a brief introduction to ice age theories

> [The objective of geology is] "to confirm the evidences of natural religion; and to show that the facts developed by it are consistent with the accounts of the creation and deluge recorded in the Mosaic writings."
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> -- William Buckland,
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> Oxford Professor of Mineralogy and Geology
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> in *The Connection of Geology with Religion Explained* (1820)

To the modern reader, it may seem surprising that astronomical forces drive global climate change. In the 1950s, changes in the weather were attributed by many people to nuclear testing; in the 1990s, they were attributed to emission of carbon dioxide and other gases that enhance the Greenhouse effect. Yet in the 1840s, the obvious cause of climate change, to many people, was astronomy. It was understood at that time that the seasons were driven by astronomical causes, as is the 24 hour cycle of day and night. So when the existence of long-term changes of climate were discovered, it was natural to see if they could be attributed to astronomical forcing. This was long before the 100 kyr and 41 kyr cycles of the ice ages had been discovered.

By the 1840s, astronomers had already shown that the orbit of the earth undergoes slow changes. It is not the same ellipse this year that it was last year. The orbit would be an unchanging ellipse, if the Sun were the only source of attraction. The deviations come about because of the presence of the moon and other planets. Gravity from these objects means that the force on the earth is not a simple inverse square centered on the sun, and the natural result is that the orbit is not a simple repeating ellipse.

However the effects of the planets are relatively small. Jupiter has 10^{-3} of the mass of the Sun, and it is, on average, about 5 times further away. Venus, although having a mass 390 times smaller than Jupiter, comes much closer, within 0.28 AU (where the Astronomical Unit, or AU, is the average Earth-Sun distance) vs. 4.2 AU for Jupiter. Since gravity varies as 1/(distance squared), and tidal gradients vary as 1/(distance cubed), the effect of Venus is often more important than that of Jupiter. But all these effects are small enough that they can be treated as perturbations, small changes, on the classical elliptical orbit. The nice consequence of this is that the Earth's orbit is always *approximately* an ellipse, and we can treat the perturbations of the planets as extra forces that gradually alter the parameters of that ellipse. For example, the major axis of the Earth slowly precesses or rotates relative to the "fixed" stars. This effect is big enough that it was discovered experimentally in 120 BC by the astronomer Hipparchus, who found differences between his own measurements and those of earlier astronomer Babylonian records.

By 1749, Alexis Claude Clairaut had shown, using Newton's laws, that the north pole of the Earth precesses with a period of 25,800 years. So, for example, 13,000 years from now, the North Pole of the Earth will not be pointing towards the "North Star," but will be pointing away by an angle of about 47 degrees, close to the star Vega. This happens because the Sun and Moon exert a torque on the equatorial bulge of the Earth. This causes the axis of rotation of the Earth to wobble, an effect completely analogous to the wobble of a tilted top under the torque of gravity.

Precession implies that the signs of the zodiac change, or "advance." When astrology was defined, about two thousand years ago, a person born in January was said to be under the sign of Capricorn, since the sun was in the constellation Capricorn at that time. Since then, the precession of the axis of the earth has changed by 2000/26000 = 1/13 of a cycle; this corresponds to a change by about one sign of the zodiac. This means that a person who is born in January any time in the last few hundred years, was born when the Sun was actually in Sagittarius – not Capricorn. Nevertheless, following tradition, such a person is still said to be "born under the sign of Capricorn." The more educated astrologers are aware of this change, and claim that they compensate for it .

Another consequence of the Earth’s precession is that the location of the sun at the spring equinox also changes. It is presently leaving the constellation Pisces and entering Aquarius. Astrologers say that this change could have a profound effect on our lives, and it is why they talk about the future (and sometimes the present; it depends on exactly where you draw the constellation boundaries) as "the Age of Aquarius."

Evidence for ancient glaciation, including polished bedrock and erratic boulders, is extensive. But in early 1800s, the prevailing paradigm to explain these was diluvianism – belief that they were artifacts of the great flood of the Bible. According to William Buckland, one of the most widely respected geologists of the time, the goal of geology was "to confirm the evidences of natural religion; and to show that the facts developed by it are consistent with the accounts of the creation and deluge recorded in the Mosaic writings." (quoted in , page 35). A detailed scientific case for ancient glaciation was first synthesized in detail by Jean de Charpentier in the early 1830s, and the great geologist Louis Agassiz became an early convert. By 1841 Charles Lyell, and even Buckland, had been won over, and over the next 20 years, the theory of ancient periods of extensive ice became generally accepted.

Soon after the existence of the ice ages was postulated, they were attributed to these orbital changes. The first person to create a detailed theory was Joseph Adhémar, who published a book on the subject in 1842 called *Revolutions de la Mer, Deluges Periodics*. He believed that the 26,000 year precession cycle was the cause, and he suggested that it was the direct gravitational attraction of the sun and moon on the ice caps, a result that many scientists at the time correctly rejected as absurd.

One person who was inspired, in part, by Adhémar’s book, was James Croll. In many ways, Croll is the true hero of the astronomical theory of the ice ages. For a moving account of his life and tribulations, we urge you to read the delightful and informative book, "Ice Ages, Solving the Mystery," by John Imbrie and his daughter Katherine Palmer Imbrie . Croll was a carpenter who became disabled from an accident, and was forced to take a menial job as a janitor. But his janitorial duties were at the Andersonian College and Museum in Scotland, and there he discovered a wonderful library. He found that he could finish his mopping and polishing work early, and spend the rest of the night reading books on physics in the library. Among these was the book by Adhémar, and new calculations of the Earth's orbit by the astronomer Urbain Leverrier (one of the discovers of Neptune). Croll taught himself advanced physics, and set to work on the origins of the ice age. He decided that the most plausible driving force changing climate was variations in insolation, the sunlight hitting the Earth. He managed to get his papers published, and his theories received favorable attention. Eventually he accepted a job at the Geological Survey. In 1876, a year after his own book was published, Croll was given the high honor of being named a Fellow of the Royal Society of London.

Croll contributed many insights that are still recognized as important. He realized that the presence of large glaciers would reflect sunlight, and that this would enhance further the chill of the ice ages. He recognized the importance of ocean currents in climate, and incorporated them into his theories. He took into account not only precession, but the changes in the eccentricity of the Earth's orbit – an effect that can contribute a 100 kyr cycle to the glaciation (which, of course, had not yet been discovered).

But Croll published several predictions that proved to be very wrong, and that eventually caused his theory to be abandoned. Since the insolation in the Northern Hemisphere is out of phase with the insolation on the Southern Hemisphere, he thought that the ice ages in the two hemispheres would alternate, and we now know they are synchronous. He also estimated that the time since the last ice age to be 80,000 years ago, much older than the true value; we now know it ended between 14,000 and 10,000 years ago.

The insolation theory of Croll was revived in the early 1900s by Milutin Milankovitch, a Serbian originally employed as an engineer, but who had become a professor at the University of Belgrade where he taught physics, mathematics, and astronomy. He took on the riddle of the ice ages as a challenge. Ludwig Pilgrim had recently completed new and more detailed orbital calculations, and Milankovitch made use of these. He had the critical insight that insolation on the Northern Hemisphere might completely dominate, since that is the location of two thirds of the Earth's land area. The ice ages in both the Northern and Southern Hemispheres are in synchrony because they are both driven by the same force: insolation on the Northern Hemisphere land. With this Gordian slice, Milankovitch solved the problem of alternating hemispheric ice ages.

Milankovitch then set out on the heroic task (at that time) of doing detailed insolation calculations based on Pilgrim's orbital work. Today these calculations are an interesting task for an undergraduate to do over the course of a summer, using a desktop computer. But Milankovitch had to do all the calculations by hand, and it took him many years (interrupted by war and imprisonment – again we urge you read the book by Imbrie and Imbrie!). Milankovitch's calculations showed (correctly) that the insolation was dominated by a 23,000 year cycle; we have modern data for this plotted on page *. Milankovitch concluded that the ice ages would be most intense when the insolation dropped below a certain threshold. Since the envelope of the insolation curve has an approximately 100 kyr cyclicity, his theory has implicit in it a prediction that such a cycle might be seen in the ice ages.

Milankovitch concluded, somewhat prematurely, that the problem was completely solved, and he devoted much of his time in later years to writing popular accounts of the ice ices, including a series of letters to a (presumably fictional) young girl. This effort did a lot to increase the public interest in the ice ages, and undoubtedly led to the artwork shown in Figure 1-7.

But Milankovitch's theory was abandoned when precise age estimates, made possible by Willard Libby's invention of radiocarbon dating, appeared to show that the timing of the ice ages were in conflict with Milankovitch's detailed calculations. In retrospect, this was unfair. The Milankovitch theory actually explains many of the phenomena that we now see in the data. Do we throw out the astronomical theory of the seasons, simply because the first day of Spring is not always Spring-like? The warm weather of spring can be delayed by a month, or it can come early by a month; the important fact is that it always comes. We demand too much of a theory if we require it to predict all the details in addition to the major behavior.

In fact, it was the observations of the regularity of the ice age cycles that led to the revival of the insolation theory. Science and technology advanced, thanks to the work of many people. Harold Urey, Cesare Emiliani, and others developed and promoted the use of isotopes as proxies for changes in the Earth. The technology for obtaining sea floor cores rapidly improved. In 1970, Wally Broecker and Jan van Donk published a seminal paper that showed for the first time that the dominant variation in the ice ages was a repeating cycle of 100,000 years. This was a frequency that appeared in the insolation theory. The use of geomagnetic reversals in sea floor cores allowed an vastly improved time scale. In 1976, James D. Hays, John Imbrie, and Nicholas Shackleton published their paper showing the presence of both a 41 and 23 kyr cycle in data derived from sea floor sediments. The same frequencies were dominant in spectral analysis of the insolation. Even if the details of the theory were wrong, the presence of the same frequencies as those present in the orbits of the planets was a strong reason to revive the astronomical theory.

Although it had been resuscitated, the insolation theory continued to have problems. In the glacial data, the 100 kyr cycle dominated, with the 41 kyr cycle weaker, and the 23 kyr precession signal weakest of all. Yet in insolation theory, it is the 23 kyr cycle that dominates, with a weaker 41, and an extremely weak 100. Why were these strengths reversed? A possible answer came from the old threshold idea of Milankovitch, which had been revived by Kenneth Mesolella and George Kukla, and put into an elegant mathematical form by Imbrie and Imbrie. They showed that a nonlinear response of the climate to insolation could greatly strengthen the 100 kyr cycle, through a mechanism that we discuss on page later in this book. This was both physically plausible, and seemed to solve the amplitude problem.

But there was another issue: the nonlinear ice model strengthened even more an additional cycle with a 400 kyr period that was not observed. In fact, the 400 kyr cycle should have been the strongest cycle of all, according to that theory. One way to get rid of this was to make the *ad hoc* assumption that the 400 kyr cycle was so long that it was suppressed by the more rapid time constants that are natural in ice production and destruction processes. At least one such assumption should certainly be allowed in any complicated theory.

Other problems continued to nag the insolation theory. In 1992, measurements of climate with precise dates became available from a water-filled cave in Nevada called Devils Hole. The sudden rise in temperature at this location appeared to precede the increase in insolation that was supposed to trigger it. This was a "causality problem," since the presumed effect appeared to precede the cause. This problem persists, and has recently become critical with the vindication of the Devils Hole chronology by radiometric dates from coral records. We will discuss the causality problem at length in Section 8.3.

Another problem with the insolation theory is called the "Stage-11 problem." Stage-11, in the jargon of paleoclimate, refers to a period about 400,000 years ago when variations in insolation were very weak, and yet the cyclical behavior of the ice ages was very strong. A similar problem exists at present: insolation variations are weak, and yet there was a great termination just 10-14 thousand years ago; this might be called the "Stage-1 problem." Various solutions have been proposed to address these problems, but they all involve ad hoc assumptions and the introduction of arbitrary parameters.

The set of problems continues to grow. It has led some to abandon the astronomical theory altogether, and postulate that the cycles of the ice ages are driven by natural oscillations of the ocean/continent/atmosphere system. Yet it is hard to dispute that the astronomical theory can account for the values of the observed frequencies. This agreement, more than anything else, gives life to the astronomical theory. It is also the reason for the central role played by spectral analysis in this book. Moreover, it is possible to make a general argument, independent of the frequency agreement, that the ice ages are astronomically driven. This was first done by the authors of this book in a paper in Science Magazine . The argument is based on the narrow structure seen in the spectrum of the data, and is explained on in Section 2.1.

The attention given to line shape has created another serious problem for the insolation theory. A high-resolution analysis of the 100 kyr cycle shows that the insolation theory, and its variants, all predict that the peak will have a split structure: it will be resolved into a 95 kyr line and a 125 kyr line. (An exception to this general rule is a model recently published by W. Berger, and explained in Section 6.4.8.) The bulk of the data shows that this prediction is contradicted. The 100 kyr cycle is a single narrow line. *Ad hoc* mechanisms that were plausible for eliminating the 400 kyr line are not plausible for turning the predicted doublet into a singlet. It is remarkable that this problem was not noticed until 1994. The seriousness of the problem was emphasized in an article in Science Magazine in 1997. Although there had been many theories published to account for the ice ages, none of them predicted the narrowness of this peak. A review of the theories published in 1993 included a "short list" of nine different "groups" of models, and yet every one of these theories was contradicted by the simple observation that the 100 kyr peak was narrow.

It is dangerous to dismiss a theory based on any one contradiction, since minor modifications of the theory can often solve apparently intractable difficulties. But the growing number of problems with the insolation theory is cause for serious concern. It may be the fact that the insolation theory predicted the correct values of the frequencies that leads to its tenacity in holding the minds of paleoclimatologists. But there are alternatives now appearing. In 1993, it was discovered that there is another astronomical oscillation (orbital inclination) that could contribute to climate that has a spectrum that is an excellent match to the narrow 100 kyr peak. The theory based on this does not have a Stage-11 problem (or a Stage-1 problem), nor a causality problem. It does not predict a nonexistent

400 kyr peak, and it accounts in a natural way (no adjustable parameters) for the shift of frequencies that took place about one million years ago, when the dominant frequency of ice age oscillation changed from 41 kyr to the present value of 100 kyr. This is, however, a new theory, and although we like it (it is our theory), it is not yet widely accepted, so we relegate detailed discussion of it to near the end of this book, Chapter 7.