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Hypothesis Article

A Possible Role for Stochastic Astrophysical Ionizing Radiation Events in the Systematic Disparity between Molecular and Fossil Dates

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Abstract

Major discrepancies have been noted for some time between fossil ages and molecular divergence dates for a variety of taxa. Recently, systematic trends within avian clades have been uncovered. The trends show that the disparity is much larger for mitochondrial DNA than for nuclear DNA, also that it is larger for crown fossil dates than stem fossil dates. It has been argued that this pattern is largely inconsistent with incompleteness of the fossil record as the principal driver of the disparity. A case is presented that, given the expected mutations from a fluctuating background of astrophysical radiation from such sources as supernovae, the rate of molecular clocks is variable and should increase back to a few million years, before returning to the long-term average rate. This is a possible explanation for the disparity. One test of this hypothesis is to look for an acceleration of molecular clocks at 2 to 2.5 Ma due to one or more moderately nearby supernovae known to have happened at that time. Another is to look for reduced disparity in benthic organisms of the deep ocean. In addition, due to the importance of highly penetrating muon irradiation, the disparity should be magnified for megafauna. Key Words: Extreme events in Earth history—Molecular clock—Radiation physics—Evolution. Astrobiology 17, 87–90.

1. Introduction

There has been a long-acknowledged disparity between ages determined from the fossil record and those derived from molecular divergence dating (*e.g.*, Pulquerio and Nichols, 2007; Ho, 2014; Hoareau, 2014). The sign of this disparity is nearly always in the direction of much older molecular ages but is reduced for very recent clades including domesticated animals (Ho and Larson, 2006). A variety of effects may cause biases of either sign in the molecular ages; but due to incompleteness of the fossil record, fossil ages are (aside from outright errors) lower bounds to the age of the taxon, so that the ages of originations are always underestimates. Since this could in principle account for most of the observed effect, much discussion has centered on this option.

A recent systematic study of trends within the disparities in avian clades (Ksepka *et al.*, 2014) asserts that a variety of patterns, not to be enumerated here, are inconsistent with attributing all of the age disparity to gaps in the fossil record. We are urged to consider any possible systematic biases in molecular dates as well as calibration strategy. At this point it is relevant to mention that the whole basis of molecular dating has been accused of systematic underreporting of errors (*e.g.*, Graur and Martin, 2004). However, we shall for the purpose of this paper assume that the disparities between fossil and molecular dates have a basis in reality.

One possible bias in molecular dates concerns a variable rate of molecular clocks due to changes in the mutation rate. An unknown but substantial fraction of mutations comes from radiation of various kinds (Alpen, 1997). The radiation background in Earth's environment fluctuates strongly, so that it is expected to find events of increasing strength when looking further back in geological time, since we are now not near a major energetic event (Erlykin and Wolfendale, 2010; Melott and Thomas, 2011). There is a normal operational assumption that molecular clocks move at a constant rate, but fluctuating radiation backgrounds would vary this rate. In the absence of selection pressures, isolated communities, and so on, this variable mutation rate need not correspond to a correlated variable rate of evolution.

I wish to stress the following: this is a physics-based hypothesis; there are many other biological explanations that may explain all or part of the phenomenon. I do not intend to claim that it is the best possible explanation but only to introduce it for discussion.

High-energy events are those that direct unusual amounts of ionizing radiation at Earth. Examples are gamma-ray bursts and supernovae (Melott and Thomas, 2011) as well as

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outbursts from the Sun often called solar proton events (Melott and Thomas, 2012). A crucial characteristic is the amount of energy carried by individual protons, photons, or other constituents. If this energy is large, such as that carried by protons (cosmic rays) from a nearby supernova, it can produce air showers that have strong effects on the ground. In an air shower, the primary particle interacts with the atmosphere and then produces a large number of other secondary particles in reactions with the atoms of the atmosphere. This shower cascades, ionizing the atmosphere, which ultimately blocks most of the shower. Aside from the ionizing effect of the shower, only muons reach the ground in sufficient abundance to have direct radiation effects on organisms living there or in the ocean. Since such very strong events are not occurring now (see, *e.g.*, Overholt *et al.*, 2015), molecular clock rates determined from very recent data would not include this acceleration. The purpose of this note is to suggest further examination of this possibility, with attention to possible tests.

Ksepka *et al.* (2014) reported that the disparity between fossil and molecular clocks is greater with mitochondrial DNA than with nuclear DNA. This observation is consistent with our hypothesis of a radiation link for the disparity, because mitochondrial DNA is more subject to damage from radiation and to oxidative stress, one of the primary mechanisms of radiation damage to DNA (Yakes and Van Houten, 1997; Kam and Banati, 2013).

In what follows, we give more detail on recent advances in knowing the history of the radiation background near Earth, and some of the characteristics of the radiation that reached the surface. Then we suggest some expectations, which show ways that the hypothesis of radiation-coupled mutation might be tested.

2. Radiation Events and Earth

There are a variety of possible types of astrophysical radiation and likely sources for events at Earth (Melott and Thomas, 2011). Dominant among these are the Sun (see Wdowczyk and Wolfendale, 1977) and other stars in our galaxy. It has been known for some time that supernovae and gamma-ray bursts from other stars in our galaxy are likely, based on their intensity and frequency of occurrence, causal agents in mass extinction every few 100 million years (Melott and Thomas, 2011, and references therein). The Sun has X-ray flares, but the dominant form of solar radiation for biological consideration is in solar proton events. There was in 775 AD an event indicated by ^{14}C in tree rings that exceeds anything in the modern era (Miyake *et al.*, 2012; Jull *et al.*, 2014) and is probably attributable to the Sun (Melott and Thomas, 2012; Usoskin *et al.*, 2013). All of these are potentially dangerous sources (*e.g.*, Thomas *et al.*, 2013), although interpreting the new data on the Sun and Sun-like stars is an emerging area.

The atmosphere provides considerable shielding, but effects on the ground can still potentially include radiation in the form of muons (Atri and Melott, 2011; Marinho *et al.*, 2014) and neutrons (Overholt *et al.*, 2013, 2015). Neutrons rarely penetrate below the stratosphere. Most muons are stopped by a kilometer of water, so any potential muon damage would not include benthic organisms in the deep ocean. In addition, the ionizing radiation can deplete the stratospheric ozone layer (Thomas *et al.*, 2013, and references therein), admitting increased damaging ultraviolet B (UVB) from the Sun. Nearby supernovae will bombard Earth with much higher energy cosmic rays (nuclei of atoms, mostly protons) than are likely to come from the Sun.

The primary mechanism of radiation damage to the biosphere emphasized to date is UVB from a depleted ozone layer (Melott and Thomas, 2011). All the events described can cause this to a varying degree. This UVB may be damaging to plankton and induce skin cancer, but it is unlikely to penetrate deeply enough inside metazoans to cause germ line mutation. Most forms of primary and secondary radiation do not penetrate in great amounts lower than the stratosphere—where they can damage the ozone layer. Muons from most events studied are too few in number to significantly add to the radiation background on the ground (Overholt *et al.*, 2015).

Recent results (Thomas *et al.*, 2016) change the picture. Computing the effects of an indicated (Melott, 2016, and references therein) supernova at 100 pc from Earth, we found that (for an event inside the Local Bubble, a region of hot gas in which Earth resides) most effects were negligible—except for those caused by the muons. The reason is that the very high energy cosmic rays from a supernova far exceed the intensity found at Earth from any other type of event that has been considered. We found that a 20-fold increase in muons on the ground was indicated for thousands of years from a single burst event, effectively tripling the local radiation level. Muons are very different from most other sources of ionizing radiation. They interact very weakly, so that they penetrate all living things and even up to a kilometer of water. On the other hand, they are so abundant that in spite of very little interaction, they comprise a significant level of background radiation. Most kinds of ionizing radiation will not penetrate far into living organisms, but muons will pass right through. For this reason, they will reach inside even the largest animals. Effects of muons will be a nearly unique signature of nearby supernovae. In the local supernova case (Thomas *et al.*, 2016), other radiation effects were relatively small. The amount of time the irradiation lasts can be increased if the cosmic rays generating the muons are trapped with Earth inside a structure such as the Local Bubble.

It is worth mentioning that the other novel effect associated with nearby supernovae is ionization of the troposphere (Thomas *et al.*, 2016) with effects as yet not well understood. However, this is unlikely to be related to the topic at hand.

Newer estimates suggest that the events associated with the ^{60}Fe detections are more likely to have been at 50 pc than at 100 (Fry *et al.*, 2016; Mamajek, 2016). We have work in progress to more fully describe the effects of such events, which will certainly be more intense than at 100 pc.

3. Reasonableness of the Idea

Most astrophysical radiation, including the indirectly increased UVB, can be stopped by 10 m of water, which would exclude many benthic organisms. However, DNA of such organisms may be affected in the pelagic larval stage for those larvae that spend most of their time near the ocean surface. Organisms that are shielded from the radiation should not show effects of strong fluctuations. In particular, deep-water benthic organisms should display more congruence between the fossil and molecular dating methods. It now appears (Thomas *et al.*, 2016) that, although ozone depletion/UVB enhancement is important for a variety of events, the episodic nearby supernovae at 50–100 pc will have their dominant impact through muons. Muons will affect everything except organisms below about 1 km of water (or hundreds of meters of rock). So UVB effects stop at about 10 m depth and muon effects at about 1 km depth.

Ksepka *et al.* (2014) noted that, for very old dates (many times 10 million years), there is better congruence between molecular and fossil estimates than for younger dates. This would be consistent with a high rate of mutation in the last few million years and a return to a geological mean rate over longer periods. These trends are also suggested by Ho and Larson (2006), who put the high mutation rate at 1–2 Ma and also suggested that the mutation rate has been low in the last few tens of thousands of years. The combined picture is then of a lull at the present, a peak at the last few million years, and a return to moderate rates over tens of millions of years.

We note that an increased mutation rate may facilitate, but does not necessarily imply, a speeding up of evolution. There are many other important effects, such as isolation of populations, changes in environmental factors, and so on, which are equally important, such as the closing of the Isthmus of Panama near the P-P boundary.

There is a large amount of new data in the form of ^{60}Fe in sediments that suggest (Fry *et al.*, 2015, 2016; Breitschwerdt *et al.*, 2016; Melott, 2016; Wallner *et al.*, 2016) that one or two supernovae went off within one or a few hundred light years of Earth around the beginning of the Pleistocene. Breitschwerdt *et al.* (2016) used numerical modeling to suggest that as many as 14 more went off in the previous 8 million years, giving rise to the Local Bubble as a kind of blast region. The isotope data are found in ocean sediments (Wallner *et al.*, 2016), lunar rock samples (Fimiani *et al.*, 2016), cosmic rays collected directly in space (Binns *et al.*, 2016), and fossil magnetotactic bacteria (Ludwig *et al.*, 2016). These data constitute a dramatic confirmation and extension of earlier terrestrial samples (Knie *et al.*, 1999, 2004). This would indicate an enhanced radiation environment persisting for at least several thousands of years for each event. Therefore, if this idea has merit, there should be an acceleration of the molecular clocks relative to the fossil record around 2.5 Ma. The transport modeling work that examined the distribution of the isotopes through the interstellar medium, and the formation of the Local Bubble by the blast waves from the supernovae (Breitschwerdt *et al.*, 2016), was published simultaneously and done without knowledge of the new data from the other studies. Improved modeling is in progress that should better constrain the dates.

In the meantime, our modeling work suggests increases in ionizing radiation on the surface and in the upper ocean persisting for at least thousands of years for each supernova, and longer if we are trapped in the Local Bubble with it. We note that the suggested timing for the increased mutation rate (Ho and Larson, 2006) is roughly coincident with the times estimated for the nearby supernovae.

4. Testing the Hypothesis

We have argued that this suggestion appears reasonable based on existing data on isotope distribution at Earth, times of higher mutation rate, and simulations of the radiation that may penetrate to the ground from the supernovae that generated the isotopes. We will now try to go beyond the reasonableness argument based on existing data and make some predictions that we would expect to be true based on the hypothesis that astrophysical ionizing radiation events episodically increase the mutation rate in the molecular clock.

(1) Even muons will not penetrate much beyond a kilometer of water. We therefore expect major reduction in the disparity between molecular and fossil clocks for deep-sea organisms.
(2) Very large organisms, which were common during the Pliocene and Pleistocene, would still be easily penetrated by muons and not by other forms of ionizing radiation (except for inhaled radon, which is not expected to be a significant result of supernovae). Therefore, the 20-fold or larger increase in muons indicated by supernova events in the last few million years would be more significant for these organisms, and we would see a concomitant significant increase in the clock disparity for them around the P-P boundary.
(3) Mitochondrial DNA, which shows an increased mutation rate, should show a disparity concentrated around the P-P boundary.
(4) Improved data on molecular clock rates and times of increased radioisotope deposition on Earth from supernovae should continue to coincide beyond the crude up-then-down rate trend presently observed. There may be a second maximum around 7 Ma (*e.g.*, Breitschwerdt *et al.*, 2016).

In closing, it should be emphasized that we do not claim that this is better than other existing explanations for this disparity, but it is a possibility that should be considered and can be tested by looking for the effects listed above.

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Author Disclosure Statement

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