ASTR 421

Stellar Observations and Theory

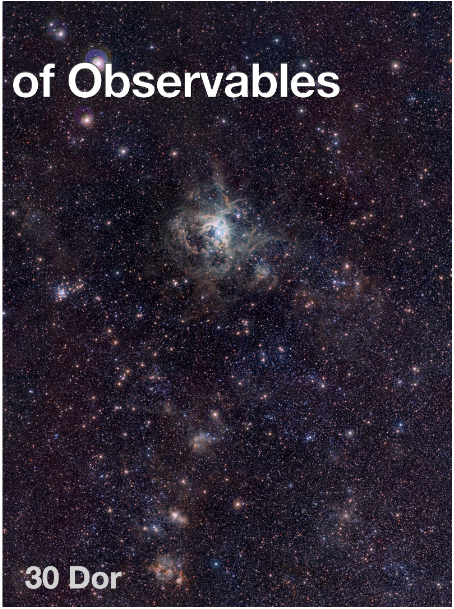
Lecture 02

Measuring the Properties of Stars

Prof. James Davenport (UW)

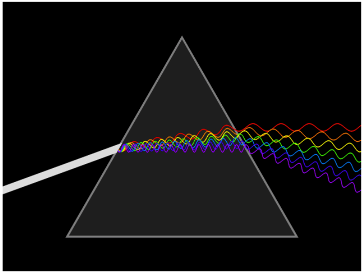
Today's Goal: An Overview of Observables

- Much of the class will focus on theory (with observations mixed in, of course!)
- Today we're doing a survey of all the "fundamental properties of stars"
- This will be full of *many* methods, but will probably be incomplete



Light

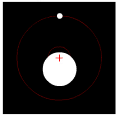
- **Only a few observable properties… must use them well to learn the physics of stars!**
  - Intensity
  - Spectral/color
  - Polarization
  - Direction
  - Time*

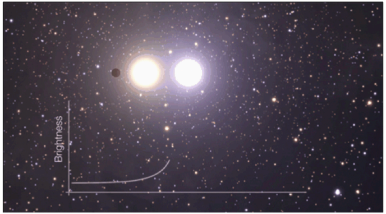


https://en.wikipedia.org/wiki/Light#/media/File:Light_dispersion_conceptual_waves.gif

Mass

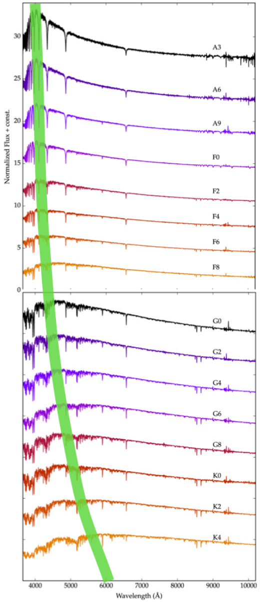
- **Mass is probably the most important/fundamental property for a star**
- It factors into all timescales at work, most other general properties (e.g. radius, temp, etc) are directly related to mass
- However, not much about the star itself is actually a direct measurement of mass
- This makes mass relatively easy to estimate by proxy, and difficult to directly measure.
- Enter: Kepler's laws (esp. eclipsing binary stars & exoplanets)
- Also useful: lensing!





Temperature (T_{eff})

- Probably the most common property to measure
- Many ways to constrain!
- Spectroscopically (e.g. Wien's Law)
- The "effective temperature" is the Temp that a star would have if it were a perfect blackbody with the same luminosity $L = 4\pi R^2 \sigma_{SB} T^4$
  - Very close to the surface temp for some stars
  - Harder to estimate for cool stars



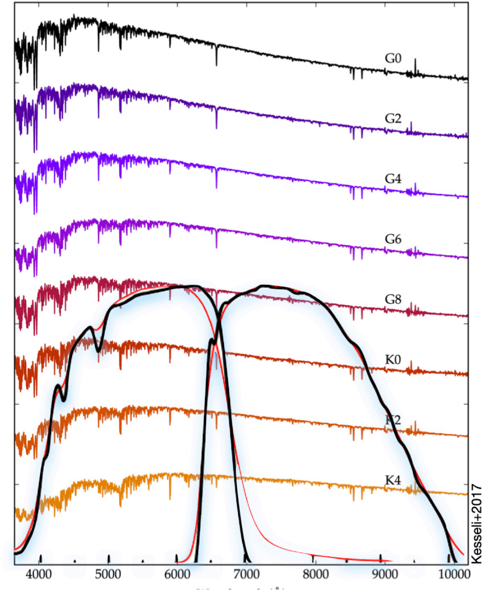
Kesseli+2017
https://arxiv.org/abs/1702.06957

Temperature (T_{eff})

- Also can constrain with photometry via the "color"

$$m_i = -2.5 \log_{10}\left(\frac{F_i}{F_0}\right)$$

$$B - V \equiv m_B - m_V \equiv M_B - M_V$$



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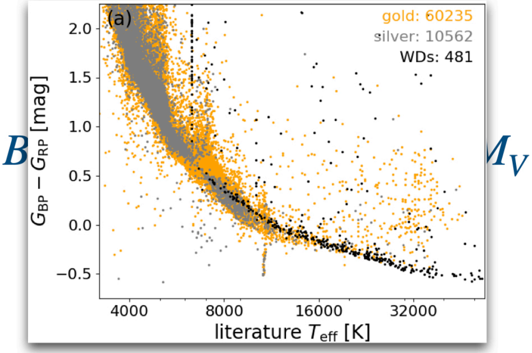
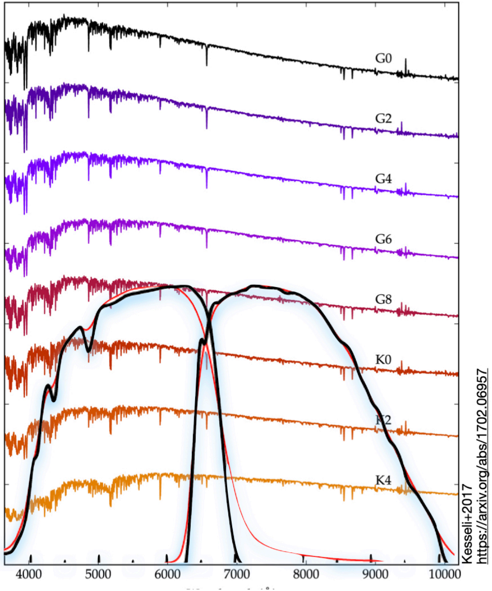
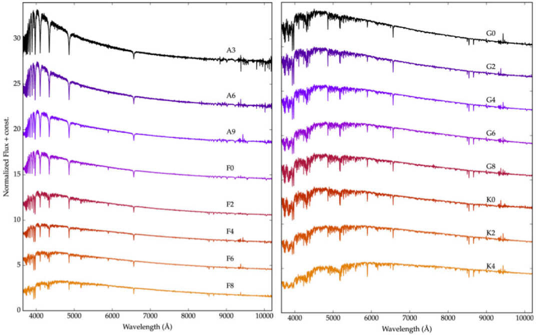




Temperature (T_{eff})

Spectral Types: not a fundamental property

OBAFGKMLTY



Luminosity

$$L = 4\pi R^2 \sigma_{SB} T^4$$

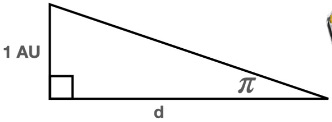
- Easy to constrain, difficult to directly measure
- **Usually need to know distance**

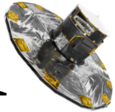
$$m_i = -2.5 \log_{10}\left(\frac{F_i}{F_0}\right)$$

$$m - M = 5 \log_{10} d[pc] - 5$$

- The total luminosity @ all wavelengths, known as “bolometric” luminosity (or absolute magnitude)
  - Typically you estimate luminosity in a given band, and then add a “bolometric correction”
  - $M_{bol,\odot} \approx 4.74$ https://www.iau.org/static/resolutions/IAU2015_English.pdf

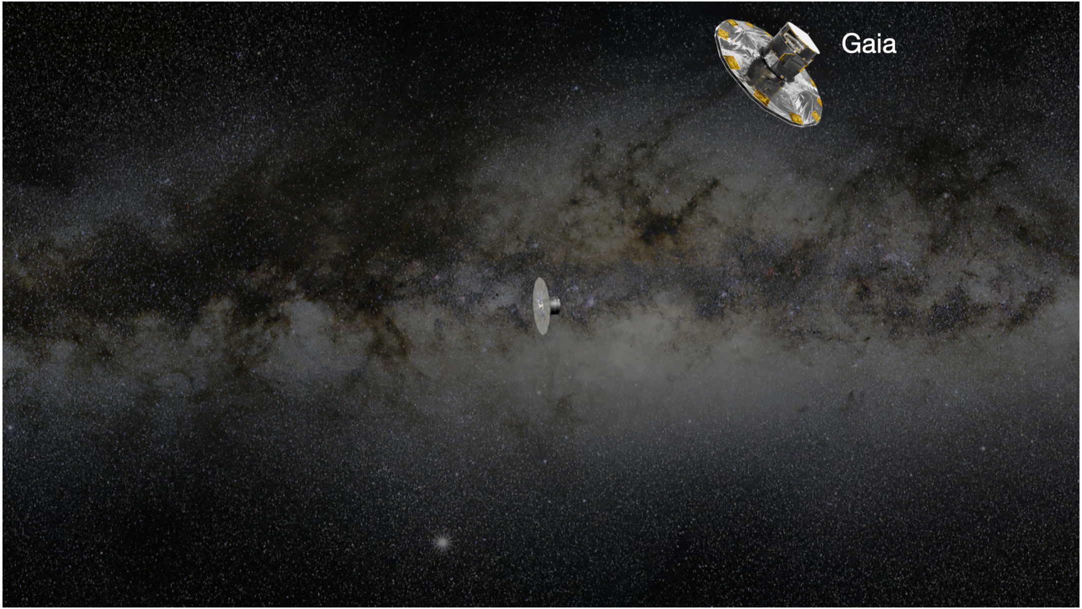
Distance





- Parallax! The best! But only for nearby stars
  (Gaia is making this *better, +1Billion stars*, but not perfect!)

- Many other clever ways:
  - Stellar clusters $m - M = 5\log_{10} d[pc] - 5$
  - RR Lyr, standard candles, the "distance ladder", etc…
  - Eclipsing binaries
    - e.g. LMC distance to 2% Still the benchmark Pietrzyński et al. (2013)
- Can be estimated for a star if you assume it is main sequence
  (e.g. "photometric parallax") or take a spectrum


Gaia

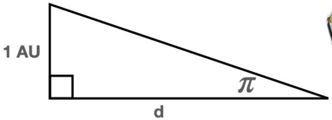
We'll see Gaia data/results throughout this course, and MORE TO COME SOON!

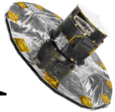
Gaia

	# sources in Gaia DR3	# sources in Gaia DR2	# sources in Gaia DR1
Total number of sources	**1,811,709,771**	**1,692,919,135**	**1,142,679,769**
	Gaia Early Data Release 3		
Number of sources with minimally 5 astrometric parameters	1,467,744,818	1,331,909,727	2,057,050
Number of 5-parameter sources	585,416,709		
Number of 6-parameter sources	882,328,109		
Number of 2-parameter sources	343,964,953	361,009,408	1,140,622,719
Gaia-CRF sources	1,614,173	556,869	2,191
Sources with mean G magnitude	1,806,254,432	1,692,919,135	1,142,679,769
Sources with mean G_{BP}-band photometry	1,542,033,472	1,381,964,755	-
Sources with mean G_{RP}-band photometry	1,554,997,939	1,383,551,713	-
	New data in Gaia Data Release 3 (pending validation)		
Sources with radial velocities	≈ 33,000,000	7,224,631	-
BP/RP spectra	> 100,000,000	-	-
RVS spectra	≈ 1,000,000	-	-
Variable source classifications	≈ 13,000,000	550,737	3,194
Object classifications	≈ 1,000,000,000	-	-
Sources with astrophysical parameters	≈ 500,000,000	161,497,595	-
Non-single stars	≈ a few 100,000	-	-
QSO host and galaxy morphological characterisation	≈ a few 1,000,000	-	-
Solar system objects	≈ 150,000	14,099	-
Reflectance spectra for solar system objects	≈ 50,000	-	-
Average BP/RP reflectance spectra of asteroids	≈ 10,000	-	-
Gaia Andromeda Photometric Survey (GAPS)	≈ 1,000,000	-	-

Data Release 3: Q2 2022

Distance





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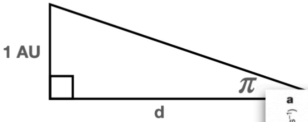
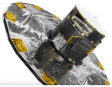
Distance





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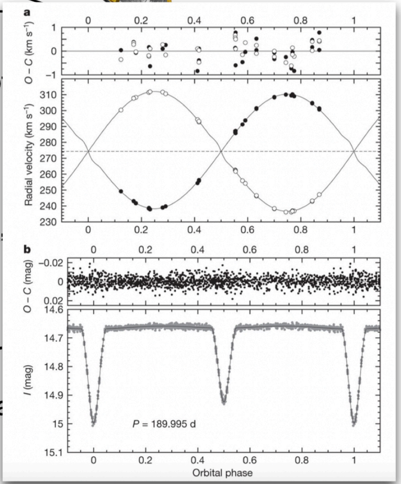


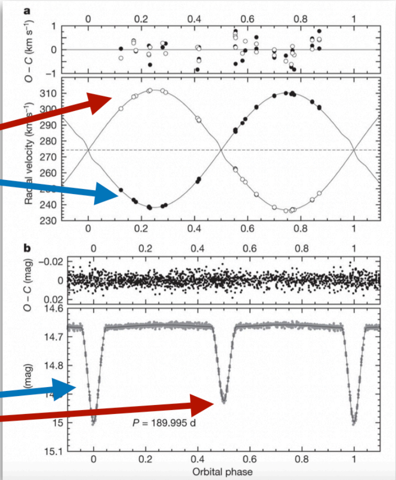
on Binaries…

The BEST:

“double-line” spectroscopic

AND

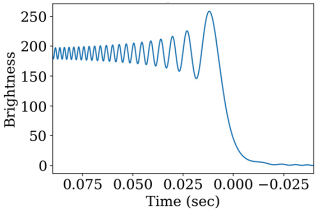
eclipsing binaries



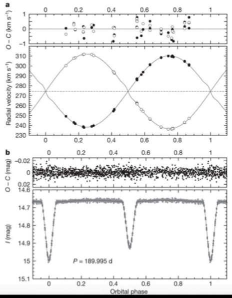
Pietrzyński et al. (2013)

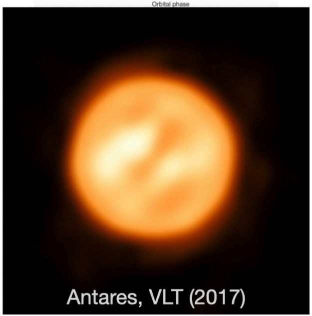
Radius

- Eclipsing systems again a critical benchmark
- $L = 4\pi R^2 \sigma_{SB} T^4$
- Occultation (esp. lunar)



- Actually *resolve* the surface with interferometry!
    - Limited to nearby & mostly giant stars




Antares, VLT (2017)

Density & Surface Gravity

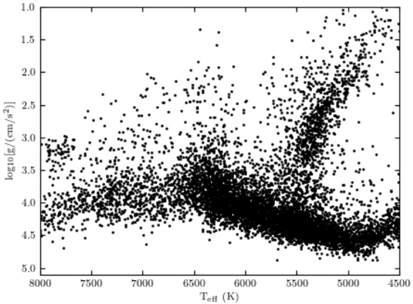
- **Mean stellar density:** $\rho = M/V = \dfrac{3M}{4\pi R^3}$

  O star ~ 0.005 g/cm^3
  G star (Sun) ~ 1.4 g/cm^3
  M star ~ 5 g/cm^3

http://www.astronomy.ohio-state.edu/~thompson/1144/Lecture10.html

- **Surface gravity:** $g = GM/R^2$, usually measured w/ spectroscopy (line broadening)

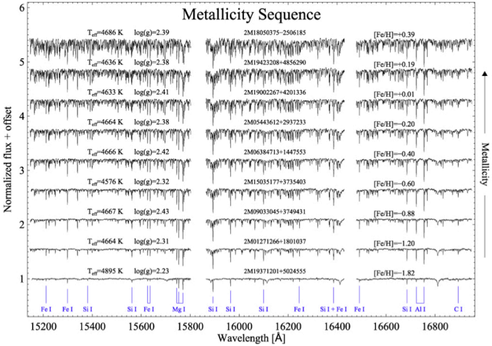
  - Typically expressed as $\log g$
    stars: ~4
    giants: 3-2
    white dwarfs: 6-9



SDSS "SSPP"

Composition (aka Metallicity)

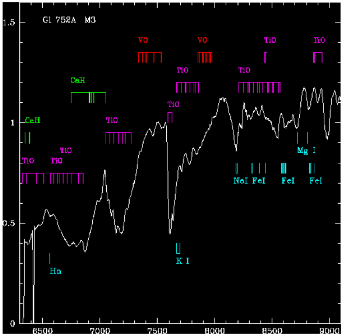
- Typically summed up as [Fe/H], i.e. the log ratio of Fe/H *relative* to the solar amount
  - Also abundances of individual elements are studied, as well as groups (e.g. [α/Fe])
- Primarily determined via spectroscopy, modeling atomic absorption lines
  - High resolution VERY helpful

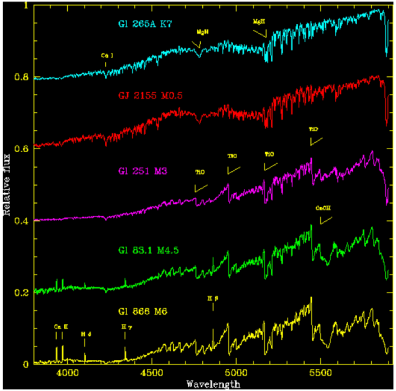


Majewski+2017 (APOGEE)

Composition (aka Metallicity)

- The situation is… more difficult for low-mass stars
- Cool temperature, spectra dominated by *molecules*
  - Molecules are *wild…*

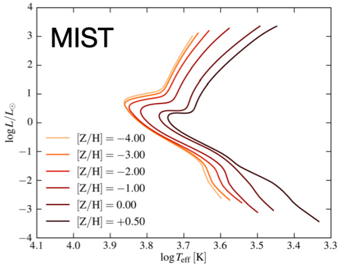


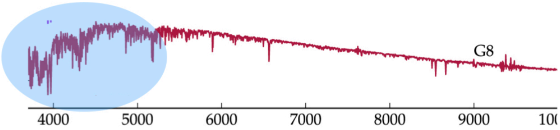


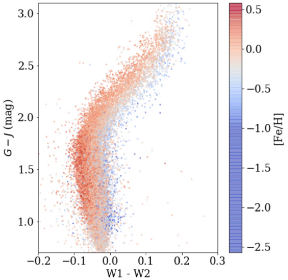
N. Reid

Composition (aka Metallicity)

- Can be studied (coarsely) with photometry
  - Big error bars, but big samples
- In general, metal-poor: bluer (hotter T_{eff})
  metal-rich, more lines, redder
- Typically use blue (e.g. *u*-band) filters
  BUT, some sensitivity in the IR too



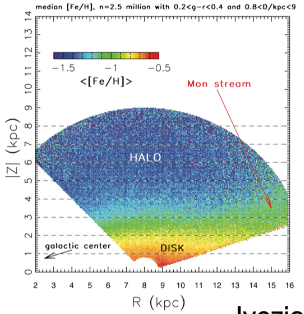




Davenport & Dorn-Wallenstein

Composition (aka Metallicity)

- Doing this for hundreds of thousands (or even millions) of stars enables new studies of the composition of our galaxy!
- Wonderful new term: chemical cartography

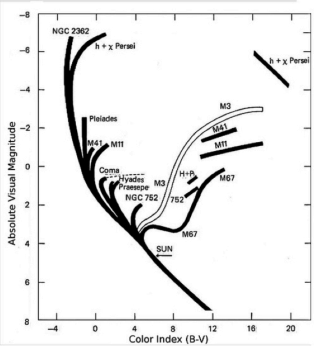


Ivezic+2008

Age

- For main sequence stars, incredibly difficult to constrain, cannot be "measured" directly…

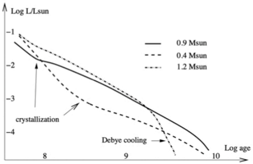
- 10% uncertainty considered very good!
- A good review: [Soderblom (2010)]
- Cluster ages (open and globular)
a critical historical benchmark, still key!
  - Mostly information in the "turn off"



[Sandage (1957)]

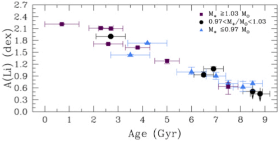
Age

- A few other ways to estimate ages, none work for all stars/timescales:
  - White-dwarf cooling sequence



Althaus+2010

  - Lithium abundance



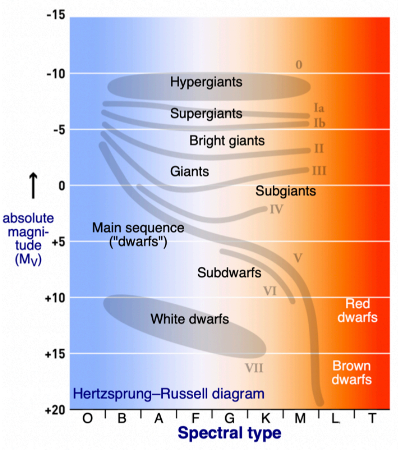
Carlos+2016

  - “Gyrochronology” - i.e. a spin-clock
    Stars lose angular momentum over time, perhaps predictably*
    Key paper establishing this idea: Skumanich (1972)

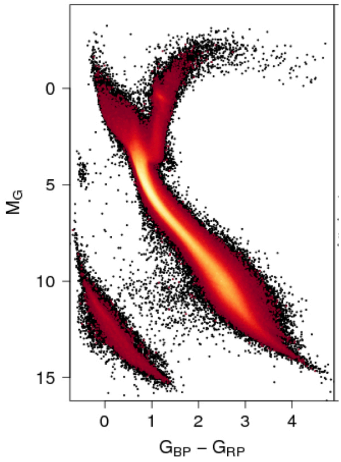
The H-R Diagram

- <u>Theorists</u>: Temp, Lum
  or
  Temp, log g

- <u>Observers</u>: Color, Mag

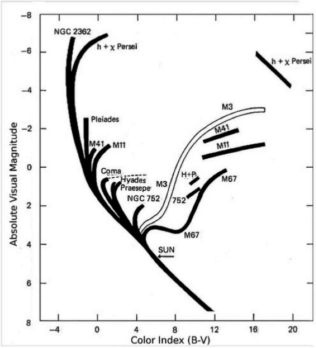


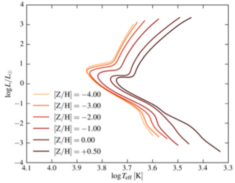
Gaia DR2 CMD

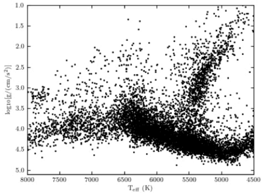


The H-R Diagram

A Rosetta Stone for understanding the lives & properties of stars







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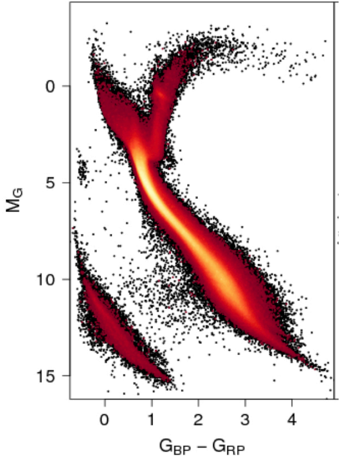

Next time:

- **“Introduction to Spectroscopy”**
  - Watch the Lecture 03 video
  - Submit Q’s by 9AM on Monday
- HW 1 is due Jan 10
  - Dropbox upload link is already live