Star and Planet Formation Role-Playing Exercise

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Original Version April 1997. This version March 10th 1998

1 The Puzzle

Many giant gas clouds exist in space: they are about 10^{16} m in size, and have masses of around 3×10^{30} kg. They contain all the right chemical elements to form a sun and its planets. Your mission: to work out how one of these clouds could turn into a solar system.

2 Condensation Experts

Many astronomers tend to forget that solid objects exist: after all, nearly all of the universe we observe is made of gas and radiation. You, however, are experts on solid materials, and how they form out of gas clouds. Perhaps you were fascinated by meteorites during your childhood, and decided to figure out how they formed, or maybe pictures of swirls of dust in space (tiny grains of solid material floating amidst the interstellar gas) got you into this field. You do a great deal of work in the lab, using electron microscopes to study tiny grains of solid interstellar material collected on space missions.

You know that any gas cloud containing reasonable quantities of heavy elements (such as carbon and silicon) will slowly form tiny lumps, as molecules bump into each other and (occasionally) stick. This process is normally very very slow: most interstellar clouds have such low densities that atoms and molecules rarely touch, and the formation of grains would take more than 10^{10} years.

If, however, a cloud of gas was squashed down to a size of only $\sim 10^{13}$ m or less, the density would be so high that the gas would start to coalesce into tiny grains. Atoms of gas would brush against these grains, and some would stick, causing the grains to slowly grow. The process would take around 10^5 years, but the gas cloud would, at the end of this time, have formed tiny lumps, the size of grains of sand (~ 1 mm). By this time, most of the heavy elements will have been used up in forming grains, and the condensation process stops.

3 Hubble Space Telescope Experts

You are an observer: you get fed up with all these theorists waffling on about how stars and planets might form: you decided to go and look at some nearby gas clouds for yourself to try and *see* how stars and planets form.

You turned the Hubble Space Telescope on several nearby giant gas clouds. In all of them, you found dense regions containing new-born stars. Curiously, most of these stars were surrounded by spinning disks of gas and dust, about 10^{13} metres across.

What does this mean? You're not sure. 10^{13} m is about the size of the solar system, so you think that these spinning disks might have something to do with planet formation.

4 Gravity Experts

You are experts on gravity. This means that you are very important people, as gravity is the most powerful force in the universe! Gravity is also a mathematically beautiful force: you probably got into this field because you were attracted by the mathematical elegance, and you are probably very good at solving equations. You spend your professional lives calculating orbits, and the dynamics of satellites, planets, stars and galaxies.

Gravity attracts everything towards everything else: this includes different parts of the gas cloud. So, *in the absence of any other forces*, the different parts of the cloud will start accelerating towards each other. If nothing else stops it, the cloud will shrink down to a black hole of mass around 3×10^{30} kg in about 3×10^6 years.

This black hole will attract other black holes, and over a period of $\sim 10^{11}$ years will swallow any nearby black holes and stars, getting more and more massive as it does so.

5 Meteorite Experts

You are a unique type of astronomer: one who actually gets to handle what you study. Your speciality is meteorites: lumps of rock that fall from space. You search the Nullarbor Plain and the dry Antarctic valleys to find them, and once you've got them in your lab, you show them no mercy!

You have recently been concentrating on a class of meteorite called Chondrites. These seem to date right back to the very earliest moments of the solar system: 4.6 billion years ago when the sun and planets had just started to form. Remarkably, most of these meteorites seem to be made up of thousands of tiny millimetre-sized grains, loosely stuck together. It seems that at this crucial moment in solar-system formation, vast clouds of tiny grains must have been orbiting the Sun, slowly sticking together to form these bigger meteorites.

Other meteorites contain solid rock: these may once have been chondrites, but seem to have been melted at some point, perhaps by a collision with something bigger.

6 Planet Experts

You spend your life studying pictures of the planets. Many a happy hour has been spent, magnifying glass to your eye, counting craters on Mercury, volcanos on Mars or canyons on Venus.

One thing that has struck you is that all the oldest bodies in the solar system have badly scarred surfaces. For example, you know that most of the moon dates back to the very first days of the solar system (from radioactive dating of moon rocks brought back by the Apollo missions). And the moon has taken an awful beating: every square centimetre is covered with craters and debris, created by collisions with meteorites.

There certainly aren't that many meteorites around today: what these pictures are telling you is that, back in the early days of the solar system, meteorites must have been very common; constantly raining from the skies. Some must have been huge: there are craters thousands of kilometres across.

The puzzle is: where did all these lumps of rocks (meteorites orbiting the Sun) come from, and where did they go?

7 Rock Experts

Throughout the solar system, rocks are flying. We call them meteorites, until they hit one of our spacecraft, when we call them less polite things. Many hit the Earth: most burn up in the upper atmosphere, but a few reach the ground, and can be collected. You are experts on theories of these fascinating lumps of rock. Perhaps your passion for meteorites started as an undergraduate, unable to decide between geology and astronomy courses...

You are particularly interested in what happens when you have a large number of little grains in a small region of space: say 10^{13} m in size or less. If the grains are too small: less that 0.1 millimetres or so, they almost never touch each other, so the cloud of grains stays as just that: a cloud of grains. If, however, the grains are larger, something very different starts to happen. Grains start hitting each other and sticking together, so they rapidly grow in size.

Once they are a few metres in size, the process gets faster still: their mutual gravity sucks them towards each other, causing more and more collisions. These rocks get bigger and bigger: after only a few thousand years, they could be many kilometers across: you would now call them asteroids. But still the collisions would continue: huge violent collisions as kilometer size blobs of rock smash into each other, travelling at dozens of kilometers per second. This violent phase would last only a short time: soon, nearly all rocks would have been sucked into these huge lumps, which might be thousands of kilometers across.

These huge rocks can have so much gravity that the pressure in their centres liquifies the rock: they would then slump down into spherical shapes. If they are big enough, they could even suck in any gas around them and acquire atmospheres!

8 Rotation Experts

Everything in the universe is spinning. The earth spins around its axis, all the planets spin around the sun, and the sun spins around the centre if the Milky Way galaxy. Despite all this rotation, however, many astronomers ignore rotation in their calculations. Not you: you are experts on rotation, and you delight in going to conferences and gently (or not so gently) pointing out the errors of those who ignore rotation.

The giant gas cloud, like everything else in the universe, is spinning. This is probably because all the gas that makes it up came from stars, which are themselves spinning around the centre of the galaxy. This spin is very slow: far too small to have any significant influence on the gas cloud.

However: the laws of physics state that if a spinning object shrinks, it has to spin faster (or if it grows, it has to spin slower). Springboard divers use this phenomenon to make themselves spin faster, by hugging themselves into tight balls.

So, if the gas cloud got larger, it would spin even more slowly, but if it shrinks, it will spin faster and faster. This isn't important as long as the cloud stays large. If, however, some force was able to squeeze the cloud down by a thousand times (so it was only about $10^{13}m$ big), it would be spinning 1000 times faster. This rapid spin would cause such strong centrifugal force that the cloud couldn't shrink any further.

It would form a spinning disk of gas around a central lump. The central lump would weigh around 2×10^{30} kg, with the remaining matter left in a dense disk of gas spinning around it.

9 Star Experts

Nearly everything you see in the night sky is either a star, or made up of stars. You are experts on stars, which requires a bit of a contrary streak. After all, many astronomers think that we understand stars: that they are basically pretty simple, and that only boring people study them. You know that this is complete rot: we may understand the basic principles behind stars, but just like people, every star is an individual, and every star has its fascinating quirks and oddities worthy of study. And anyway, if we can't understand stars well, we have no hope with the rest of the universe, most of which is made up of stars! You spend half your time taking spectra of unusual types of stars, and half in running detailed computer simulations of the nuclear reactions taking place deep within their cores.

Any cloud of gas will turn into a star if it gets hot and dense enough that nuclear fusion begins. You need a dense lump of gas of around 10^{29} kg to trigger fusion. This vast mass must be squeezed into a volume of radius less than about 10^9 m. Once fusion starts, hydrogen atoms fuse to form helium, releasing floods of energy in the process.

The radiation from the star will blow away any light gassy elements within about 10^{12}m of the newborn star. The star will look much like the sun, and will shine for about 10^{10} years, until it runs out of hydrogen in the core. At this stage, it will swell up into a red giant star, around 10^{11}m in size, and then collapse to form a white dwarf star, only a few thousand kilometers across. This white dwarf will then sit there for billions of years, slowly cooling.