{d}{10}\right)$$

Inserting the given data,

$$M_v = (6.60) - 5\log\left(\frac{(4.873)}{10}\right)$$

$$\therefore M_v = 8.20$$

To calculate uncertainty in this measurement, it is necessary to understand uncertainties in logarithms. In a logarithm base 10, the uncertainty is measured with

$$0.434\left(\frac{x_{unc}}{x}\right)$$

Where; X_{unc} is the uncertainty in the measurement

X is the value used

The calculation below is an example (using Groombridge 1618)

$$unc = 0.434\left(\frac{0.019}{4.873}\right)$$

$$\therefore unc = 0.0017$$

The formula derived for this uncertainty comes from the uncertainty for the natural logarithm, which is corrected using the constant 0.434.

Below is the processed data after Stage 1 step 1

Star Name	Absolute Visual Magnitude (M_v)
Tau Ceti	5.690
Groombridge 1618	8.161 +/- 0.002
Wolf 359	16.56
Ross 154	13.64 +/- 0.003

EP Eridani	8.502 +/- 0.001

b. Step two (Calculating the bolometric magnitude)

The formula for this calculation is as follows:

$$M_{bol} = M_v + BC$$

Using the above calculated absolute visual magnitude, and the bolometric constants listed above, the following data was collected:

Star Name	Bolometric Magnitude (M_{bol})
Tau Ceti	5.290
Groombridge 1618	7.361 +/- 0.002
Wolf 359	14.56
Ross 154	11.64 +/- 0.003
EP Eridani	7.702 +/- 0.001

A sample calculation is included below (Groombridge 1618)

$$M_{bol} = M_v + BC$$
$$M_{bol} = (8.161) + (-0.8)$$
$$\therefore M_{bol} = 7.361\ (1\ sf)$$

Because there is no change in the value, aside from correcting with the constant, the uncertainties remain untouched.

c. Calculating the absolute luminosity of the stars

Using the formula $\frac{L_{star}}{L_{sun}} = 10^{\left[\frac{M_{bol\,star} - M_{bol\,sun}}{-2.5}\right]}$, the absolute luminosity can be found.

Star Name	Absolute Luminosity (Watt)
Tau Ceti	0.5916
Groombridge 1618	0.08782 +/- 0.00034
Wolf 359	0.0001159
Ross 154	0.001706 +/- 0.000015
EP Eridani	0.06415 +/- 0.00016

Below is a sample calculation (Tau Ceti).

$$\frac{L_{star}}{L_{sun}} = 10^{\left[\frac{M_{bol\,star} - M_{bol\,sun}}{-2.5}\right]}$$

$$\frac{L_{star}}{L_{sun}} = 10^{\left[\frac{(5.290)-(4.72)}{-2.5}\right]}$$

$$\therefore \frac{L_{star}}{L_{sun}} = 0.5916\ (4\ sf)$$

12. Stage two, determining the inner and outer radii of the circumstellar habitable zone of each star

The method for determining the CHZ was already explained in part four of the report. The two formulas are:

$$r_i = \sqrt{\frac{L_{star}}{1.1}}$$

And,

$$r_o = \sqrt{\frac{L_{star}}{0.53}}$$

The processed data is below.

Star Name	Inner radius of CHZ (AU)	Outer radius of CHZ (AU)
Tau Ceti	0.7333	1.056
Groombridge 1618	0.2826 +/- 0.0001	0.4071 +/- 0.0001
Wolf 359	0.01026	0.01479
Ross 154	0.03938 +/- 0.00013	0.05674 +/- 0.00019
EP Eridani	0.2415	0.3479

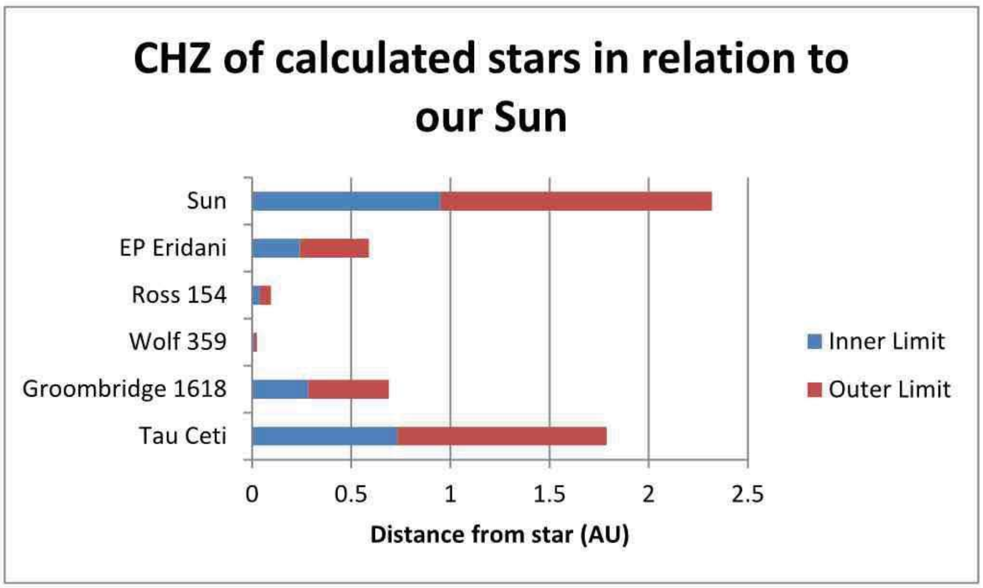
Since the two calculations are near identical, the sample calculation is only of r_i (using EP Eridani).

$$r_i = \sqrt{\frac{L_{star}}{1.1}}$$

$$r_i = \sqrt{\frac{(0.06415)}{1.1}}$$

$$\therefore r_i = 0.2415\ (4\ sf)$$

Plotting what was found in a bar graph gives an easier visual representation of the CHZs of the stars in relation to our Sun's. Note that the uncertainties in the measurements were negligible and can therefore not be seen on the graph.



Conclusion & Evaluation

When analyzing the processed data, a few conclusions may be drawn. Firstly, The G class star, Tau Ceti, had the largest CHZ relative to the four other stars. This is likely because G class stars have a larger visual magnitude than K and M class stars. The stars in who resided in the same classification had similar CHZs. Groombridge 1618 and EP Eridani both had a similar CHZ range, as well as their distance from the star being similar. This is also supported by the M class stars. However, the small M class stars (commonly called Red Dwarfs) have CHZs which are negligible. It would be difficult to assume that a planet supporting water could orbit a star so closely. These findings support my hypothesis partially; as it disagrees with the claim in my hypothesis that the range of all CHZ are all the same. After analysis, this is due to the fact that visual magnitudes are not directly proportional to boundary ranges of the CHZ, and therefore smaller stars have smaller ranged CHZs while larger ones have larger ranges. Also interesting is that due to the methods of calculation the uncertainties within the measurements grew relatively small.

The assumption made in this calculation for CHZs, liquid water being the denominating factor for life on a planet has reason. All life we know is in one way or another dependent on water. However, assuming that every exoplanet circling a star within the star's CHZ automatically houses water is difficult. This is because of requisites for liquid water that are not dependent on the energy of the star (which is the only factor taken into account when calculating the CHZ) such as atmospheric pressure surrounding the planet.

My method and data sources are reliable to an extent. The internet stellar database for example, is a database compiled by a hobbyist astronomer; however the sources of his data are referenced as older databases from reliable sources. Also, my source for apparent magnitude did not include any uncertainties, which questions the reliability. Another notable issue in my data is that the Bolometric Constants I use are only accurate to two significant figures, which affects the final measurements through propagation.

A possible improvement to my conclusion would be the use of different methods of determining the CHZ of a star, as there are many different (and often conflicting) ideas in calculating the habitable zone. This could have allowed me to discuss the limitations of each method, broadening the scope of this report. In the future, I would like to further analyze the stars that I studied, looking for planets within their CHZ, which would extend my research into habitable exoplanets.

To further fulfil my interest in exoplanets, I developed an excel document, which after inserting apparent magnitude and distance from Earth of a star, will calculate the inner and outer ring of any star. I then compiled a database which dictates all the CHZs of stars I have inputted, which allows for much faster analysis in future research towards those stars.

(Total Word Count: 2 128)

Works Cited

Heron. Diagram of parsec. *Wikipedia Commons*. N.p., n.d. Web. 5 Feb. 2016.

Jk-digital. "Pretty Stars." *Flickr*. N.p., 5 Sept. 2011. Web. 5 Feb. 2016.

Morris, Tom E. "Calculating the Habitable Zone." *Planetary Biology*. N.p., Oct. 2010. Web. 22 Oct. 2015.

W, Roger M. *Internet Stellar Database*. N.p.: n.p., n.d. Print.

Wenger et al. *SIMBAD Astronomical Database*. N.p.: U of Strasbourg, n.d. Print.