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THE ROLE OF EXTRATERRESTRIAL PHENOMENA IN EXTINCTION

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ABSTRACT

In the several years since the Alvarez report of anomalously high iridium concentrations at the Cretaceous-Tertiary boundary, evidence for the involvement of meteorite impacts in biological extinction has increased dramatically. Much more research will be needed, however, before meteorite impact is established as a general causal factor in extinction. Of ever greater long-term interest is the posibility that other extraterrestrial forces have had important influences on the evolution of life. To recognize the effects of such forces, it will be necessary to coordinate the research of astronomy and paleontology so that testable predictions can be formulated. It is possible that known, systematic changes in the Solar System or Galaxy have had effects on global biology and that these effects have been preserved in the paleontological record.

Keywords: Meteorite impacts, Geochemical anomalies, Biological evolution, Cretaceous-Tertiary boundary.

RESUMEN

Desde hace años en que el reportaje de Alvarez dio a conocer la presencia de concentraciones altas de iridio en el límite Cretácico-Terciario, las evidencias de una actuación meteorítica sobre las extinciones biológicas se han incrementado extraordinariamente. Sin embargo, se necesita mucha más investigación antes de que los impactos de meteoritos se establezcan como un factor general en la extinción. La posibilidad de que otras fuerzas extraterrestres tuvieran influencias importantes sobre la evolución de la vida es aún de mayor y más amplio interés. Para reconocer los efectos de tales fuerzas, será necesario coordinar la investigación paleontológica y astronómica para que puedan formularse predicciones comprobables. Es posible que los cambios conocidos regulares en el Sistema Solar o en la Galaxia hayan tenido efectos sobre la biología global y que dichos efectos se hayan preservado en el registro fósil.

Palabras clave: Impactos de meteoritos, Anomalias geoquímicas, Evolución biológica, Límite Cretácico-Terciario.

INTRODUCTION

The possibility that events in space have been responsible for major episodes of biological extinction on earth has been suggested frequently in the history of paleontology. In this century, notable examples include Schindewolf's (1962) proposal that the mass extinction near the end of the Permian was due to the effects of a nearby exploding star (supernova) and Urey's (1973) claim that several of the series-level extinctions in the Tertiary were caused by comet impacts.

Until recently, proposals for cosmic interpretations of extinction have enjoyed almost no support among paleontologists. The negative reaction has many roots, of which the most important may be: (1) the Lyellian thesis that it should be possible to explain events in earth history without recourse to "extraordinary" agents, and (2) the lack of supporting evidence for extraterrestrial influence in specific cases of mass extinction. It has been conventionally argued that hypotheses of extraterrestrial influence are fundamentally untestable and therefore not amenable to scientific inquiry. This argument is clearly

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flawed but has nevertheless had great weight in the scientific community.

It is indeed true that until Urey's 1973 work, there was no good observational evidence available to support the claims of cosmic influence. Urey's main contribution was to present empirical data on the timing of extinctions and large-body impacts and to analyse these data statistically. He concluded that the similarity in timing was close enough to make a case for cause and effect. His analysis was based on few data and the statistical conclusions could have been challenged. Instead, his paper went virtually unnoticed.

The climate in this field changed dramatically in 1980 with the publication by Alvarez, Alvarez, Asaro, and Michel of data on iridium anomalies at the Cretaceous-Tertiary (K/T) boundary with the proposal that the K/T mass extinction was a consequence of a large meteorite impact (comet or asteroid). This produced a storm of controversy which continues to the present. As a result, the scientific literature devoted to mass extinction and its causes has grown exponentially to the point of being virtually out of control. Because the problem is so highly interdisciplinary, involving important elements of paleontology, geochemistry, geophysics, and astronomy, it has become difficult for any one person to make independent judgments on the merits of the many arguments and counter arguments.

My purpose in this paper is to review some of the basic evidence for and against the Alvarez claim of impact-induced extinction and to try to establish a "coordinate system" for a general evaluation of broader questions of cosmic influences in the history of life on earth. Because the literature on mass extinction has become so vast, a comprehensive review is impossible but I will attempt to identify some of the salient published papers on the subject.

THREE INDEPENDENT QUESTIONS

The current debate about the events near the end of the Cretaceous must be separated into three component questions:

(1) Did one or more large comets or asteroids collide with earth at or near the end of the Cretaceous?

(2) Was there a major mass extinction near the end of the Cretaceous?

(3) If the answer to the first two questions is YES, did the collision(s) cause the mass extinction?

There has been a tendency to confuse these questions. One occasionally hears statements like: "There probably was no impact at the end of the Cretaceous because impacts do not cause extinctions". In fact, there may have been one or more K-T impacts with no biological effects.

THE QUESTION OF IMPACT AT THE K/T BOUNDARY

The recognition by geologists of large-body impacts on earth is a surprisingly recent development. Impact craters on the moon, terrestrial planets and their satellites have long been known —although they have often been interpreted as volcanic— but until the last few decades, geologists tended to assume that they resulted from events early in the history of the solar system and thus were not relevant to discussion of the later part of earth history. Several crater-like topographic features in Phanerozoic terrains were interpreted by some as impact features but very few of these proposals were accepted by the geological community.

This situation changed markedly in the 1960s because of several important developments, including (1) the recognition of high-pressure forms of quartz as clear evidence of meteorite impact, (2) the association of tektites and microtektites with impact, (3) photography from orbiting satellites of craters on earth, and (4) the discovery of large numbers of asteroids in earth-crossing orbits (Apollo objects).

As a result of these discoveries, geologists now have a catalog of more than one hundred well-authenticated impact features and the number is increasing rapidly (see Grieve, 1982, for list). Also, estimates of impact rates can now be made with considerable confidence although the uncertainties are still relatively high because crater loss by erosion and subduction of sea floor is high. The general conclusion is inescapable, however: the earth continues to be bombarded with large and small meteorites.

Under current estimates (Shoemaker, 1984), the Phanerozoic earth has been hit by about 3,600 objects of > 1 km diameter and about 12 objects of > 10 km diameter. The uncertainties in these estimates are such that the latter number may be as small as six or as large as 24. There is some indication that the impact rate has increased slightly during the Phanerozoic (Shoemaker, 1984).

Whereas impacts on earth were once viewed by geologists with great skepticism, the phenomenon is now clearly established as part of the basic paradigm of historical geology and is seen as an integral part of Lyellian uniformitarianism. For example, Wetherill and Shoemaker (1982) commented as follows:

> *"Although the physical encounter with the earth of these objects can properly be termed 'catastrophic,' in terms of the magnitude of the effects they produce, they are at the same time 'uniformitarian' in that they represent the extension of presently observed processes to earlier geologic time."*

It is thus not surprising that most geologists easily accepted the evidence presented by Alvarez *et al.* (1980) for a large-body impact at the K-T boundary. The "signature" of anomalously high iridium concentrations was novel but totally reasonable in view of its worldwide distribution in terminal Cretaceous sediments and the well-established presence of iridium in meteorites and its near-absence in crustal rocks. If the impact had not been linked to mass extinction, it is doubtful that the geologic community would have asked for additional evidence. Without the extinction link, the Alvarez group would have merely provided one more case of large body impact. Also, the estimate of the diameter of the impacting body (10 km), based on iridium concentrations, was completely credible because bodies of this size were expected to have collided with earth every 50 million years (on average) during the Phanerozoic.

Because of the proposed link to mass extinction, however, the scientific community demanded more evidence. Research groups in several countries added the following lines of evidence to support the impact hypothesis: (1) microtektites (Smit and Klaver, 1981), (2) osmium isotope ratios indicating an extraterrestrial source (Luck and Turekian, 1983), and (3) shock-metamorphosed quartz typical of known impacts (Bohor *et al.*, 1984).

At the same time, alternative interpretations of several of the impact signatures were presented. Rampino (1982) suggested that the iridium concentrations at the K-T boundary could have resulted from simple changes in ocean chemistry. Officer and Drake (1985) argued that the iridium could have come from mantle volcanism, following the report (Olmez *et al.*, 1986) of iridium in the volatiles associated with eruptions of Kilauea volcano. It is also argued that the spherules called microtektites were incorrectly identified and that the shocked quartz could have had a volcanic origin (Officer *et al.*, 1987). There has also been considerable debate about the meaning of the total trace element chemistry of the K-T boundary clays: some geochemists have claimed that the chemistry is clearly cosmic while others have argued for a crustal or mantle origin.

A major point of contention has been the absence of a clearly identified, large crater of terminal Cretaceous age. Some see this as a major deficiency of the impact hypothesis while others find it quite reasonable in view of the possibility that the crater would be difficult to recognize if it were in the deep ocean and because major portions of the sea floor have been lost throuhg subduction since the end of the Cretaceous.

At present, the majority of geologists, geophysicists, and geochemists appear to accept the evidence for large-body impact at the end of the Cretaceous but there are a few strong proponents of the volcanic alternative. In support of the latter idea is the fact that a major episode of mantle volcanism –the Deccan traps in India– appears to coincide with the end of the Cretaceous (Courtillot *et al.*, 1986; see also Officer *et al.*, 1987). There is the possibility, of course, that both points of view are correct: a large-body impat may have penetrated the crust to trigger the Deccan volcanism. This would explain the lack of an impact crater but there is no independent evidence for this interpretation.

In summary, we can conclude that the hypothesized impact at the K-T boundary is plausible and supported by considerable geochemical and geophysical evidence but that a possibly viable alternative (volcanism) exists.

There is a potentially important subsidiary question: Could there have been several large-body impacts near the end of the Cretaceous? This becomes important if one interprets the fossil record as indicating that the late Cretaceous extinctions took place in several pulses over a considerable period of time. It has been suggested that the osmium isotope data are most compatible with a multiple-impact scenario (Luck and Turekian, 1983) but this is the only direct evidence for more than one impact. On the other hand, some astronomers have argued that stars passing close to our solar system should be expected to produce showers of comets lasting for one to two million years. The question of multiple impacts must remain open until better dated evidence of individual impact events is available.

THE QUESTION OF MASS EXTINCTION AT THE END OF THE CRETACEOUS

To most paleontologist and biostratigraphers, the end of the Cretaceous was marked by one of the five most severe mass extinctions in the history of life. Indeed, it is no accident that this event marks the boundary between the Mesozoic and Cenozoic eras: times of major faunal turnover are imbedded throughout the geologic time scale. Still, there are a number of highly respected paleontologists who do not see the late Certaceous extinctions as representing a single, discrete event. Rather, the argument is made that the extinctions are spread over a considerable interval in the late Cretaceous and that some groups of organisms passed through the interval unscathed.

Unfortunately, problems of geologic dating and of taphonomic loss of fossil record make definitive answers to the question of the suddenness and severity of late Cretaceous extinctions elusive. Although there is ample evidence that the Maastrichtian stage was a time of significantly high extinction, when compared with most other intervals in the Phanerozoic, it is at present impossible to say for sure whether the extinctions took place in a matter of a few days or years or whether they covered several million years. Whereas it is fairly clear that some major groups of microplankton and large reptiles suffered dramatic extinctions within a few centimeters (or at most meters) of the K-T boundary, a similar case is difficult to establish for the great majority of Maastrichtian extinctions. As noted above, a theory of extinction caused by impact *may* be compatible either with a model of a single impact event or with one that postulates multiple events.

For the purposes of this discussiion, I will adopt the view that the late Cretaceous was indeed a time of unusual mass extinction and that the event or events were limited at least to the final stage (Maastrichtian) of the Cretaceous and possibly to a much shorter interval.

THE QUESTION OF CAUSE AND EFFECT

Unfortunately, an extinction caused by large-body impact does not leave a clear signature comparable to the geochemical or geophysical signatures of impact alone. Although all geophysicists agree that a collision between earth and a 10 km body, or even a 1 km body, would have devastating consequences in human terms —with energy release equivalent to many times the combined nuclear arsenals of the present-day world— the effects on general biological diversity are poorly understood.

Much attention has been given in the recent literature to the so-called "dust cloud scenario" —the blanketing of the earth by a dust-clogged atmosphere causing severe temperature changes and reduction of sunlight (Toon *et al.*, 1982) —but this is but one set of possible consequences of a large-body impact. Major alterations of atmospheric and/or oceanic chemistry may be much more important environmental consequences of impact. Much depends on whether the impact occurs in the ocean or on land and whether at high or low latitudes. Some of the suggested consequences of impact would be highly selective biologically and would be expected to affect some kinds or organisms or habitats and not others. But not enough is known yet to make truly definitive predictions possible. It may turn out ultimately that the fossil record itself is the best guide to the kinds of environmental shock associated with impact —whether at the K-T boundary or at other times in the Phanerozoic.

We are left, therefore, with only two arguments in favor of the causal link between mass extinction and large-body impact at the end of the Cretaceous —assuming, of course, that both events occurred:

(1) The temporal coincidence of mass extinction and large-body impact, each of which is a relatively rare event in the Phanerozoic record, and

(2) Similar pairings of extinction and impact at other times in the Phanerozoic.

Both arguments are probabilistic and thus do not yield black-and-white answers. But they are tractable arguments, given a careful analysis of the distribution of rare events in geological time.

The mathematics of coincidence

Much of modern statistical analysis is based on formal techniques for evaluating the probability that collections of events could have occurred by chance alone. If the probability is very low, one is justified in suggesting that the events have a common cause. If the probability is not low, one is not justified in claiming cause and effect. Louis Alvarez (1983) presented a probability argument in the context of the similarity in timing of the extinctions and impact at the K-T boundary in Italy and I will extend this in the discussion that follows.

Suppose we are concerned with a span of geologic time (such as the Phanerozoic) with a duration of *D* years and with a small interval within the total span (such as the Maestrichtian) with a duration of *d* years. Suppose further that *P* physical events and *B* biological events are "dropped" on the total span independently and at random. Depending on the numbers of random events (*P* and *B*), the short interval may receive one or more physical and/or biological events or none at all. The probability of *at least* one physical event *and at least* one biological event occurring in the same small interval may be computed as:

$$[1 - (1 - d/D)^{P}] \times [1 - (1 - d/D)^{B}]$$

Note that this calculation does not depend on the geologic time scale being divided into equal time intervals.

As an example, suppose we are interested in estimating the probability that a rare mass extinction *and* a rare large body impact could occur in the Maastrichtian stage by chance alone: let the total duration (*D*) of the Phanerozoic = 600 myr and the duration (*d*) of the Maastrichtian stage = 7.5 myr. Now, let the number of large mass extinctions (*B*) equal 5 and the number of 10 km impacts (*P*) equal 12 (from above).

Substituting these numbers into the expression given earlier yields 0.009. In other words, if the dates of extinction and impact events are known only to the stage level (Maastrichtian in this case), there is a chance of approximately one percent that the co-occurrence could have happened by chance alone —without any causal relationship required.

If the times of mass extinction and large-body impact are better known, the probabilty of chance co-occurrence decreases. Suppose, for example, that both are known to have occurred in the final two million years of the Maastrichtian. In this case, $d = 2$ and the calculated probability is lowered to 0.001 or one-tenth of one percent.

These calculations suggest strongly that the coincidence between large-body impact and mass extinction near the end of the Cretaceous by chance alone is unlikely **—even if neither event is well constrained in geologic time**.

There is an important related question of probability that can be asked: Given a mass extinction somewhere in the Maastrichtian, what is the probability that a large-body impact also occurred (by chance) in the same interval of time? This is simply the probability of at least one impact occurring in any given interval and can be computed as:

$$1 - (1 - d/D)^{P}$$

Using $D = 600$ and $d = 7.5$, with $P = 12$, the probability is 0.15. Thus, if a major mass extinction has already been located and the question of causation by impact is raised, there is a 15 % probability that an impact would occur in the same time interval by chance alone. If time resolution is improved to two million years, as before, this probability drops to 0.039, or about 4 percent.

The foregoing calculations merely codify and make somewhat more rigorous the basic probability argument that has been used in favor of an extinction-impact link in the late Cretaceous. It is argued that two rare events in geologic history are unlikely to occur together by chance. The calculated probabilities are quite low even though the assumed accuracy of dating is conservative (7.5 or two million years in the Maastrichtian case) and this is a powerful counterargument to the claims that the dating of extinctions and impacts is too imprecise for a causal analysis.

The calculations assume, of course, that current estimates of the number of very large impacts in the Phanerozoic are reasonably accurate. If there were as many as 24 impacts of bodies > 10 km in diameter, as is possible (above), then the probability of chance co-occurrence is increased somewhat.

A yet more important caveat is a problem common to all such probabilistic analyses of past events. In almost any history, very unusual events occur occasionally and it is always possible to choose pairs of events, **after the fact**, as candidates for causal interpretations. If, for example, a red Mercedes automobile crashes into a church in England at precisely the same time as a politician in an Asian country is assassinated, one would not suggest that the two events are causally linked even though both events are rare. In the case of the Cretaceous extinction, the same logic could be used to discount the significance of the probabilistic arguments.

It becomes vitally important, therefore, to establish the **plausibility** of the extinction-impact link and this has not yet been done to everyone's satisfaction. Nevertheless, the probabilistic argument has considerable force and deserves to be taken seriously.

The obvious answer to the " Mercedes-assassination" challenge is to find out whether the extinction-impact hypothesis has predictive power. That is, can other extinction-impact pairs be found? If so, this would greatly reduce the estimated probability of co-ocurrence by chance alone.

Other extinction-impact pairs

To date, iridium and/or microtektite evidence of large body impact has been reported for several other times of major biological extinction, as follows:

1) 11.7 myr BP: late Middle Miocene (Alvarez, 1987).

2) 38 myr BP: terminal Eocene (Alvarez, W. *et al.*, 1982; Ganapathy, 1982).

3) 163 myr BP: terminal Middle Jurassic (Brochwicz-Lewinski *et al.*, 1984).

4) 248 myr BP: Permo-Triassic boundary (Sun *et al.*, 1984).

5) 367 myr BP: Frasnian-Famennian boundary (Devonian) (Playford *et al.*, 1984).

A few other cases could be included (such as the terminal Cenomanian at 91 myr BP and the Precambrian-Cambrian boundary) but evidence for these is not yet even reasonably firm.

With the exception of the Eocene case, all reports listed above have serious difficulties of analysis or interpretation. The Middle Miocene iridium anomaly is new, having been found only recently in a single deep-sea core and work is proceeding at Lawrence Berkeley Laboratory to explore comparable sequences elsewhere (Asaro, pers. comm, 1987). The Middle Jurassic and Devonian cases have clear iridium anomalies but the iridium is found only in fossil bacterial mats (stromatolites) and there is the possibility that the organisms were simply concentrating ambient iridium. In the Permo-Triassic case, a strong iridium anomaly has been reported but attempts to reproduce the analyses in other laboratories have so far been unsuccessful.

The extinction-impact pairs just discussed have two additional problems. First, because of the expense of iridium analysis it has been difficult to sample the geologic record evenly. It has been inevitable, therefore, that geochemists have sampled horizons at which major extinctions are known to occur and this raises the possibility that the finding of iridium anomalies is sample-dependent and that such anomalies are in fact common throughout the geologic record. To counter this tendency, Kyte and Wasson (1986) have reported analyses throughout the latest Cretaceous and early Tertiary records in deep-sea cores. They found only the K-T anomaly. Kyte and Wasson did not find the late Eocene anomaly probably because of the coarseness of their sampling regime. Fortunately, the problem of sampling is being eliminated because of the development and operation of the new, high-speed Iridium Coincidence Spectrometer at the Lawrence Berkeley Laboratory.

The second problem has to do with the definition and identification of major extinction events. The extinction at the end of the Middle Miocene and that at the Middle-Upper Jurassic boundary may not be significant enough to merit consideration in this context. This raises the question of the definition of a mass extinction. To some paleontologists, the term should be reserved for the five truly severe extinction events of the Phanerozoic (Ashgill in the Ordovician, Frasnian-Famennian in the Devonian, Permo-Triassic, late Triassic, and terminal Cretaceous events). To other paleontologists, an interval of time qualifies as an extinction event if its extinction rate (for the biota as a whole) stands above the normal background rate by a statisticaly significant amount.

Opinions on this question are quite polarized. My own view is that any event of multiple extinction that can be shown not to be a simple product of biases in fossil preservation or study is a candidate for interpretation and that the array of possible causes, not limited to large-body impact, should be evaluated. In the context of large-body impact, there is no reason to say that the biological effects of impact must be global or truly devastating.

To summarize the evidence for impact as a cause for extinction at the K-T boundary, we have the circumstantial but rather powerful evidence from the probability calculations for the late Cretaceous and we have some supporting evidence for the general extinction-impact link from other parts of the record. But the total evidence still falls short of the ideal of absolute proof.

ALTERNATIVE EXPLANATIONS FOR EXTINCTION

Several non-cosmic explanations for the near-simultaneous extinction of large numbers of species in the Phanerozoic fossil record are available and some of these enjoy strong support in the paleontological community. The principal alternatives can be classified as follows:

1) Intrinsic biological factors, including competitive exclusion of taxa caused by the evolution of adaptively superior organisms,

2) Earth-bound environmental perturbations which develop too quickly to allow evolutionary adjustment, including changes in global climates, major transgressions or regressions of the world oceans, and unusual environmental events such as extreme volcanism.

Each of these has some evidence favoring it for the K-T event as well as for other, selected extinction events but space does not permit a full and fair treatment of these alternatives here. Suffice to say that each should be evaluated as carefully and as rigorously as possible. This must perforce include full statistical analysis of the association in time between extinctions and evidence for the suspected causes. Taking the Phanerozoic record as a whole, there are so many extinctions and so many episodes of environmental perturbation that simple anecdotal comparisons are not sufficient. Application of the kind of probability calculations discussed earlier in this paper is clearly indicated.

PERIODICITY OF EXTINCTION

The proposals by several workers that major extinction events from the late Permian onward are uniformly spaced in time (Fischer and Arthur, 1977; Raup and Sepkoski, 1984, 1986; Rampino and Stothers, 1984; Sepkoski and Raup, 1986; Fox, 1987) constitute a partially independent question bearing on the influence of extraterrestrial phenomena on biological extinction. Expecially important in support of periodicity is the new analysis of generic extinctions by Sepkoski (1986). The case for periodicity of extinction has been challenged on statistical grounds by Hoffman (1986) although this challenge has been answered in papers by Gilinsky (1986), Kitchell & Estabrook (1986) and by Sepkoski & Raup (1986b).

Because similar periodicities have been found also in the records of impact craters (Alvarez and Muller, 1984) and magnetic reversals (Negi and Tiwari, 1983; Raup, 1985; Pal and Creer, 1986; Stothers, 1986), the periodicity question is germane to the question of the extinction-impact link. The question of magnetic reversals is relevant because of empirical and theoretical arguments for impact as a cause of magnetic reversal (Glass *et al.*, 1979; Muller and Morris, 1986).

Also, if extinctions are uniformly spaced every 26-30 million years, that fact can be an important guide to a search for further evidence for an association between large body impact and extinction.

OTHER POSSIBLE EXTRATERRESTRIAL INFLUENCES

Although the emphasis in recent years has been on large body impact as a possible explanation for mass extinction, there are many other aspects of our cosmic environment which must be considered to have evolutionary implications. The Phanerozoic earth has witnessed at least two complete galactic years (complete revolutions of the galaxy), a substantial increase in the luminosity of the sun, about 20 crossings of the plane of the galaxy, a significant increase in day length, and the gravitational effects of numerous passing stars, to mention just a few of the known events which may have influenced the history of life on earth.

It is not clear yet how many of these cosmic factors have had biological effects which are both significant and detectable in the fossil record. Nor is it known which, if any, could cause extinctions of species. The best candidate so far, with the exception of large-body impact, is the regime of Milankovich cycles produced by gravitational interactions in the earth-moon-sun system (Imbrie and Imbrie, 1980). From the work of Imbrie and others, Milankovich cycles on the order of 20, 41, and 100 thousand years have had a significant effect on the climate of the past 700,000 years and were probably responsible for the major advances and retreats of continental ice sheets during the Pleistocene. Although important, the glaciations may or may not have caused extinctions either through the direct effects of climatic change or through glacially-controlled sea level changes.

In view of the potential effects of the variety of known cosmic factors, it may turn out that the greatest contribution of the present debate over extinction and large body impact will be to encourage research in other areas of extraterrestrial influence on terrestrial biology. The most important consequence of the work of the Alvarez group may thus have been to convince paleontologists that organisms have lived in a cosmic as well as an earthly environment.

CONCLUSION

The case for large-body impact as a cause of mass extinction is very strong but more study will be needed before the proposition can be said to be verified beyond all reasonable doubt.

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