THE SOLAR SYSTEM

Wing-Huen Ip
National Central University, Chung-Li, Taiwan

Keywords: solar system formation, planets, biosphere, photosynthesis, chemosynthesis

Contents

Summary

The solar system is the only laboratory in which we can test ideas and theories of the origin and evolution of life in the universe. It is indeed our privilege to be a part of its living system. This article includes a very brief account of current thinking on the formation of planets, the co-evolution of the biosphere and hydrosphere of Earth, and other possibilities of life in the Galaxy and elsewhere. Humankind is finally at the threshold of exploring the biological universe and we expect rapid progress in the next decade by astronomical observations and laboratory research.

1. Introduction

In the context of life support systems, the only place in the Universe that we have found to be home to life so far is our own solar system. Is it unique? Or could it be possible that some galaxies in the universe are filled with life-forming communities. Generations of astronomers and scientists have searched for an answer without definite results. The recent breakthrough in the astrometric detection of large Jovian-sized planets orbiting around stars has brought much excitement and stimulation to research in this field. Perhaps, we are finally at the threshold of finding ocean-carrying planets and hence potential abodes for life in our Galaxy. As a consequence, study of our own solar system now has a deeper meaning and more urgency than before. We want to know how and when life originated on Earth. How did it evolve? What setbacks has it experienced? We also want to know whether life can exist elsewhere in the solar system. Has life ever flourished on Mars and/or other planets and planetary satellites?

What is the story of the rise and fall of life on individual planetary bodies? All these fundamental questions must eventually lead to knowledge of the origin and evolution of the solar system as a whole. It is with this train of thought that we describe the process of solar system formation and early evolution.

2. Accretion

The solar system formed around the Sun, which is an active star (see Figure 1). The formation of the solar system must have been preceded by the gravitational collapse of an interstellar molecular cloud. Because of the initial rotation of the molecular cloud, the collapsing mass formed a flat disk called "accretion disk." Figure 2 shows an example.

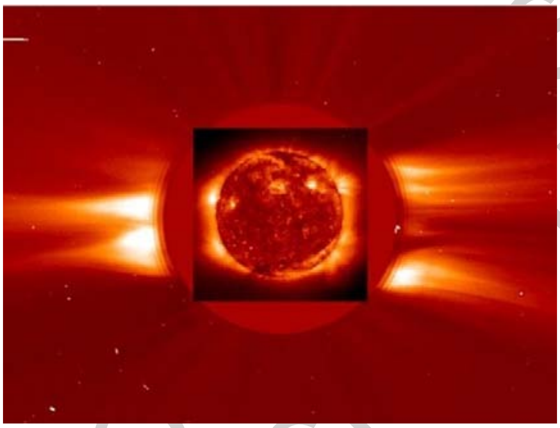

Figure1. The image of the sun in X-ray emission superimposed on the extended coronal structures taken by using coronographic technique. Both observations were obtained by the instruments on the Solar and Heliospheric Observatory of the European Space Agency.

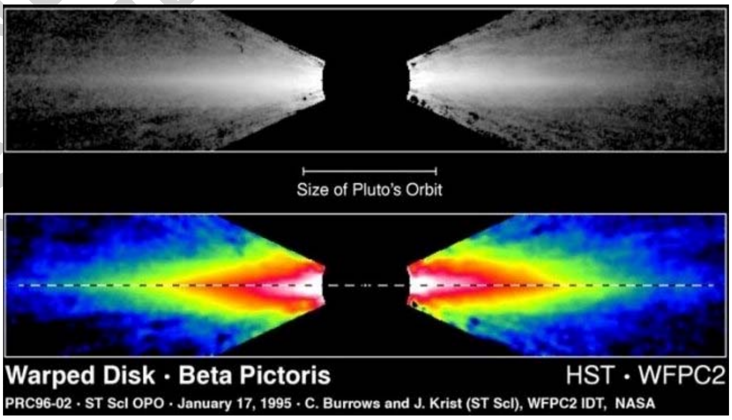

Figure 2,Spatial distribution of particulate matter surrounding Beta Pictoris as observed by the Hubble Space Telescope. The central star was masked so that the circumstellar dust disk could be imaged. Data source: NASA.

This disk is filled with gas and interstellar dust particles. Because of its viscosity, the mass in the accretion disk will drift inward, feeding the growing central body, the proto-sun. The luminosity of the proto-sun and the viscous interaction of the material will lead to heating of the accretion disk. The high temperature of the disk particles produces radiation in the infrared wavelength. This is the reason that young stars of the solar type are characterized by excessive infrared emission in their surrounding areas. These systems are called T-Tauri stars (TTS). Besides the infrared excess, some TTS also exhibit strong ultraviolet and X-ray emissions. The large time variations in the optical luminosity of a few TTS suggest that evolution of accretion disks could be highly dynamic and violent. Strong winds are generated in TTS which might lead to the sweeping and clearing of the residual matter in the planetary systems. The time span of the T-Tauri phase has been estimated to be about one million to ten million years. This age determination is based on the level of infrared emission and radio-wave radiation that are associated with the circumstellar gas and dust disks. However, observations by the Infrared Space Observatory (ISO) have shown that disks of solid dust can be present for as long as a few hundred million years.

3. Dust Condensation

The chemical composition of the solid particles in the solar nebula is determined by the temperature gradient of the accretion disk. Theory and observations suggest that the surface temperature is proportional to r^{-a} where r is the radial distance from the central star and the spectral power index a is 0.5–0.75. Close to the proto-sun, say, within one astronomical unit (AU; the distance between Earth and the Sun), the temperature could be as high as 800 K. Therefore only nonvolatile substances like SiO_2, MgO, and Al_2O_3 can condense. These materials will then determine the rocky composition of the terrestrial planets. As the radial distance increases, the thermal temperature will decrease accordingly. It is generally believed that the temperature of the solar nebula near the orbit of Jupiter will reach a value below about 150 K at which point water ice will condense. Such a concept of the so-called water line is similar to the boundary (e.g., snow line) in high mountains separating ice-covered regions from regions of lower altitude without ice. The important thing is, once water ice is made available to planet formation, the planetary mass can become much larger than that of a terrestrial planet made up of rocky material. This is the basic reason why there is such a mass difference between the outer planets (Jupiter, Saturn, Uranus, and Neptune) and the terrestrial planets (Mercury, Venus, Earth, and Mars) in the inner solar system.

4. Planetesimals

At the beginning of the condensation process, the dust grains are only of micron size (one micron is one millionth of a meter, comparable to the size of a cell). Once condensed, they will settle towards the mid-plane of the solar nebula and form a thin dust layer. There are currently two schools of thought on how these tiny dust grains eventually assemble into small planetesimals of about one kilometer in diameter. One idea, championed by the Russian astronomer V.A. Safronov and the American astronomers P. Goldreich and W.R. Ward, suggests that gravitational instability is the key process. That is, if the thickness or the thermal velocity of the dust layer of a certain surface density becomes less than a critical value, the dust layer becomes unstable and the solid mass collapses into ensembles of loosely bounded dust clouds. The dust ensembles eventually form more compact objects. This is the most direct way to bypass the seemingly daunting task of building kilometer-sized planetesimals from grains of only a few microns. For this scenario to work, it is essential that the dust layer be extremely cold and the random velocity of the dust particles of just a few centimeters per second. It is for this reason that an alternative mechanism was proposed by the American astronomers S. Weidenschilling and J. Cuzzi. These researchers theorized that, because of the aerodynamic turbulence generated by the interaction of the dust layer with the gas component, it is difficult for the solar nebula to maintain the laminar condition. High turbulent velocity of the gas will be generated. Thus the turbulent dust layer will likely not be thin enough for gravitational instability to take place. The only way for the dust particles to grow is to follow the track of collisional sticking and agglomeration. However, it cannot be ruled out that the structure of the solar nebula could alternate between the laminar and turbulent state, thus permitting the above two mechanisms to operate alternately at different times.

5. Planetary Accretion

Planetesimal formation may be a very rapid process. The evidence for the presence of large amounts of the aluminium isotope (^{26}Al) in meteorites argues for a timescale as short as one million years. The short Keplerian orbital periods of the terrestrial planets means that the timescales of stochastic collisional interaction among the planetesimals should also be short.

Theoretical results from numerical computations imply an accretion time of a few million years for the growth of Earth and other terrestrial planets. If one of the planetesimals gains sufficient mass such that its gravitational force becomes important in capturing materials in neighboring regions, the enhanced cross-section will enable this body to reach the condition of runaway growth until it exhausts the condensed matter in its accretion zone. As a result, the final phase of the accretion process is usually characterized by the presence of a single dominant protoplanet.

The formation of the outer gaseous planets is more complicated. For Jupiter and Saturn, the bulk of the planetary mass is composed of hydrogen molecules and helium atoms. Besides the collisional interaction of solid bodies, hydrodynamic effect of the gas component must have been important. A model pioneered by the Japanese astrophysicist H. Mizuno, describes the formation scenario as follows.

When the core of Jupiter, composed of rocky material and ice, grows by collisional accretion to a mass about 10 times the mass of Earth, hydrostatic instability sets in, forcing the extended gaseous envelope to collapse onto the central core. It is interesting to note that all of the giant planets have core masses of similar values. Jupiter, Saturn, Uranus, and Neptune could all have experienced the hydrostatic collapse effect described above. The subsequent accretion is then dictated by the hydrodynamic interaction of the growing protoplanet with the solar nebula. In spectroscopic observations of TTS, there are indications that some accretion disks have gaps of finite width that might have been opened by accreting bodies.

-
-
-

Bibliography

Cook A.H. (1988). *Interiors of the Planets*. 348 pp. Cambridge, UK: Cambridge University Press. [This provides a description of ideas about the structure and interiors of various planets.]

Takahashi E., Jeanloz R., and Rubie D.C., eds. (1993). *Evolution of the Earth and Planets*. 159 pp. Washington, D.C.:American Geophysical Union/International Union of Geodesy and Geophysics. [This is a collection of papers dealing with the evolution of Earth and other solar system planets.]

Taube M. (1985). *Evolution of Matter and Energy on a Cosmic and Planetary Scale*. 289 pp. Berlin: Springer. [This is good introductory book for evolution of solar system and its cosmic environment.]

Biographical Sketch

Wing-Huen Ip, was born on March 10, 1947 in Nanjing. After a brief sojourn to Taiwan, he went to Macau and grew up there. He studied physics at the Chinese University of Hong Kong and continued to pursue his graduate education in the United States. He was graduated from the University of California at San Diego in 1974 with a PhD degree in space physics. His thesis work was on small bodies of the solar system. After three years of postdoctoral research at the same institution, he went to work as a research scientist at the Max Planck Institute for Aeronomy in Germany. In 1998 he left Germany for Taiwan where he is Professor of Astronomy and Space Science at the National Central University and is currently serving a tenure as Dean of Science. His research interests cover cometary physics, planetary formation, the evolution of exoplanets, planetary atmospheres and magnetospheres, solar physics, cosmic rays, and astrophysics. Reading and painting are his hobbies.