NASA Exoplanets

CSI 703 // Spring 2019

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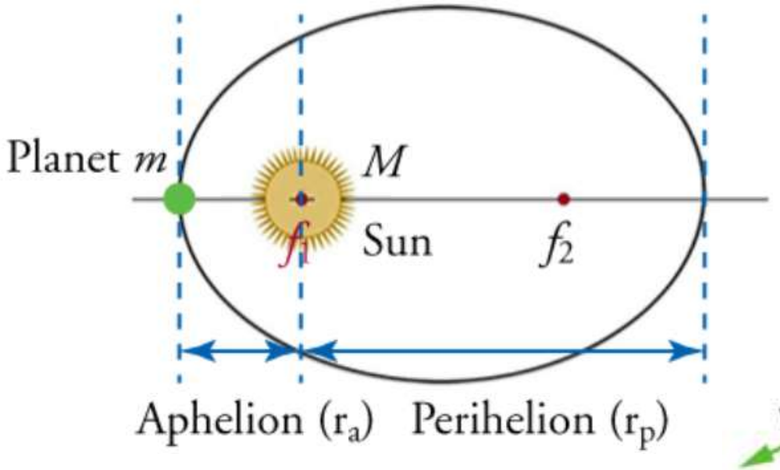
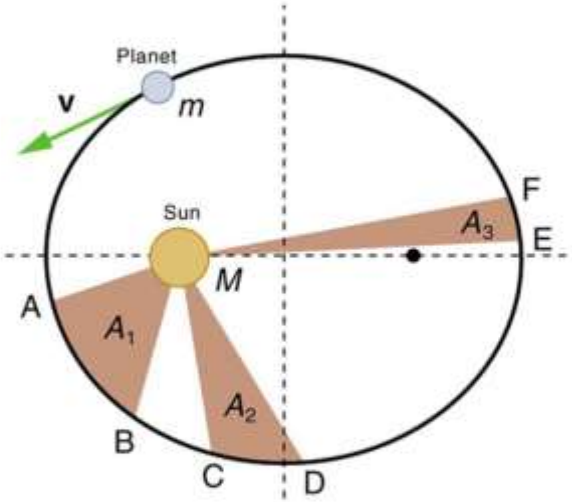
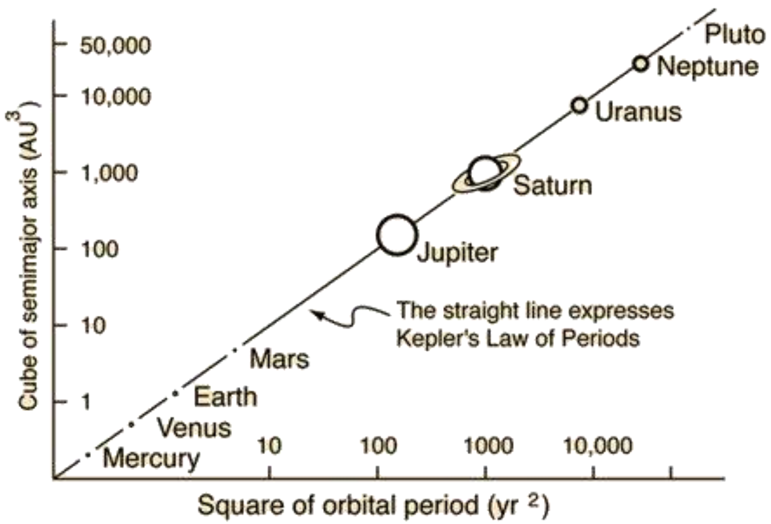
Keper’s Laws of Planetary Motion

1. The orbit of every planet is an ellipse with the Sun at one of the two foci.
2. A radius vector joining any planet to the Sun sweeps out equal areas in equal lengths of time.
3. The square of the orbital period of a planet is directly proportional to the cube of the semi-major axis of its orbit.







1 Astronomical Unit (AU) = Distance from Earth to the Sun ~ 9.296e+7 miles (92.96 Mil Mi)

Understanding the Data:

Part 1: Planet Parameters

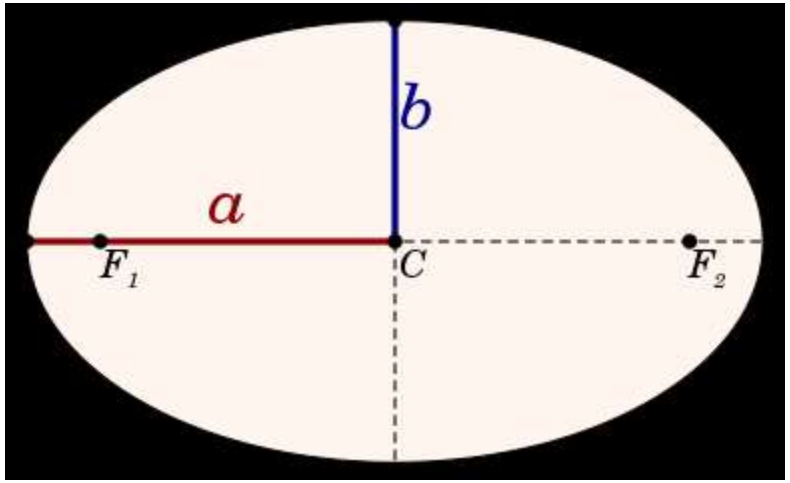
Orbit Semi-Major Axis [AU]

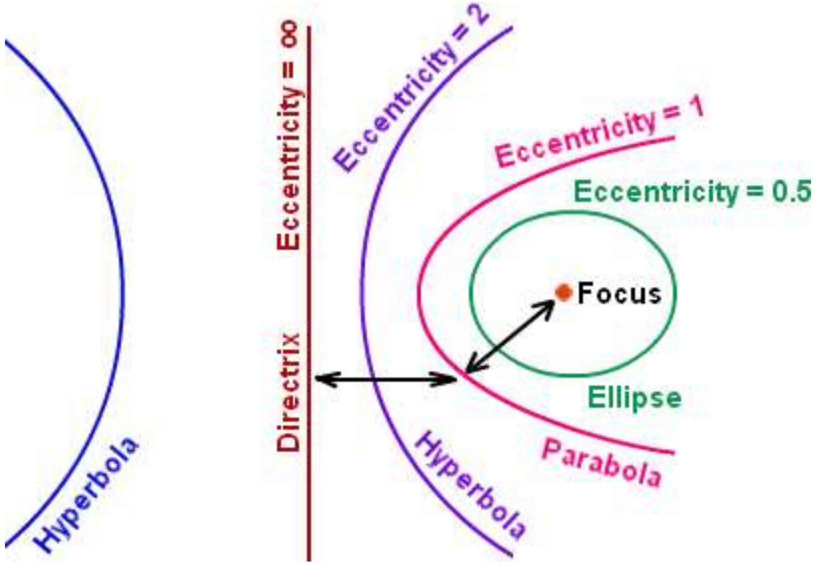
Semi-major axis α

➢ Half the major axis of the elliptical path

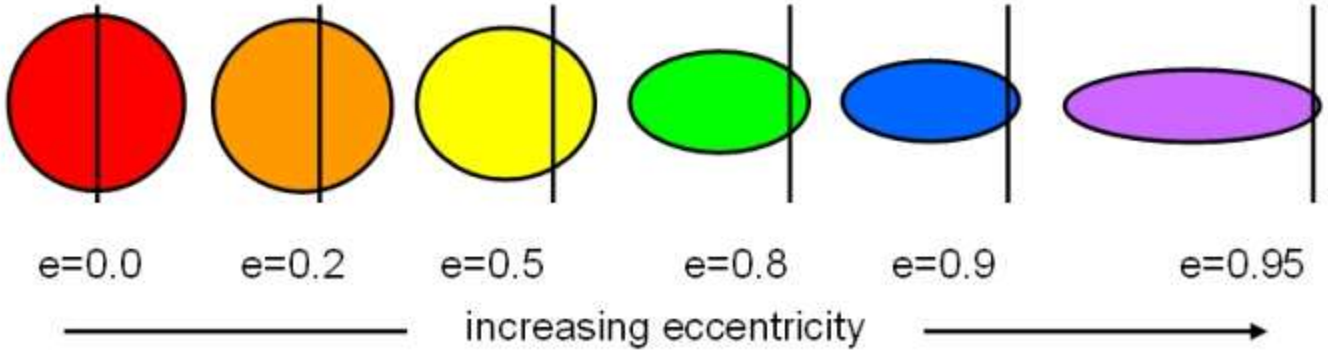
Semi-major axis b

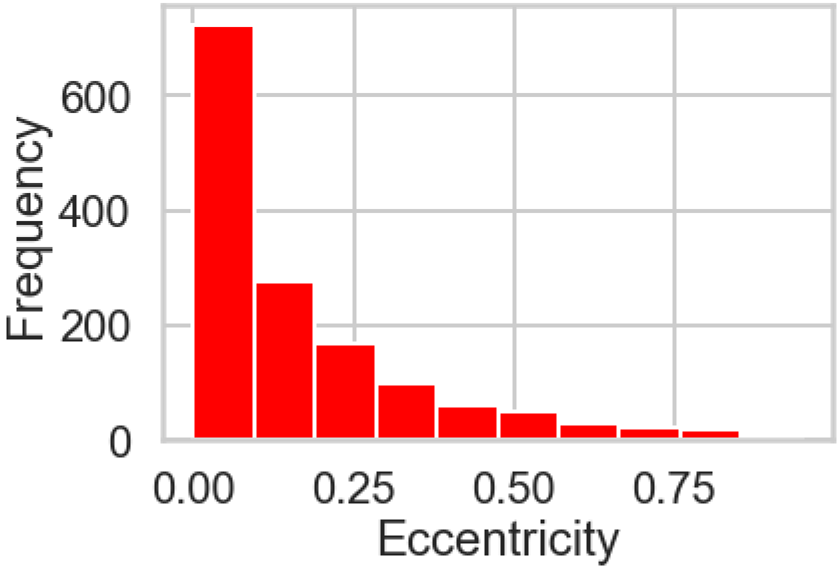
➢ Half the minor axis of the elliptical path





Eccentricity





$0 \leq eccentricity\ of\ eliptical\ orbit \leq 1$

$parabolic\ trajectory\ e = 1$

$hyperbolic\ trajectory\ e > 1$

$line\ e = \infty$

Planet Mass or M*sin(i) [Earth mass]

```
df['fpl_bmassprov'].value_counts()

M-R relationship    2268
Mass                 948
Msini                681
Msin(i)/sin(i)         5
Name: fpl_bmassprov, dtype: int64
```

Best planet mass estimate available, in order of preference:

- Mass,
- M*sin(i)/sin(i),
- M*sin(i)

Probabilistic mass-radius relation (M-R relation) is evaluated within a B which takes into account material composition (density).

- Assumes M-R relation can be described as a power lab with a dispersion that is constant and normally distributed.

Minimum Mass M*sin(i) → the mass of planet is directly proportionate to star's actual wobble

- Lower-bound calculated mass for exoplanets detected by the radial velocity method, and is determined by using the binary mass function.
  - Radial velocity method reveals planets by measuring changes in the movement of stars in the line-of-sight, so the real orbital inclinations and true masses of the planets are generally unknown. If inclination can be determined, the true mass can be obtained with:

$$M_{true} = \frac{M_{minimum}}{\sin(i)}$$

  - Inclination of 0° or 180° → face-on orbit (cannot be determined by radial velocity)
    - Wobble of star perpendicular to observer's line of vision, no part of its movement will be towards or away from Earth and no spectrum shift will be detected.
  - Inclination of 90° corresponds to an edge-on orbit (true mass equals the minimum mass)

Less Complicated Columns

→ Planet Radius [Earth radii]

→ Planet Density [g/cm^3]

→ Planetary Equilibrium Temperature [K]
- The equilibrium temperature of the planet as modeled by a black body heated only by its host star, or for directly imaged planets, the effective temperature of the planet required to match the measured luminosity if the planet were a black body.

→ Insolation Flux [Earth Flux]
- Insolation flux is another way to give the equilibrium temperature. It's given in units relative to those measured for the Earth from the Sun.

Understanding the Data:

Part 2: Stellar Columns

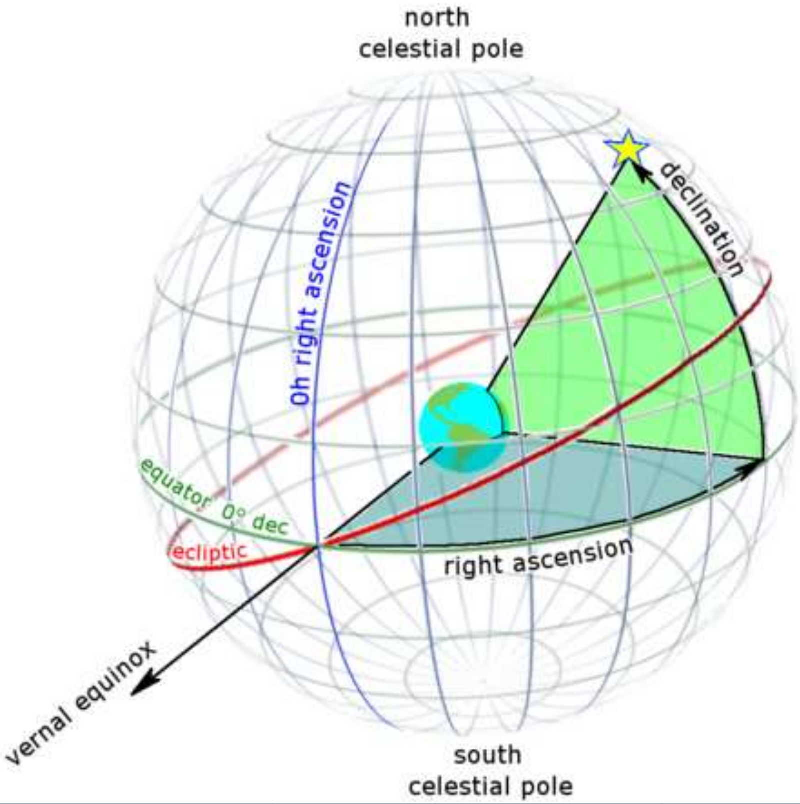
Right Ascension and Declination
[sexagesimal/decimal degrees]

Precession
- Earth's axis rotates slowly westward about the poles of the elliptic, completing one cycle in about 26,000 years

Right Ascension
- The celestial equivalent of terrestrial longitude

Declination
- The celestial equivalent of terrestrial latitude

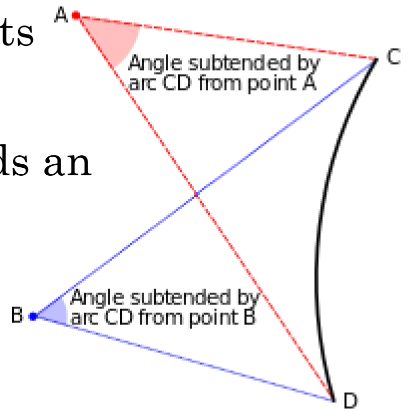
RA + DEC → Direction of a point on the celestial sphere



Unit	Value	Symbol	Sexagesimal system	In radians
Hour	1/24 circle	h	15°	π/12 rad
Minute	1/60 hour, 1/1440 circle	m	1/4°, 15′	π/720 rad
Second	1/60 minute, 1/3600 hour, 1/86400 circle	s	1/240°, 1/4′, 15″	π/43200 rad

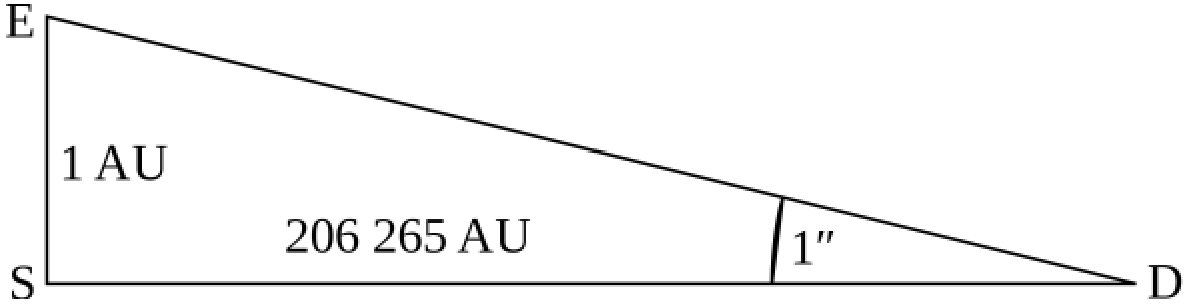
Distance [parsecs]

The parsec (pc) is a unit of length used to measure distances to astronomical objects outside the Solar System.



One parsec is defined as the distance at which one astronomical unit (AU) subtends an angle of one arcsecond, which corresponds to $\frac{648{,}000}{\pi}$ AUs

- 1 pc = 3.26 light-years = 31 trillion km = 19 trillion mi
- Nearest star, Proxima Centauri is about 1.3 parsecs (4.2 light-years from the Sun)



S = Sun
E = Earth at one point in it's orbit
∠SDE = one arcsecond (1/3600th of a degree)
D is a point in space at a distance of one parsec from the Sun

Source 11

Optical Magnitude

Magnitude (astronomy) is a unitless measure of the brightness of an object in a defined passband, often visible or infrared spectrum.

- Logarithmic scale where one step of one magnitude changes the brightness by a factor of the fifth root of 100, or ~2.512
- Negative values are brighter

Mag Category	Relative Brightness
6	1
5	2.512
4	6.310
3	15.851
2	39.818
1	100.023

```
df['fst_optmagband'].value_counts()
```

```
G (Gaia)        2349
V (Johnson)     1468
Kepler-band       24
Name: fst_optmagband, dtype: int64
```

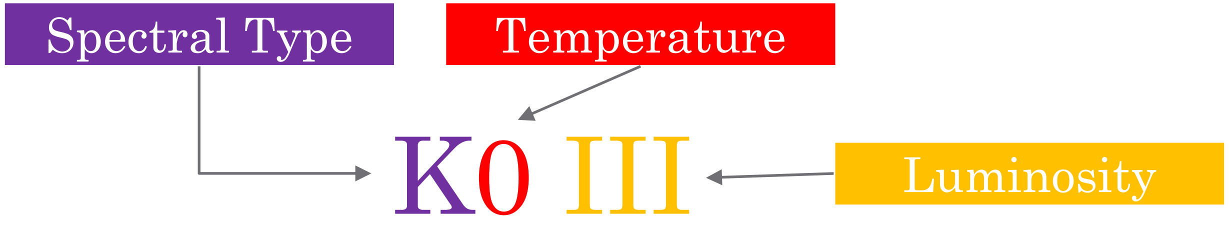
```
df['fst_nirmagband'].value_counts()
```

```
Ks (2MASS)    3823
Name: fst_nirmagband, dtype: int64
```

Methods for magnitude measurement:

1. Brightness of the host star as measured using the G (Gaia), V (Johnson) or the Kepler-band in units of magnitudes.
2. Brightness of the host star as measured using the Ks (2MASS) or the J (2MASS) in units of magnitudes.
   - Uses near-infrared

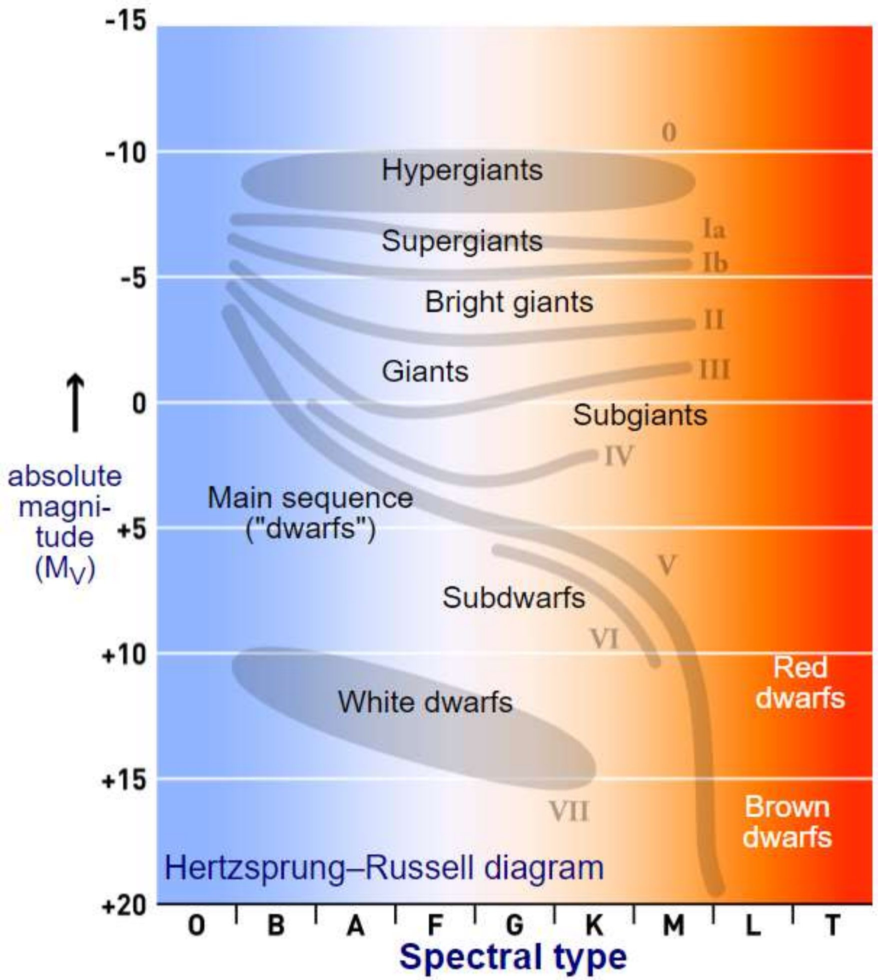
[16] Spectral Type



Stellar classification is the classification of stars based on their spectral characteristics. Electromagnetic radiation from the star is analyzed by splitting it with a prism or diffraction grating into a spectrum exhibiting the rainbow of colors interspersed with spectral lines. Each line indicates a particular chemical element or molecule, with the line strength indicating the abundance of that element.

Classification of the star based on their spectral characteristics following the Morgan-Keenan system.

- Most stars are currently classified under the Morgan-Keenan (MK) system using the letters O, B, A, F, G, K, and M, a sequence from the hottest (O type) to the coolest (M type). Each letter class is then subdivided using a numeric digit with 0 being hottest and 9 being coolest (e.g. A8, A9, F0, and F1 form a sequence from hotter to cooler). The sequence has been expanded with classes for other stars and star-like objects that do not fit in the classical system, such as class D for white dwarfs and classes S and C for carbon stars.
- In the MK system, a luminosity class is added to the spectral class using Roman numerals. This is based on the width of certain absorption lines in the star's spectrum, which vary with the density of the atmosphere and so distinguish giant stars from dwarfs. Luminosity class 0 or Ia+ is used for hypergiants, class I for supergiants, class II for bright giants, class III for regular giants, class IV for sub-giants, class V for main-sequence stars, class sd (or VI) for sub-dwarfs, and class D (or VII) for white dwarfs. The full spectral class for the Sun is then G2V, indicating a main-sequence star with a temperature around 5,800 K.



Stellar Metallicity [dex] and Metallicity ratio

Stellar Metallicity is used to describe the presence of elements in an object that are heavier than hydrogen and helium (most abundant elements in universe, especially in stars)

- Stars with high amounts of carbon and oxygen are called “metal-rich”

$$Z = \sum_{i>He} \frac{m_i}{M} = 1 - X - Y$$

X = hydrogen mass fraction of M where M is total mass of the star (Xsun = 0.7381)
Y = helium mass fraction of M (Ysun = 0.2485)
Z = remainder of “metals”/metallicity mass fraction (Zsun = 0.0134)

- Overall stellar metallicity in this dataset is defined using the total iron content since it is the easiest to measure with spectral observations even though oxygen is the most abundant heavy element.

Abundance ratio is defined as the log of the ratio of star’s iron abundance compared to that of the Sun:

$$\textbf{[Fe/H]} = \boldsymbol{log_{10}\left(\frac{N_{Fe}}{N_H}\right)_{star} - log_{10}\left(\frac{N_{Fe}}{N_H}\right)_{sun}}$$

Where N_{Fe} and N_H are the number of iron and hydrogen atoms per unit of volume.

- The output is a decimal exponent [dex] where:
  - Positive Value → Higher metallicity than the Sun
  - Negative Value → Lower metallicity than the Sun

dex	Metallicity Ratio Star:Sun
1	10
0	1
-1	0.1

Less Complicated Columns

Number of Stars in System

Effective Temperature [K]

- Temperature of the star as modeled by a black body emitting the same total amount of electromagnetic radiation.

Stellar Surface Gravity [$\log_{10}(cm/s^2)$]

- Gravitational acceleration experienced at the stellar surface.

Stellar Luminosity [$\log_{10}$(Solar luminosity)]

- Amount of energy emitted by a star per unit time, measured in units of solar luminosities. Synonymous with power.
- The International Astronomical Union (IAU) has set a nominal solar luminosity of 3.828×10^{26} W (luminosity of the sun)

Stellar Mass [Solar Mass]

- Amount of matter contained in the star, measured in units of masses of the Sun.

Stellar Radius [Solar radii]

- Length of a line segment from the center of the star to its surface, measured in units of radius of the Sun.

Stellar Age [Gyr = Giga Years = Billion Years]

[13]

Band	G	G_{BP}	G_{RP}	G_{RVS}
λ_{min} (nm)	350	350	650	847
λ_{max} (nm)	1000	650	1000	874
λ_o (nm)	638	517	786	860
$\Delta\lambda$ (nm)	433	263	277	28

- **How precise are Gaia's measurements?**
- Gaia detects and measures celestial objects (stars, galaxies, quasars and Solar-System bodies) down to magnitude 20.5, about 650,000 times fainter than an unaided eye can see. The precision of the measurements – astrometric, photometric, and radial velocity – is a function of the type of object and their magnitude, with brighter objects being measured more precisely than fainter objects.
- The measurements provided in the first Gaia Data Release are substantially more precise than those in existing catalogues and these will improve dramatically as increasingly longer stretches of Gaia data are used.
- In the final Gaia catalogue, expected in the early 2020s, brighter objects (3-13 magnitude) will have positions measured to a precision of 5 microarcseconds, parallaxes to 6.7 microarcseconds, and proper motions to 3.5 microarcseconds per year. For the faintest stars (magnitude 20.5), the equivalent numbers are several hundred microarcseconds. (To aid in visualising this consider that ten microarcseconds is the size of a euro coin on the Moon as viewed from Earth.)
- The photometry measurements in the final catalogue will be precise at the level of milli-magnitudes. For the subset of objects for which radial velocity measurements are obtained these will be measured with a precision of 15 km per second for the fainter stars and as precise as 1 km per second for the brighter stars.
- The accuracy of the distances obtained by Gaia at the end of the nominal mission will range from 20% for stars near the centre of the Galaxy, some 30,000 light-years away, to a remarkable 0.001% for the stars nearest to our Solar System.

Filter	Effective Wavelength Midpoint	Full Width Half Maximum[2]	Variant(s)	Description	Gaia	Johnson System (UBV)	2MASS
Letter	λeff for Standard Filter[2]	(Bandwidth Δλ)					
Ultraviolet							
U	365 nm	66 nm	u, u', u*	"U" stands for ultraviolet.		1	
Visible							
B	445 nm	94 nm	b	"B" stands for blue.	1	1	
V	551 nm	88 nm	v, v'	"V" stands for visual.	1	1	
G[3]	464 nm	128 nm	g'	"G" stands for green.	1		
R	658 nm	138 nm	r, r', R', R_c, R_e, R_j	"R" stands for red.	1		
Near-Infrared							
I	806 nm	149 nm	i, i', I_c, I_e, I_j	"I" stands for infrared.	1		
Z	900 nm[4]		z, z'				
Y	1020 nm	120 nm	y				
J	1220 nm	213 nm	J', J_s				1
H	1630 nm	307 nm					1
K	2190 nm	390 nm	K Continuum, K', K_s, K_{long}, K^8, nbK				1
L	3450 nm	472 nm	L', nbL'				
Mid-Infrared							
M	4750 nm	460 nm	M', nbM				
N	10500 nm	2500 nm					
Q	21000 nm[5]	5800 nm[5]	Q'				

Sources

[1] https://en.wikipedia.org/wiki/Semi-major_and_semi-minor_axes
[2] https://www.britannica.com/science/Keplers-laws-of-planetary-motion
[3] http://hyperphysics.phy-astr.gsu.edu/hbase/kepler.html
[4] http://astronomy.swin.edu.au/cosmos/O/Orbital+Eccentricity
[5] https://en.wikipedia.org/wiki/Minimum_mass
[6] https://en.wikipedia.org/wiki/Planetary_equilibrium_temperature
[7] https://en.wikipedia.org/wiki/Right_ascension
[8] https://en.wikipedia.org/wiki/Parsec
[9] https://en.wikipedia.org/wiki/Subtended_angle
[10] https://www.cosmos.esa.int/web/gaia/science-performance
[11] By The original uploader was Heron at English Wikipedia.; Later version(s) were uploaded by Stw, SCEhardt at en.wikipedia. Derivative work: Iceblock - Derivative work from File:Parsec (1).png, which was transferred from en.wikipedia, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=7926084
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[17] https://en.wikipedia.org/wiki/Luminosity
[18] Mamajek, E. E.; Prsa, A.; Torres, G.; Harmanec, P.; Asplund, M.; Bennett, P. D.; Capitaine, N.; Christensen-Dalsgaard, J.; Depagne, E.; Folkner, W. M.; Haberreiter, M.; Hekker, S.; Hilton, J. L.; Kostov, V.; Kurtz, D. W.; Laskar, J.; Mason, B. D.; Milone, E. F.; Montgomery, M. M.; Richards, M. T.; Schou, J.; Stewart, S. G. (2015). "IAU 2015 Resolution B3 on Recommended Nominal Conversion Constants for Selected Solar and Planetary Properties".
[19] https://en.wikipedia.org/wiki/Metallicity