STATISTICS
TEXAS A&M UNIVERSITY

The Cosmic Distance Ladder and Expansion of the Universe

James Long

September 14, 2016

Distance Determination

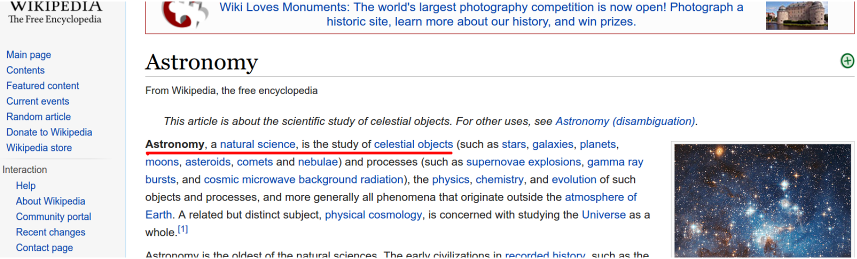
The Universe is Expanding

Statistical Issues

Non–Distance Motivations for Time Domain Astronomy

Outline

Astronomy


WIKIPEDIA
The Free Encyclopedia

Main page
Contents
Featured content
Current events
Random article
Donate to Wikipedia
Wikipedia store

Interaction
Help
About Wikipedia
Community portal
Recent changes
Contact page

Wiki Loves Monuments: The world's largest photography competition is now open! Photograph a historic site, learn more about our history, and win prizes.

Astronomy

From Wikipedia, the free encyclopedia

This article is about the scientific study of celestial objects. For other uses, see Astronomy (disambiguation).

Astronomy, a natural science, is the study of celestial objects (such as stars, galaxies, planets, moons, asteroids, comets and nebulae) and processes (such as supernovae explosions, gamma ray bursts, and cosmic microwave background radiation), the physics, chemistry, and evolution of such objects and processes, and more generally all phenomena that originate outside the atmosphere of Earth. A related but distinct subject, physical cosmology, is concerned with studying the Universe as a whole.[1]

Astronomy is the oldest of the natural sciences. The early civilizations in recorded history, such as the

Where are these celestial objects located?

Source: `https://en.wikipedia.org/wiki/Astronomy`

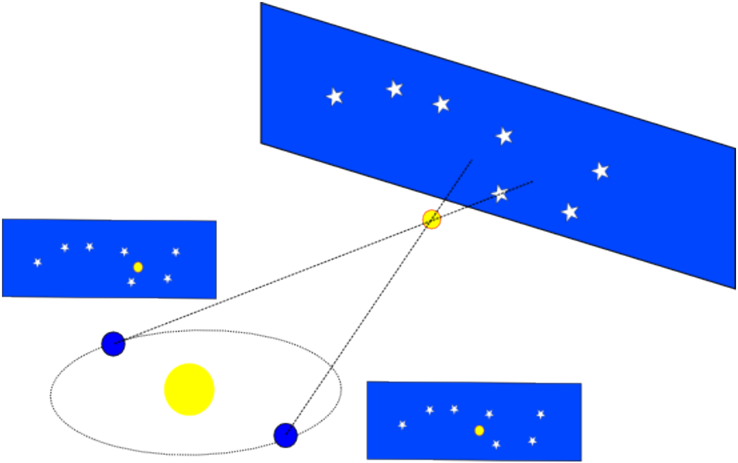
Problem: Distance Is Degenerate with Luminosity

$$
\begin{aligned}
f &= \text{apparent brightness of object} \\
L &= \text{absolute luminosity (inherent brightness of object)} \\
D &= \text{distance to object}
\end{aligned}
$$

$$f \propto L D^{-2}$$

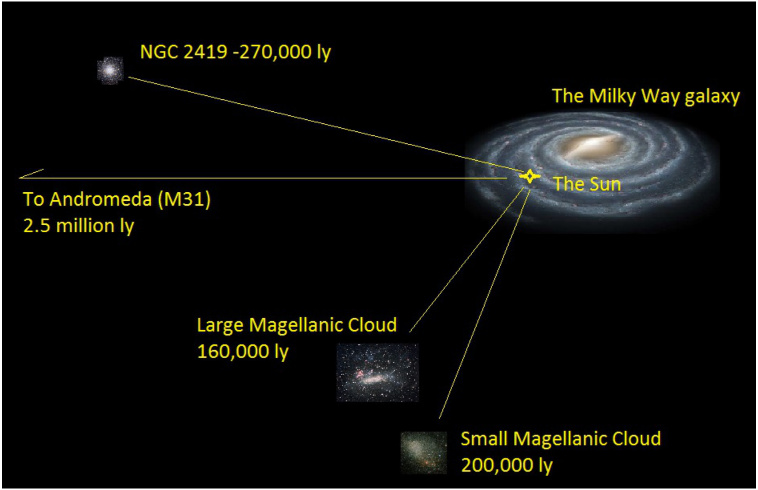
In general, we do not know L or D.

Parallax



Source: CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=443459

Parallax Accuracy



Best parallax measurements accurate out to $\sim 30,000$ ly.

Source: http://cdn.phys.org/newman/gfx/news/hires/2015/1-isngc2419awa.jpg

Henrietta Leavitt: Data Science in 1904

1777 VARIABLES IN THE MAGELLANIC CLOUDS.

By Henrietta S. Leavitt.

In the spring of 1904, a comparison of two photographs of the Small Magellanic Cloud, taken with the 24-inch Bruce Telescope, led to the discovery of a number of faint variable stars. As the

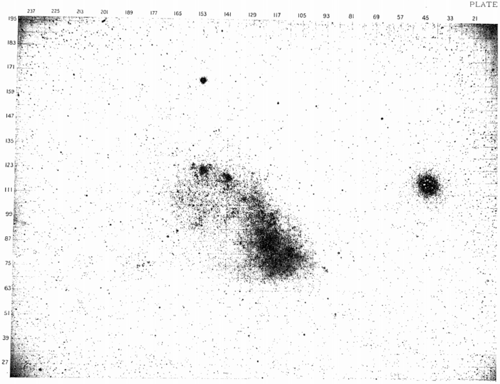
Harvard College Observatory.

CIRCULAR 173.

PERIODS OF 25 VARIABLE STARS IN THE SMALL MAGELLANIC CLOUD.

The following statement regarding the periods of 25 variable stars in the Small Magellanic Cloud has been prepared by Miss Leavitt.

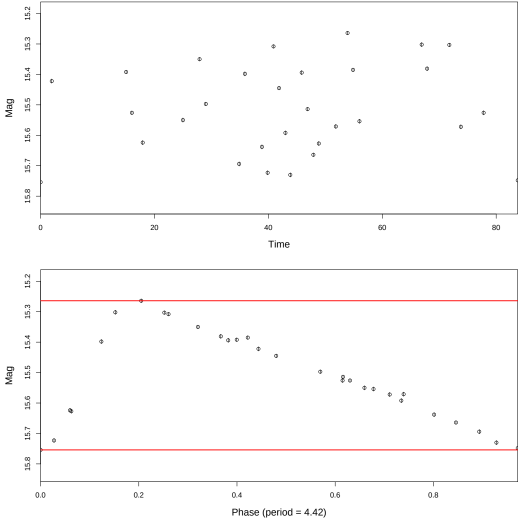
PLATE I.



SMALL MAGELLANIC CLOUD.

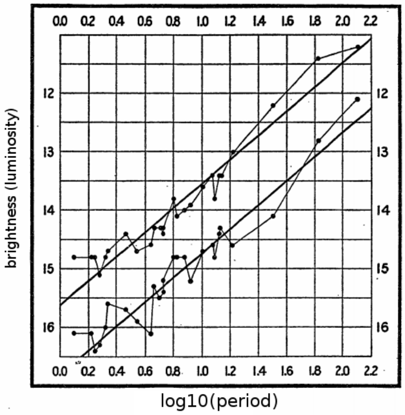
Source: `http://adsabs.harvard.edu/abs/1908AnHar..60...87L`, `http://adsabs.harvard.edu/abs/1912HarCi.173....1L`

Period and Brightness of Cepheid



Brightness: max mag (≈ 15.27) or min mag (≈ 15.75).

Period–Luminosity Relation for 25 Cepheids



"A straight line can be readily drawn among each of the two series of points corresponding to maxima and minima, thus showing that there is a simple relation between the brightness of the Cepheid variables and their periods."

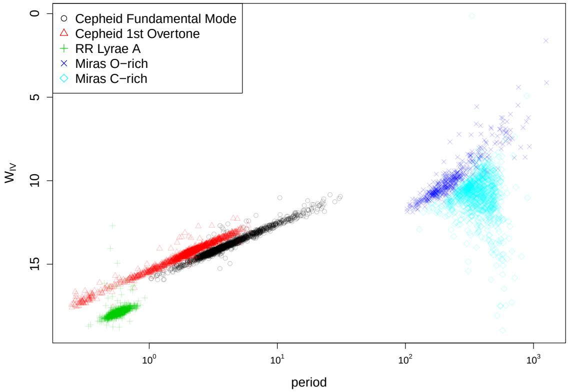
– Henrietta Leavitt

Calibrating the PL Relationship with Parallax

- SMC Cepheids all at approximately the same distance
- PL relation: longer period cepheids are more luminous
- for nearby Cepheids
  - know distance through parallax
  - use to calibrate PL relationship
- Ejnar Hertzsprung makes first extragalactic distance determination (30,000 ly to SMC)
- still being improved today

See "The Period–Luminosity Relation: A Historical Review" `http://adsabs.harvard.edu/full/1969PASP...81..707F`

Period Luminosity Relations in the LMC



Computed using OGLE–III data.

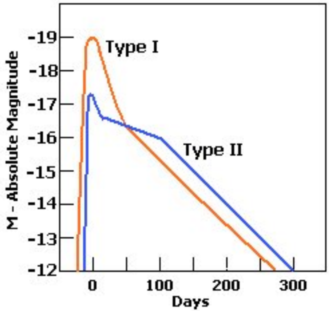
Limits of Cepheid Distances: NGC 3370

Cepheid variables detected as far as 100 million lyr in NGC 3370.

Source: By NASA/ESA, The Hubble Heritage Team and A. Riess (STScI) - http://www.spacetelescope.org/images/html/opo0324b.html (direct link)

Type Ia Supernovae: A Powerful Standard Candle

Supernovae involving two binary stars, one which is a white dwarf.

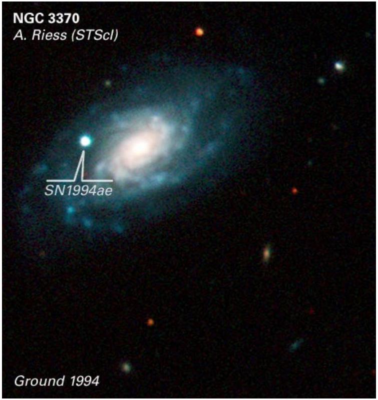


Type Ia Supernovae produce consistent peak luminosity

Video: https://upload.wikimedia.org/wikipedia/commons/transcoded/a/a7/Artist%E2%80%99s_impression_of_two_white_dwarf_stars_merging_and_creating_a_Type_Ia_supernova.ogg/Artist%E2%80%99s_impression_of_two_white_dwarf_stars_merging_and_creating_a_Type_Ia_supernova.ogg.480p.webm

Source: http://www.uni.edu/morgans/astro/course/Notes/section2/sntypes.jpg

Supernovae in NGC 3370

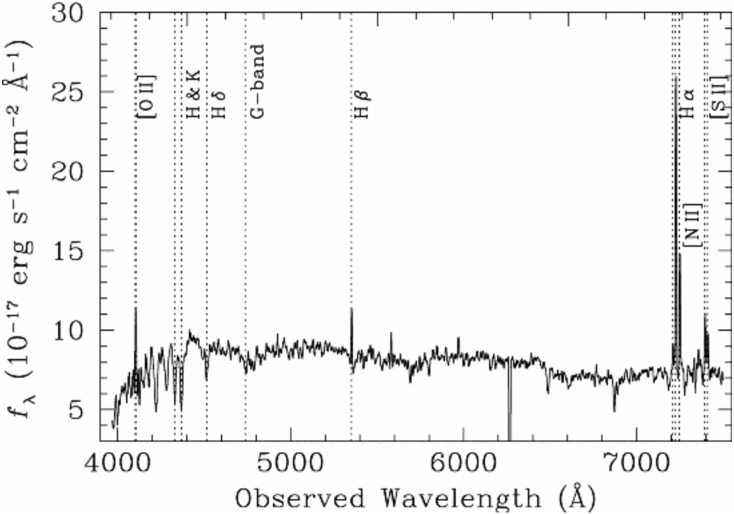


Supernovae found out to about 10 billion + ly.

Source: http://hubblesite.org/newscenter/archive/releases/2003/24/image/c/

Outline

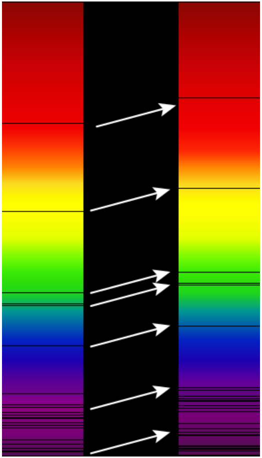
Spectrum of an Object



Measure intensity of light as a function of wavelength

Source: `http://spiff.rit.edu/classes/phys301/lectures/doppler/starburst_gal_small.gif`

Using Redshift to Measure Radial Velocity



- **radial velocity:** rate of change of distance between x (us) and y (star, galaxy)
- **redshift:** shift in spectrum due to radial velocity

$$\textit{spectrum} \rightarrow \textit{redshift} \rightarrow \textit{radial velocity}$$

Further Away Objects Are Moving Away Faster?

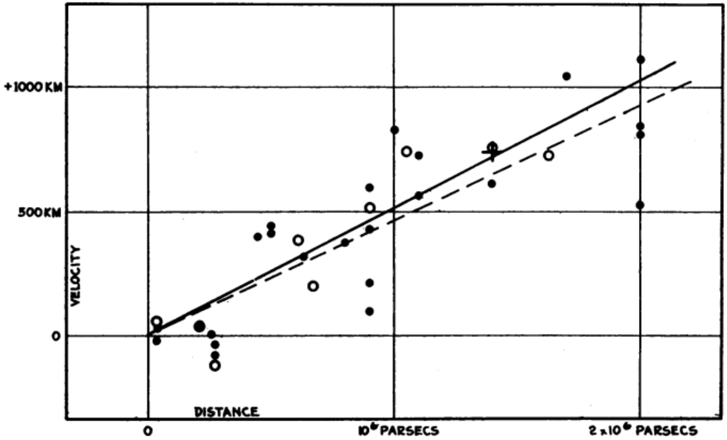
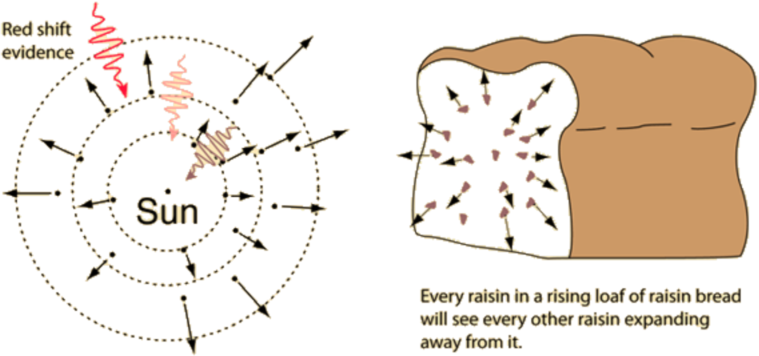


FIGURE 1

Velocity-Distance Relation among Extra-Galactic Nebulae.

Source: `http://www.pnas.org/content/15/3/168.full.pdf`

Expanding Universe



Hubble constant ($H_0 \approx 71km/s/Mpc$) is current expansion rate

Source: `http://hyperphysics.phy-astr.gsu.edu/hbase/astro/imgast/uexp.gif`

Metric Expansion of Space

If $x, y \in \mathbb{R}^3$ are positions, the Euclidean distance is:

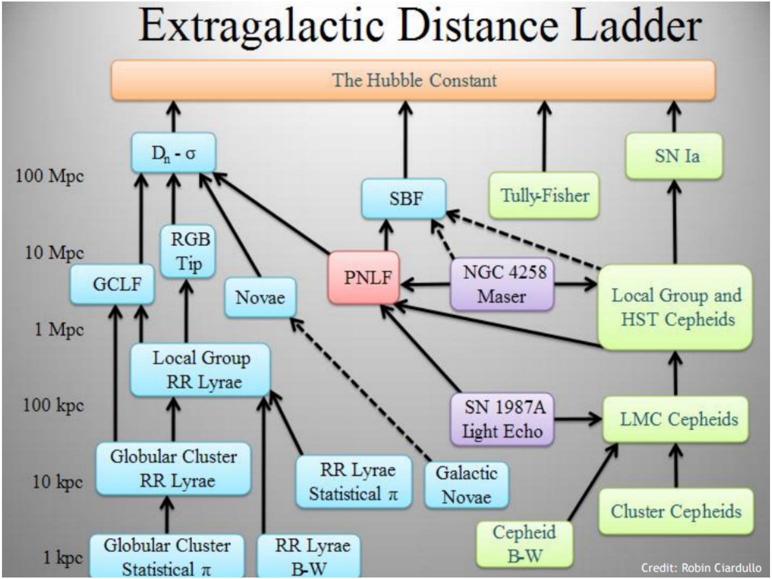
$$d(x, y) = \sqrt{(x_1 - y_1)^2 + (x_2 - y_2)^2 + (x_3 - y_3)^2}$$

But universe is non–Euclidean and expanding with time:

$$d_{t_1}(x, y) > d_{t_0}(x, y)$$

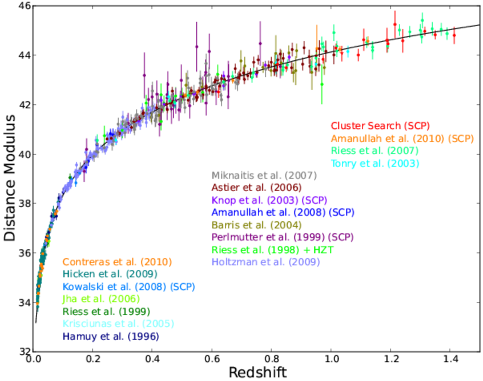
for $t_1 > t_0$.

Distance Ladder



Expansion of the Universe is Accelerating

- 1998 discovered using Supernovae
- 2011 Nobel Prize
- dark energy hypothesized to cause acceleration



Source: `http://supernova.lbl.gov/union/figures/Union2.1_Hubble_slide.png`

Outline

Distance Determination

The Universe is Expanding

Statistical Issues

Non–Distance Motivations for Time Domain Astronomy

Classification for Parameter Estimation

Classification is rarely the final step, eg

- classify stars
- estimate PL relation for Cepheids
- compute distance to galaxy

How do we propagate uncertainty through the whole process?

A Framework for Statistical Inference in Astrophysics

Chad M. Schafer

Department of Statistics, Carnegie Mellon University, Pittsburgh, Pennsylvania 15213;
email: cschafer@cmu.edu

Cepheid PL Relation: 100 Years Later

Cepheid light curve demography via Bayesian functional data analysis

Toward better Cepheid luminosities

Tom Loredo,[1] Martin Hendry,[2] Dan Kowal,[3] and David Ruppert[3]

[1]Center for Radiophysics & Space Research, Cornell University; [2]SUPA School of Physics & Astronomy, University of Glasgow; [3]Dept. of Statistical Science, Cornell University

1. Introduction

Motivation

- ***The dark energy equation of state:*** To learn the DE-EOS—e.g., the w parameter—we need to know the Hubble parameter H_0 to 1% accuracy or better.
- ***Cepheid variables:*** The main H_0 measurement bottleneck is the limited precision of the Cepheid variable period-luminosity relation (PLR), a foundation for the cosmic distance ladder.

Our project

- ***Goal:*** Improve our ability to infer Cepheid luminosities from light curve observations
- ***Objective:*** Move beyond standard PLR analyses
  - Explicitly model light curve diversity about the "average" PLR
  - Generalize the PLR to more flexible light curve-luminosity relations (LCLRs)
- ***Approach:*** Bayesian functional data analysis (FDA)
  - *FDA:* "Function demographics" (vs. demographics of scalars or multivariate vectors)—an important emerging area of statistics
  - *Bayesian:* Probabilistic modeling of light curves as stochastic processes

2. Multilevel modeling

3. Bayesian FDA for Cepheids

Conventional Cepheid calibration

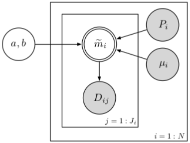
- Estimate periods from light curves via periodograms/harmonic fitting; treat as precise
- Estimate the average Cepheid magnitude, $\tilde{m}$, from light curve data D
- For Cepheids with known distance moduli, perform linear regression to estimate Leavitt law parameters

Leavitt law & observation model:

$$M_i = a + b\log\left(\frac{P_i}{10\text{d}}\right)$$

$$\hat{\tilde{m}}_i = M_i + \mu_i + \epsilon_i$$

Graph for conventional approach



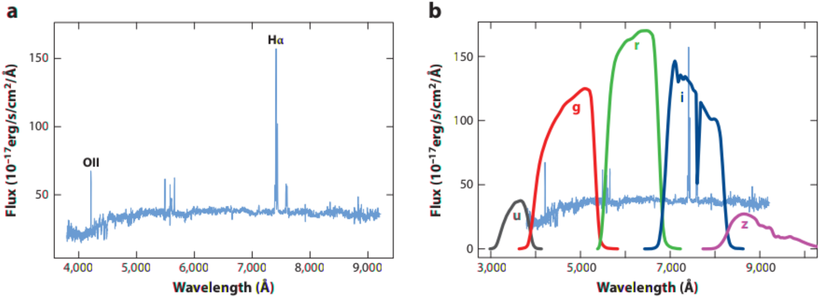
Bayesian FDA Cepheid calibration

Importance of Redshift

- spectrum $\rightarrow$ redshift
- redshift $\propto$ distance
- redshifts are very important

problem: spectra are very expensive to take

Photometric Redshift Estimation



With spectroscopy (left) we can easily calculate redshift. Spectroscopy is expensive so we collect much more photometric data (right). Want to predict redshift only using photometric measurements.

Source: "A Framework for Statistical Inference in Astrophysics." Schafer

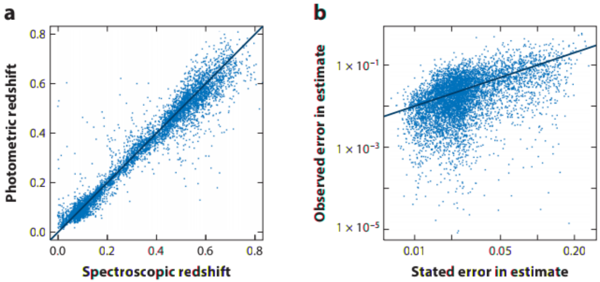
Quasar Photoz Dataset

13 rows out of $\approx 50,000$

SDSS_J	R.A.	Dec.	z	u_mag	sig_u	g_mag	sig_g	r_mag	sig_r	i_mag	sig_i	z_mag	sig_z
000009.26+151754.5	0.038605	15.298476	1.1986	19.921	0.042	19.811	0.036	19.386	0.017	19.165	0.023	19.323	0.069
000009.38+135618.4	0.039088	13.938447	2.2400	19.218	0.026	18.893	0.022	18.445	0.018	18.331	0.024	18.110	0.033
000009.42-102751.9	0.039269	-10.464428	1.8442	19.249	0.036	19.029	0.027	18.980	0.021	18.791	0.018	18.751	0.047
000011.41+145545.6	0.047547	14.929353	0.4596	19.637	0.030	19.466	0.024	19.362	0.022	19.193	0.025	19.005	0.047
000011.96+000225.3	0.049842	0.040372	0.4790	18.237	0.028	17.971	0.020	18.025	0.019	17.956	0.014	17.911	0.029
000013.14+141034.6	0.054786	14.176303	0.9491	19.519	0.034	19.281	0.028	19.115	0.016	19.155	0.024	19.071	0.053
000017.38-085123.7	0.072421	-8.856607	1.2499	19.151	0.034	18.722	0.020	18.263	0.021	18.276	0.036	18.260	0.037
000024.02+152005.4	0.100116	15.334840	0.9885	19.413	0.044	19.183	0.035	18.988	0.015	19.079	0.023	19.133	0.060
000026.29+134604.6	0.109578	13.767970	0.7678	19.345	0.030	18.998	0.023	18.922	0.023	19.010	0.022	18.838	0.042
000028.82-102755.7	0.120086	-10.465496	1.1377	20.461	0.086	19.697	0.030	19.176	0.016	19.143	0.023	19.105	0.061
000035.75-103305.3	0.148966	-10.551496	1.2177	19.404	0.041	19.455	0.029	19.045	0.015	19.006	0.023	19.181	0.066
000038.99-001803.9	0.162498	-0.301102	2.1224	19.204	0.044	19.076	0.022	18.886	0.017	18.894	0.018	18.794	0.044
000042.89+005539.5	0.178746	0.927660	0.9512	18.353	0.037	18.150	0.015	17.941	0.011	17.899	0.021	17.802	0.024

z column is calculated from spectroscopy. Use `filter_mag` and `sig_filter` columns to predict z.

Photometric Redshift Estimation Accuracy



a) Spectroscopic redshift (truth) versus redshift predicted by photometry.

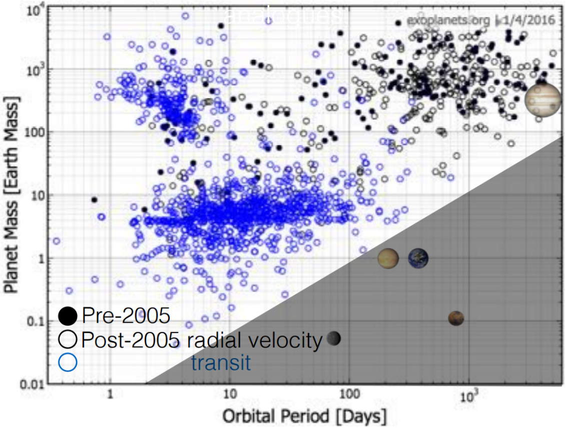
Possible Project

Source: "A Framework for Statistical Inference in Astrophysics." Schafer

Outline

Exoplanet Science

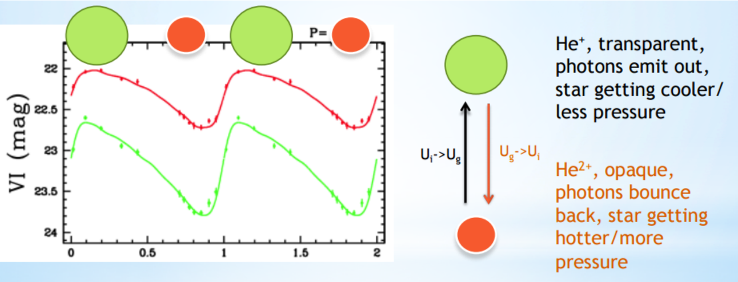
- fraction of stars with planets? multiple planets?
- population distribution of planet masses? orbital periods? etc?
- are there earth like planets? do aliens exist?



Source: R. Dawson, SAMSI ASTRO, 08/22/16
https://www.samsi.info/wp-content/uploads/2016/08/Dawson-SAMSI-Exoplanets-Farm-to-Table.pdf

Variable Star Science

Use variable star data to better understand pulsation mechanisms, deviations from strict periodicity, dust, etc.



Source: http://www.stat.tamu.edu/ jlong/astrostat/fall2015/cephpl.pdf