Gravity Wins

This text is a modified and shortened version of Chapter 12 from David A. Weintraub (2010)

Some terminology defining a few kinds of celestial objects:

The *Sun* is the closest star to Earth.

- Stars power themselves via the process of nuclear fusion (Lecture 3!)

The *Solar System* is the Sun and the collection of objects that orbit the Sun,

- including planets, dwarf planets, asteroids, and comets.
- And extending outwards to tens of thousands of astronomical units (AU)
- Note: 1 AU is the distance from the Sun to Earth

Stars are rotating, nearly spherical balls of hot gas with masses from tens of thousands to a few million times greater than that of the Earth.

- Stars are made mostly of hydrogen (70% of the mass) and helium (28% of the mass).
- The process of nuclear fusion, which takes place in the central cores of stars, converts the hydrogen to helium.
- This process generates heat in the core, which slowly radiates outwards to the surface of the star.
- Thus, the surfaces of stars become hotter than the interstellar space that surrounds them, which causes them to emit heat, in the form of light.

Galaxies are collections of tens of millions to hundreds of billions of stars, bound together by the force of gravity.

- The Sun is one of about 400 billion stars in the Milky Way galaxy.
- The Milky Way is part of a small group of a few dozen galaxies called the Local Cluster.
- The Milky Way and Andromeda are the two big galaxies in the Local Cluster;
- Some galaxies are spirals, others ellipticals, and others have irregular shapes.

Interstellar clouds are enormous, irregularly shaped volumes of space, located inside of galaxies.

- They have sizes of a few light-years to a few hundred light-years in diameter.
- They are filled mostly with gas (single atoms and simple molecules).
- They are characterized by a temperature (or a narrow range of temperatures through the cloud), size, mass, composition, and speed of rotation.
- Typical gas densities in these clouds are incredibly low, only one to ten atoms per cubic centimeter; in comparison, the density of the gas in Earth's atmosphere is about 30 billion billion atoms (or molecules) per cubic centimeter.

Gravity

In Isaac Newton's mathematical formula for the theory of gravity[1], gravity is the force of attraction between any two objects in the universe.

- The magnitude of the force of gravitational attraction between any two objects in the universe depends on the masses of the two objects and the distance between their centers.
- The amount of mass matters: more massive objects attract each other more strongly than less massive objects. The magnitude of the force of gravity increases in direct proportion to the magnitudes of the attracting masses.
- Distances matter: objects located close to each other attract each other more strongly than do objects separated by greater distances. The magnitude of the force of gravity decreases in proportion to the square of the distance between the two masses.
- The force of gravity between any two objects can be very small (e.g., if they are very far apart), but can never become zero. No matter how far apart two objects are in the universe, they will always pull on each other.

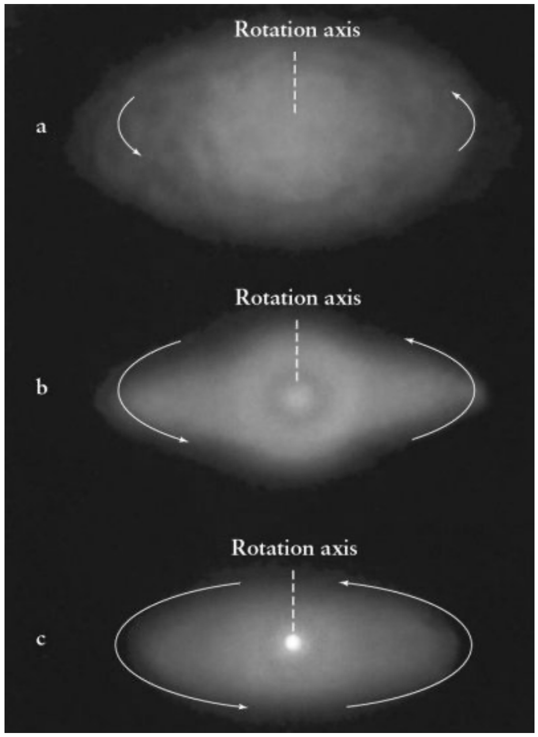
Now let's do a thought experiment: imagine two atoms located a fixed distance apart. Given their masses and their distance, they are attracted together by the force of gravity.

1. Because of the gravitational pull they exert on each other, the force generates motion of both particles toward each other; consequently, the two atoms move closer together.
2. Because they are now closer, the attractive force of gravity between them increases; and if they are more strongly attracted to each other, they will pull on each other harder and move even closer together, which in turn will increase the force of gravity which will make them move even closer together.
3. This process must continue until the two objects collide, unless another process intervenes to resist the pull of gravity.

Thermal pressure

Hot volumes of gas expand; cool volumes of gas shrink. Why? Heat is a measure of how fast particles are moving. Imagine air inside a balloon. All those hundreds of billions of molecules inside the balloon are zipping around at high speeds. They collide with each other and also with the confining, inside surface of the balloon. When they bounce off the inside surface of the balloon, they exert a push outwards on the balloon material. All those trillions of collisions cause the balloon to expand. The hotter the gas inside the balloon, the faster the particles are moving. The faster they move, the harder they push outward on the balloon. The harder the push, the bigger the balloon gets. If the gas cools off, the particles move more slowly and push less hard on the balloon. In this case, the

[1] Albert Einstein's mathematical formulation of the theory of gravity is a modern, improved version of Newton's theory of gravity. But Newton's simpler version is a better place to start for developing a conceptual understanding of how gravity works.



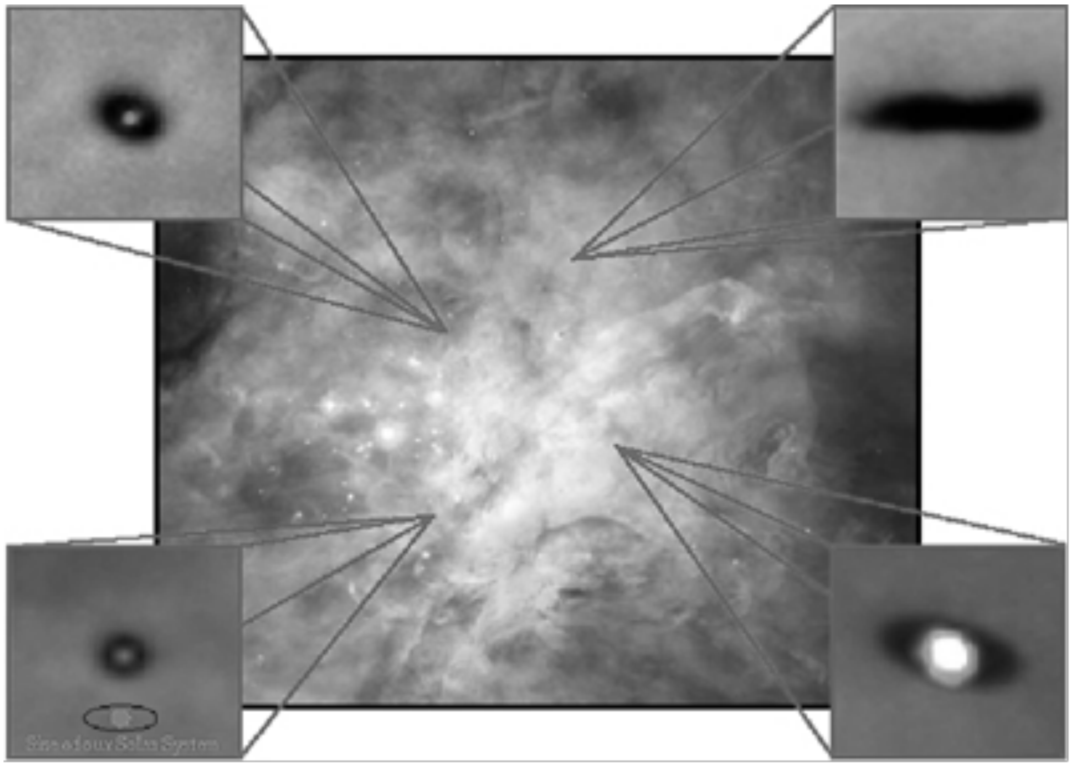
balloon gets smaller.

The competition between gravity and thermal pressure

Stars are born regularly in the Milky Way, from fragments of giant interstellar clouds in in regions like the Orion Nebula, S106, and 30 Doradus. The temperature of the cloud describes how fast the individual atoms or molecules in the cloud are moving. The overall size and mass of the cloud characterize the gravitational strength of the cloud. Since gravity is an attractive force, gravity naturally acts to make the cloud smaller in physical size. Heat, however, provides a natural pressure that acts to resist gravity and, if possible, to expand the cloud. Hot clouds will expand and disperse. Cold clouds will shrink. And rotation provides a mechanism that resists gravity in one direction (perpendicular to the rotation axis) but has no effect on the cloud in the direction parallel to the axis of rotation. These clouds are locations where the competition begin between gravity pulling inwards and thermal pressure pushing outwards take place. These struggles between these two physical processes determine the life stories of stars, from birth to death.

Figure 1: Illustration of theory of the formation of stars from rotating clouds of gas in space.

In the eighteenth century, both Immanuel Kant and Pierre Simon Laplace suggested that the Sun and planets and smaller objects that orbit the Sun could have formed from pieces of a swirling interstellar cloud that cooled off and collapsed.



Two centuries later, astronomers have confirmed this hypothesis by identifying many such interstellar clouds and studying the star formation process that takes place within these clouds. These flattened, spinning pieces of interstellar clouds are known as proplyds (for protoplanetary forming disks). Examples include ones in the Orion Nebula, the Carina Nebula, and the Flame Nebula.

Figure 2: Hubble Space Telescope images show flattened disks around newborn stars in the Orion Nebula. (Image courtesy of Robert O'Dell, of Vanderbilt University, and NASA)

Star Formation

In general, interstellar clouds are in a precarious balance between expansion and collapse. The internal heat of an interstellar cloud generates expansive pressure while the gravity from the matter in the cloud works to pull the particles in the cloud closer together.

Some interstellar clouds are hot and have little mass. In these clouds, expansion wins and stars do not form.

In other interstellar clouds, the masses are large enough and the temperatures are low enough in sufficiently small volumes of space that gravity dominates and makes the cloud fragment into smaller pieces. When the balance of forces tips too far in favor of gravity, *gravitational collapse* ensues, and a star forms.

Initially, when gravity is able to pull the particles that make up an interstellar cloud fragment into a smaller volume, the separations between particles are smaller while the masses of these particles are unchanged; therefore, as the separations decrease the self-gravity of the cloud increases dramatically. As a result, the cloud squeezes itself even more and becomes even smaller and since, initially, the cloud does not warm up much, gravity quickly gains a huge advantage, and the collapse of the cloud accelerates.

As the cloud is squeezed and becomes denser, it becomes less transparent. Much of the heat that is generated will be radiated away but over time more and more of the heat will be retained, trapped inside an increasingly opaque cloud. While the now opaque cloud will continue to squeeze itself further, it begins to warm up just a little bit more. Once more, the battle is joined, with thermal expansion getting a second chance to resist gravity.

Now, we have a protostar, an object from which only the outer layer of the star can radiate heat out into space. Any heat generated deep inside the protostar is trapped inside until it can work its way to the surface. The center of the protostar gets hotter and hotter; the increasing thermal pressure within the protostar pushes back harder, resisting the compressive force of gravity. For a time, thermal pressure will slow or even halt the gravitational contraction of the protostar, but the protostar continues to radiate heat into space from its surface and thus it cools off. And so it gets squeezed even more.

Over time, as the surface loses heat to space, more heat from the inside of the protostar is transported to the surface; this heat is radiated away and the inside of the protostar cools. Gravity still has the advantage. When the inside cools, the protostar shrinks a little, heats up a little, again cools off a little, and again shrinks a little. With each infinitesimal change, the core and the surface of the star get hotter. Thermal pressure refuses to yield. Yet, the forming star is simply not able to generate enough heat fast enough to hold off gravity. Gravity will continue, inexorably, to squeeze the cloud smaller and smaller unless the collapsing cloud can find a heat source that can generate energy as quickly as the cloud radiates energy into space.

In fact, most collapsing protostars will find an additional heat source in the form of nuclear fusion, which will be the subject of our next lecture.

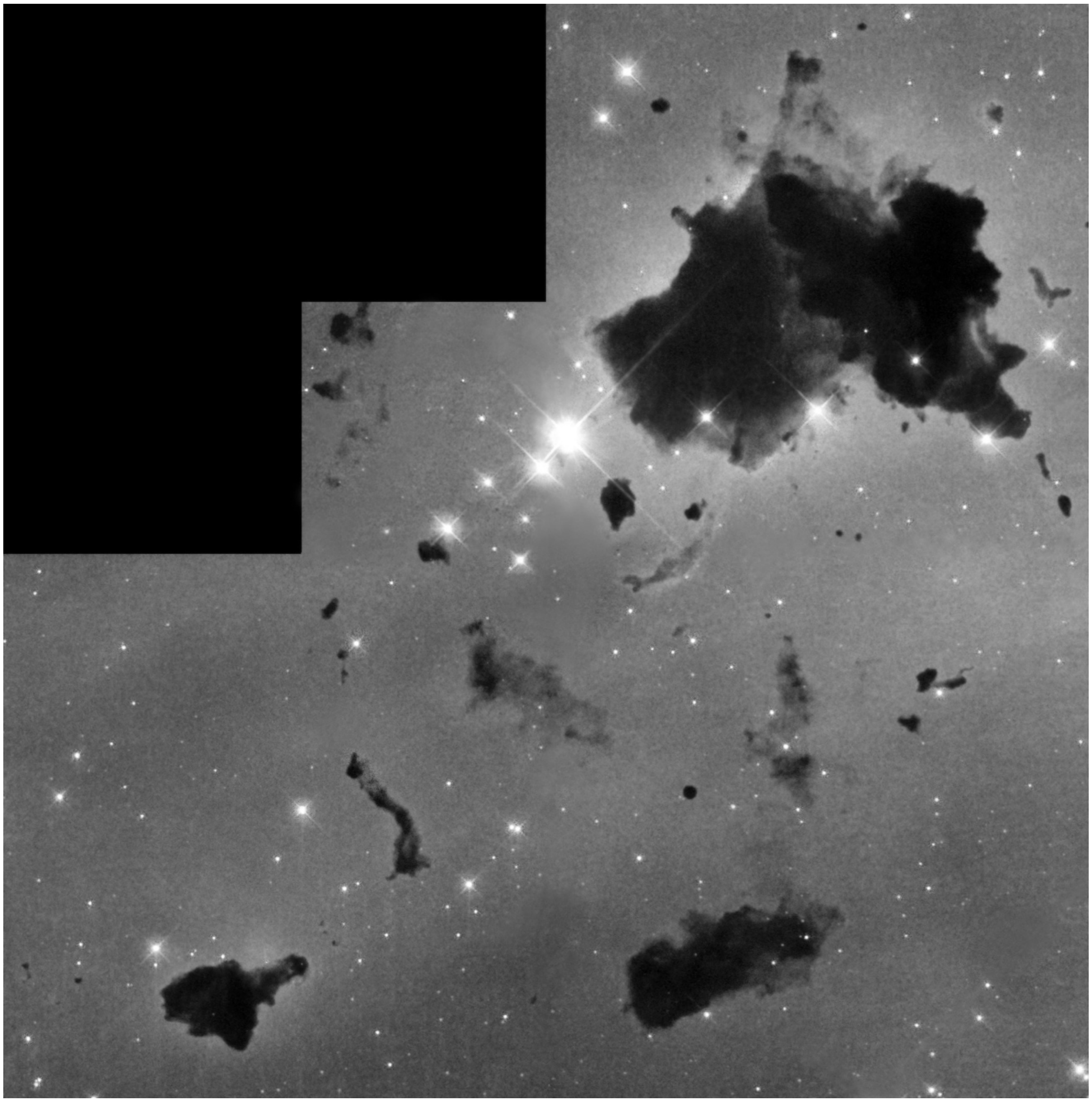


Figure 3: Thackeray's globules are dense, opaque clouds of gas and dust in which stars may be forming. Thackeray's globules are seen silhouetted against nearby, bright, newborn stars in the star forming region known as IC 2944. (image courtesy of Bo Reipurth (University of Hawaii), NASA and The Hubble Heritage Team (STScI/AURA))

Planet Formation

The rotational motion of the collapsing cloud, however, prevents all of the material in the cloud from falling all the way to the center; instead, while the cloud shrinks it also flattens. At the center, a star forms. Meanwhile, around the star, a flat disk of gas and dust forms that revolves around the newborn star at the center. Sticky collisions of particles in the disk make some particles begin to grow, first into pebbles, then into large rock-sized objects (asteroids), finally into moon-sized and Earth-sized objects known as planetesimals. Some of these objects grow large enough to become rocky planets like Mercury, Venus, Earth and Mars.

When some of the growing planetesimals become large enough (the equivalent of ten times the mass of Earth), their gravity pulls gas and dust from the disk down onto their surfaces. These objects become gas-rich planets like Jupiter (318 Earth masses), Saturn (95 Earth masses), Uranus (14.5 Earth masse) and Neptune (17 Earth masses). The planets that orbit the Sun formed in such a disk. The asteroids and comets that orbit the Sun are planetesimals that failed to grow as large as planets. Asteroids formed closer to the Sun than comets and are made mostly of rocky and iron-rich materials. Comets, which formed much further from the Sun, are made of "ices" (water ice, carbon dioxide and carbon monoxide ices, methane ice, ammonia ice), with a little bit of rocky/iron material.

We now understand the physics of the process of star and planet formation well enough to know that the formation of a star and its planetary system involves a set of associated events. The physical processes involved in the gravitational collapse of an interstellar cloud lead directly to the formation of both the star and the system of planets, asteroids, and comets that orbit the star.

The Formation of Galaxies and the Large Scale Structure of the Universe

Galaxies formed from gravity acting on normal matter, atoms and molecules, as well as a kind of matter known only as *dark matter.* Astronomers do not yet know what dark matter is, but they know that it has mass and therefore interacts with other particles through the force of gravity. Because certain locations in the universe, through random processes, had slightly greater densities (and thus masses) than other locations, those higher-mass volumes of space had greater forces of gravity than lower density volumes in the universe. In these locations, the force of gravity gradually pulled particles closer and closer together, forming giant spider-webby structures known as into cosmic filaments. Inside these filaments, the matter fragmented into smaller pieces. Within the smaller pieces, gravity gradually pulled the gas into denser structures: these are the galaxies, clusters of galaxies, and superclusters of galaxies that exist today.

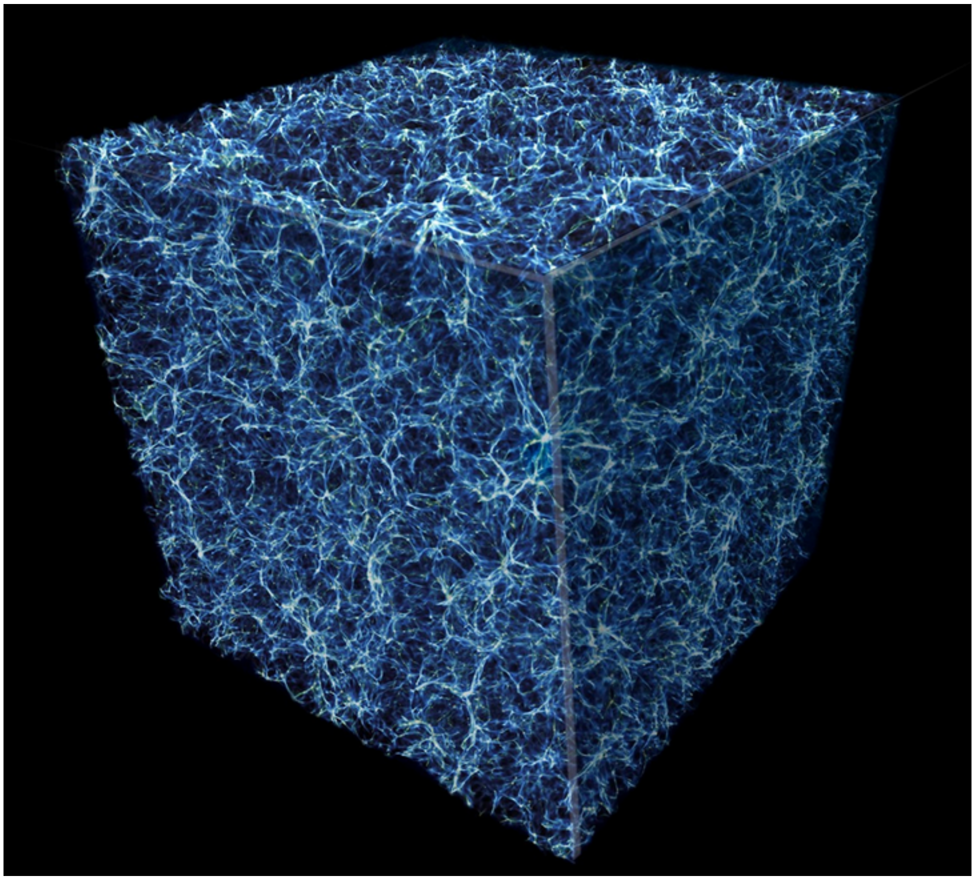


Figure 4: A computer simulation of the cosmic web, i.e. the large-scale structure of the Universe. Early in the history of the universe, matter, via gravity acting on over-dense regions of the Universe, formed clumps. These clumps, again via gravity, become linked together in enormous filaments, with lengths of 100s of millions of light years. Galaxies and clusters of galaxies formed along these cosmic filaments. Credit: NASA, Frank Summers (STScI), and Martin White and Lars Hernquist (Harvard University)