Earthquakes temporal occurrence: a statistical study

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Abstract
The distribution of inter-occurrence time between seismic events is a quantity of great interest in seismic risk assessment. We evaluate this distribution for different models of earthquakes occurrence and follow two distinct approaches: The non homogeneous Poissonian and the non Poissonian one. In all cases we obtain either a power law or a power law damped by an exponential factor behaviour. This feature of the distribution makes impossible any prediction of earthquakes occurrence. Nevertheless it suggests the interpretation of the earthquake occurrence phenomenon as due to some non-linear dynamics to be further investigated.

1 Introduction

Seismology can be defined as the science of earthquakes and studies mainly the physics of the earthquakes sources, the elastic wave propagation and the occurrence of earthquakes in space, time and energy. The investigation of earthquakes sources and wave propagation are based on the analysis of the seismograms under the assumption that linear theory of elasticity holds and are treated in a huge amount of literature (see e.g. Ref. 1 and references therein). On the other hand the study of earthquake occurrence regards the construction and the investigation of seismic catalogues, whose content is generally the time of occurrence, the location and the energy of earthquakes. The great interest dedicated by many researchers to the statistics of these quantities is obviously linked to the interest in predicting the time, the location and the energy of the next
earthquake. These questions are still rather unclear and we shall discuss some aspects at the origin of the question. In particular, we suggest that difficulties in prediction are intrinsic to the occurrence mechanism.

The energy release in a seismic event is generally expressed by the magnitude, which is proportional to the logarithm of the maximum amplitude of the recorded seismic signal. The distribution of magnitudes is described by an exponential law usually referred as the Gutenberg-Richter distribution, by the names of the researchers who firstly observed this feature of seismic catalogues. They found that the frequency of occurrence of earthquakes with magnitude greater than \( M \) behaves as

\[
\log N = a - bM
\]

where \( a \) indicates the overall seismicity and \( b \) is a scaling parameter which has typically values close to one. Fluctuations (up to 30%) of the value of \( b \) around its typical value are widely observed depending on the catalogue, the estimating method and the magnitude range [2]. Regional variation of the \( b \) value are also observed by many authors (see e.g. [3, 4]). Such features could be an indication that scaling properties of earthquakes are not universal.

However, it has been suggested that this discrepancy in \( b \) values could be due to systematic errors in magnitude determination [5, 6]. For this reason, it is often studied the distribution of the seismic moment \( M_0 \) defined as \( M_0 = \mu A \Delta u \) where \( \mu \) is the shear modulus, \( A \) is the area of the seismic fault involved and \( \Delta u \) is the slip of the fault due to a single seismic event [6, 7, 2, 8, 9]. This is a more physical quantity compared to the magnitude and can be obtained by inverting the seismic signals with a standard procedure [10]. The cumulative distribution of the seismic moment exhibit a power law behavior followed by a sharp cutoff after a \( M_0^{max} \) well represented by a Gamma distribution

\[
f(M_0) = CM_0^{-(1+\gamma)}e^{-\frac{M_0}{M_0^{max}}}\]

where \( C \) is a constant and \( \gamma \) is a scaling parameter, having a very stable value \( \gamma \approx 0.7 \) [6, 11].

The fractal nature of the spatial distribution of earthquakes has been shown for the CMT catalogue [12, 13] and the fractal dimension \( D_f \) of the hypocenter distribution has been determined. However, the fractal dimension could be not sufficient to describe all the scaling properties in a given problem and a spectrum of dimensions turns out to be necessary in order to fully characterize the scaling behavior. If this happens, the distribution is said to be multifractal [14]. It has been shown [15, 16] that the spatial distributions of earthquakes in Kanto region, in eastern Japan, in California and in Greece have a multifractal structure. The multifractal distribution of earthquakes hypocenters has been also confirmed for some Italian regions [17, 18] and it has been suggested [19, 20] that the temporal changes of \( D_f \) could be a good precursor parameter for earthquake occurrence prediction.

On the other hand, the rate of occurrence of seismic events in time has been widely investigated (see e.g. [21, 22, 23]) because the existence of a charac-
Figure 1: The experimental distribution of the waiting times for a) the Californian catalogue of earthquakes (De Natale et al., 2003), b) the Colfiorito (Italy) sequence (De Natale et al., 2003).

A characteristic time scale could make possible the prediction of the next earthquake. Unfortunately this is not the case since the distribution of waiting times between earthquakes exhibits a two power law behavior [24, 25, 26] (figure 1). More precisely, the data exhibit a first power law regime with an exponent close to 0.8 for both catalogues, followed by a second power law with an exponent 1.8 for Colfiorito and 2.6 for California. The experimental results suggest that inter-arrival times are possible at all time scales, making the prediction of earthquakes occurrence extremely difficult. The non-Poissonian behavior of earthquake occurrence is clearly due to the phenomenon of clustering, suggested by the power law distribution of the inter-arrival times. In fact, for a Poissonian process, the distribution would have an exponential behavior.

The existence of power law behaviors and the multifractal distribution of hypocenters, leads to the interpretation of earthquake as a critical phenomenon [27, 28, 29], proposing a new point of view for the features of earthquake occurrence.

Finally in recent years it has been proposed that Self Organized Criticality (SOC) [30] could explain the observed self-similar properties of earthquakes [27, 28], in particular could be able to reproduce the earthquake size distribution. Within this approach, the lithosphere structure derives from the self-organization of the earth crust in a continental plate. A field theory can be also derived from symmetry and conservation laws to explain the earthquakes size distribution and viewing the earthquakes as fluctuation of the elastic energy in the crust [31].

In this paper we focus on the waiting time distribution, we derive the analytical expression of the inter-arrival time distribution for some existing models and we discuss the scaling behavior of the distributions depending on parameters. More precisely, in Section 2 we shortly present some of the most commonly used models and, in section 3, we derive the analytical expression of the probability density function using a non homogeneous Poissonian approach for the Omori law and the ETAS (Epidemic Type Aftershock Sequences) model. In section 4 we derive the p.d.f. using a non Poissonian approach for the Omori law and the Poisson Generalized model. In all the cases there exists a choice of the parameters fitting some data set. In the final section we present conclusions and considerations for earthquakes occurrence prediction.

2 The earthquake clustering and the Omori law

It is widely observed that earthquakes tend to occur in bursts. These bursts may start suddenly immediately following a large main event, giving rise to the well known main - aftershocks sequences, or may build up and die very gradually in
time, generating swarms of events. The most important implication of this kind of occurrence is that we cannot assume a Poissonian occurrence of earthquakes, where a Poissonian process is characterized by a constant rate of occurrence, but rather a clustered one. In his pioneering paper, Omori [32] investigated the problem of earthquake occurrence within a single cluster of events and proposed that the non-Poissonian behavior of seismic catalogues could be well fitted with the Omori law, stating that the number of aftershocks \( n(t) \) decays in time as

\[
n(t) = \frac{k}{(t + c)^p}
\]  

where \( p \) is generally very close to 1 ranging from 0.7 to 1.7, \( c \) is an initial time introduced in order to avoid the divergence at \( t = 0 \) and \( k = n(0)c^p \) is an experimental constant.

A widely used approach to earthquakes clustering is provided by ”trigger model” [33]. This assumes a Poissonian occurrence of main events, whereas the occurrence of the ”triggered” earthquakes is described in terms of a correlation function \( g(t - t_i) \), where \( t_i \) is the time of occurrence of the \( i \)-th event. The function \( g(t - t_i) \) describes the correlation of each event occurring at time \( t \) with all the events occurred at previous times. Thus the rate of occurrence will be

\[
\lambda = \mu + \sum_{i:t_i < t} g(t - t_i)
\]  

where \( \mu \) is the Poissonian rate of the main events. Among the trigger models a widely used one is the Poisson Generalised model [34]: this assumes the sequence of events as composed by uncorrelated main events which generate clusters of aftershocks distributed as the Pareto power law [33]

\[
q(j) = \frac{j^{-\beta}}{\zeta(\beta)}
\]  

where \( \zeta(\beta) \) is the Riemann function and \( j \) is the number of events in the cluster. This approach has been applied for many areas of the world, as California [34], Messina Strait area [35] and Campi Flegrei (Italy) [36], in order to determine the \( \beta \) value, found to be between 2.5 and 4.

A more appropriate choice of \( g(t - t_i) \) is provided by the ETAS model [37], which considers the existence of many clusters described by the Omori law. The model states that the intensity function (the rate of occurrence) of the earthquakes is given by:

\[
\lambda = \mu + \sum_{i:t_i < t} \frac{k e^{\alpha(M_i - M_0)}}{(t - t_i + c)^p}
\]  

where \( \mu \) is again the Poissonian rate, \( \alpha \) an experimental constant, \( M_0 \) is the smallest magnitude in the catalogue and \( M_i \) is the magnitude of the \( i \)-th event. The meaning of equation (6) is that each earthquake can generate "its own
aftershocks” and that the number of these aftershocks depends exponentially on the magnitude of the "main". In other words the clustering degree varies in time, leading to a clustering within the clustering.

A completely different approach is the fractal one [25]. A Poissonian process would fill stochastically all the temporal axis and thus would have a fractal dimension equal to 1, whereas a clustered process is characterized by a fractal dimension less then one depending on the clustering degree. Using the box counting method it has been found that the New Hebrides seismicity is clustered with a fractal dimension ranging between 0.126 and 0.255 [25]. Moreover other authors [38] found that many catalogues in the world have a multifractal distribution of inter-arrival times. This result is in good agreement with the predictions of the ETAS model.

3 The non homogeneous Poissonian approach

The problem of earthquakes inter-arrival time distribution has never been treated from the theoretical point of view. In order to explain the temporal clustering properties of seismic events occurrence, the most of efforts were dedicated to the study of the rate of occurrence. Nevertheless the waiting time distribution is very important in the seismic risk assessment because it is very useful in the definition of the probability of the occurrence of next earthquake. In this section we derive the distribution of the waiting times for a single cluster following the Omori law and for the ETAS model.

The cumulative distribution of waiting times $F(\Delta t)$ can be written as [39]

$$F(\Delta t) = 1 - F_0(\Delta t)$$ (7)

where $F_0(\Delta t)$ is the probability of observing zero events in $\Delta t$. Since for a Poissonian process

$$F_0(\Delta t) = e^{-\mu \Delta t}$$ (8)

the probability density function (p.d.f.) is found to be

$$f(\Delta t) = \frac{dF(\Delta t)}{d\Delta t} = \mu e^{-\mu \Delta t}$$ (9)

which is the well known result for a Poissonian process.

This approach can be generalized also for processes for which $\mu$ is not constant in time and we shall have a non homogeneous Poissonian process. In this case the probability of having zero events in $\Delta t$ is given by

$$F_0(\Delta t) = e^{-\int_0^{\Delta t} \lambda(t) \, dt}$$ (10)

where $\lambda(t)$ is the time dependent rate of occurrence thus inserting the (10) into the (7) and the result into the (9) we obtain the waiting times p.d.f. Note that the Poissonian behavior is more restrictive then the independence of events,
Figure 2: The p.d.f. of the waiting time within a cluster of events for different values of the model parameter

since it is obtained under the assumption that the probability of observing more than one event in any small time interval, is negligible.

As a first application of this approach we shall derive the waiting time distribution within a cluster of events. In this case the rate of occurrence $\lambda(t)$ is given by the Omori law, thus for $p \neq 1$

$$F_0(\Delta t) = e^{-\int_0^{\Delta t} \frac{\lambda}{(t+c)^p} dt}$$  \hspace{1cm} (11)$$

and the p.d.f. of the $\Delta t$ will be

$$f(\Delta t) = k e^{\frac{k^{1-p}}{1-p} (\Delta t + c)^{1-p} e^{\frac{k}{1-p} (\Delta t + c)^{1-p}}}$$  \hspace{1cm} (12)$$

which, except for some constant factors, is a Weibull distribution, i.e. a power law damped by a stretched exponential decay. Figure 2 shows the p.d.f. for different parameter values: the Omori law exponent $p$ controls the decaying exponential factor which is dominant at long times for $(\Delta t + c)^{1-p} > \frac{1-p}{k}$ when $p < 1$ and at short times for $(\Delta t + c)^{1-p} < \frac{1-p}{k}$ when $p > 1$. We observe that the p.d.f. for $p > 1$ are not in agreement with experimental observations.

In the case $p = 1$ from equation (11) we obtain

$$F_0(\Delta t) = (\Delta t + c)^{-k}$$  \hspace{1cm} (13)$$

and

$$f(\Delta t) = k e^{\frac{k}{1-p} (\Delta t + c)^{1-p}}$$  \hspace{1cm} (14)$$

which is a power law and does not exhibit any exponential decay as equation (12).

A more complex formula is obtained if we adopt the ETAS model. In this case we consider the existence of many clusters of events as described in section 2. The rate of occurrence is given by the equation (6). If we take the continuum limit, that is

$$\sum_{i: \tau_i < t} \frac{k(M)}{(t - \tau_i + c)^p} \rightarrow \int_{0}^{t-\Delta t} \frac{k(M)}{(t - \tau + c)^p} d\tau$$  \hspace{1cm} (15)$$

where $k(M) = ke^\alpha (M_t - M_0)$ we will get for $p \neq 1$

$$F_0(\Delta t) = e^{-\mu \Delta t + \frac{k(M)}{(t+c)^{1-p}\Delta t^{1-p}} ((\Delta t+c)^{1-p}[\Delta t(1-p)+c]-c^{2-p})}$$  \hspace{1cm} (16)$$

which provides for the p.d.f.
Figure 3: The p.d.f. of the waiting times for the ETAS model and $p \neq 1$.

Figure 4: The p.d.f. of the waiting times for the ETAS model in the case $p = 1$ for different values of $k$

$$f(\Delta t) = \left[ \mu - \frac{pk(M)}{1 - p} (\Delta t + c)^{-p} (\Delta t + \frac{c}{p}) \right]$$

$$e^{-\mu \Delta t + \frac{k(M)}{1 - p} (\Delta t + c)^{1-p} [\Delta t (1 - p) + c] - c^{-p}}$$

(17)

Equation (17) is well defined i.e. is a positive quantity, only for $p > 1$ and assumes the shape of a Weibull distribution (figure 3).

Analogously the case $p = 1$ gives

$$F_0(\Delta t) = c^k (\Delta t + c)^{-ck} e^{-\Delta t(\mu + k \ln \frac{c + \Delta t}{4 \Delta t})}$$

(18)

and for the p.d.f.

$$f(\Delta t) = \left[ \mu + k \ln \frac{c + \Delta t}{4 \Delta t} \right] e^{ck} (\Delta t + c)^{-ck} e^{-\Delta t(\mu + k \ln \frac{c + \Delta t}{4 \Delta t})}$$

(19)

We find again a power law damped by an exponential factor. Note that the term in the square brackets is negative for $\mu < k \ln \frac{c + \Delta t}{4 \Delta t}$ because $c + \Delta t < 4 \Delta t$, however it is possible to obtain positive values of the p.d.f. for $k < 0.36$ if we set $\mu = 0.5$ (figure 4).

It is noteworthy that the non homogeneous Poissonian approach does not provide a good agreement with experimental data since does not predict the two power regime shown in figure 1. This feature could be due to the Poissonian assumption which assumes negligibly small the probability of two events occurring in any small time interval.

4 The non Poissonian approach

In this Section we derive the analytical expression of the p.d.f. assuming only that the probability of cluster occurrence is independent on the probability of earthquake occurrence within a cluster. If we call $Q_n(\Delta t)$ the probability of having $n$ events in a cluster and $P_N(\Delta t)$ the probability of having $N$ clusters in $\Delta t$, we will have

$$F_0(\Delta t) = P_0(\Delta t)Q_n(\Delta t) +$$

$$P_0(\Delta t)[1 - Q_n(\Delta t)] + P_N(\Delta t)[1 - Q_n(\Delta t)]$$

(20)

The three terms in equation (20) represent respectively the probability of having zero clusters of $n$ events, zero clusters of zero events and $N$ clusters of zero events. Firstly we determine the p.d.f. of the $\Delta t$ within a single cluster.
In this case $P_N(\Delta t) = 1$ and $P_0(\Delta t) = 0$. The number of events $j$ in a time interval $\tau$ for $p \neq 1$ will be given by

$$j(\tau) = \int_0^\tau \frac{k}{(t+c)^p} dt = \frac{k}{(1-p)}[(\tau + c)^{1-p} + c^{1-p}]$$  \hspace{1cm} (21)

Assuming the power law distribution (5) for $j$, we have

$$Q_n(\Delta t) = \frac{1}{\zeta(\beta)} \sum_{j=1}^n j^{-\beta}$$  \hspace{1cm} (22)

Noticing that in the continuum limit $\sum_j \rightarrow \int dt$ and neglecting the quantity $c^{1-p}$, we have

$$Q_n(\Delta t) = \frac{1}{\zeta(\beta)} \left[ \frac{k}{(1-p)} \int_{(1-p)^{\frac{1}{p}}+c}^{\Delta t} (\tau + c)^{-\beta(1-p)} d\tau = \frac{k^{-\beta}(1-p)^\beta}{\zeta(\beta)\delta} \left[ (\Delta t + c)^\delta - (1-p)^{\frac{1}{p}} \right] \right]$$  \hspace{1cm} (23)

where $\delta = 1 - \beta(1-p)$. Finally we obtain the p.d.f.

$$f(\Delta t) = \frac{1}{\zeta(\beta)} \left[ \frac{k}{(1-p)} \right]^{-\beta} (\Delta t + c)^{-\beta(1-p)}$$  \hspace{1cm} (24)

which is a power law well defined only for $p < 1$. This constraint is due to the assumption that $c^{1-p} \ll (\tau + c)^{1-p}$, which implies from (21) that, if $p > 1$, the number of events $j$ would became negative. In the case $p = 1$ we obtain a p.d.f. whose behavior is inconsistent with the experimental data and thus will not be reported here.

Next we apply the non Poissonian approach to the "trigger" model which assumes a Poissonian occurrence of clusters and a power law decrease of the number of events within the clusters (equation (5)). Under these assumptions we have

$$F_0(\Delta t) = \frac{e^{\mu \Delta t}}{\zeta(\beta)} \left[ \sum_{j=1}^n j^{-\beta} + (\zeta(\beta) - \sum_{j=1}^n j^{-\beta}) + \frac{(\mu \Delta t)^N}{N!} \left( \zeta(\beta) - \sum_{j=1}^n j^{-\beta} \right) \right]$$  \hspace{1cm} (25)

Observing that for a Poissonian process the total number of clusters is $N = \mu \Delta t$ and that $(\mu \Delta t)!$ in the continuum limit becomes $\Gamma(1 + \mu \Delta t)$, we have

$$F\left( \frac{\tau}{\mu} \right) = \frac{e^{-\tau}}{\zeta(\beta)} \left[ 1 + \frac{\tau}{\Gamma(1 + \lambda \Delta t)} \left( \zeta(\beta) - \sum_{j=1}^n j^{-\beta} \right) \right]$$  \hspace{1cm} (26)

where $\tau = \mu \Delta t$. Using equation (22) in order to evaluate $Q_n(\Delta t)$ and neglecting again the quantity $c^{1-p}$ we obtain
Figure 5: The p.d.f. of the waiting times for the Poisson generalized model at fixed values of $\beta = 3.5$ and $p = 0.85$ and for different values of $\mu$.

Figure 6: The p.d.f. of the waiting times for the Poisson generalized model at fixed values of $\beta = 3.5$ and $\mu = 0.01$ and for different values of $p$.

\[ f\left(\frac{\tau}{\mu}\right) = e^{-\frac{\tau}{\mu}} \left\{ \frac{\tau^{\gamma}}{\Gamma(1+\gamma)\zeta(\beta)} \left[ K + \mu(\delta\zeta(\beta) + a\phi\left(\frac{\tau}{\mu}\right)\left(\frac{\Gamma(1+\gamma)}{\Gamma(1+\gamma)} - \ln\tau\right) \right] \right\} \] (27)

where $a = \frac{k}{(1-p)}$, $\delta = 1 - \beta(1-p)$, $K = a\delta$, $b = \left(\frac{1-p}{k} + c(1-p)\right)^{\frac{1}{1-p}}$ and $\phi(x) = (b+c)^{-\delta} - (c+x)^{\delta}$. Equation (27) is a very complex function and does not allow any simple fit of experimental data. Moreover the number of parameters involved in the function is too high for a stable fit. However we notice that it is possible to find some plausible relations among some of the parameters. For instance, $\mu$ and $k$ can be related since they are both rates of occurrence: the first one concerns the cluster occurrence, whereas the second one states how many earthquakes occur at the beginning of a given cluster. In order to evaluate equation (27), we choose $k = 20\mu$. Any other choice for $k$ and $\mu$ does not influence the shape of equation (28), but only the level of the seismicity, that is the total number of events. Obviously the value of $\mu$ and $k$, representing the time scale in the system, implies as a consequence the value of the constant $c$ of the Omori law and therefore we choose $c = 0.3/k$. This means that we have three free parameters $\mu$, $\beta$ and $p$. By varying these parameters, we obtain two possible behaviors: either a two power law regime or a two power law regime damped by an exponential decay at high $\Delta t$.

In figure 5 we show the p.d.f. with fixed $\beta$ and $p$ for different values of $\mu$. At lower values of $\mu$, therefore for clusters more sparse in time, we observe the two power law regimes behavior, whereas for increasing $\mu$ we observe the onset of an exponential cut-off at long waiting times. Note that the exponents are in the range 0.2 - 0.5 for the first power law and 1.3 - 1.9 for the second one.

Figure 6 shows the behavior of p.d.f. at fixed $\beta$ and $\mu$ for a range of values of $p$. In this case we observe for decreasing values of the Omori exponent $p$, i.e. for clusters lasting a longer time, the onset of an exponential cut-off at long waiting times after the two power law regime. In this case the exponents vary between 0.4 and 0.7 for the first power law and between 1.0 and 1.3 for the second one. Any variation of the parameter values does not change substantially the behavior in figures 5 and 6. On the contrary, we will see that the p.d.f. function is more sensitive to combined variations of $\beta$ and $p$.

Figure 7 shows for $p = 0.75$ the onset of an exponential cut-off at long waiting times for high values of $\beta$ as observed in figures 5 and 6 (slopes are in
the ranges 0.5 - 0.7 and 1.6 - 1.4). On the other hand, for \( p = 0.95 \) the two power law behavior is substantially insensitive to \( \beta \) variations (figure 8). This suggests that scaling properties of equation (27) are dominated mainly by \( p \) than by \( \beta \). In this case the power law exponents are 0.4 and 1.0.

The two power law regime is widely observed for many catalogues in the world (figure 1) and generally interpreted as due to catalogue incompleteness. Within the Poissonian Generalised approach we find that the two power law behavior is quite robust with respect to parameter changes. Therefore we suggest that this feature is an intrinsic property of earthquake occurrence related to the P. G. model.

5 Conclusions

We evaluate the probability density function of the inter-occurrence time between earthquakes following two different approaches. We first assume a non homogeneous Poissonian behavior and find for different models of earthquakes occurrence always a single power law, eventually followed by an exponential decay.

Next we investigate a non Poissonian approach for different models. The obtained p.d.f. has a power law behavior in the case of a single cluster of events described by the Omori law. On the contrary, in the case of the Poisson Generalised model the p.d.f. exhibit a more complex behavior depending on parameters. For all values of \( p \neq 1 \) we find consistently a two power law regime. This situation, occurring for small \( \mu \), corresponds to long waiting times between clusters of seismic events, which is the situation more frequently observed in nature. Depending on parameters, the value of the exponents are in agreement with the experimental data.

Moreover, for high values of \( \beta \), i.e. fast decay in the number of events in a single cluster, and a high Poissonian rate \( \mu \) the two power laws are followed by an exponential decay. This feature characterizes a weak clustering in the distribution of events in time or a frequent cluster occurrence.

The two power law behavior is observed for many catalogues relatives to different areas in the world. This feature, often interpreted as a sign of the incompleteness of the catalogue, is here obtained as a specific characteristics of the p.d.f. for the Poisson Generalised model. Finally we notice that for all the discussed approaches and model the power law behavior implies the absence of a characteristic inter-occurrence time and therefore impossibility of any prediction.
of earthquake occurrence.

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