WELCOME TO ASTR 102!

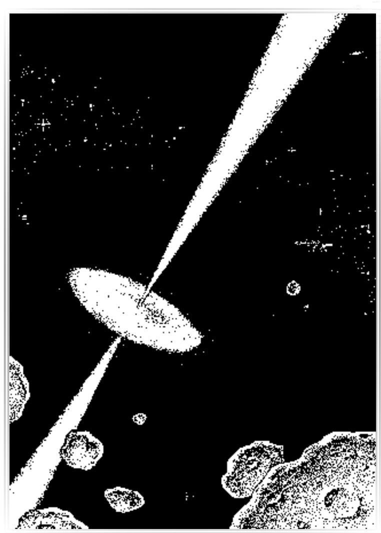
RELATIVITY, BLACK HOLES & THE BIG BANG

ASTRONOMY 102: RELATIVITY, BLACK HOLES & THE BIG BANG

What do black holes, wormholes, time warps, space-time curvature, hyperspace, and the Big Bang all have in common?

- Explanations with their origins in Einstein's theories: the special theory of relativity (1905) and the general theory of relativity (1915)

This semester, we will discuss all these exotic phenomena, mostly quantitatively, in the context of Einstein's theories.

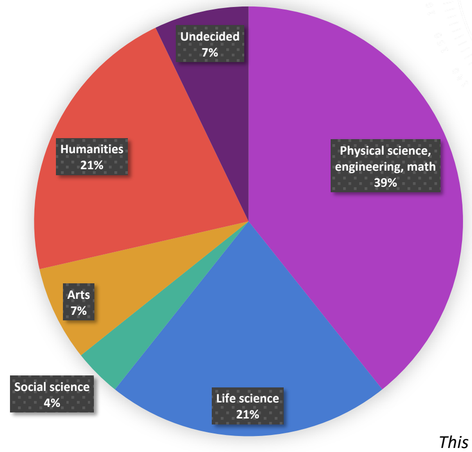


Artist's conception of the quasar 3C 273

OUR PRIMARY GOALS IN TEACHING ASTRONOMY 102

- To **demystify** black holes, the Big Bang, and relativity, so that you can critically evaluate the things you find about them in the media
- To show you how scientific theories are conceived and advanced in general

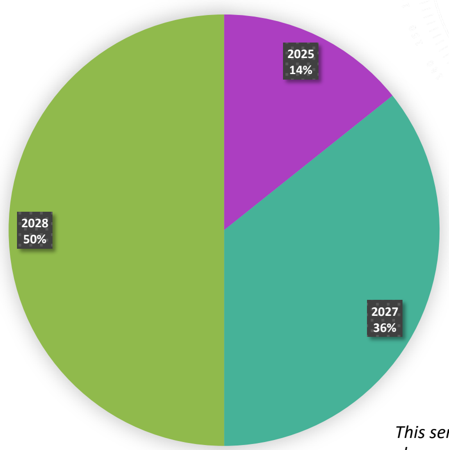
In doing so, we aim primarily at **non-science majors**.



This semester's ASTR 102 class, plotted by major

OUR PRIMARY GOALS IN TEACHING ASTRONOMY 102

By the end of the course, we hope that you will understand and retain enough to be able to offer correct explanations of black holes and such to your friends and family, and that you will retain a permanent, basic understanding of how science works.

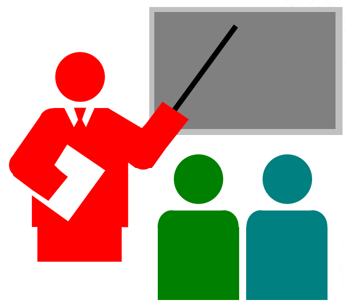


This semester's ASTR 102 class, plotted by class

HUMAN AND PRINTED FEATURES OF ASTR 102

People:

- **Kelly Douglass**, professor
- **James McKeown**, teaching assistant
- **Srujamya Sampathi**, teaching assistant



Textbooks (one required, two recommended):

- Kip S. Thorne, *Black Holes and Time Warps* (1994)
- Michael A. Seeds, *Foundations of Astronomy* (2008)
- Stephen Hawking, *A Brief History of Time* (1988)

ELECTRONIC FEATURES OF ASTRONOMY 102

Computer-projected lectures, for greater ease in presentation of diagrams, astronomical images, and computer simulations.

Website, including all the lecture presentations, schedule, and much more.

- **Primary reference for course**

WeBWorK, a computer-assisted personalized homework generator.

ONEROUS FEATURES OF ASTRONOMY 102

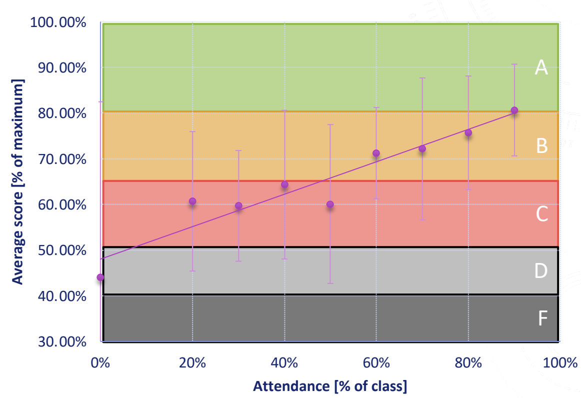
- The minimum of mathematics required to tell our story (but no less than the minimum)
- Eight homework assignments, all using WeBWorK
- Three in-class exams (but no *comprehensive* final exam)
- Grades (on a straight scale, not a curve)

90% OF SUCCESS IS SHOWING UP

All members of the class are expected to attend all the lectures and one recitation per week.

- Attendance will be recorded in lecture and recitation.

This is for your own good. **You will very probably get a better grade if you go to class,** as is demonstrated by these average overall grade and average attendance data from past ASTR 102 classes.



PROLOGUE IN OUTER SPACE

The "Coalsack," a dark nebula in the Southern Cross, is quite black but is unrelated to black holes.

Image taken with the Wide Field Imager on the MPG/ESO 2.2-meter telescope.

WHAT ARE BLACK HOLES LIKE?

A black hole is a highly-gravitating object from which nothing, not even light, can escape once it has fallen in.

As is done in Thorne's book, we now consider a hypothetical trip to some representative, celestial black holes with a wide range of mass.

Many strange effects will be encountered along the way. **We will eventually explain all these effects this semester,** but for now we just want you to see an overview of the effects, and what life is like in the neighborhood of black holes.

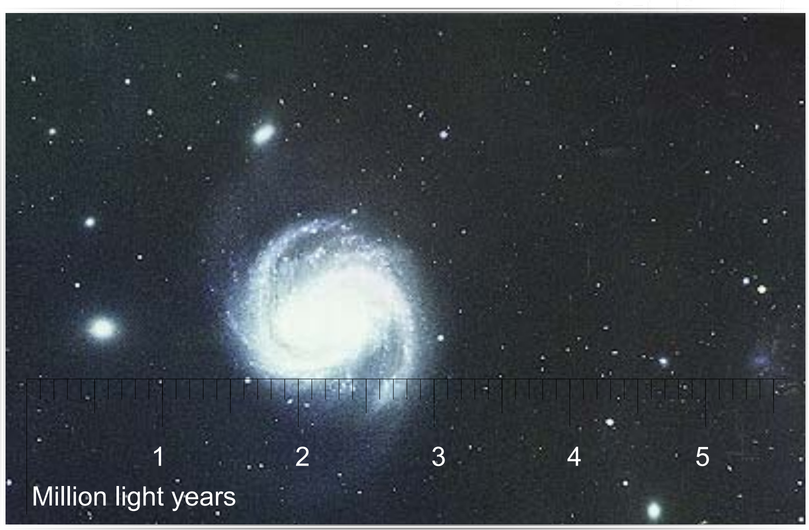
JOURNEY TO HADES

Hades is a hypothetical black hole near the bright star Vega (in the constellation Lyra), 26 light years from Earth.

HOW BIG IS THAT?

To discussing black holes, the Big Bang, and other celestial objects and phenomena, we need to become

- Familiar with distances, time scales, masses, luminosities, and speeds of astronomical importance
- Proficient at **unit conversion**



SIZES AND DISTANCES IN ASTRONOMY

	Centimeters	Kilometers	Miles	Light years
Diameter of a hydrogen atom	1.1×10^{-8}			
Diameter of a human hair	8.0×10^{-3}			
Diameter of a penny	1.9			
Diameter of Rochester	2.0×10^{6}	20	12	
Diameter of the Earth	1.3×10^{9}	1.3×10^{4}	7.9×10^{3}	
Diameter of the Moon	3.5×10^{8}	3.5×10^{3}	2.1×10^{3}	
Diameter of Jupiter	1.4×10^{10}	1.4×10^{5}	8.8×10^{4}	
Diameter of the Sun	1.4×10^{11}	1.4×10^{6}	8.6×10^{5}	
Diameter of the Milky Way galaxy	1.6×10^{23}			1.7×10^{5}
Distance to Buffalo	1.0×10^{7}	100	62	
Distance to the Moon	3.8×10^{10}	3.8×10^{5}	2.4×10^{5}	
Distance to the Sun	1.5×10^{13}	1.5×10^{8}	9.2×10^{7}	
Distance to the next nearest star, α Centauri	3.8×10^{18}			4
Distance to the center of the Milky Way	2.6×10^{22}			2.7×10^{4}
Distance to the nearest galaxy	1.6×10^{23}			1.7×10^{5}

TYPICAL LENGTHS AND IMPORTANT CONVERSIONS

- Diameter of normal stars: millions of *kilometers* (km)
- Distance between stars in a galaxy: a few *light-years* (ly)
- Diameter of normal galaxies: tens of *kilo-light-years* (kly)
- Distances between galaxies: a *million light-years* (Mly)
- 1 ly $= 9.46052961\times10^{17}$ cm $= 9.46052961\times10^{12}$ km
- 1 km $= 10^{5}$ cm; 1 kly $= 10^{3}$ ly; 1 Mly $= 10^{3}$ kly $= 10^{6}$ ly

Prefixes

milli (m)	10^{-3}	0.001
centi (c)	10^{-2}	0.01
kilo (k)	10^{3}	1000
mega (M)	10^{6}	1,000,000
giga (G)	10^{9}	1,000,000,000

Example: The Andromeda nebula (a galaxy very similar to our Milky Way) lies at a distance $D =$ 2.5 Mly. How many centimeters is that?

$$D = 2.5\text{ Mly} \times \frac{10^{6}\text{ ly}}{1\text{ Mly}} \times \frac{9.46\times10^{17}\text{ cm}}{1\text{ ly}} = 2.4\times10^{24}\text{ cm}$$

MORE DETAILS ON NUMERICAL ANSWERS

Note that the last answer was written as 2.4×10^{24} cm.

- Not just 2.4×10^{24} – numerical answers in the physical sciences and engineering are incomplete without units.
- And not $2.36513240 \times 10^{24}$ cm, even though that is how your calculator would show it. Numerical answers should be rounded off: **Display no more than one more significant figure than the least precise input number**.
  - If we had been told that the distance to the Andromeda galaxy is 2.5000000 Mly, then the conversion factor would have to have been put in with more significant figures, and the correct answer would have been $2.36513240 \times 10^{24}$ cm.

MORE DETAILS ON UNIT CONVERSION

Previous example: Repeated multiplication by 1. You can *always* multiply anything by 1 without changing its value.

The unit conversions always give a couple of useful forms of 1. For example, take the conversion 1 ly = 9.46×10^{17} cm:

$$\frac{9.46 \times 10^{17}\ \mathrm{cm}}{1\ \mathrm{ly}} = 1 = \frac{1\ \mathrm{ly}}{9.46 \times 10^{17}\ \mathrm{cm}}$$

Choose forms of 1 that cancel out the units that you want to get rid of and that insert units to which you want to convert to. Sometimes, this requires repeatedly multiplying by 1, as in the case of the previous example:

$$D = 2.5\ \cancel{\mathrm{Mly}} \times \frac{10^6\ \cancel{\mathrm{ly}}}{1\ \cancel{\mathrm{Mly}}} \times \frac{9.46 \times 10^{17}\ \mathrm{cm}}{1\ \cancel{\mathrm{ly}}} = 2.4 \times 10^{24}\ \mathrm{cm}$$

HOW ARE YOU DOING?

How comfortable are you with these concepts and doing these calculations?

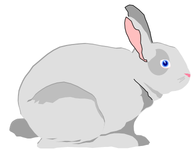
A. Pretty uncomfortable
B. OK, but reminders are needed
C. Perfectly comfortable
D. Expert

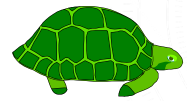
JOURNEY TO HADES

Hades is a hypothetical black hole near the bright star Vega (in the constellation Lyra), 26 light years from Earth.

Travel in a starship: acceleration = Earth's gravity ("$1g$"), speed close to the speed of light for most of the time. **Nothing traveling through physical space can go faster than the speed of light.**

SPEEDS IN ASTRONOMY





	cm per second [cm/s]	km per second [km/s]	miles per hour [mph]
NYS Thruway speed limit	3.0×10^{3}	3.0×10^{-2}	65
Earth's rotational speed at the equator	4.7×10^{4}	0.47	1050
Speed of Earth in orbit	3×10^{6}	30	
Speed of Sun in orbit around the center of the Milky Way	2.5×10^{7}	250	
Speed of Milky Way with respect to local Universe	5.5×10^{7}	550	
Speed of light	2.9979×10^{10}	2.9979×10^{5}	

TYPICAL SPEEDS AND IMPORTANT CONVERSIONS

- Planetary orbits in a Solar System: tens of km/s
- Stellar orbits in a normal galaxy: hundreds of km/s
- Speed between nearby galaxies: hundreds of km/s
- Speed of light: 2.99792458×10^{10} cm/s
- Conversion factors: use those given for distance and time

Example: One mile is equal to 1.61 kilometers. What is the speed of light in miles per hour?

$$c = 2.9979\times10^{10}\,\frac{\text{cm}}{\text{s}}\times\frac{\text{km}}{10^{5}\text{ cm}}\times\frac{\text{mile}}{1.61\text{ km}}\times\frac{3600\text{ s}}{\text{hr}} = 6.70\times10^{8}\text{ mph}$$

(670 *million* miles per hour!)

JOURNEY TO HADES

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Travel in a starship: acceleration = Earth's gravity ("$1g$"), speed close to the speed of light for most of the time. Nothing traveling through physical space can go faster than the speed of light.

The trip takes 6 years as measured on the starship, but 26 years as measured by an observer on Earth.

TIMES AND AGES IN ASTRONOMY

	Seconds [s]	Hours [hr]	Days	Years [yr]
Earth's rotation period	8.64×10^{4}	24	1	
Moon's revolution period	2.3606×10^{6}	655.73	27.322	
Earth's revolution period	3.1558×10^{7}	8.7661×10^{3}	365.25	1
Century	3.16×10^{9}			100
Recorded human history	1.6×10^{11}			5000
Milky Way galaxy's rotation period (at the Sun's orbit)	7.5×10^{15}			2.4×10^{8}
Age of the Sun and Earth	1.44×10^{17}			4.56×10^{9}
Total lifetime of the Sun	4.7×10^{17}			1.5×10^{10}
Age of the Universe	4.4×10^{17}			1.4×10^{10}

TYPICAL TIMESPANS AND IMPORTANT CONVERSIONS

- Planetary revolution period: around 1 year
- Life expectancy for normal stars: around 10^{10} years
- Life expectancy for giant stars: $10^6 - 10^8$ years
- Rotation period of normal galaxies: $10^7 - 10^9$ years
- 1 year= 3.16×10^7 seconds
- 1 hour = 3600 seconds

Example: How many seconds is a normal human lifespan (US)?

$$t = 75 \text{ years} \times \frac{3.16 \times 10^7 \text{s}}{1 \text{ yr}} = 2.37 \times 10^9 \text{s}$$

JOURNEY TO HADES

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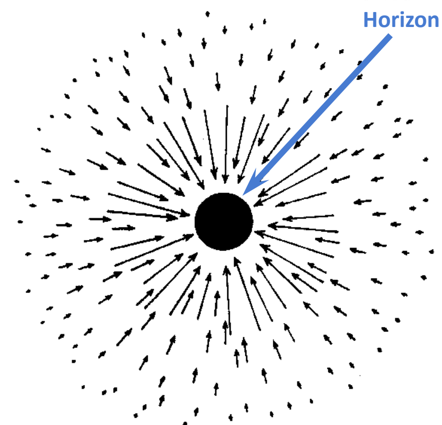
The trip takes 6 years as measured on the starship, but 26 years as measured by an observer on Earth.

- This difference is a prediction of Einstein's theory of relativity: **length contraction.** The distance to Hades looks shorter from the moving starship than from the stationary Earth (or Hades). (We will discuss this in detail next week.)

PROPERTIES OF HADES

- Mass = $10M_\odot$
- Horizon circumference = 186 km
- Rotation period = infinite (it is not spinning)
- Not very much interstellar gas falls into the hole; what does is accelerated to very high speeds (close to the speed of light) and emits *light* (notably X-rays and gamma rays) on its way in due to this acceleration.

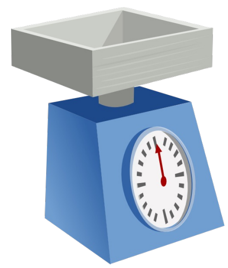


MASSES IN ASTRONOMY

	Grams [g]	Pounds [lb]	Solar masses [$M_\odot$]
Hydrogen atom	1.67×10^{-24}		
Penny (uncirculated)	3.2	0.0071	
Ton	1.02×10^{6}	2240	
Earth	6.0×10^{27}	1.3×10^{25}	3.0×10^{-6}
Moon	7.4×10^{25}		3.7×10^{-8}
Jupiter	1.9×10^{30}		1.0×10^{-3}
Sun	2.0×10^{33}		1
Milky Way galaxy	6×10^{45}		3×10^{12}

TYPICAL MASSES AND IMPORTANT CONVERSIONS

- Smallest stars: 0.08 solar masses ($M_\odot$)
- Normal stars: about one $M_\odot$
- Giant stars: tens of $M_\odot$
- Normal galaxies: $10^{11} - 10^{12} M_\odot$
- Clusters of galaxies: $10^{14} - 10^{15} M_\odot$
- $1M_\odot = 2.0\times10^{33}$ grams = solar mass = mass of Sun
- 1 pound = 454 grams



Example: Vega, the brightest star in the Northern sky, has a mass of about $2.5M_\odot$. What is its mass in grams?

$$M = 2.5M_\odot \times \frac{2\times10^{33}\mathrm{g}}{1M_\odot} = 5.0\times10^{33}\mathrm{g}$$

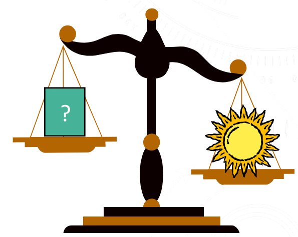
HOW MANY EARTHS IN THE SUN?

By what factor is the Sun (2.0×10^{33} g) more massive than the Earth (6.0×10^{27} g)?

THERE IS NOTHING SACRED ABOUT CENTIMETERS, GRAMS, OR SECONDS

Units are generally chosen to be **convenient amounts** of whatever is being measured. For example,

- The **light-year (ly)** is far more convenient than the centimeter for expressing length in astronomy; on large scales, we even use millions of ly (Mly).
- The convenient unit of **mass** in astronomy is the **solar mass**: the mass of the Sun.



Values of physical quantities are **ratios** to the values of the unit quantities.

THE FUNDAMENTAL DIMENSIONS

Distance, time, and mass are fundamental dimensions.

- Distances along each of the three different perpendicular directions of space determine the location of a given body with respect to others.
- Time determines the instant in which the given body has that location.
- A given body's mass determines how strongly the force of **gravity** affects it.

Each given body has an additional fundamental dimension (like mass) that corresponds to each of the forces of nature. Electric charge, for example, dictates how strongly the electrostatic force influences a given body.

THE FUNDAMENTAL DIMENSIONS

The dimensions of all other physical quantities are combinations of the fundamental dimensions (distance, mass, and time).

- For instance: the dimension of **velocity,** and velocity's magnitude **speed,** is distance divided by time.
- The dimension of **energy** is mass times distance squared divided by time squared (i.e. mass times the square of the dimension of speed).

Units are the scales of the *quantities* that go with the *qualities* that are dimensions.

Thus: four fundamental dimensions for location (three space, one time), and in principle four for response to forces (gravity, electricity, and the strong and weak nuclear forces).