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Cepstrum Analysis of Terrestrial Impact Crater Records

Heon-Young Chang[1] and Cheongho Han[2†]
[1]Dept. of Astronomy and Atmospheric Sciences, Kyungpook National Univ., Daegu 702-701, Korea
[2]Dept. of Physics, Institute for Basic Science Research, Chungbuk National Univ., Chongju 361-763, Korea
email: hyc@knu.ac.kr, cheongho@astroph.chungbuk.ac.kr

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Abstract

Study of terrestrial impact craters is important not only in the field of the solar system formation and evolution but also of the Galactic astronomy. The terrestrial impact cratering record recently has been examined, providing *short-* and *intermediate-term* periodicities, such as, $\sim$ 26 Myrs, $\sim$ 37 Myrs. The existence of such a periodicity has an implication in the Galactic dynamics, since the terrestrial impact cratering is usually interpreted as a result of the environmental variation during solar orbiting in the Galactic plane. The aim of this paper is to search for a *long-term* periodicity with a novel method since no attempt has been made so far in searching a *long-term* periodicity in this research field in spite of its great importance. We apply the cepstrum analysis method to the terrestrial impact cratering record for the first time. As a result of the analysis we have found noticeable peaks in the Fourier power spectrum appearing at periods of $\sim$ 300 Myrs and $\sim$ 100 Myrs, which seem in a simple resonance with the revolution period of the Sun around the Galactic center. Finally we briefly discuss its implications and suggest theoretical study be pursued to explain such a *long-term* periodicity.

Keywords: comets: general – meteors, meteoroids – methods: data analysis – solar system: general

1. INTRODUCTION

There are probably about 1000 objects over 1 km in diameter and possibly as many as a million over 50 meters in diameter whose orbits cross or closely approach that of the Earth (e.g., Kraal et al. 2008). Two to three of those objects, about 1 km in diameter, hit the Earth every 1 Ma (Bae et al. 2005, Kim et al. 2005, Mihn et al. 2005). From a geological perspective they are a common occurrence, although on the scale of a human lifetime impacts are rare. This is why impact cratering is by far the most widespread process shaping the surfaces of solid bodies in the Solar system.

Impacts are intimately associated with the formation and evolution of planets. In fact, it is an interesting issue as to whether a periodicity can be found in the terrestrial impact crater record (Alvarez & Muller 1984, Davis, Hut, & Muller 1984, Rampino & Stothers 1984a,b, Whitmire & Jackson 1984, Rampino & Caldeira 1992, Clube & Napier 1996, Matsumoto & Kubotani 1996, Napier 2006, Stothers 1998, 2006), since it is a crucial implication on the solar system formation and evolution (Bailey, Wilkinson & Wolfendale 1987, Clube & Napier 1984a,b, Davis, Hut, &

†corresponding author

Muller 1984, Grieve 1987, 1991, Rampino & Stothers 1984b, Stothers 1992, van den Bergh 1994, Nurmi, Valtonen, & Zheng 2001, Whitmire & Jackson 1984). Several values for the period have been derived, depending on what data set one adopts for testing and how one analyzes the data set. Analyses so far carried out give a *short-term* periodicity ranging from $\sim$ 26 to $\sim$ 37 Myr (e.g., Rampino & Stothers 1984b, Stothers 1998, Yabushita 1991, 1992, 1996, 2002), though some authors claim that there is no periodicity at all (Jetsu 1997, Jetsu & Pelt 2000, Grieve & Shoemaker 1994, Tremaine 1986, Weissman 1985, 1990). Recently, the impact cratering record of the surface of the Earth has been re-examined in the time domain (Chang & Moon 2005, Chang 2006). The authors have demonstrated there exists a $\sim$ 26 Myr periodicity in the impact cratering rate over the last $\sim$ 250 Myrs. Such a periodicity can be found consistently in their subsamples regardless of the lower limit of the impact crater diameter up to $D \sim 35$ km.

Moreover, impact cratering is related to an astronomical issue in the context of the Galactic dynamics as well. For instance, several astronomical models were proposed which act as astronomical clocks of the impact cratering. Currently, the only model for such a *short-term* periodicity, which is based on astronomical observation and has theoretical plausibility, is the one in which the sun's motion above and below the Galactic mid-plane plays the required role. In other words, the possible origin of such an apparent periodic behavior of impact cratering was ascribed to a periodic comet influx caused by Oort cloud disturbance by oscillations of the Solar system in the Galactic plane, which may also be subject to a periodic modulation. It is also expected that the period of the terrestrial impact rate may be modulated in a longer timescale.

Therefore, it is a very interesting and important to search for a *long-term* periodicity in the terrestrial impact cratering data, which in turn requires a dynamical model for the solar motion. The aim of this paper is to investigate a *long-term* periodicity with a novel approach in this field. We employ the cepstrum analysis method. In applying the discrete Fourier Transform (DFT) method to oscillatory data $S(t)$ one may require a homomorphic deconvolution of the signal $O(t)$ and the noise $E(t)$ to suppress spurious peaks in the power spectrum generated by the random noise. One of deconvolution techniques was first developed by an electronic engineer (Oppenheim 1965). Since then, this approach was adopted by geophysicists who have echoes in their signal because of reflections on geological layers (e.g., Ulrych 1971), and later used in many fields of physics and engineering, such as, acoustics, geophysics, helioseismology, image processing, etc (e.g., Baudin, Gabriel, & Gilbert 1993, Chang 2007). We have applied this method, for the first time, to terrestrial impact cratering records.

This paper begins with descriptions of the analysis method in section 2. We present periods of the impact cratering rate obtained with the wavelet analysis, and discuss results on the impact rate in section 3. Finally, we summarize and conclude in section 4.

2. CEPSTRUM ANALYSIS

The technique to deconvolve is divided into three main stages: discrimination, filtering, and reconstruction. The discrimination of the two parts (signal and noise) of data is made after some mathematical manipulation of a data set in the Fourier space. In the next step, we take the complex logarithm of the Fourier transform. The following step is very important since this is where the two functions are discriminated. This is the computation of the inverse Fourier transform of the result above. This is what is called the cepstrum. That is,

$$\text{Cepstrum} = \mathcal{F}^{-1} \log \hat{S}(\nu), \tag{1}$$

where $\hat{S}(\nu)$ is the Fourier transform of the data $S(t)$. This cepstrum is a real function (imaginary

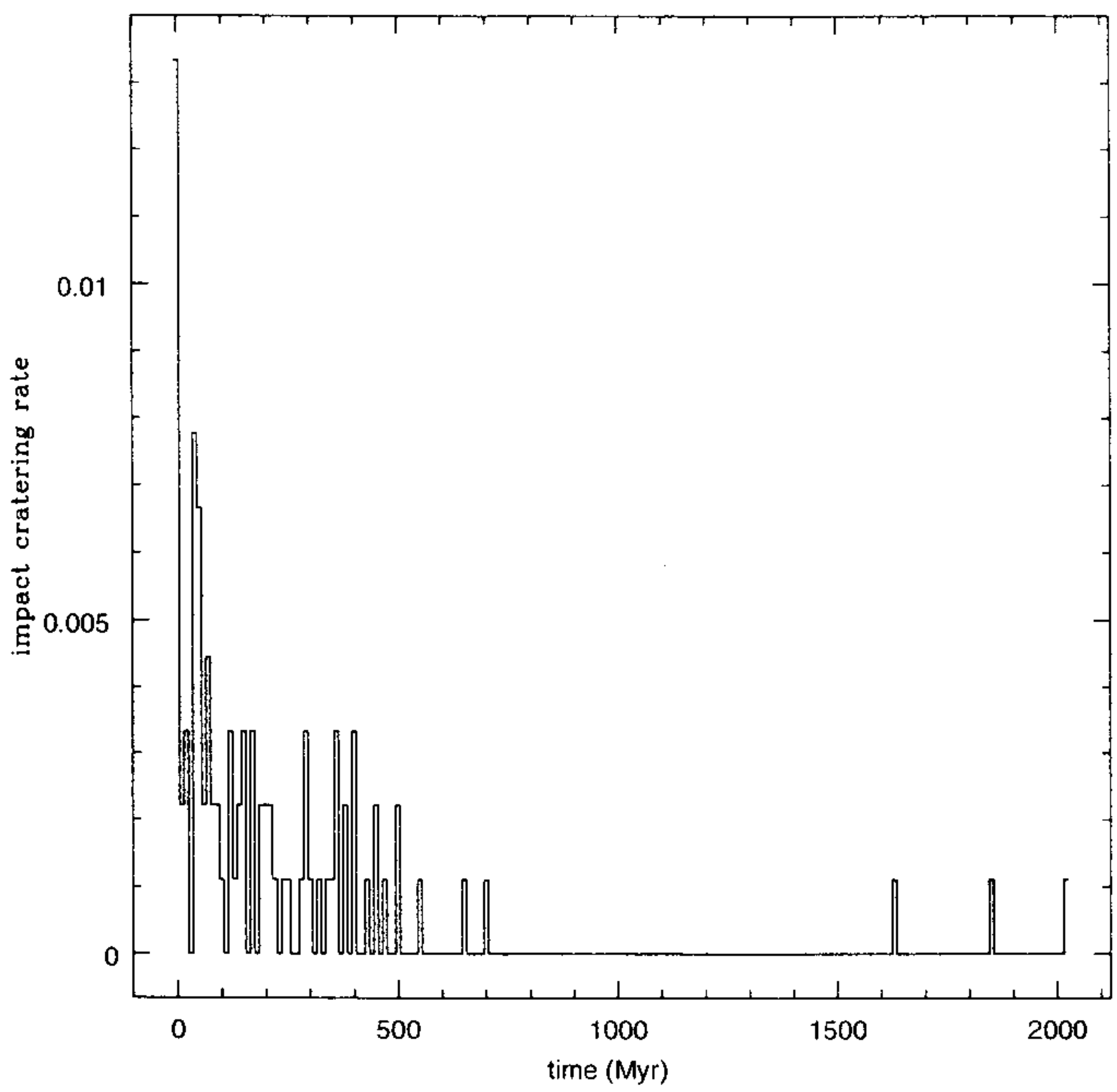

Figure 1. Terrestrial impact cratering rate histogram per interval of 10 Myr. The horizontal axis represents time in Myr, and the vertical axis the impact cratering rate. It is normalized such that the total area under the histogram is equal to unity. Note that most of impact crates whose age is well constrained can be found in a time interval earlier than the Cambrian period (510 − 570 Myr).

part equal to zero), and describes the variation of the 'maplitude' versus the 'quefrency'. It should be noted that

$$\mathcal{F}^{-1} \log \hat{S}(\nu) = \mathcal{F}^{-1} \log \hat{O}(\nu) + \mathcal{F}^{-1} \log \hat{E}(\nu). \tag{2}$$

The filtering is the most important, since at this stage there is an elimination of random noise while one must be sure that the required information of the signal remains. The issue of this step is how to remove the noise without contaminating the information. The simplest way is to choose which part of the cepstrum to be reconstructed as a signal and then to replace rest parts by zeros. Since the real information is generally concentrated at very low quefrency, this simplest solution can be used. Another way to achieve the filtering is to make an average of the cepstrum of several samples of the time series. For each sample, the information is supposed to be the same and the noise may be different. So the contribution of the noise will cancel out while the contribution of the information will stay. Combination of two approaches is also, of course, possible.

The final stage is simply a reversal of the first stage in order to recover the required part of the signal. Final results can be in the time domain or in the Fourier domain, depending on their use.

3. DATA AND RESULTS

We have applied the method described in the previous section to the terrestrial impact crater

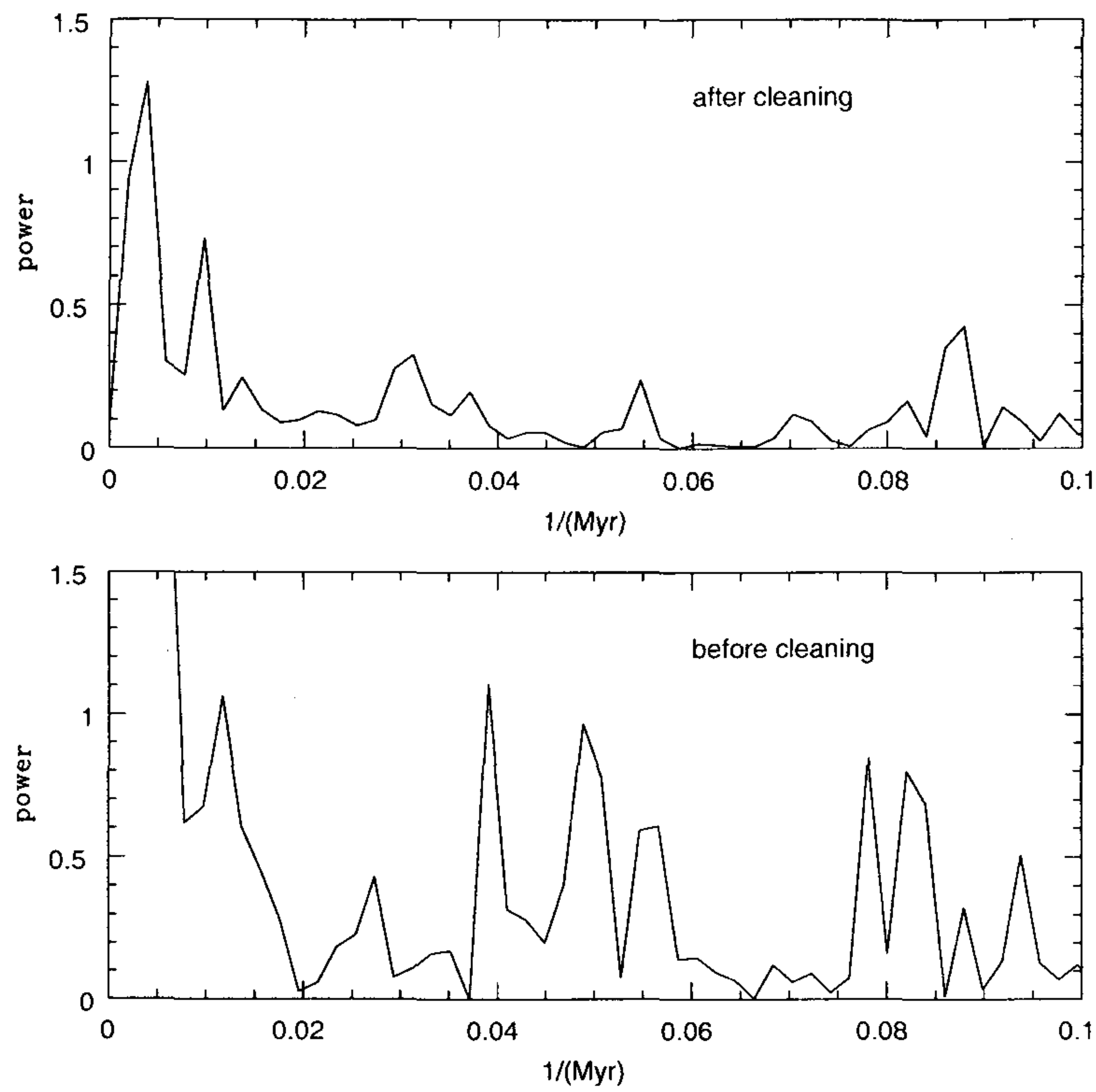

Figure 2. Fourier power spectra of the impact cratering rate. The horizontal axis and the vertical axis represent the frequency in unit of 1/ Ma and the amplitude of the power spectrum in arbitrary unit, respectively. In the lower panel the power spectrum without deconvolution is shown. In the upper panel, we show the *cleaned* power spectrum after deconvolution using the cepstrum technique. In the *cleaned* power spectrum the most significant peak corresponds to the periodicity of $\sim$ 300 Ma. The second peak corresponding to $\sim$ 100 Ma.

data set, as collected in Chang & Moon (2005). They used the ages and diameters of impact craters from the updated Earth impact database (Earth Impact Database 2004) [1]. They selected the impact craters with error estimates in age, and discarded ones with only upper or lower limits for their age (see also Moon et al. 2001). By applying these criteria, they ended up with 90 craters among 173 impact craters in the original database. One may find the craters selected for the data set in their Table 1 (Chang & Moon 2005). In Figure 1, we show the terrestrial impact cratering rate histogram per interval of 10 Myr for our data sets that we analyze. The horizontal axis represents time in Myr, and the vertical axis the impact cratering rate. It is normalized such that the total area under the histogram is equal to unity. In general, the number of impact craters decreases as one goes back in time. This is why one sometimes requires to set the limit of the age in sampling. One may notice that most of impact crates whose age is well constrained can be found in a time interval earlier than the Cambrian period (510–570 Myr).

[1]http : //www.unb.ca/passc/ImpactDatabase/index.html

In Figure 2, we show the traditional discrete Fourier power spectra of the impact cratering rate. The horizontal axis and the vertical axis represent the frequency in unit of 1/ Ma and the amplitude of the power spectrum in arbitrary unit, respectively. In the lower panel the power spectrum without deconvolution is shown for comparison. It is very hard to identify any significant peaks. In fact, according to Chang & Moon (2005) there was no conspicuous periodicity in this particular data set. For instance, the peak corresponding to $\sim$ 26 Ma (that is, frequency $\approx$ 0.04) periodicity can be found among noisy peaks, which cannot be identified as statistically significant. In the upper panel, we show the *cleaned* power spectrum after deconvolution using the cepstrum technique. To filter the noise part from data we cut off the cepstrum at quefrency $\approx$ 20 and substitute zeros for the maplitude. We have found that resulting power spectrum is insensitive to the cut-off quefrency as long as quefrency is greater than several decades. We have compared several *cleaned* power spectra resulted from different cut-off quefrencies and failed to find discrepancy. In that way, we can be sure that no information in the signal is thrown away. The *cleaned* power spectrum shows significant reduction of the spurious background noise. It should be noted that peaks corresponding to short- and intermediate term periodicities are suppressed. In the cleaned power spectrum the most significant peak corresponds to the periodicity of $\sim$ 300 Ma. The second peak corresponding to $\sim$ 100 Ma. They turn out to be statistically significant compared with other peaks in the power spectrum. Currently, we do not have any viable model in the Galactic dynamics to explain $\sim$ 300 Myr, $\sim$ 100 Myr periodicities yet.

4. SUMMARY AND CONCLUSION

It is a quite interesting issue whether a periodicity does exist in the terrestrial impact crater records and, if true, what the period would be. Up to date, only short- and intermediate-term periodicities draw attentions, leading discussions on their origin. Possible impactors which may yield such a short-term periodicity fall into two broad populations: asteroids and comets. Apart from having distinct compositions, they also have substantial differences in relative velocities, source regions and delivery mechanisms. Asteroids are relatively dense, composed of silicate rock and metal, and most originate in the asteroid belt. Comets are low-density objects made of ices and minor amounts of silicates, which originate in the Kuiper Belt near the orbit of Pluto or the Oort cloud. Little is known, however, about the ratio of asteroid to cometary impactors in the inner Solar System. Is the ratio modulated with a longer timescale? We do not have an answer for this question yet.

We attempt to search for a long-term periodicity using a new and promising approach, that is, the cepstrum analysis method. It is for the first time to apply this technique to cratering records of the surface of the Earth. Having applied the technique to the data sample, selected from the original database according to the upper limit of the age and the lower limit of the diameter, we have found the presence of $\sim$ 100 Ma, $\sim$ 300 Ma periodicities in the terrestrial record over the last $\sim$ 2 Gyrs. We note that these periodicities are comparable with the revolution period of the Sun around the Galactic center. Unfortunately, however, there exists no dynamical model to explain such a long-term periodicity. Longer period solutions of the Galactic dynamics seem to be required to explain such a long term periodicity. However, it should be stressed that other stochastic episodes, such as, sporadic encounters with spiral arms, or stars, may also result in such a long-term periodicity.

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