Modeling of Solar System Formation Using ACRETE

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Abstract

With the present structures of the Solar System as well as many new extrasolar planets recently discovered around solar-like stars, it is important to reexamine the theory of solar system formation. We will use a simple accretion model, built for the first time by Dole (1970), to generate planetary systems. In this model, some new adaptations are made to take into account new features of the solar system. The model will also be used to generate extrasolar planetary systems, and a special case of 47 UMa system will be investigated. The dynamical evolution of the generated systems will also be evaluated to determine the stability of the system.

Keywords : *Solar System, dynamic stability, n-body problem, planetary system.*

I. Introduction

The origin of the Solar System is one of the most fundamental problems in astronomy. Most models of planetary formation are developed based on a single example of our Solar System. But recently, many extrasolar planets have also been discovered.

The theories up to 1960 were representative of the two schools of thoughts – first, monistic theories, in which the Sun and planets are formed from the same pool of material and dualistic theories where the Sun and planets originate from different sources of material and at different times. Each theory has their own successes and failures. In planetary formation of Schmidt-Lyttleton accretion theory and the monistic theories assume a disc of material as starting points.

The monistic theory has to resolve the problem of how single nebula could evolve spontaneously to give virtually all the angular momentum to a tiny fraction of the material. The dualistic theories of the two star interactions have been no more successful than monistic theories in handling angular momentum. While they avoid the problem of slowly spinning Sun by assuming its pre-existence, they cannot find mechanisms to remove material to a sufficient distance from the Sun, or in other words, to give it enough angular momentum (Woolfson 2000). However, the Schmidt-Lyttleton dualistic accretion theory does resolve the angular momentum problem by capturing material in a spread-out form which possesses the right amount of angular momentum to explain the planetary motions at the time of its capture. One of the simulation models of planetary formation is developed using Schmidt-Lyttleton accretion theory, namely ACRETE, originally developed by Dole (1970), a simple planetary generator to form our Solar System. This first model gave a complete set of planetary system, with numbers of planet formed in the system, its orbital distance, mass and eccentricity.

In this paper, we present a progress report of a planetary formation study using ACRETE, which will also be developed to determine the stability of the system.

II. Initial Model

ACRETE hypothesized that stars and planetary systems form within cold, dark globule of dust and gas, through accretion of grains and inelastic collisions of particle, and was critically studied by Isaacman and Sagan (1977). Since then, there have been several different versions of ACRETE, with bits and pieces added and modified by others over the years. Based on Burrows ACRETE-STARGEN model (1998), we develop the model with several changes and add an *n*-body problem to examine the motion of the objects in a given interval of time. Hence, we can determine the stability of the systems, and also have some information on its evolution.

First assumption in ACRETE is a star of one solar mass has been formed at the center of the cloud. The star is surrounded by a spherically-symmetrical cloud of dust and gas. The density of the cloud decrease monotonically with distance from the star, assumed to be low enough so that the particles of which the cloud composed may be considered to be moving about the centre of mass on independent Keplerian orbit. In a cloud of particle where inelastic collisions can occur, particle orbits that are highly inclined to the invariable plane or revolution are gradually converted into lower inclination orbit. Particles on retrograde orbits are gradually eliminated from the cloud through inelastic collisions with particles moving on direct orbit. The result is a gradual and continuing flattening of the cloud, so the spherical shape is lost, and formed an exocone (Fig. 1).

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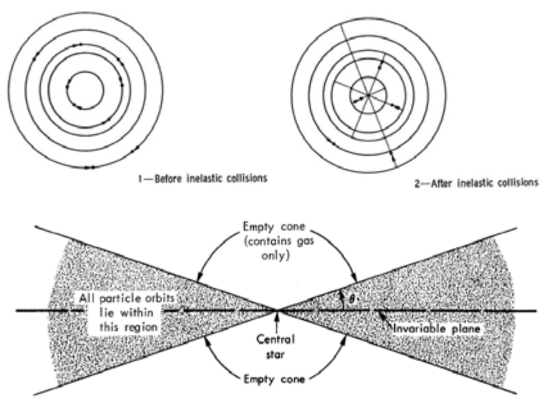


Fig. 1 (a). Particle motion before and after inelastic collisions. (b) Cross-section of exocone, perpendicular to invariable plane.

In the original simulation, planetary nuclei will randomly injected to the cloud and grow after it swept particles in the cloud. When a planet stop growth, another nuclei injected. As planetary nucleus grew, it sweeps out clear lanes of dust in the cloud. Some of the gas are also swept out in the vicinity of orbit of planets having masses greater than its critical mass (m_c). It sometimes occurs, during the course of the run that two planets come within a distance x of each other. When this happens they are allowed to collide inelastically and to coalesce forming a single planet. After coalesce, the body formed may continue to grow if conditions are suitable. Planetary nuclei injected to the cloud untill all dust being swept. If there is no more dust, the experiments end and the system is completely formed.

ACRETE itself has been modified several times, and in our model we use Jim Burrows model named STARGEN. In this model, several modifications have been done, without touching the basic ACRETE engine. Burrows had modified the handling of systems that reach "critical mass", and start to accrete gas as well as dust. He also change some features like greenhouse effect, to determine the surface temperature, and the amount of the surface covered by water, ice and clouds and the albedo of the planet. He adapted two features from Keris' starform, min/max temperatures and simple atmosphere simulation. And he takes into account the habitable zone problem and evaluated it for every planet.

III. Our Development

ACRETE–STARGEN is a Solar System Generator with HTML output that gave us big picture about full conditions of the system itself. In this model we develop some aspect, like change in the initial parameter for inner and outer distance. We take 0.08 AU for inner bound and 100 AU for outer bound. In the initial model, the outer bound is set to be 50 AU. However, taking into account recent discovery of dwarf planets, it is reasonable to set the outer bound to be 100 AU. In our model, we also account for the gravitational perturbation. Other modification we made is the close encounter condition. We used Gladman criterion, to see the close encounter problem between the bodies. When close encounters occur, the system will keep stable if the separation between the two planets $\geq \Delta_{\min}$. Gladman criterion (Gladman, 1993) for minimum separation is expressed by $\Delta_{\min} = 2.4(\mu_b + \mu_c)^{1/3}$, with μ_b, μ_c are the ratios of the planet masses to the stellar mass and Δ, fractional orbit separation of the two planets for $\Delta = \frac{(a_c - a_b)}{a_b}$. If close encounters between the two planets not occur, the system will remain stable.

We also perform long-term numerical orbital integrations of planetary objects with n-body integrations. We combine the n-body integrations with the parameter output by ACRETE–STARGEN to see the orbital motion. In this integration we also permit close encounters between bodies to see the dynamical stability of the system.

Perturbation function in n-body system, when the mass which perturbs the other mass identified by m_i, will be :

$$R = Gm_i'\left(\frac{1}{\rho_i} - \frac{xx' + yy' + zz'}{r'^3}\right) \tag{1}$$

This perturbative function is a consequence of perturbation from another body, and so we have :

$$\ddot{x} = -\frac{GMx}{r^3} + \sum_{i=1}^{n-2}\frac{\partial R_i}{\partial x} \tag{2}$$

$$\ddot{y} = -\frac{GMy}{r^3} + \sum_{i=1}^{n-2} \frac{\partial R_i}{\partial y} \qquad (3)$$

$$\ddot{z} = -\frac{GMz}{r^3} + \sum_{i=1}^{n-2} \frac{\partial R_i}{\partial z} \qquad (4)$$

With $M = m_1 + m$ and

$$\rho = \left[(x - x')^2 + (y - y')^2 + (z - z')^2 \right]^{1/2}$$

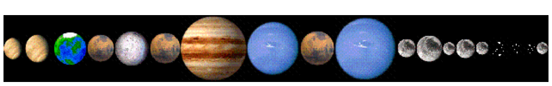
In this model we also determine how long it takes to build a system and apply this model to extrasolar system to examine possible characteristics of the planets.

IV. Result and Discussion

All simulations in STARGEN were performed until all planets are generated. Collisions and coalesce between bodies will occur when the close encounter takes place and their separation is less than their minimum value. After all planets form, STARGEN will continue to take into account all planetary dynamical stability. In this paper, we generate a system with 1 solar mass, random cloud eccentricity (maximum at 0.25), randomly planetary nuclei injection. Random injection is also made simultaneously, not successively as the old ACRETE. An example of the result is displayed in Fig 2, having various parameters, such as planet type, planet distance to the star, it mass, and it radius.

The system generated with 1 solar mass shows that this system contains 19 planets with: 2 venusian, 1 terrestrial, 3 Martians, 2 sub jovian, 1 jovian, 1, icy planet, 5 rocky, and 3 groups of asteroids between 88 AU to 98 AU. Habitable ecosphere radius is 0.143 AU, that means at this distance planet can have liquid water.

The generated system will provide planet parameters (Fig. 4) such as planetary type, atmosphere conditions, albedo, surface gravity, pressure, temperature, density, equatorial radius, day length, molecule retained in the planet, water boiling point, escape velocity, cloud cover, hydrosphere, and ice cover. With habitable ecosphere radius 0.143 AU, there is no planet that could have liquid water. Even terrestrial planet in this system (1.193 AU) only have hot icy cloudy thick atmosphere. Molecule retained here are Kr, O, O_3, Ar, N, NH_3, Xe, CH_4, He, H_2O, H, CO_2, and Ne. This planet is abundant in hydrogen 66.0% and helium 34%.



	Type	Distance	Mass	Radius
1	Venusian	0.334 AU	0.257 EM	0.640 ER
2	Venusian	0.642 AU	0.695 EM	1.184 ER
3	Terrestrial	1.193 AU	2.019 EM	1.666 ER
4	Martian	1.421 AU	0.529 EM	1.083 ER
5	Ice	1.824 AU	2.489 EM	1.779 ER
6	Martian	2.634 AU	1.131 EM	1.385 ER
7	Jovian	4.372 AU	39.580 EM	6.459 ER
8	Sub-Jovian	6.329 AU	7.959 EM	4.172 ER
9	Martian	11.159 AU	2.375 EM	1.753 ER
10	Sub-Jovian	17.395 AU	19.628 EM	5.906 ER
11	Rock	30.189 AU	0.060 EM	0.529 ER
12	Rock	36.789 AU	0.458 EM	1.034 ER
13	Rock	41.083 AU	0.006 EM	0.248 ER
14	Rock	51.946 AU	0.072 EM	0.561 ER
15	Rock	71.066 AU	0.007 EM	0.256 ER
16	Asteroids	88.754 AU	0.001 EM	0.130 ER
17	Asteroids	92.873 AU	0.000 EM	0.075 ER
18	Asteroids	97.274 AU	0.000 EM	0.073 ER
19	Rock	97.848 AU	0.003 EM	0.205 ER

Fig. 2 Example of generation of one solar mass planetary system and its planets parameters.

Stellar Characteristics	
Stellar Mass	1.00 solar masses
Stellar Luminosity	0.02 (Sol = 1.00)
Age	1.528 billion years (489.607 billion left on main sequence
Habitable Ecosphere Radius	0.143 AU

Fig. 3 Stellar Characteristic of the generation in Fig.2

Planet 3 Statistics		
Planet Type	TERRESTRIAL Low-G Hot Icy Cloudy Thick atmosphere (He H - Poisonous)	
Distance From Primary	1.785E8 KM	1.193 AU
Mass	1.207E25 KG	2.019 Earth masses
Surface Gravity	713.5 cm/sec squared	0.73 Earth G
Surface Pressure	2,212.474 millibars	2.184 Earth atmospheres
Surface Temperature	29.301 ° C 84.743 ° F	+15.3 ° C Earth temperature +27.5 ° F Earth temperature 193.9 ° C greenhouse effect
Normal Temperature Range	Night: 25.4 ° C 77.8 ° F – Day: 32.9 ° C 91.2 ° F Min: 8.8 ° C 47.9 ° F – Max: 48.7 ° C 119.6 ° F	
Equatorial Radius	10623.6 KM	1.666 Earth radii

Density	2.40 grams/cc	0.44 Earth densities
Orbital Eccentricity	0.026	
Escape Velocity	12.3 KM/sec	
Molec Weight Retained	0.1 and above	Kr, O_3, O_2, Ar, N_2, NH_3, Xe, CH_4, He, H_2O, H_2, CO_2, Ne **Helium** 34.0% 752 (ipp: 731) **Hydrogen** 66.0% 1459 (ipp: 1418)
Axial Tilt	29 °	
Albedo	0.98	
Exospheric Temp	18.20 ° K	-1254.80 ° C Earth temperature
Year Length	476.16 Earth Days	635.31 Local Days 1.30 Earth years
Day Length	17.99 Hours	
Water Boiling Point	123.1 ° C 253.6 ° F	
Hydrosphere Percent	67%	
Cloud Cover Percent	112%	
Ice Cover Percent	20%	

Fig. 4 Output sample of planet characteristic. (3 rd planet)

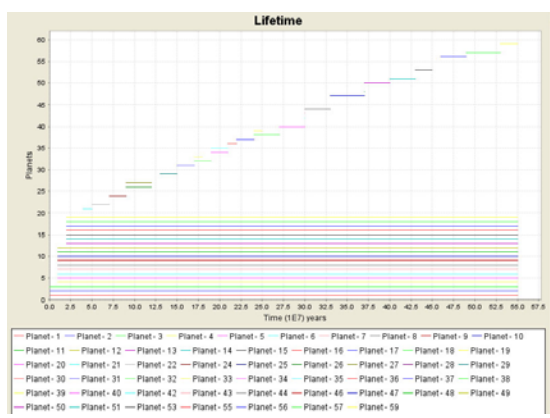


Fig. 5 Lifetime of the system formation.

This system reaches its final configurations for 550 million years as shown in Fig. 5 for each planet formation. In the chart, the line represent each planetary nuclei injected to the cloud and formed the planet. The line begins when nuclei injected and it stops when the planet formed. But some of the line end before 550 million year represent that the planet form from this nuclei has been in collision and coalesce with another planetary body. After the formation of the system, STARGEN continue to show the dynamical evolution (its life time) until it reaches the present age (1.528 billion years). The system is stable since in its orbital motion the close encounter never reaches its minimum separation.

In fig 6, the chart shows mass variation for each planet. The green line represents jovian planet mass variation from the nuclei injected until the planet is formed by accreting dust and gas. When the line in Fig. 6 ends, it means that the mass has no more change.

Changes we made in outer bound show that most planets have maximum distance of 150 - 200 AU. At distance more than 50 AU (mostly at more than 70 AU), all bodies have low masses almost like Pluto, and can be categorized as dwarf planet or Kuipert Belt object. Here many asteroids are also found.

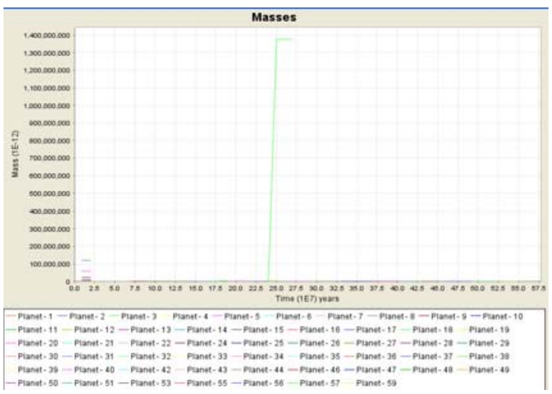


Fig. 6 Mass variation for each planet during the formation

We also applied several computation for 47 UMa (1.03 $M_{\odot}$, G0V, 43.8 ly) star to generate the corresponding system. The system shows possibility that 47UMa could have 15-21 planets, with 3 jovian at the distance range between 3-18 AU, almost similar to the actual finding (2 planets are found in 47 Uma, located at 2.11 AU and 7.73 AU). The system is generated completely after 475 Myr.

V. Concluding Remarks

As a continuation of this study, we will make further study on various possible planetary models to be generated using this modification of STARGEN programs. They will be explored statistically and dynamically, and subsequently compared to the existing data of extrasolar planets.

Acknowledgments. This research was supported by "Hibah Penelitian Tim Pascasarjana - Dikti" to which the authors gratefully appreciated. AY. wishes to thanks M. J. Fogg for his help during the preparation of this work.

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