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RESEARCH PAPER

The solar and lunar effect of earthquake duration and distribution

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Abstract Phase folding algorithms are conventionally used in periodicity analyses using X-ray astronomy pulsar. These allow for accurate identification of the cycle and phase characteristics of the physical parameters of the periodic variation. Although periodic variations in earthquake activity have long been studied, this paper is the first to apply the phase folding algorithm to the analysis of shallow (<70 km) seismic data for the period 1973–2010. The goal is to study the phase distribution characteristics of earthquake frequencies and we see a connection between earthquake occurrence and solar and lunar cycles. First, the rotation of the Sun may play a significant role in impacting on the occurrence time of earthquakes with magnitudes of less than 6.0. This may be especially pertinent for earthquakes with magnitudes between 5.0 and 6.0, when the modulation ratio reaches 12 %. The Moon's gravity, which is generally thought to have the greatest influence on the global environment, may actually play less of a role on earthquake timing than the rotation of the Sun. Second, when we consider the world to be divided into 72 local regions based on latitude and longitude, we can see that there are more than a dozen regions with significant non-uniform distributions of earthquake occurrence time. In these regions, the ratio of χ^2 to the number of degrees of freedom far exceeds five. As a result, we posit that some factors associated with the Sun–Earth–Moon relationship may trigger earthquake activity under certain temporal and spatial conditions.

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1 Introduction

Earthquake frequencies tend to take on a certain periodicity, which has always been the subject of much research. Kilston and Knopoff (1983) found that the cyclical characteristics of large earthquakes in Southern California are strongly correlated to the time and direction of the daily and semi-daily tidal stress. Ding et al. (1994) showed that earthquake frequency is modulated by the lunar phase, resulting in elevated magnitudes of up to 25 %. Du and Li (1992) studied the relationship between solar and lunar cycles and earthquakes in the lower Changjiang River region. Earthquakes in this region were associated with several periodic phases, including the half-day cycle, the half-month cycle and the 1-year cycle. Lin et al. (2003) studied earthquakes that might have potentially been triggered by tidal forces, but found that larger earthquakes ($M > 5$) were caused predominantly by tectonic forces and were not associated with tidal forces. Conversely, using statistical analyses, Feng and Wei (2007) built a probability density distribution of the zenith distance among the Sun, the Moon, and the location of the earthquake and concluded that large earthquakes are more likely to occur around the projection point of the Sun and the Moon.

As early as the 1860s, Simpson (1967) published an article discussing the potential for solar activity as a trigger for earthquakes. He noticed that solar activity and seismic activity had similar and consistent cycles and explored the possibility that solar flares might trigger earthquakes by causing an electric surge in the earth. Arcangelis et al. (2006) performed a comparative analysis of the occurrence of solar flares and earthquakes and found that the frequencies of both follow a similar law of occurrence, changing with the level of the exponential distribution. Likewise, the time distribution of aftershocks and small flares following large flares obeys Omori's law. As a result, the authors suggest that the occurrence of solar flares and earthquakes may obey a similar physical mechanism. Fidani and Battistion (2008) analyzed data based on four satellites: NOAA-15, 16, 17, 18. They then tested the correlation between seismic activity and the effect of solar wind and cosmic rays on the ionosphere and found that the temporal distributions of the particle burst showed some correspondence with the occurrence and duration of earthquakes.

Whether or not earthquakes are related to celestial orbits and especially whether they are predictable has long been a question on the mind of geologists. Several scientists oppose the theory, including seismologist Gardner and Knopoff (1974) who asserts that the rotation of the Sun and Moon have no influence on earthquakes in Southern California. In 1997, Geller et al. (1997) issued a document announcing bluntly "earthquakes are not able to be predicted." The theoretical basis for his arguments were that earthquakes are a nonlinear system, so any small earthquakes are likely to evolve into large earthquakes. On the other hand, Zhao et al. (2011) recently issued a document stating that earthquakes should, in fact, be predictable. Their data analysis of global earthquakes larger than magnitude 7.8 as well as Wenchuan and Chilean aftershocks suggest that these occurred primarily during the 23rd and 24th solar cycle. Not only did their study validate the temporal relationship between earthquake occurrences and solar and lunar orbits, but it also applied the concept of the degree of aggregation. The study suggests that the location of the shocks tended to occur in the direction of the magnetic field generated by solar wind.

By applying the phase folding algorithm used in the analysis of astronomical cycles, we analyzed the cyclical nature of the timing of earthquakes in an attempt to discover phase characteristics associated with solar and lunar cycles.

2 Phase folding analysis

"Beat analysis" refers to the time-varying photometric study of X-ray radiation in astronomy. Folding analysis is one of the important methods used to perform beat analysis (Wang and Zhou 1999).

In detail, we select different punctuality parameters such as the cycle and the change rate of the cycle, etc. We then calculate the phase from the observed events and perform the phase distribution statistics. If we define t_0 as a point at time zero, the phase of the particles with t_i arrival time is described by the following formula:

$$\phi = (t_i - t_0)f + \frac{(t_i - t_0)^2 f'}{2} + \frac{(t_i - t_0)^3 f''}{6} \quad (1)$$

where f, f', f'' are the frequency of the periodic movement, its first order derivative, and its second order derivative, respectively. Optional punctuality parameters from the statistical distribution are folded into a phase interval representing a complete cycle. In the absence of a periodic signal, the folded events will be evenly distributed. While the homogeneity test may determine the presence of a periodic distribution, the Poisson χ^2 distribution is very applicable in this case. Assuming the phase interval [0, 1] is divided into k number of channels, the total number of particles is $N = \sum_{i=1}^{k} n_i$, where n_{i} is the number of particles in the ith-channel. Then:

$$\chi^2 = \sum_{i=1}^{k} \frac{(n_i - N/k)^2}{N/k} \quad (2)$$

The equation should obey the χ^2 distribution with degrees of freedom $k - j$, where j is the number of punctual parameters.

Assuming the search frequency to be N_{p}, the confidence level can be described as:

$$\xi = [1 - P_r(> \chi^2)]^{N_p} \quad (3)$$

3 Data selection and periodic analysis using phase folding

In this paper, we performed data analysis on earthquake data downloaded from the global seismic records website [http://earthquake.usgs.gov/earthquakes/eqarchives/epic/] for the period 1973–2010. Figure 1 shows the distribution of these earthquakes with a 1 × 1° pixel resolution. The color represents the number of earthquakes for each pixel.

The phase folding analysis is carried out using three selected cycles of the Sun, Earth, and Moon according to their dictates of the rotational relationship. These include the Earth tropical year cycle, the rotation of the Earth and the orbital period of the Moon around the Earth. The specific cycle value and the divided interval for each cycle are shown in Table 1. The phase t_0 is set to 0:00:00 on January 1, 1973 and the time t_{i} is the time of the i-th earthquake occurrence. In Eq. (1), f is the reciprocal of the cycle value listed in Table 1, which is taken to be constant, so the first and second order of the derivative respective to the time are both 0.

3.1 Global phase folding analysis of earthquake distribution

We performed global seismic phase folding analysis for each of the three cycles for different earthquake

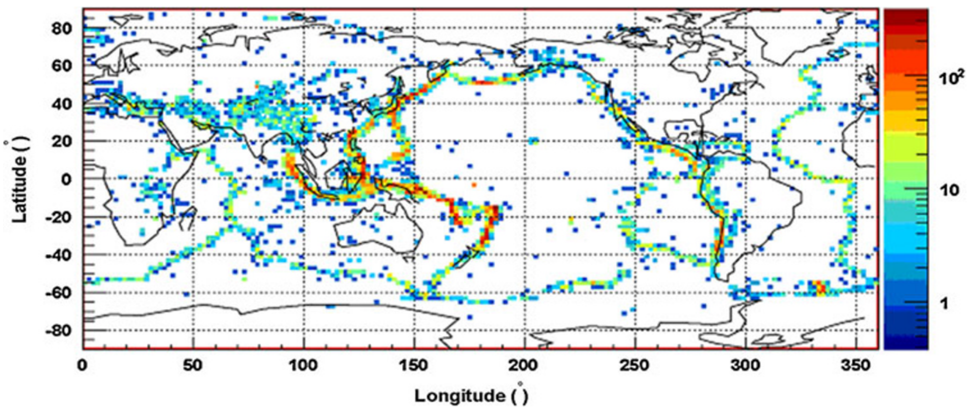

Fig. 1 The distribution of earthquakes with magnitudes greater than 2.5 during 1973–2010. Pixel resolution is 1° by 1° and the *color* indicates the number of earthquakes for each pixel

Table 1 Period selection and interval divisions

Cycle	Time	Number of divided regions
Earth tropical year cycle	365.24219879	12
Earth's rotational cycle	24	24
Lunar orbital period	27.32166	28

magnitudes, and gave each a significance value for the phase analysis. From Fig. 2, depicting the phase distribution for the Earth's tropical year cycle, we see that earthquakes of magnitude 2.5–3.0 occur more frequently around the time of the autumnal equinox than the vernal equinox. In contrast, earthquakes of magnitude 3.0–5.0 take on opposite characteristics to those of earthquakes of

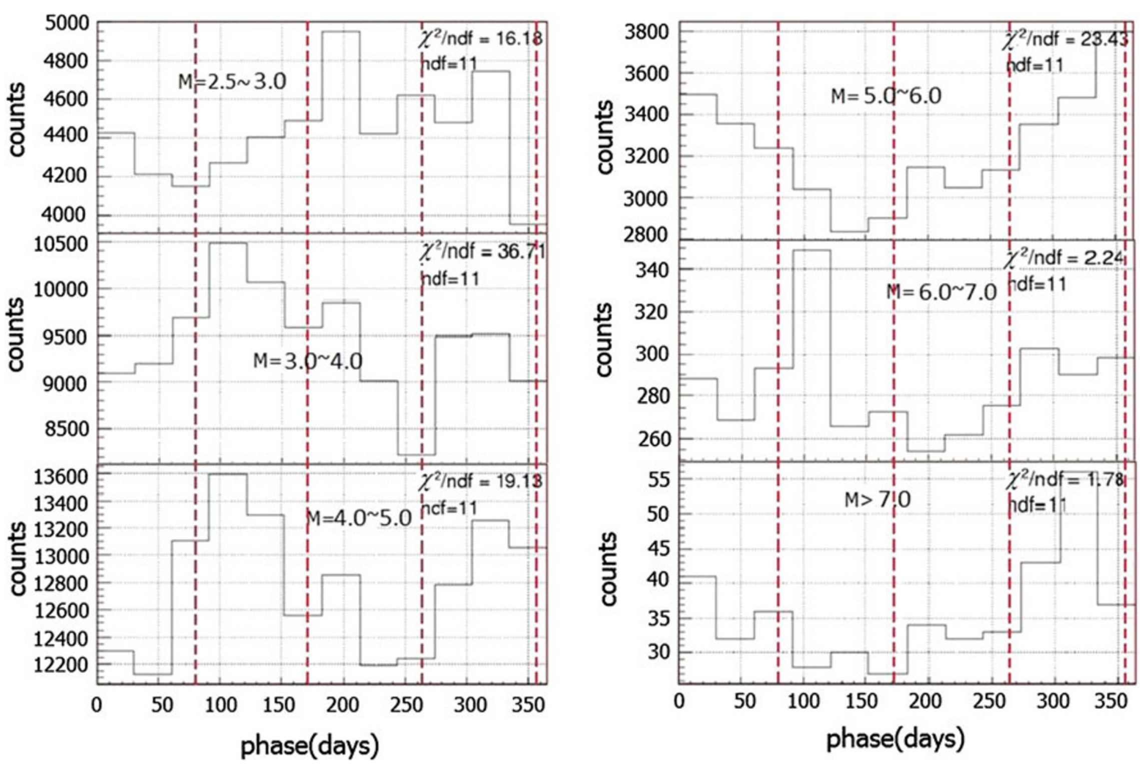

Fig. 2 The phase-folding distribution of earthquakes with magnitudes greater than 2.5 for the Earth tropical year cycle, because the abscissa covering the 365 days in 1 year is related to the Earth tropical year cycle. The four *red dashed lines* from *left to right* in the plots denote the position of vernal equinox, summer solstice, autumnal equinox, and winter solstice, respectively

magnitude 2.5–3.0 and they tend to be distributed more frequently near the vernal equinox than the autumnal equinox. The more destructive earthquakes of magnitude 5.0–6.0 appear to be significantly impacted by solar activity. The phase of the seismic frequency enhancement is concentrated on or near the winter solstice, and reaches its minimum during the summer solstice. From Fig. 2, we can see that earthquakes with a magnitude greater than 6.0 are not affected by the solar year, with very small χ^2/Ndf (Ndf indicates the number of degrees of freedom in seismic cycle distribution) values reflecting the characteristics of cycle distribution.

Figure 3 shows the phase folding analysis associated with the lunar cycle. The χ^2/Ndf values for all earthquakes are all <5 suggesting that the lunar cycle plays only a minor role in the timing of major earthquakes.

Figure 4 shows that earthquakes with magnitudes of less than 5.0 are more likely to be affected by the Earth's rotation. Earthquakes with magnitudes of 2.5–3 have inverse distribution characteristics to earthquakes with magnitudes of 3.0–5.0. Earthquakes of magnitude 2.5–3.0 occur more frequently during the day with maxima at noon and midnight, local time. Earthquakes with magnitudes between 3.0 and 5.0 occur more frequently at night, reaching a maximum at 01:00 local time. The timing of earthquakes with magnitudes greater than 5.0 is not obviously affected by the rotation of the Earth.

In Figs. 2, 3, 4, the earthquakes of different magnitude from statistical results take on obviously non-uniform timing distribution. Because the final behavior of lithosphere movement are determined by many kinds of factors together, including the lithosphere structure, gravity, the effect of the magnetic field, solar activity, and so on. Those factors will provide different effects to the earthquakes with different magnitudes. So it is possible that the rotation of the Sun plays different role in impacting on seismic occurrence times for the earthquakes with different magnitude, although the precise reason still need to be obtained by further study.

Because of their destructive power, people always pay more attention to earthquakes that have magnitudes above 5.0. According to the above figures that compare the phase folding analysis for each of the earthquakes with magnitudes greater than 5.0, there appears to be a significant seismological non-uniformity in the Earth's tropical year cycle. The corresponding χ^2/Ndf values are up to 23.35 for earthquakes with magnitudes between 5 and 6. This indicates that the Earth's rotation around the Sun may, in some way, affect the occurrence time of earthquakes, making them accumulate in the end of each year. In total, there are 43,889 earthquakes categorized as magnitude 5.0–6.0, of which the distribution of 5,236 seem to be modulated by the rotation of the Sun. As a result, the rotation of the Sun plays a role in impacting the timing of approximately 12 %

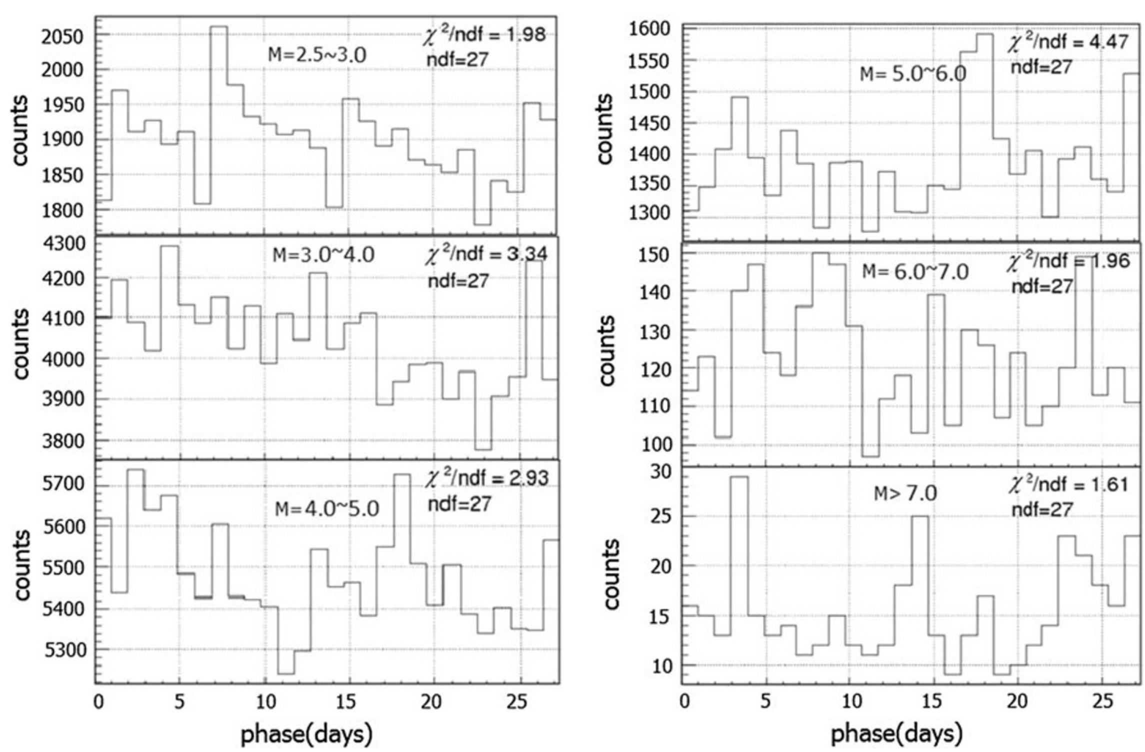

Fig. 3 The phase-folding distribution of earthquakes with magnitudes greater than 2.5 for the lunar cycle, because the abscissa covering the 30 days in 1 month is related to the lunar cycle

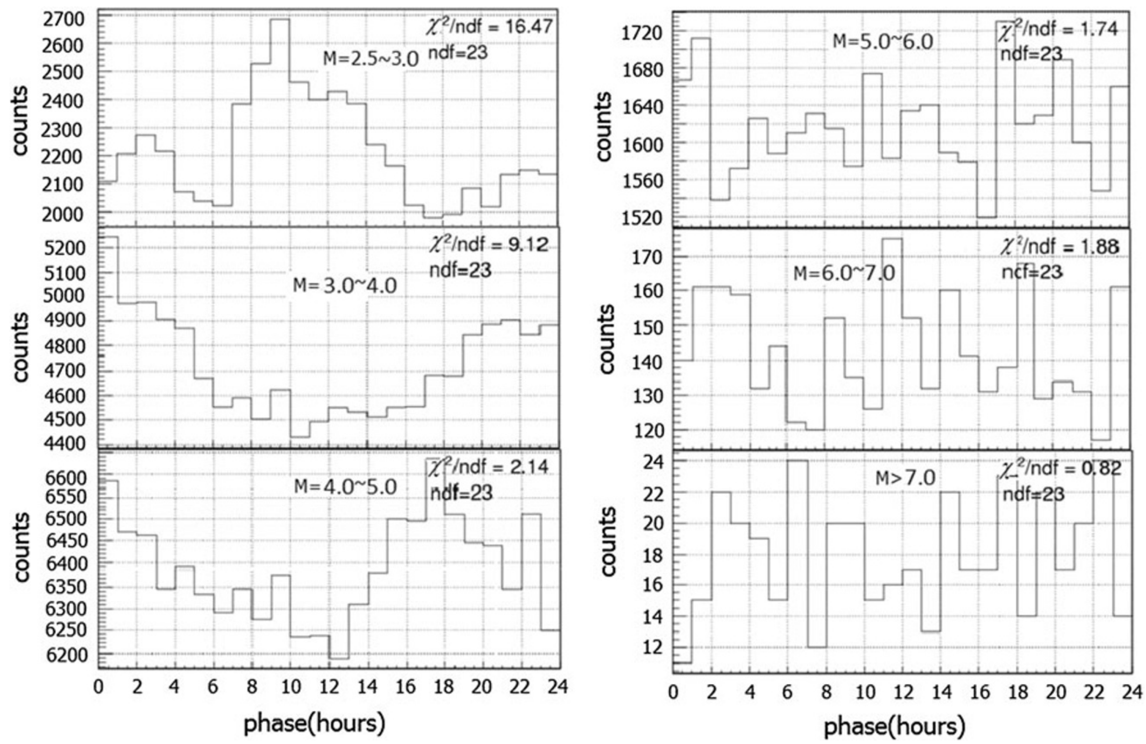

Fig. 4 The phase-folding distribution of earthquakes with magnitudes greater than 2.5 for the rotation of the Earth, because the abscissa covering the 24 h in 1 day is related to the rotation of the Earth

Table 2 χ^2/Ndf values for each region corresponding to the solar cycle

Long Lat	0–20	20–40	40–60	60–80	80–100	100–120	120–140	140–160	160–180
45–90	0.58	2.00	5.25	1.22	1.94	0.44	1.03	8.10	9.18
0–45	4.75	1.08	1.97	3.19	35.28	4.21	1.44	13.05	0.55
0 to −45	0.64	2.16	1.14	1.96	2.36	12.81	4.69	7.94	7.55
−45 to −90	1.66	0.68	0.91	2.23	1.46	0.55	1.12	1.28	3.58

Long Lat	180–200	200–220	220–240	240–260	260–280	280–300	300–320	320–340	340–360
45–90	5.17	1.71	1.24	3.25	1.27	1.09	1.00	1.46	1.65
0–45	1.00	0.55	1.22	1.49	3.19	2.32	1.56	1.31	1.60
0 to −45	7.76	0.91	3.72	1.87	0.94	25.11	1.07	0.96	1.84
−45 to −90	1.69	1.17	1.83	1.66	0.64	0.55	1.35	0.90	0.59

Values in the first row indicate the longitude and those in the left-hand column indicate the latitude in degrees

of earthquakes with magnitudes between 5.0 and 6.0. On the other hand, the timing of seismic events associated with the lunar cycle and the Earth's rotation follow a more uniform distribution.

3.2 Local phase folding analysis of earthquakes

The local properties of earthquakes and the internal structure of the Earth play a crucial role in the occurrence of earthquakes. So, in the following section, we performed a local phase folding analysis of earthquakes with magnitudes greater than 5.0 because these have the greatest destructive power. Longitude is divided into 18 sections, each with 20°, and latitude is divided into four intervals, each with 45°, forming a grid of 72 regions of 20 by 45°. The phase analysis is carried out for a different cycle length for each individual region. In accordance with the division intervals listed in Table 1, we

Table 3 χ^2/Ndf values for each region corresponding to the rotation of the Earth

Long Lat	0–20	20–40	40–60	60–80	80–100	100–120	120–140	140–160	160–180
45–90	0.94	0.96	2.7	16.08	0.76	1.5	0.62	1.94	1.85
0–45	1.51	1.32	1.15	1.67	0.92	1.07	1.74	1.06	1.13
0 to −45	0.83	1.55	0.96	0.64	0.98	0.92	1.24	1.01	1.51
−45 to −90	1.08	1.03	0.96	0.87	0.74	1.39	0.82	1.07	0.84
Long Lat	180–200	200–220	220–240	240–260	260–280	280–300	300–320	320–340	340–360
45–90	1.76	0.92	0.98	1.03	0.87	0.87	1.00	1.07	1.16
0–45	1.00	1.04	1.28	2.03	0.97	1.02	1.09	1.16	0.98
0 to −45	0.87	0.96	13.32	1.43	1.28	1.04	1.24	1.40	1.35
−45 to −90	0.93	1.39	1.03	1.46	1.24	0.86	1.32	1.65	1.21

Values in the first row indicate the longitude and those in the left-hand column indicate the latitude in degrees

Table 4 χ^2/Ndf values for each region corresponding to the lunar orbit

Long Lat	0–20	20–40	40–60	60–80	80–100	100–120	120–140	140–160	160–180
45–90	1.11	1.00	2.71	0.65	1.34	1.03	0.90	3.28	2.63
0–45	1.30	1.10	1.04	2.20	11.50	2.49	2.17	2.33	0.81
0 to −45	0.85	1.79	1.05	1.38	2.61	3.68	1.86	2.67	2.14
−45 to −90	2.40	2.06	0.96	1.48	0.76	1.34	1.41	1.00	1.17
Long Lat	180–200	200–220	220–240	240–260	260–280	280–300	300–320	320–340	340–360
45–90	2.45	1.84	1.07	1.70	0.89	1.11	1.00	1.16	1.05
0–45	1.00	1.10	1.83	1.16	1.29	1.66	1.27	1.08	1.01
0 to −45	1.55	0.96	0.89	1.30	1.18	8.69	0.85	0.86	1.35
−45 to −90	1.46	0.99	1.86	1.31	0.85	1.80	1.00	1.13	1.39

Values in the first row indicate the longitude and those in the left-hand column indicate the latitude in degrees

performed phase folding analysis on each of the 72 regions. Each of the resulting χ^2/Ndf values for these regions are shown in Tables 2, 3, 4.

In order to study the phase distribution characteristics with values of χ^2/Ndf exceeding 5, we list the phase distribution of these regions for different cycles in Figs. 5, 6, 7.

From Table 2 and Fig. 5, for the 72 regions analyzed, we can see that there are 11 regions with a significant non-uniform phase distribution (χ^2/Ndf exceeding 5) for the timing of earthquakes on the Earth's tropical year cycle. Selecting a specific 4-month (October to January) time interval, 8 regions have a significant non-uniform phase distribution within this time interval. Assuming that the timing of earthquakes is evenly distributed, the probability that regions with a significant non-uniform phase distribution have earthquakes that occur within this time interval should be 1/3 (4/12), but instead the probability value is $5.59 \times 10^{-3}\left(\frac{C_{11}^{8}C_{3}^{1}C_{2}^{1}}{(C_{3}^{1})^{11}}\right)$. This suggests that, in addition to the random seismological mechanisms operating in the Earth's tropical year cycle, there must also be another mechanism related to the Earth's rotation around the Sun. This mechanism must exist in order to trigger earthquakes and make them occur specifically during the winter (October to January). In addition, these areas seem to be geographically isolated, with 7 of the 11 regions located on the western side of the central Pacific Plate.

As can be seen from Table 3 and Fig. 7, the non-uniform phase distribution of earthquakes which are affected by the rotation of the Earth lies in two regions (0°–45°S, 120°–140°W), (45°–90°N, 60°–80°E), where the ratio of χ^2/Ndf is much more than 5 and the strong non-uniform feature is concentrated in the afternoon and before dawn for a 24-h period. Meanwhile, it can be seen from Fig. 6 and Table 4, for the lunar cycle, there is also a non-uniform phase distribution with a ratio of χ^2/Ndf exceeding 5 in two regions: (0°–45°N, 80°–100°E), (0°–45°S, 60°–80°W). The significantly uneven distribution of these earthquakes

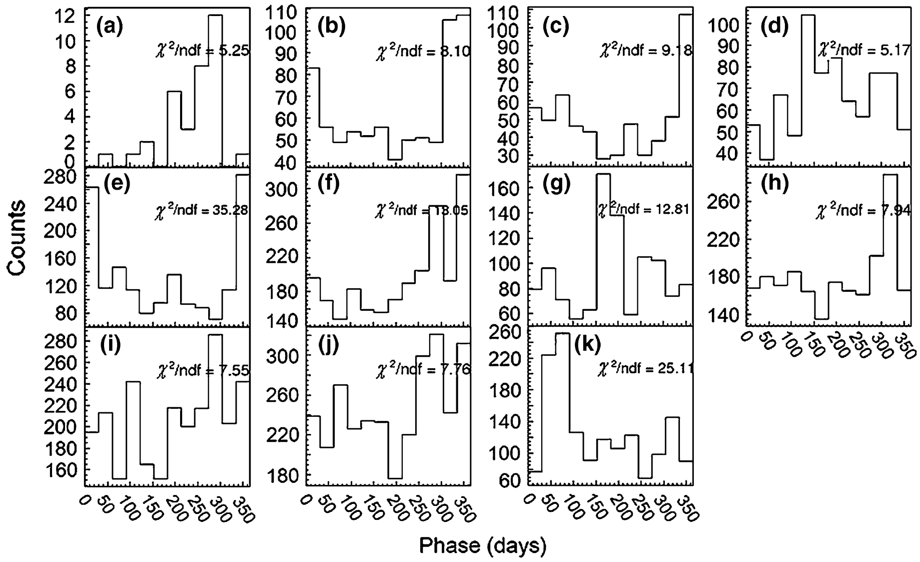

Fig. 5 The phase distribution of earthquakes with magnitudes greater than 5 with corresponding χ^2/Ndf value exceeding 5 for the Earth's tropical year cycle. The corresponding region in each diagram is as follows: **a** 45°N–90°N, 40°E–60°E, **b** 45°N–90°N, 140°E–160°E, **c** 45°N–90°N, 160°E–180°, **d** 45°N–90°N, 160°W–180°, **e** 0°–45°N, 80°E–100°E, **f** 0°–45°N, 140°E–160°E, **g** 0°–45°S, 100°E–120°E, **h** 0°–45°S, 140°E–160°E, **i** 0°–45°S, 160°E–180°, **j** 0°–45°S, 160°W–180°, **k** 0°–45°S, 60°W–80°W

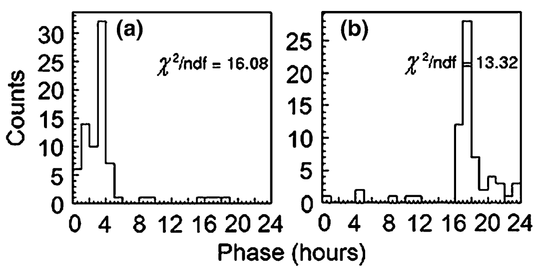

Fig. 6 The phase distribution of earthquakes with magnitudes greater than 5 with corresponding χ^2/Ndf values also exceeding 5 for the lunar cycle. The corresponding region in each diagram is as follows: **a** 45°N–90°N, 60°E–80°E, **b** 0°–45°S, 120°W–140°W

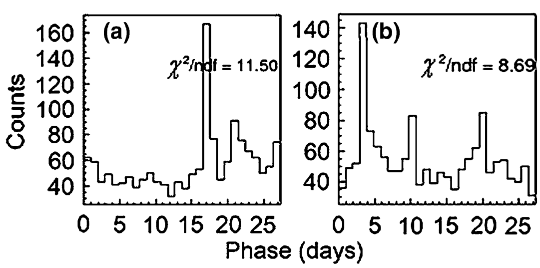

Fig. 7 The phase distribution of earthquakes with magnitudes greater than 5.0 with corresponding χ^2/Ndf values exceeding 5 for the Earth's rotation. The corresponding region in each diagram is as follows: **a** 0°–45°N, 80°E–100°E, **b** 0°–45°S, 60°W–80°W

cycles implies that the underlying mechanism may be related to the rotational dynamics of the Sun, Earth, and Moon, which may play different roles in each of the geographic fault structures within the Earth.

4 Conclusions

Earthquake prediction is dependent on whether or not earthquakes are random events. In order to judge whether an earthquake is random, one must first carry out an objective statistical analysis. In order to address this, we introduce an astronomy phase folding algorithm to the analysis of the number of earthquakes for different periods. We then attempt to find a law corresponding to the occurrence of an earthquake in each of the different cycle lengths.

Using this technique, we conclude:

(1) The Sun's rotation may play some role in the influence of the timing of earthquakes with magnitudes of less than 6.0. Approximately 12 % of earthquakes that occur at the end of the year with magnitudes of 5.0–6.0 are affected by the rotation of the Sun.
(2) Earthquakes with magnitudes of 2.5 to 3.0 tend to occur either at noon or at midnight.
(3) For the lunar cycle, earthquake times show very uniform distribution characteristics. The Moon's gravity, which is generally thought to have the greatest impact on the global environment, may actually play less of a role on earthquake timing than the rotation of the Sun.
(4) Although the rotation of the Sun plays some role in affecting seismic occurrence times, it does not seem to affect earthquakes with magnitudes above 6.0.

(5) When considering each of the three cycle types, 13 out of the 72 grid regions have significant non-uniform earthquake distributions with much larger χ^2/Ndf values.
(6) Considering only the effect of the Earth's tropical year cycle, a total of 11 of the regions listed in this paper have seismic occurrence times that follow a significant non-uniform distribution. These earthquakes have obvious seasonal characteristics and geographical features: eight regional peaks occur in the winter and seven regions are located on the western side of the Pacific Plate. The probability that 8 out of 11 regions with significant non-uniform earthquake distributions have the majority of their earthquakes happen in the winter is extremely low, only about one out of ten thousandth.

In summary, the seismic data for this study spans nearly 40 years leading greater confidence to our results. We infer that the Earth, as part of the Sun–Earth–Moon rotational system, is bound to be affected by the rotational activity of the Sun and the Moon, through gravity, the effect of the magnetic field, the impact of solar activity, etc. However, in order to calculate what fraction of earthquakes these parameters trigger, further comprehensive integrated analyses are needed using large statistics, wide areas, and multi-magnitude ranges. In addition, we suggest that the rotation of the Sun and the Moon is only one of many kinds of external factor that triggers earthquakes. The internal structure of the Earth, for example, will always be an important and dominant factor. As a result, the dynamics that control the timing of earthquakes are extremely complex, in particular for the regions that have uneven occurrence of seismic events. Much work still needs to be done to solve these issues including studies on earthquake mechanisms in various regions. Analyses should include determining the local orientation of the earthquake fault plane and the direction of the dislocation of the rock mass and collecting data on the rupture and the motion characteristics of the rock near the epicenter, and on the relationship between these characteristics and the focal radiation seismic wave.

Therefore, in addition to the analysis of the relationship between earthquake timing and the rotation of the Sun and the Moon, an analysis that combines these parameters with the study of the Earth's interior is also necessary. We also yet to understand why shallow earthquakes of small magnitude show high significant non-uniformity in their distribution related to the Earth tropical year cycle and the Earth's rotational cycle, i.e., the phenomenon is not random and, therefore, merits further study.

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