

Let's Make a Star!

What is a star?

Everyone knows what a star is: a faint, twinkling point of light in the nighttime sky. For the nearest stars, we can detect the parallactic back-and-forth motion as the Earth orbits the Sun, giving their distances: the nearest is ~1 parsec = 3×10^{16} m away. Combined with their apparent brightness, we derive their intrinsic luminosities which are similar to our Sun's luminosity. Our Sun is a star, and the stars are Suns. This is an astronomical answer.

But what is a star physically?

What is it made of? What makes it shine so brightly? How does it arise, and does it shine forever? Why are there planets around stars? These are astrophysical questions. We address them with a Gedanken experiment based on physical laws.

Consider a box in a totally empty space with a bunch of atoms placed randomly inside. Now make a movie showing the how it evolves.

First, let's pretend it is in the 18th century and the only physics we know are Newton's Law of Gravity and his Laws of Motion:

$$F = -G m_i m_j / r_{ij}^2 = m_i a_{ij}$$

where m_i is the i -th atoms's mass, r_{ij} is the distance between two atoms, and a_{ij} is the acceleration of the two atoms towards each other. The first equation says that gravitational force is proportional to the two masses involved and decreases with the inverse-square of the distance between them. The second equation says that, for any force, a body responds by accelerating. The acceleration is the second derivative of the distance and, when considered to be 3-dimensional vectors, we integrate this second-order differential to determine the movement of the masses in time. That is, we make a movie.

What happens in the movie?

<>The atoms start accelerating towards each other, r_{ij} distances decrease, density rapidly increases, acceleration increases ---> an implosion! This process is called **gravitational collapse**. If gravity is the only force, the atoms should

quickly collapse to zero volume, infinite density ---> a **black hole** (Michell & Laplace, late-1700s).

But collections of atoms with finite densities do persist (e.g. ourselves, planets, Sun). There must be repulsive forces that counteract the attraction of gravity. One such force is the electric repulsion of the electron clouds orbiting each atomic nucleus. This force is stronger when the atoms bump against each other faster (i.e., when the temperature of the gas is higher).

$$\text{Gas pressure } P = n k T$$

where n is the density of atoms, k is Boltzmann's constant, and T is the temperature (Ideal gas law, Boltzmann mid-1800s)

So, the cloud of atoms starts gravitational collapse, gas heats up as density increase, and collapse stops when **hydrostatic equilibrium** is achieved; that is, **when the inward pull of gravity and outward push of gas pressure are equal everywhere**. The result is a sphere, hot & dense in the core, cooler & less dense at the edges.

Will this cloud of atoms in equilibrium persist forever without change?

No! When atoms bump into each other, the electrons are bumped into excited states. They then drop to lower state, emitting light at specific wavelengths. Or, if the cloud is opaque, its surface emits a blackbody continuum of light. Since light carries energy, the cloud of atoms must lose energy, atom motions must slow down (i.e. the temperature drops), and gravitational collapse slowly resumes. For a cloud of 10^{57} atoms ($= 1 M_{\odot} = 1$ solar mass), this cooling & contraction takes 10^6 years (Kelvin & Helmholtz, mid-1800s). The Sun should thus remain hot for this time after collapse begins.

Is this astrophysical model OK?

No! 19th century geology told us the Earth has been warmed by the Sun for 10^9 years! Darwin's theory of evolution also requires a very long time to explain the proliferation of different types of fossils in different rocks. A new long-lived source of energy is needed for the stars. Sir Arthur Stanley Eddington (in his lectures *Stars and Atoms*, 1927) suggests that it might come from Albert Einstein's 1905 revision of Newton's laws of motion, which predicted

$$E = m c^2.$$

The answer was found from the emerging field of nuclear physics (Hans Bethe 1938). The *fusion* of four hydrogen nuclei (4 protons) into a helium nucleus (2 protons + 2 neutrons) releases 0.7% of the original mass to energy via $E=mc^2$. This reaction can occur only when the temperature exceeds $\sim 10,000,000$ K. **The problem of the long lifetime of the Sun is solved: the energy is provided by the fusion of H to He.**

What about the planets?

Return to the original idea of atoms in a box undergoing gravitational contraction, but this time let the box spin slowly. Atoms starting at along the rotation axis can fall into the center, but atoms along the equator fall inwards until their angular momentum requires they orbit the central condensation. A differentially rotating Keplerian disk of atoms emerges, $v_r \sim (GM/r)^{1/2}$, within which smaller clouds of gas locally undergo some form of condensation and growth. This is how planetary systems form.

Conclusion: A main sequence star like the Sun is a sphere of $\sim 10^{57}$ atoms in approximate hydrostatic equilibrium, heated by the fusion of hydrogen to helium nuclei in its core. High angular momentum material form a flattened disk around the star where planets form. This is the basic answer to: What is a star and how does it form?