Formation of terrestrial planets

With our penchant for seeing everything in terms of ourselves, it is natural that our first instinct is to think that life is most likely to arise on a planet similar to Earth. We do have a lot of advantages: liquid water on the surface, thick enough atmosphere to protect us from high energy radiation such as X-rays, a magnetic field that deflects high-energy cosmic rays, and so on. Of course, it could be that somewhere else in the universe a species is congratulating itself on being on a perfect gas planet. We don't know. Still, it does make sense that planets would be good places for life. Stars are too hot for complicated molecules to exist, and cold places in space (such as interstellar clouds) are so low-density that it's difficult to imagine much activity taking place on time scales short enough to be of interest. We therefore need to know a little more about how stellar systems form, and how in particular Earth-like (terrestrial) planets form.

The formation of stars

The details of this process are surprisingly complicated, and there is a great deal that we still do not know. The basics, however, are reasonable. We start out with an interstellar gas cloud, which is a giant thing: many parsecs across, high-density by astronomical standards (hundreds of atoms per cubic centimeter; of course, our atmosphere is more like 10^{20} atoms per cubic centimeter, so this is a really good vacuum!), and cool to the tune of $T \sim 10$ K. Such a cloud might contain a million solar masses or more, and it thus has significant gravity within itself. Little pockets of the cloud start coming together, cooling and radiating, and getting denser and denser. You can think of this as equivalent to stuff falling in a gravitational field, which means that the kinetic energy (and thus temperature) of the stuff in the middle gets larger and larger. Eventually, the center of such a pocket gets dense enough and hot enough that it undergoes nuclear fusion and becomes a star.

Sounds straightforward, right? The difficulty is that hidden in this description is a problem. The problem is that because the pocket starts out so large, any little bit of rotation means that the gas has a huge amount of angular momentum. In fact, the lowest reasonable amount of angular momentum is many orders of magnitude greater than what any star has. But you can't just cause angular momentum to vanish, because it is conserved. Think of an ice skater who brings her arms in while spinning around. As the gas pocket contracts, it spins faster and faster. This causes it to flatten out into a disk, but to become something as tiny as a star the gas that forms the star has to transfer almost all its angular momentum to something else.

This is a problem that isn't 100% solved. Most of the angular momentum probably leaves via the outermost portions of the gas disk escaping from the system. However, a lot of the rest can end up in planets. That is, if you think about the current-day Solar

System, Jupiter's orbit has about 100 times as much angular momentum as the Sun's spin does. What we do know is that the angular momentum barrier means that matter can't just plunge in and form a star. Instead, a gas disk is formed, with matter near the inner edge flowing slowly in to form the star while the outer matter moves away. This disk is thought to last a few million years, based on observations of stars at this stage. It is from the disk that planets must form, so let's examine that process.

Formation of planets: considerations of composition

How can planets form out of the disk? One thing that might occur to you is that this could be a smaller version of the original formation of stars from interstellar gas clouds. That is, perhaps some extra-dense pocket of the gas in the disk could become self-gravitating, pulling itself together to form a planet. This is something that may indeed happen for some large extrasolar planets. However, it has difficulties explaining the composition of many planets. Let's explore this a bit.

The Sun contains some 99.8% of the mass of the entire Solar System, so we would expect that the mass fractions of different elements in the Sun would be representative of the whole nebula from which it formed. Additionally, we can check out the mass fractions of elements in current nebulae. In both cases, we find that by mass, hydrogen is about 74% of matter and helium is about 24%, with the remaining elements making up about 2%.

How about for the Earth? Here the fractions are dramatically different. Iron is the most common element by mass, constituting some 32% of the Earth. Oxygen is next, at about 30%, followed by silicon, magnesium, sulfur, and others. Hydrogen and helium aren't even remotely competitive. The same is true for the other inner planets (Mercury, Venus, and Mars, as well as our Moon). Jupiter and Saturn's overall composition are close to that of the Sun, but for Uranus and Neptune we again run into discrepancies. There must be some other mechanism.

Planet formation: the standard model

Rather than straight collapse from a gas cloud, how else could a planet come to be? The key is to realize that atoms and molecules can stick together in grains (for rocky stuff like silicon and iron) or small ice particles. These grains then have enough electric charge on them that they can come together in larger and larger groups. These rocks/iceballs/whatever then collide, grow larger, and eventually produce planets. The mass of the planets, however, depends on how far out they are. Close enough to the host star, things are hot enough that water ice and other ices cannot be formed. This means that hydrogen is a gas rather than being in a solid form with oxygen, so very little mass can be brought together. This restricts the inner planets to starting out with iron, silicon, and their oxides. Since this is a tiny fraction of the original nebula, the inner planets are small.

However, far enough out, water ice can form. This involves hydrogen, by far the most abundant element. It is then thought that as the ice balls get big enough, the gravity can attract and retain the gaseous helium and hydrogen that is floating around (this in itself is made easier because far away from the star the temperature is low enough that the hydrogen and helium move slowly). At the right location, then, giant gaseous planets can form. Jupiter, being the closest giant planet, was able to scoop up more mass than the others.

Caveat: much of this picture was developed before other solar systems were formed, hence we might be arguing more specifically than we should. Still, we do get some bits of useful insight:

- Planets that *form* close to their host star are likely to be pretty small, because ices can't form. There may be ways to form giant planets far out and then *bring* them close, but that is a different story.
- Innumerable grains/rocks/planetesimals would have formed early on, and they would grow by collisions with their fellows. This means that the early solar system was a violent and dangerous place. As an example, it is thought based on many independent lines of evidence that our Moon was formed when a Mars-sized object hit the proto-Earth (note that it wasn't Mars itself, just a similar-sized object). Any life that somehow cropped up at this stage (from 4.6 billion years ago to about 4 billion years ago) was almost certainly wiped out by these collisions. Indeed, as we'll discuss when we hit mass extinctions, the baby versions of such collisions still happen occasionally.

  Let's sum this up and then think about what it means. Our current understanding is that Earth and the other terrestrial planets are mainly made out of stuff that could make grains even in the hot solar system. That's why we have lots of iron, silicon, and their oxides (iron oxide is rust; silicon dioxide is sand). It is *not* the case that "heavy stuff sank to near the Sun", which is something you commonly hear. Initially, all the nebula everywhere had the primordial composition; it's just that light gases such as hydrogen and helium didn't take part in grain formation.

  Reflections on terrestrial planets

  If life really does require terrestrial planets, what does the formation scenario mean for how common life is? To answer that question partially, we can imagine a first-generation star, i.e., one that forms in the universe early enough that nuclear fusion plus winds and supernovae haven't had enough time to populate the interstellar medium with heavy elements. In that case, a star will form with only hydrogen and helium. No ices can form, so the only path to a planet would be direct collapse. Even this wouldn't make a terrestrial planet.

We therefore realize that formation of Earth-like planets requires plenty of heavy elements. Indeed, even a second-generation star would likely not have nearly enough iron, silicon, and oxygen to make a planet like Earth. Therefore, the formation of terrestrial planets, as well as the development of complex chemistry, seems to require that significant time go by so that the interstellar medium be somewhat enriched in heavier elements. There is some evidence that even more massive planets form more easily around stars that have extra amounts of heavy elements, but this is disputed. It is even possible that our Solar System is one of the earliest systems that had enough heavy elements, but (1) we don't know what the threshold is, and (2) a billion years here or there would make no significant difference compared to variations in the local environment.

Properties of the Earth

When we compare the different inner planets in our Solar System in a few lectures, we will realize that apparently small differences in mass or orbit can make a huge difference. Let's start with the Earth's size.

As you may have gathered from the formation scenario we discussed, when the Earth and the other planets were formed they were rather hot (indeed, molten) due to the violence of their many collisions. However, the inner planets cooled off at different rates. You can think of it like this: imagine that you have taken a freshly-cooked pie out of the oven. If you want to cool it off as quickly as possible, are you better off letting it stand as is, or cutting it into many smaller pieces and letting those cool off? The latter, of course. This also works for planets. Large ones, such as the Earth, cool off much more slowly than small ones, such as Mercury or Mars (or the Moon, if you want to consider that an honorary planet).

This has a surprising number of important consequences. One is that the Earth has a relatively thin crust on top of a molten interior. Convection in that molten interior breaks up and moves the crust around in plates, leading to plate tectonics (and causing earthquakes, volcanoes, the beautiful fit of Africa and South America, and lots of other good stuff). Historically, this has caused ecosystems to shift around as the shore-to-interior ratio of continents has altered. This may have played an important role in evolution. The liquid nature of the Earth's interior has also allowed us to sustain a magnetic field that is strong enough to deflect high-energy charged particles from the Sun. It's difficult to forecast what would have happened to life here without the field, but current life would be severely damaged by those particles. In addition, of course, the size of the Earth allows us to retain a significant atmosphere.

In contrast, the Moon and Mercury are small enough to have cooled off almost completely. There do appear to be liquid components in both, but not enough for plate tectonics. The same is true for Mars. Venus, which is just slightly smaller than the Earth, is a special case. We see no active tectonics at the moment, but at the same time it appears that there are no craters older than about 500 million years on the surface. Why might this be? One intriguing possibility is that the crust is thicker than on Earth, but that energy continues to be released in the center because of radioactive decay. In this picture, when the energy buildup is large enough, the granddaddies of all eruptions explode in many places, causing lava to resurface Venus. This might have happened many times in the past, but in this picture the last one was half a billion years ago.

By the way, let me forestall one possible misconception. We think of the Sun as providing our heat, so it would be natural to imagine that the inner planets Mercury and Venus would be kept hot mainly by the Sun, with their interior heat playing a minor role. However, note that here we are concerned with whether *rock* is solid or molten, and the Sun's heat is nowhere close to enough to melt rock even at Mercury. Therefore, yes, the surface temperature does depend significantly on the Sun's illumination, but the thickness of the crust depends on how long the interior takes to cool.

How special is Earth? A first look

As we move through the course we'll occasionally return to the issue of how special our situation is. We can now revisit this by noting that some people think that Earth is in a uniquely privileged environment, so that very few planets should be expected to support life. Examples of some of the proposed specialness include:

- Earth had to have formed right about now in cosmic history. Earlier, and not enough heavy elements would be present. Much later, and maybe so much mass would be present that the surface would be constantly wracked with quakes or even molten.
- The low eccentricities of the Solar System are unusual. Stuff smashing into other stuff tends to decrease eccentricity because the random motions average out, but near the end of major planet formation there are a few large bodies moving around and these deflect each other gravitationally rather than colliding. Simulations indicate that this leads to high eccentricities, and indeed many extrasolar systems are like that as well.

What do you think?

In any case, even if we have a planet of the right type in the right orbit, life still has to develop. The origin of life is difficult to constrain strongly (although we'll discuss it in a later class). However, once life has taken hold, further development occurs via a powerful and elegant mechanism called evolution. We will discuss many aspects of evolution over the next four lectures.