A LUNAR TIME SCALE FROM GEODYNAMIC EVOLUTION PERSPECTIVE. Dijun Guo[1, 2], Jianzhong Liu[1], Fuqin Zhang[3], Ying Sun[4], Jinzhu. Ji[1, 2], Jingwen Liu[1, 2], Juntao. Wang[1, 2] and Lin Luo[1, 2], [1]Lunar and Planetary Science Research Center, Institute of Geochemistry, Chinese Academy of Sciences, 99 Lincheng West Road, Guiyang 550081, China [2]University of Chinese Academy of Sciences, Beijing 100049, China [3] Institute of Geology and Geophysics, Chinese Academy of Sciences, 19 Beitucheng West Road, Beijing 100029, China [4]Jilin University, Changchun, 130000, China (guodijun@mail.gyig.ac.cn).

Introduction: The lunar time scale was generated by Shoemaker and Hackman (1962) on the basis of geologic mapping the Copernicus region [1]. With the development of Apollo program, the lunar time scale had been modified many times and was systematically expounded by Wilhelms (1987) [2-5]. However, the current time scale has defects in the expression of lunar geodynamic evolution especially in the pre-Nectarian Period. Geodynamic processes of the Moon can be divided into two groups, the endogenic process and the exogenic process [5]. The lunar endogenic geological processes include the magma ocean crystallization, magma convection, volcanic activities and mare eruption, while the exogenic geological processes mainly refer to comet and meteorite impacts, some other processes like space weathering can be ignored because of their little influence on lunar evolution. These two types of geodynamic processes both have contributed much to the evolution of the Moon, but their degrees of influences varied over time. According to the evolution of lunar geodynamic processes, the lunar history can be divided into three stages.

Three Stages of Lunar Geodynamic Evolution: The three stages of lunar geodynamic evolution are stage of endogenic processes dominating, stage of both endogenic and exogenic processes working, and the stage of exogenic processes dominating.

Stage I. Among the hypotheses to explain the formation of the Moon, the giant impact is the most plausible [6-9]. According to the giant impact theory and Apollo samples, the primitive moon was covered by a thick layer of melt known as lunar magma ocean (LMO) [10-13]. With the cooling of the magma ocean, plagioclase and some other igneous rocks formed through crystallization, and the pristine anorthositic crust was formed during hundreds of million years [14, 15]. The evolution of magma ocean was the most important endogenic process that decided the structure frame of the Moon.

During this stage, impact event may have not happen or the soft and hot LMO could not preserve the impact events even they may have happened. What's more, the possible impact has little influence on the evolution of the Moon in this stage. So this stage is the period when endogenic process dominated the lunar evolution, and it ended by the formation of South Pole-Aitken basin, also known as the SPA basin.

Stage II. The SPA impact marked the beginning of the second stage. As the most spectacular exogenic event happened on the Moon, it reshaped the consolidated moon so heavily that it created an elliptic basin with the axes 2400 by 2050 km [16] and might cover the Moon with kilometers thick of ejecta [17]. In the following of the SPA was the other several tens of basin impact events and innumerable relatively small impacts, which is called the Late Heavy Bombardment (LHB) by some scientists because of the intense impacts occurred in a short period [18, 19]. The exogenic process lasted until now and meteorites will continue to impact on the Moon. However the scale of the impacts decreased dramatically after the formation of Orientale basin. These impacts played great roles in lunar evolution. They shaped the surface of the Moon; induced magma activities; and formed shallow structures.

As for the post-LMO endogenic processes, they still influenced lunar evolution because interior energy of the Moon was abundant at the beginning [20]. Represented by volcanism and maria eruption, the late endogenic processes broke out during Imbrian Period and diminished in Eratosthenian Period, but didn't cease until about 1.5 billion years ago [20, 21], which closes to the end of Eratothenian and beginning of Copernican.

So, the second stage started from the SPA impact and ended at the stop of endogenic processes around 1.5 b.y. ago. Both endogenic and exogenic processes strongly affected the evolution of the Moon during this stage, and they have made the appearance of the Moon almost the same of today.

Stage III. After the endogenic process ceased, only small scale impacts happened on the Moon since then. This stage is obviously the exogenic processes has dominated the lunar evolution, which is actually very weak. The third stage mainly included in Copernican Period, but its early part belongs to Eratothenian [5].

Lunar Time Scale: From the perspective of lunar geodynamic processes, the lunar time scale can be divided into three units, corresponding to the three stages of lunar geodynamic evolution. To better express the three units, names coinciding with the regulation of geochronology nomenclature should be given. Here we tentatively name them from early to late as Eolunarisian Eon, Paleolunarisian Eon and Neolunarisian Eon respectively, abbreviated as EL, PL and NL (Table 1).

The Aitkenian Period. According to the presently popular lunar time scale which was depicted by Wilhelms (1987) [5], the pre-Nectarian Period includes the Eolunarisian Eon as well as the early part of the Paleolunarisian Eon, indicating a disagreement with the geodynamic process evolution.

It is described above that the SPA impact represents the start of Paleolunarisian, so it can be used to separate the Eolunarisian out from pre-Nectarian. According to the tradition, the period from SPA to Nectaris can be named as the South Pole-Aitkenian Period, temporarily simplified as the Aitkenian Period. Therefore, the period before SPA impact can be named as pre-Aitkenian Period temporarily, and is included by Eolunarisian Eon (Table 1).

Aitkenian basic rock-stratigraphic unit. To establish the South Pole-Aitkenian Period or the Aitkenian Period, the ejecta deposits of SPA basin must be recognized to mark the basic rock-stratigraphic unit of this Period and to define the relative age to other geologic formations. However, the ejecta of SPA basin has been obscured too heavily because of the several billions of years geological activities. On the other hand, one reality is unarguable that the ejecta deposits of several kilometers thick were layered around SPA basin during its formation.

Conclusions: Three Eon geochronological units consist of Eolunarisian, Paleolunarisian and Neolunarisian, and two Period geochronology units including Aitkenian or South Pole-Aitkenian and pre-Aitkenian or pre-South Pole Aitkenian are proposed to form a lunar time scale better agree with the lunar geodynamic process evolution (Table 1). With emphasizing the geodynamic evolution, the lunar time scale will provide a clear clue to the evolution of lunar geological processes. In addition, the three-stage geodynamic evolution may represent a common principle of terrestrial planets and supplies references to the future evolution of the Earth.

References:

[1] Shoemaker E. M. and Hackman R. J. (1962) *The Moon*. Academic Press, 289-300. [2] Shoemaker E. M.(1964) *Sci Amer*, 6, 38-47. [3] Wilhelms D. E. (1970) *Summary of lunar stratigraphy: Telescopic observations*. US Government Printing Office, 1-45. [4] Stuart-Alexander D. E. and Wilhelms D. E.(1975) *Jour Reaseech US Geol Survey*, 1, 53-58. [5] Wilhelms D. E., Mccauley J. F. and Trask N. J. (1987) *The geologic history of the Moon*. US Government Printing Office. [6] Hartmann W. K. and Davis D. R.(1975) *Icarus*, 4, 504-515. [7] Cameron A. G. W. and Ward W. R. (1976) *LPSC VII*, 120-122. [8] Canup R. M.(2004) *Icarus*, 2, 433-456. [9] Hartmann W. K., Phillips R. J. and Taylor G. J. (1986) *Origin of the Moon*. [10] Wood J. A., *et al.*(1970) *Geochim Cosmochim AC*, 965. [11] Smith J. V., *et al.*(1970) *Geochim Cosmochim AC*, 897. [12] Wood J. A. (1975) *LPSC VI*, 881. [13] Warren P. H.(1985) *Annu Rev Earth Pl Sc*, 201-240. [14] Nemchin A., *et al.*(2009) *Nat Geosci*, 2, 133-136. [15] Meyer J., Elkins-Tanton L. and Wisdom J.(2010) *Icarus*, 1, 1-10. [16] Garrick-Bethell I. and Zuber M. T.(2009) *Icarus*, 2, 399-408. [17] Petro N. E. and Pieters C. M.(2008) *Meteorit Planet Sci*, 9, 1517-1529. [18] Tera F., A. P. D. and J. W. G.(1974) *Earth Planet Sc Lett*, 1, 1-21. [19] Cohen B. A., Swindle T. D. and Kring D. A.(2000) *Sci*, 5497, 1754-1756. [20] Head J. W. and Wilson L.(1992) *Geochim Cosmochim Ac*, 6, 2155-2175. [21] Morota T., *et al.*(2011) *Earth Planet Sc Lett*, 3-4, 255-266. [22] Jolliff B. L., *et al.* (2006) *New views of the Moon*. Mineralogical Society of America.

Table 1: Lunar time scale derived from geodynamic evolution

Eon	Period	Period[5]	Geodynamic Pattern	Geological Processes	Age (b.y.) *
Neolunarisian (NL)	Copernian	Copernian	Exogenic dominates	Impacting	0.8~
	Eratothenian	Eratothenian		Impacting; Weak mare volcanism	3.16~0.8
Paleolunarisian (PL)	Imbrian	Imbrian	Exogenic & Endogenic	Impacting; Volcanic activities;	3.85~3.16
	Necterian	Necterian		Impacting; Volcanic activities	3.92~3.85
	Aitkenian	Pre-Necterian		Impacting Volcanic activities	4.2~3.92
Eolunarisian (EL)	Pre-Aitkenian		Exogenic dominates	Lunar magma ocean	4.52 (?)~4.2

*The ages refer to [5, 22]. The boundary between NL and PL is in dashed line because the early stage of Eratothenian Period may have relatively abundant endogenic processes, but as a whole the Eratothenian Period was dominated by Exogenic processes. As the longest Period of lunar time scale, maybe the Eratothenian Period can be separated into two Periods or be divided into two Epochs.