5. The Adaptation from the Moon to Mars

In order to gain an understanding of the geologic evolution of a terrestrial planet, it is vital to place the different geological processes involved in shaping the planetary surface into chronological order. At regional or local scales, a relative stratigraphy can be derived by analyzing superposition relations and differences in the state of degradation between different geomorphological surface units. Global stratigraphic schemes for planetary bodies are based on the most common resurfacing process: the impacts of planetesimals that form crater or crater-related features on planetary surfaces. Through this random cratering process, counting of the accumulated number of impact craters offers a valuable procedure in understanding the chronostratigraphy. Absolute ages of cratered surfaces of solid surface bodies are derived by extrapolation from the impact flux for the Moon. Apart from Earth, the Moon is the only planetary body for which we have both a detailed stratigraphic history and rock samples that can be related to specific geologic or morphologic units. Therefore, the Moon has become a reference system for Mars (and other planetary bodies).

5.1. The Reference System, Moon: Cratering Record

The determination of relative and absolute ages of planetary surfaces is based on the random process of projectiles hitting planetary bodies and leaving scars, mainly as surface impact crater structures. The cratering record shows the bombardment integrated through the entire geological lifetime of a certain body. The record also reveals the geological history of a specific surface unit due to spacial variations of the crater frequencies and temporal variations of the crater-forming projectile flux. Prerequisites to the interpretation of crater size-frequency data for various geologic units of different ages include:

1. the determination of the shape of the crater–production function, implying the primary source of projectiles that impacted the planetary surface, and
2. the application of a cratering–chronology models.

The characteristics of the lunar crater size–frequency distribution and the derivation of the lunar chronology model has been described in Chapter 4. During the last decades, the investigation of the "true" Martian crater size-frequency distribution has been the focus of many studies and here the "state of the art" for Mars will be introduced.

5.2. The Reference System, Moon: Impactor Flux

It has been shown that asteroids from the main belt provided the primary source of impactors on the terrestrial planets in the inner solar system. This is inferred from the complex shape of both the crater production functions of these bodies, and the asteroid size distribution (Neukum, 1983; Neukum and Ivanov, 1994; Neukum *et al.*, 2001; Ivanov *et al.*, 1999, 2001; Ivanov, 2001; Werner *et al.*, 2002).

The lunar production function is the best studied among terrestrial planetary surfaces, based on an enormous amount of image data at all resolutions. The lunar production function is described as a polynomial function of 11^{th} degree (Neukum, 1983), and has recently been refined for the larger crater diameter range based on new counts in the Orientale basin region (Ivanov *et al.*, 1999, 2001). Since the same projectile population impacted inner solar system bodies (bodies derived from the asteroid belt, Ivanov *et al.*, 2001), the lunar production function can be scaled to impact conditions on these bodies, taking into account parameters such as impact velocity and angle of the projectile, surface gravity, atmospheric effects as well as density and rheologic properties of the target surfaces. A Martian production function polynomial, updated from older versions (Neukum and Wise, 1976; Neukum and Hiller, 1981; Neukum, 1983), has recently been constructed from the refined lunar production function, based on an estimation of crater scaling parameters (Ivanov, 2001).

In order to derive a cratering chronology model for Mars, cratering rates must be estimated from observations of planet-crossing asteroids.

5.3. The Mars–Moon Cratering Rate Ratio

Ivanov (2001) described a method to adapt the lunar production function and chronology model to Mars. In order to do this, he investigated the nature of crater–forming projectiles, the impact rate differences and the scaling laws for the crater formation.

From his discussion of possible projectile sources, it is clear that the best candidates are asteroids which developed from the main belt asteroids (having almost circular orbits around the sun between Mars and Jupiter) to so–called planet–crossing asteroids with orbits of higher eccentricity (compared to main belt asteroids). These asteroids or asteroidal fragments left their former orbits by injection to resonance phase space and/or close encounters with terrestrial planets. Both situations change the orbital parameters and force the body to higher eccentricities. The specific dynamic regime determines the fate of a certain body, which include ejection from the solar system, impact into a planet or for most the "solar sink", that is impacting into the sun (for review: Morbidelli, 1999).

Today, the population of planet-crossing asteroids in the larger size–range is well known, and observational effects are debiased by various approaches. Thus, it supplies us with a representative set of orbital parameters that are used to compare impact rates on Mars and the Moon. Based on this, impact probabilities and velocities were calculated (for details see Ivanov, 2001). Due to Martian orbit characteristics (eccentricity variation in the range of about 0.01 to 0.1 within a period of 2 Ma; Ward, 1992) the number of impactors are variable within a factor of 20 (Ivanov, 2001). Therefore, Mars and Moon impact rates are compared as time averages. The average impact rate for Mars is two times higher than the Moon for asteroids of the same size (Hartmann and Neukum, 2001). To compare the crater size–frequency distributions of the Moon and Mars, modern crater scaling laws for calculating the crater diameter ratio between Mars and the Moon are used (Schmidt and Housen, 1987).

These laws are based on the idea of describing the transient crater diameter with respect to the projectile diameter, impact velocity, impact angle (the efficiency of cratering), the target as well as projectile densities and gravity acceleration of the target body. For smaller craters the crater formation is dominated by composition (strength of the target rock) while for larger craters the crater growth is more influenced by the target gravity acceleration. Schmidt and Housen (1987); Neukum and Ivanov (1994); Ivanov (2001) included the transition diameter between the strength and gravity regime to be able to transfer the lunar crater size–frequency distribution to other planets. The final crater diameter is a result of gravitationally driven collapse of the transient cavity. This diameter depends again on the target material strength and gravity. Here an empirical rule (Pike, 1980b) is used, where the critical diameter varies inversely proportional to the surface gravity. This short overview reflects the guidelines to transfer the well–known lunar crater size–frequency distribution to any other terrestrial body (Schmidt

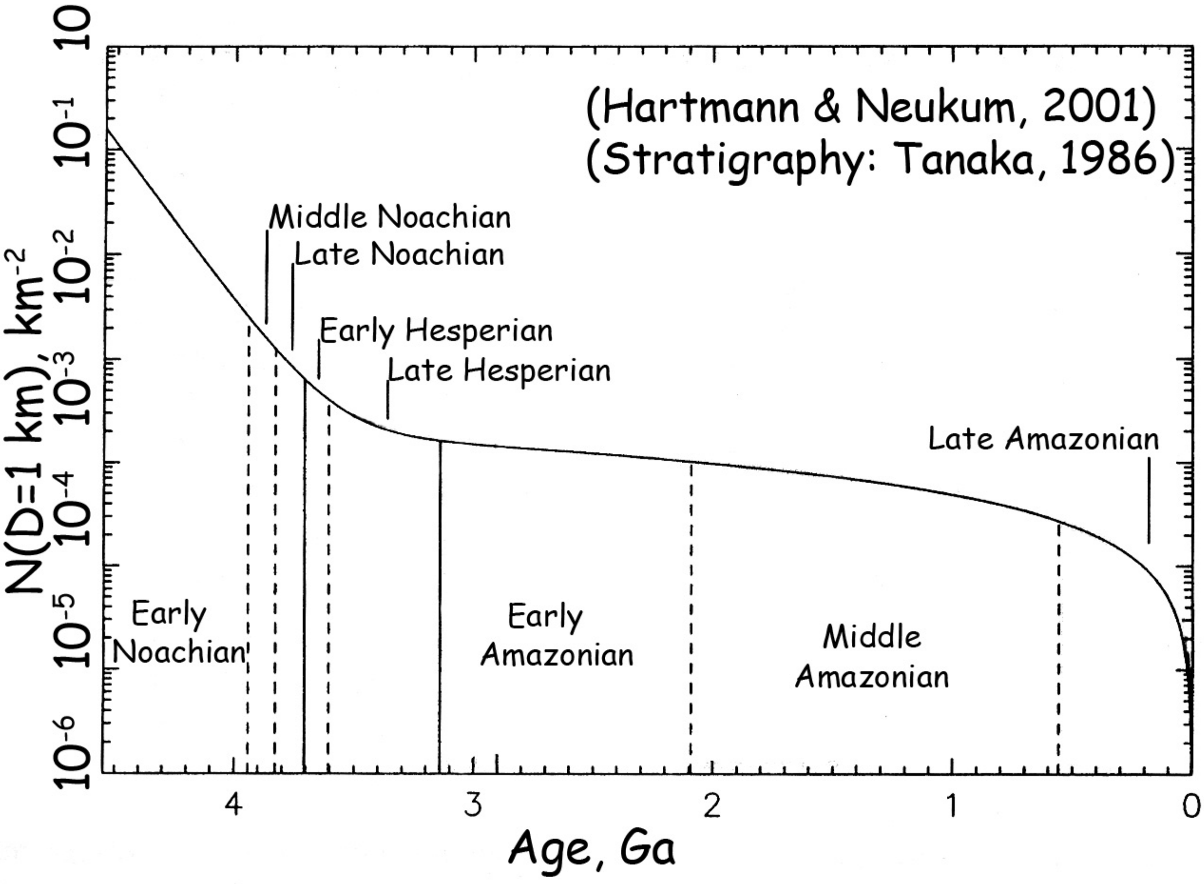

Figure 5.1.: Martian impact cratering chronology curve, showing the chronologic periods and epochs after the time-stratigraphic system of Tanaka (1986), with redefinition of the Lower (Early) Amazonian base crater frequency by Hartmann and Neukum (2001).

and Housen, 1987; Neukum and Ivanov, 1994; Ivanov, 2001).

Ivanov (2001) has performed the latest Moon–to–Mars re–calculation of their crater size–frequency distribution and shown that, due to different average impact velocities and surface gravity, the average crater on Mars is 1.5 times smaller than on the Moon for projectiles of the same diameter. Comparing the lunar and Martian crater size–frequency distributions, the cratering rate of Mars versus the Moon varies within a factor of 0.6 to 1.2, depending on the steepness of the production function curve [See Figure 4.4 B).

Neukum (1983); Neukum *et al.* (2001); Hartmann (1999b) and others agree that the projectile flux in the inner solar system is similar. Therefore, the Martian impact cratering chronology can also be described by a lunar–like bombardment, with an exponentially declining flux during a heavy bombardment period and a more or less constant flux from 3 to 3.3 billion years ago until present. The cumulative frequency for 1–km craters, dependent on exposure time T in billion years, can be described by the chronology curve of Neukum (1983) (see Chapter 4.2), and updated by Ivanov (2001):

$$N(1\mathrm{km}) = 3.22 \cdot 10^{-14}[\exp(6.93\mathrm{T}) - 1] + 4.875 \cdot 10^{-4} T \qquad (5.1)$$

A graph of this equation is given in figure 5.1. Earlier attempts by Hartmann (1973);

Soderblom *et al.* (1974); Neukum and Wise (1976); Hartmann *et al.* (1981); Neukum and Hiller (1981); Strom *et al.* (1992) represent similar approaches, but they had no reliable cratering rates to transfer the chronology from the Moon to Mars. At that time, the statistics and knowledge regarding the actual numbers of asteroids in near–Earth and Martian orbits were not well known. Therefore, the projectile (asteroid) flux was unknown and resultingly there was no accurate ratio for properly transferring the cratering rates. Nevertheless, the earlier approach by Neukum and Wise (1976) based on geological arguments (e. g. the marker horizon idea) could be confirmed by the most up–to–date celestial mechanial consideration (Ivanov, 2001).

Hartmann and Neukum (2001) discussed their Martian cratering chronology model with respect to "dated" surface morphologies and the results of Martian meteorite investigation. The crater counts as indicators of surface ages and the age of the meteorite ALH84001 both emphasize an approximate 4.5 Ga age for the surface and crust formation. Rock ages of meteorites of volcanic origin, one of which mineral assemblages indicating aqueous alteration can be correlated to crater counts of volcanically and fluvially shaped surfaces.

Altogether, there is now solid evidence that the age determination using crater counts leads to reliable ages, which can be used to understand the geological history of Mars.