ASTROPHYSICS AND I—MOTIVATIONS, METHODS, AND THE OUTLINE OF MY RESEARCH—

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Theoretical research in astrophysics has been a major part of my life. On this occasion, I would like to recall my past and talk about what made me choose astrophysics as my field of study, what research subjects I selected, what method I used in my researches, and what results I obtained. My research themes can be roughly classified into the following three grouping: the synthesis of elements in the early phase of the Big Bang universe; stellar structures and evolution; and the origin of the solar system, or how the earth and other planets were born. Regarding these three themes, I will briefly explain researches conducted prior to my own, and then my own research.

In 1937, I entered the Third High School in Kyoto at the age of seventeen. At that time, the Japanese-Chinese War had not yet broken out, and there were no regulations regarding publication. Accordingly, I was able to read any book I wanted. I read many literary and philosophical works. Although many philosophical works were difficult for me, I think I understood some by Descartes and Kant considerably well.

In his "Discours de la méthode" (1637), Descartes suggests many useful instructions for researchers. For instance, he states that only the following four approaches are necessary for conducting any research: 1) attitude for studying must be rational, and analysis must be clear; 2) research objects must be divided into categories as small as possible; 3) one must start with the simplest and easiest issue and proceed to more complex and difficult issues; and 4) to avoid overlooking basic issues, one must count every issue and review the entire research. These suggestions of Descartes had tremendous influence on my research approaches.

Kant describes the difference between mathematics and physics in his work written in 1799: empirical verification is necessary for physical theories, while it is not for mathematical theories. Today, the mainstream of natural science philosophy is logical positivism, of which Descartes and Kant were pioneers. According to logical positivism, both accurate theoretical development and strict verification by experimentation or observation are necessary for any scientific research. This principle has been a guideline to me throughout my research career in astrophysics.

Prior to my graduating from high school, I pondered what subject I should major at a university. Finally, I selected physics, since physics at that time seemed to me the most advanced field of theoretical and positivistic science. I obtained this impression from a book I read at that time, which described the remarkable progress in quantum mechanics. After joining the Department of Physics, Faculty of Science at the University of Tokyo, I devoted myself to studies of quantum mechanics, general theory of relativity, and statistical mechanics. All these subjects were essential for my later researches in astrophysics. When I was a junior student, I studied nuclear theory and elementary particle theory under Professor Kiichiro Ochiai. The department provided me with an opportunity to read papers by world-class scholars: the latest papers were allocated to each student to read and give presentations on. To my surprise, the paper allocated to me was the one on stellar nuclear reactions by Gamow. Since in his paper Gamow quoted from the "Internal Constitution of the Stars" by Eddington, I read the work by Eddington. This experience of reading Eddington's work influenced my later decision to select astrophysics as my research field.

After graduating from the University of Tokyo, I was permitted to remain as a research assistant under Professor Ochiai. At that time, however, World War II was already increasing in severity, and I had to serve in the navy. I served for three years in Yokosuka as a technical officer. After the war was over, I returned to the University of Tokyo.

Soon after I began a study of elementary particle theory under the direction of Professor Ochiai, I was obliged to move out of my apartment in Tokyo. Since my family was in Kyoto, I asked Professor Ochiai to allow me to join the research group under the direction of Dr. Hideki Yukawa at Kyoto University. I was admitted to Kyoto University, and returned to Kyoto in April 1946. At that time, I was determined to continue my study of elementary particle theory; however, I began to study astrophysics for the following reason.

At that time, there were two research groups under the direction of Dr. Yukawa: one focusing on elementary particle theory and the other on astrophysics. Since the laboratory used by the former group was overcrowded with researchers, Dr. Yukawa suggested that I study the nuclear reactions in stars in the laboratory of the latter group. I was already familiar with this field, since I had read the paper by Gamow, as I mentioned before. Accordingly, I decided to conduct researches on both elementary particle theory and stellar nuclear phenomena. Since I already had basic knowledge on nuclear theory, statistical mechanics, and general theory of relativity, I was able to conduct researches on stellar energy sources and the origin of elements without much difficulty. I read many papers and texts on cosmology and stellar internal constitutions.

My first research concerned the structure and energy source of red giant stars. Also, I calculated the abundance ratio of protons and neutrons during the early phase of the expanding universe. I will indicate the results of these researches later. In 1949, I became an associate professor of the Department of Physics, Faculty of Engineering in Osaka Prefectural Naniwa University, and began devoting myself to the research on elementary particle theory. My efforts during this period were rewarded: in 1954, I was invited to Kyoto University as an associate professor. At Kyoto University, I continued my research on elementary particle theory, particularly on non-local, nonlinear field theory. At that time, however, study of elementary particle theory was at an impasse, so to speak.

In 1955, Kyoto University Fundamental Physics Institute, directed by Dr. Yukawa, held a two-week seminar on stellar nuclear phenomena. Many researchers in astronomy and physics gathered from Tokyo, Sendai, and many other places to discuss the present states and future prospects of researches on stellar evolution, the origin of elements etc. After participating in this seminar, I resumed my researches on stellar nuclear phenomena. First, I reviewed the issues of red giant stars. Together with late Professor Sachio Hayakawa, I also began research on helium nuclear fusion, whereby atomic nuclei of oxygen and carbon are formed. This research was necessary for exploring stellar structures and the evolutionary process in the helium-burning phase. In 1957, I was promoted to professor, and formed a new astrophysics research group in Kyoto University. Since then, I have collaborated with young research staff members and graduate students on the synthesis of elements in stellar internals, and stellar evolution. In these researches, two important elements were the calculations of micro and macro processes, namely, that of nuclear fusion and that of change in stellar structure. I will touch on the results later in this presentation.

For 15 years, I continued researches on stellar evolution. In 1970, however, I commenced new research on the origin of the solar system, for the following reasons. First, I thought I had sufficient study on stellar evolution and I understood most of the characteristics of the stellar evolutionary processes leading to the final stage. Secondly, I began to understand the evolution of the protosun, which greatly affected the formation of the solar system. Over the 15 years until my retirement in 1984, I collaborated with young researchers on the processes of the solar system formation, developing a theory called the “Kyoto Model.” The Kyoto Model is different from many other models in the contention that a vast amount of gas remained around the planets at the time of their formation from dust. The Kyoto Model offers an integrated description of the formation of all planets, from Mercury to Pluto.

Now, I would like to proceed to my next topic, and present a bit more detailed explanation on my research themes: the synthesis of elements in the early phase of the Big Bang; stellar structure and evolutionary processes; and the origin of the solar system.

In 1929, Hubble (U.S.A.) announced his important findings that galaxies are receding from us at velocities that increase with distance. This is known as “Hubble's Law.” In accordance with Hubble's Law and the laws of thermodynamics, the earlier the time, the more compressed were matter and radiation in the universe. Looking backward into the remote past, because of this high compression, the temperature of the universe was extremely high. When the temperature was as high as one billion degrees, there were no atomic nuclei, since at this temperature nuclei were dissociated into protons and neutrons; at five billion degrees, the collisions of high energy photons caused the formation of electron and positron pairs.

In 1948, Gamow (U.S.A.) announced the Big Bang theory, stating that the universe had begun expanding from a state of extremely high temperature and high density. Moreover, he put forward the bold hypothesis that only neutrons were present in the earliest phase of the universe. Based on this hypothesis, he developed a theory, according to which, with the drop in temperature resulting from the expansion of the universe, neutrons began slowly decaying into protons, and the fusion of neutrons and the newly formed protons synthesized all elements that make up the sun, planets, and stars.

Previously, being much interested, I read many papers on the origin of elements. When I came across Gamow's paper, I thought his hypothesis was incorrect in holding that only neutrons existed at the beginning of the universe. In my view, in the earliest phase of the universe, in addition to neutrons, there were abundant electrons, positrons, and neutrinos, which catalyzed mutual transformation between neutrons and protons. When the temperature of the universe dropped to 10 billion degrees, free protons and neutrons began combining. This was the beginning of elemental synthesis. The amount of various elements synthesized depended on the abundance ratio of protons and neutrons immediately prior to the elemental synthesis. Based on elementary particle theory and the laws of statistical mechanics, I began calculating time changes in the abundance ratio of protons and neutrons at this stage.

In the Big Bang theory, the relation between the time after the beginning of the Big Bang and the temperature of matter (and also radiation) is given by the general theory of relativity, which is a macro-law. Temperature is inversely proportional to the square root of time. For instance, 0.1 seconds after the Big Bang, the temperature fell to 10 billion degrees. At this temperature, the universe was full of gamma rays, and a vast amount of electron pairs were formed via an extremely rapid reaction, shown below:

photon＋photon (gamma ray) ⇄ electron＋positron (Formula 1)

At the same time, there were relatively small amounts of protons and neutrons, and vast amounts of electrons, positrons, and neutrinos. According to the beta-decay theory, the conversion of protons and neutrons occurred as shown below:

neutron＋positron ⇄ proton＋neutrino

neutron＋neutrino ⇄ proton＋electron

neutron ⇄ proton + electron＋neutrino (Formula 2)

The speed of the above-mentioned reactions was higher at higher temperature. With a drop in temperature, the reaction speed slowed, becoming less than the expansion rate of the universe.

To clarify the non-equilibrium reaction processes of the above-mentioned reactions, I calculated the frequencies of each forward and reverse reaction in Formula 2 at various stages of temperature decline. The results are as follows: At 30 billion degrees, the speed of forward and reverse reactions shown in Formula 2 were higher than the expansion rate of the universe. Since the forward reactions and reverse reactions were about the same in speed, the ratio of protons and neutrons approximated 1 : 1 . With a drop in temperature, however, the forward reactions began exceeding the reverse reactions. As a result, protons surpassed neutrons. At 100 seconds after the Big Bang, the temperature fell to 1 billion degrees. At this temperature, protons and neutrons began to combine together to produce the nuclei of helium atoms. At that time, the proton-neutron ratio was about 4 : 1 or 8 : 2 . This means that when two protons and two neutrons combined to form one helium nucleus, six protons remained in the forms of hydrogen nuclei. This ratio of helium and hydrogen coincides with the ratio of the two elements observed on the solar surface.

In 1965, when two scientists were monitoring microwaves, they discovered that the present universe is full of 3°K black body radiation. This discovery supported the Big Bang theory. In the early phase of the Big Bang, black body radiation was in the form of gamma rays; as a result of expansion of the universe, the wavelength of those gamma rays has been lengthened, making them microwaves. Meanwhile, the discovery of black body radiation prompted many scientists to calculate the synthesis process of various elements. Their results conformed with the actual amounts of light elements observed on the solar surface, including helium, deuterium, lithium, beryllium, and boron.

Together with the discovery of 3°K black body radiation, the agreement of calculated and observed amounts of light elements offered important evidence supporting the Big Bang theory. I would like now to mention the synthesis of heavy elements. Together with helium, heavy elements (carbon and elements heavier than carbon) are synthesized in the high temperature layers of stellar interiors. Such elements are then released from stars and mixed with interstellar gas, which later form another star. Chemically, the sun consists of hydrogen (approximately 73% in weight), helium (approximately 25%), and heavy elements (approximately 2 %). Whereas light elements (boron and elements lighter than boron) were synthesized during the early phase of the Big Bang, heavy elements were (and still are) synthesized inside stars.

At the beginning of the 20th century, scientists began measuring the distance from the earth of many stars. When they knew the distance and apparent brightness of various stars, they were able to work out the luminosity of such stars. As well, the analysis of radiation spectral types revealed stellar surface temperatures. Around 1910, Hertzsprung (Denmark) and Russell (U.S.A.) invented the so-called Hertzsprung-Russell Diagram (HR diagram), whose vertical axis indicates luminosity, the horizontal axis indicating surface temperature. The majority of stars, including the sun, lie on a narrow diagonal band known as the main sequence. Most of the remaining stars belong to a red giant branch; others belong to a white dwarf branch. White dwarfs are a group of stars of very small radius (roughly 1 /100 the solar radius) and extremely high density (approximately 1 ton per 1 cubic centimeter). The HR diagram is a useful tool for confirming various theories on stellar structures and evolutionary processes.

To clarify stellar structures, we must investigate temperature and pressure distributions from the center to the surface of stars. Pressure and gravity are balanced at any point in the stellar interior. The heat flow from the center to the surface is proportional to the thermal gradient. Heat reaching the surface is radiated from the surface; the outflow of this radiation is nothing but the luminosity. The temperature and pressure distributions are expressed in non-linear differential equations.

The average solar density is about the same as that of water on the earth. Prior to 1920, scientists did not know whether stars, including the sun, were made of gas or liquid. Then in 1920, Eddington (U.K.) found a solution to this question by using the newly introduced quantum theory. According to Eddington, because of extremely high temperature, nuclei and electrons in stellar interiors do not combine; this state is very close to the ideal gas state. Also, Eddington found that heat is conveyed by radiation in stellar interiors. According to his model, the internal structure of main-sequence stars, including the sun, are as follows: the temperature in the central region is proportional to the mass of the star, but inversely proportional to its radius. The solar temperature, for instance, approximates 10 million degrees at its center. When Eddington put forward this theory, the source of stellar energy remained a great mystery. Eddington, however, derived his model from the hypothesis that the energy source is located in the stellar central region.

The problem of the energy source was eventually solved by Bethe (U.S.A.) and Weizsäcker (Germany) around 1938. As pioneers of nuclear theory, the two scientists, while investigating a series of nuclear reactions of protons with carbon/nitrogen atomic nuclei, discovered the so-called carbon-nitrogen cycle processes. In these processes, the fusion of four protons leads to the formation of one helium nucleus. In addition, Bethe discovered the so-called proton-proton chain reactions, wherein four protons combine to form one helium nucleus, as in the carbon-nitrogen cycle processes. Most carbon-nitrogen cycle processes occur at temperatures exceeding 20 million degrees, while most proton-proton chain reactions occur at temperatures below 20 million degrees. Bethe then determined temperatures in the central regions of various stars, based on the energy radiated by such nuclear fusion reactions. (Energy radiation equals luminosity; therefore, if one knows the luminosity, one can determine the temperature where such nuclear fusion occurs.) Since the calculated temperatures of the main-sequence stars agreed with the values predicted by Eddington, the problem of stellar energy sources seemed to be solved.

However, a new question then arose. If we apply Eddington's theory to a red giant star, the central region of the red giant star, that has 100 times the radius of the sun, would have 1/100 of the temperature of the sun. In reality, however, the red giant star radiates over 100 times the energy of the sun. In 1946, I commenced my research to solve this question, believing that the influence of stellar evolution as mentioned below must be taken into account.

In the central region of the sun, helium is formed at an extremely slow rate by hydrogen nuclear fusion. In other words, helium is gradually replacing hydrogen. Several billion years from now, all the hydrogen in the central region will have been replaced by helium, which will form a helium core in the central region of the sun. The core will be surrounded by a thin spherical shell, where hydrogen nuclear fusion will continue, increasing the mass of the helium core. At this stage, there will be no energy source inside the core; therefore the central temperature will not rise very much. Gravitational contraction, however, will radically increase the core density to 10kg per 1 cm^3 or more. Such high density gas is called degenerate electron gas or Fermi gas.

I would now like to briefly explain on degenerate electron gas. When gas is compressed by keeping its temperature constant, atoms in the gas begin to contact each other. If the gas is further compressed, electrons are freed from nuclear electric attraction. In accordance with quantum mechanics, electrons have discrete kinetic energy values. Moreover, electrons obey what is known as Pauli's exclusion principle, which states that two electrons cannot exist in the same state; in other words, they cannot have the same kinetic energy. When the gas is compressed, kinetic energy of free electrons increases, according to the uncertainty principle. The more the free electron gas is compressed, the higher the maximum kinetic energy of electrons. With increasing kinetic energy, gas pressure also increases. Gas has pressure even at 0°K, the pressure being proportional to the five-third power of the gas density. It is the high pressure of this degenerate electron gas that supports white dwarfs against their high gravity.

I will now go back to my main subject: the internal structure of stars consisting of an isothermal, high density helium core and an outer layer that contains abundant hydrogen, with a thin spherical shell at the interface, where hydrogen is burning. To determine the pressure and temperature distributions of such stars, I integrated differential equations numerically. Since I did not know the values of luminosity and core temperature before finding a solution, I assumed several values for these values. To know the pressure and temperature distributions in the outer layer, I integrated the equations from the surface to the core-outer layer interface; to know those distributions in the helium core, I integrated the equations from the center to the interface. Pressure and temperature values at the interface had to be equal in the two integrations; also, the amount of nuclear energy generation must agree with the stellar luminosity. I sought a solution that satisfied these two conditions.

Whereas the sun has its energy source in the central region, red giant stars have their energy source in a thin spherical shell surrounding the helium core. Red giant stars are characterized by two layers: an extremely condensed core and a low-density outer layer. The distance from the center to the energy source is about 1 /10 of the solar radius. The core density rapidly declines from the center to the core surface. The densities in the interface and the outer layer are quite low in comparison with those of the sun. The low density of the outer layer corresponds to the huge stellar radius.

Since 1955, I have devoted myself to stellar evolutionary processes induced by the growth of helium cores. I would now like to review the results of my collaboration with young researchers in my laboratory.

First, I will explain the future evolution of the sun. Several billion years from now, the helium core in the central region of the sun will grow to reach 20% of the sun's total mass. The sun will by then have grown to approximately ten times its present radius. When the core mass reaches 40% of the sun's total mass, the radius will grow to 100 times the present radius, with luminosity reaching 1,000 times the current value. At this stage, the sun will become a red supergiant. The core temperature will approximate 100 million degrees; in the central part of the core, helium nuclei will be fused to form nuclei of carbon and oxygen. This means the sun will have dual energy sources: one in the central region of the core, and the other in the interface between the core and the outer layer. At this stage, the radius will decrease to some extent. When the helium nuclear fusion progresses in the core center, a core made of carbon and oxygen will be formed newly there. Surrounding this core will be a helium interlayer. Surrounding this interlayer will be an outer layer of abundant hydrogen. With the lapse of time, the carbon-oxygen core will grow in mass. In case of the sun, however, the rise of the central temperature will stop at a certain point; therefore no carbon nuclear fusion will occur. Emitting gas from its surface, the sun will then become gradually cooler, and nuclear fusion will eventually stop. At the final stage, the low-density outer layer will peel away, leaving the high density core. In other words, the sun will become a white dwarf.

I have explained the evolution of the sun; other stars having mass similar to that of the sun will follow a similar path. The evolution of stars is determined by the stellar mass at the time of their formation. For instance, a star having ten times the mass of the sun will experience a different evolution. Until it forms a core of carbon and oxygen, the star will follow the same processes as the sun. With the growth of the core, however, the central temperature will rise until it reaches several hundred million degrees. At this temperature, nuclear reactions will start whereby magnesium is formed from carbon. At still higher temperatures, silicon will be formed from oxygen through nuclear fusion; at even higher temperature, iron will be formed from silicon. The star will have several layers. When the iron core grows in mass to reach the solar mass level, it will collapse, because the degenerate electron gas pressure will be unable to support the core against its strong gravity. The collapsed core will become a super-high density neutron star. The outer layer will begin expanding until it explodes from its innermost layer; it will take one or two days until shock waves of the explosion reach the stellar surface. The explosion at this time will make the star 1 billion times as bright as the sun. Such a phenomenon is observed as the emergence of a supernova.

In 1960, when I was conducting my research on the evolution of red giant stars, the following question occurred to me: is there a lower limit to stellar surface temperatures? To solve this question, I began to investigate the influence of surface structure on the overall stellar structures. I found that there is a limit, which can be plotted as a line in the HR diagram. I would like to touch on this topic.

In stellar interiors, heat is conveyed from the center to the surface by either radiation or convection. Where the temperature gradient exceeds a certain value, heat is conveyed by convection, as seen in the troposphere of the earth. In a red giant star, convection occurs in a vast region extending from the surface to the deep interior. If such convection occurs in the whole region of a star, the star will have a kind of limiting structure. I calculated this limiting structure of stars, and found that their locations in the diagram are represented by an almost perpendicular line. In the region of lower surface temperature, no stars can exist. The low limit temperature for stars of a mass similar to the sun ranges from 3,000 to 4,000 degrees. If the surface temperature falls below this limit, stellar gas pressure will not support a star against its own gravity.

Based on this result, I was able to clarify the stellar evolutionary processes prior to the commencement of nuclear hydrogen burning, namely, in the stage where stars have not yet reached the main sequence. Emitting gravitational energy, such young stars contract extremely slowly, holding the balance between gravity and pressure. After the stars were born, they will settle, in a relatively short time, at certain points on the limiting line. At these points, their luminosity will be ten to 100 times the solar luminosity.

The young stars will gradually contract, declining in luminosity but increasing in central temperature. Their track in the HR diagram will follow the limiting line mentioned above. If their mass is similar to the solar mass, their luminosity will decrease to the present solar level in approximately 10 million years. By this time, radiation, instead of convection, will become the means of conveying heat in the central region. The track of such stars in the HR diagram will change direction: leaving the perpendicular, they will begin to advance in a horizontal direction. When the stars reach the main sequence, hydrogen burning will start in the central region. In the Orion and Taurus nebulae, many stars having unique spectra, called T Tauri stars, are observed. It is now known that such stars are currently in the early evolutionary stage, which is called the Hayashi Phase.

The origin of the solar system has long been a source of human curiosity. Many myths and religious scriptures reflect various ideas of our ancestors concerning the origin of the solar system. Since Newton discovered universal gravitation in 1687, many scientists have applied dynamics to their researches on the origin of the solar system. For instance, Kant (a philosopher) and Laplace proposed what is known as the nebular hypothesis. In 1755, when Kant was 31, he discussed in his "Allgemeine Natugeschichte und Theorie des Himmel" the processes whereby the sun and planets were formed from a primordial nebula by contraction. His discussion well represents the cosmology of his time.

Many theories have been put forward since then. During the 1960's, research on the origin of the solar system began involving physics, chemistry, geophysics, and mineralogy. The integration of various scientific fields with astronomy has drastically increased our basic knowledge. For instance, we now know the evolutionary processes of primordial stars, such as T Tauri stars, as well as the physical structures, chemical compositions and even the ages of major components of the solar system, including planets, satellites, comets, and meteorites. As I have mentioned, the chemical composition of the solar system is as follows: hydrogen (approximately 73% in weight), helium (approximately 25%), and the other elements that form ice and rock (approximately ２%). We also know that Jupiter and Saturn have cores made of ice and rock.

During the past few decades, many models on the formation of the solar system have been developed. Over the 15 years since 1970, at my laboratory, we elaborated the Kyoto Model, which I would like to briefly outline.

In the interstellar space of the galaxy, many molecule clouds, or gas clouds mainly consisting of hydrogen molecules, are observed. These clouds are the places where stars are formed. A typical molecule cloud has approximately 1,000 times the mass of the sun. The shape of a molecule cloud is not spherical but discoid. Because of its own gravitational attraction, the cloud becomes increasingly flatter. When such a cloud becomes extremely thin, it fragments into many thin small disks due to gravitational instability. Such small disks have a mass almost equal to the solar mass, and 1,000 times the radius of the present solar system.

One such small disk began contracting because of its own gravitational attraction. Most of the gas contained in the disk slowly formed a protosun, a process taking approximately one million years. The remaining gas (only a few percent), rotating around the protosun, gradually contracted toward the protosun. At this stage, this gas disk had a size similar to that of the present solar system. This is what we call the primordial solar nebula.

The Kyoto Model explains the processes in which planets were formed in the primordial solar nebula. Although the processes are quite complex, they can be roughly classified into the following four stages.

The first stage begins with the separation of gas and dust (cosmic dust) in the primordial solar nebula, and ends with the formation of a thin dust disk. Although the original nebula was mainly composed of hydrogen molecules, small amounts of dust, 1 micron in size, composed of ice and rock were also present. Although in the region close to the sun (in the region between the earth and the sun) the ice evaporated due to the heat of the sun, it remained in the region far from the sun (especially in the region beyond Jupiter). After repeated collisions and accretions, the dust grew to several centimeters in size. Because of solar gravitational attraction, the grown dust then began accumulating on the equatorial plane of the solar nebula, forming a thin dust disk on the plane.

At the second stage, the dust disk fragments to form many minute planets as mentioned below. The dusts accumulated on the equatorial plane, and the dust disk became flatter and flatter. When the disk became extremely thin, gravitational instability caused the disk to split into a great number, (approximately 1 trillion) of fragments. Each fragment had a radius of several kilometers, and a mass similar to that of a comet. These fragments, called planetesimals, were in a solid phase, containing large amounts of gas.

The third stage involves the formation of solid planets through the accretion of planetesimals. Orbiting the sun in Kepler's circular motion, many planetesimals underwent repeated collision and accretion, gradually growing into terrestrial planets: Mercury, Venus, the earth, and Mars. The cores of Jupiter and Saturn were formed in the same processes. It is estimated that the formation of the earth took approximately 1 million years, while the formation of Jupiter's core took approximately 10 million years.

The fourth and last stage involves the growth of the giant planets: Jupiter and Saturn. The presence of large amounts of ice in that region of the solar nebula permitted the two solid planets in the region to grow over ten times the mass of the earth. Having huge gravitational force, those massive planets attracted vast amounts of gas from the surrounding areas. The gas accumulation on the solid planets formed what we now call Jupiter and Saturn. By contrast, the terrestrial planets were unable to attract gas, due to their small mass and gravity.

Part of the remaining gas in the solar nebula fell to the sun, while the rest dissipated. Uranus and Neptune were formed through the accretion of planetesimals after the gas dissipation. Accordingly, they were unable to collect gas.

Finally, I would like to predict the future of the solar system. According to stellar evolutionary theory, ５ billion years from now the sun will have a high-density core made of oxygen and carbon, as I have already mentioned. The sun will expand until it becomes a red supergiant. By then, the sun will become so huge that the solar surface will reach the earth. In other words, the sun will swallow up all the terrestrial planets, leaving only Jupiter and the further planets. Within 1,000 trillion years from now, some other star might possibly enter the solar system, such an accident being estimated to happen once every 1,000 trillion years. If that happens, the gravity of that star might attract the surviving planets, taking them away from the solar system. This would be the end of the solar system.

With the end of the solar system, I would like to end my presentation. I thank you very much for your kind attention.