The Moon and the Origin of Life on Earth

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If the Moon did not exist, the orientation of the Earth's axis would not be stable, and would be subject to large chaotic variations over the ages. The resulting climatic changes very likely would have markedly disturbed the development of organized life.

We are all familiar with the change of seasons due to the inclination of the equator with respect to the plane of the Earth's orbit around the Sun. This inclination of 23°27′, called "obliquity" by astronomers, also gives rise to the polar circles, inside of which day and night may each last several months. The distribution of solar heat over the Earth's surface also depends on the obliquity, making it an essential part of our understanding of terresterial climate. Calculations carried out at the Bureau of Longitudes in Paris show that the Moon stabilizes oscillations in the Earth's obliquity, therefore acting as a climatic regulator for the Earth.

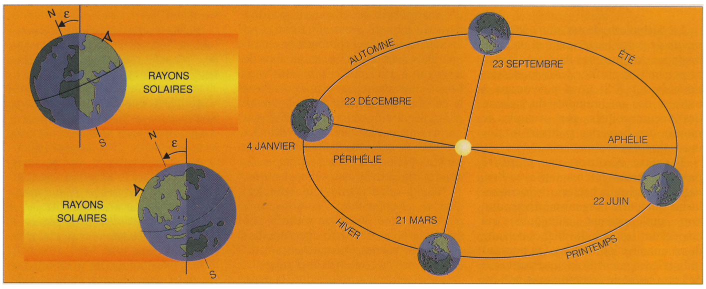

Figure 1: The change of seasons depends on the Earth's obliquity (a) and on the precession of the equinoxes (b). In summer, the amount of solar heat received in the northern hemisphere is greater than that received in the southern hemisphere. Depending on the angle of precession, the Earth may be at its point nearest the Sun (perihelion) during the northern hemisphere's summer, or during its winter, as is currently the case. The hemispheres thus experience a corresponding accentuation or dimunition of seasonal contrasts.

In 120 BC, Hipparcus discovered that the direction of the Earth's rotational axis is not fixed with respect to the stars. In fact, it traces out a cone in space roughly once every 26,000 years. This so-called precession of the equinoxes is the result of the torque exerted on the Earth's equatorial bulge by the Moon and the Sun. A similar precession of a solid body's axis of rotation can easily be observed with an ordinary spinning top. One consequence of this phenomenon is that the Earth's rotational axis does not always point toward Polaris, but instead describes a large circle in the celestial sphere. This fact sometimes disturbs the quibblings of astrologers, since the precession of the equinoxes has so greatly displaced the zodiacal calendar from the apparent motion of the Sun that presently, on the date corresponding to the sign of Aries, the Sun is in the constellation Pisces.

The precession of the equinoxes also affects the Earth's climate. The Earth's orbit is in fact not circular, but, as Kepler showed in the early 17th century, is instead approximately elliptic with the Sun residing at one focus. The eccentricity of this ellipse (which measures its elongation) is small (0.017), but is enough to measurably change the quantity of solar heat reaching the Earth at perihelion, or point of closest approach to the Sun, as compared to aphelion, its point of farthest departure from the Sun. At present, the Earth passes through its perihelion January 4th, during the boreal winter. This diminishes seasonal contrasts in the northern hemishpere, and accentuates them in the southern hemishpere. In 13,000 years, the situation will be reversed and seasonal contrasts will be more accentuated in the northern hemisphere. The precession of the equinoxes thus affects the distribution of insolation at a given location on the Earth in the course of a year. In fact, it appears possible to trace more significant climatic changes to variations in the Earth's eccentricity and obliquity.

The Astronomical Theory of Climates

In Kepler's view, the Earth's orbit was an immutable ellipse. Newton challenged this view by demonstrating that the masses of the other planets perturbed the Earth's orbit, so that it is only an ellipse to first approximation: neither its eccentricity nor its obliquity are fixed. LeVerrier (famed for his discovery in 1846 of the planet Neptune based on perturbations of Uranus' orbit) was the first to calculate possible long-term (or "secular") variations in the Earth's eccentricity. In doing so, he took up calculations of the Earth's orbital motion begun by Laplace shortly before the French Revolution. It was LeVerrier's Earth-orbit calculations that, in 1941, led the Yugoslavian astronomer Milutin Milankovich to hypothesize that the ice ages were the result of high-lattitude variations in terrestrial insolation induced by secular variations in the Earth's orbit and axial orientation. His theory did not win immediate acceptance, as the variations in insolation did

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not seem adequate to account for glaciation. But the same theory has gained wider acceptance over the last two decades. Measurements carried out by John Imbrie and coworkers of the relative concentration of the oxygen isotopes O^{18} and O^{16} present in the carbonates of marine sedimentary layers can be related to the past thickness of the polar ice caps. From this it is possible to estimate mean ocean temperatures in the distant past. Indeed, it provides some record of the Earth's past climate up to more than three million years ago. Though much less precise, geological records reflect climatic conditions as far back as 200 million years. Moreover, improved models of climatic response to variations in the Earth's orbit show that the effects of changes in insolation may be amplified through secondary effects, such as growth of the ice caps or changes in the make-up of the atmosphere.

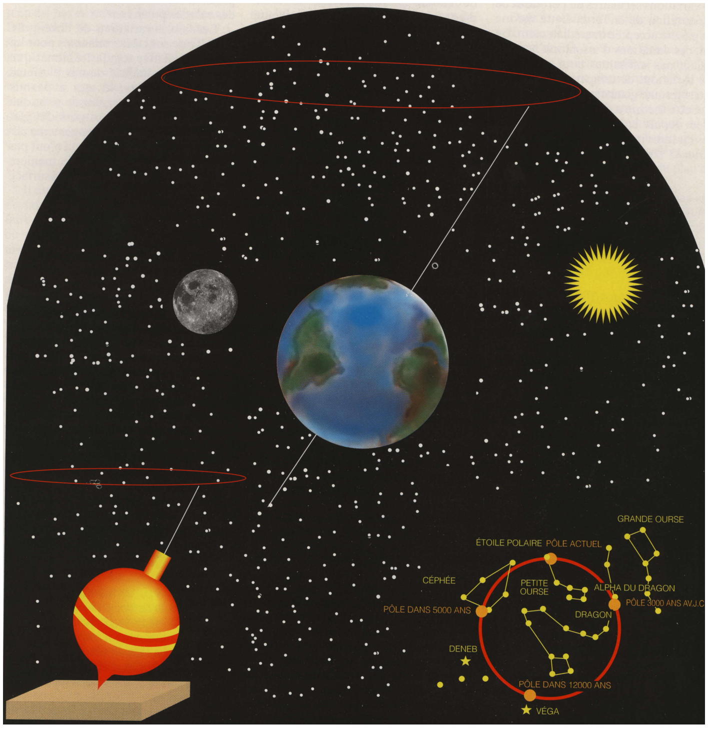

Figure 2: Precession of the equinoxes. The Earth is not perfectly spherical, but slightly oblate, with flattened poles and an equatorial bulge. Under the gravitational action of the Sun and Moon, its axis of rotation traces out a cone, much like a spinning top. The Earth's rotation axis traces out a large circle in the celestial sphere approximately once every 26,000 years. 5000 years ago the North Pole was indicated by the star Alpha, in Draco, rather than by Polaris. In 13,000 years, this direction will be indicated by Vega.

An essential part of any study of variations in the Earth's insolation is the calculation of variations in its obliquity under the influence of planetary perturbations. Over a one million year period, this variation is only ±1.3 degrees around the mean value of 23.3 degrees. This may not seem like much, but it is enough to induce variations of nearly 20 percent in the summer insolation received at 65 degrees north lattitude. The amount of additional heat received during the summer at high lattitudes is an important factor in climate studies, as it melts ice accumulated over the winter and prevents the ice caps from extending their reach. Weak variations in the Earth's obliquity are therefore a determining factor in regulating the relatively moderate climate enjoyed by the Earth over the last several million years, and in allowing the appearance of organized life as we understand it. The ice ages constitute significant climatic changes, but were not so severe as to permanently change the conditions for life on the Earth's surface.

Variations in the Earth's Obliquity

Perturbations exerted by other planets cause the Earth's orbit to turn in space with a motion that may be represented approximately as the sum of several uniform rotations, each arising from the influence of a particular planet, with periods ranging from 40,000 to several million years. It is the effect of this complicated motion on our terrestrial spinning top that gives rise to the small oscillations in its obliquity. If the excitation period produced by this motion of the Earth's orbit is close to the period of precession of its axis, the classical phenomenon of resonance may arise. Resonance occurs, for example, when a swing is pushed in the right way—each time it reaches its highest point. Even if each push is small, the swing's oscillations will be amplified (especially in the absence of friction). But if the swing is instead pushed at random intervals, nothing special takes place in general.

Instead of using the periods, we will consider the rotational speeds of these different motions. Since all the precessional motions we consider are very slow, they are expressed in units of arc seconds per year, abbreviated simply as seconds per year. A rotational speed of one second per year thus corresponds to a period of $360 \times 3,600 = 1,296,000$ years. I will introduce a slight abuse of terminology by calling these rotational speeds frequencies. With this convention, the frequency of precession of the Earth's orbit is 50.47 seconds per year, while the principal frequencies of the motion of the Earth's orbit range from 26.33 seconds per year down to nearly 0.67 seconds per year, with the main frequencies at 18.85 and 17.75 seconds per year. We are thus far from resonance, which explains the relatively small variations observed in the Earth's obliquity. This is not the case for Mars, whose frequency of precession is 7.5 seconds per year and whose obliquity is presently 25.2 degrees. William Ward, of the Jet Propulsion Laboratory in California, has pointed out that the proximity of secular orbital resonances causes Mars to undergo substantial variations in obliquity (on the order of ±10 degrees).

What if the Moon Were Removed?

To answer this question, I do not propose anything so drastic as to physically remove the Moon, but rather to study, through numerical simulations on a computer, the Moon's effect on the Earth's dynamics. We know that the Moon accounts for about two thirds of the torque acting on the Earth's equatorial bulge, with the Sun accounting for the remaining third. Without the Moon, the Earth's frequency of

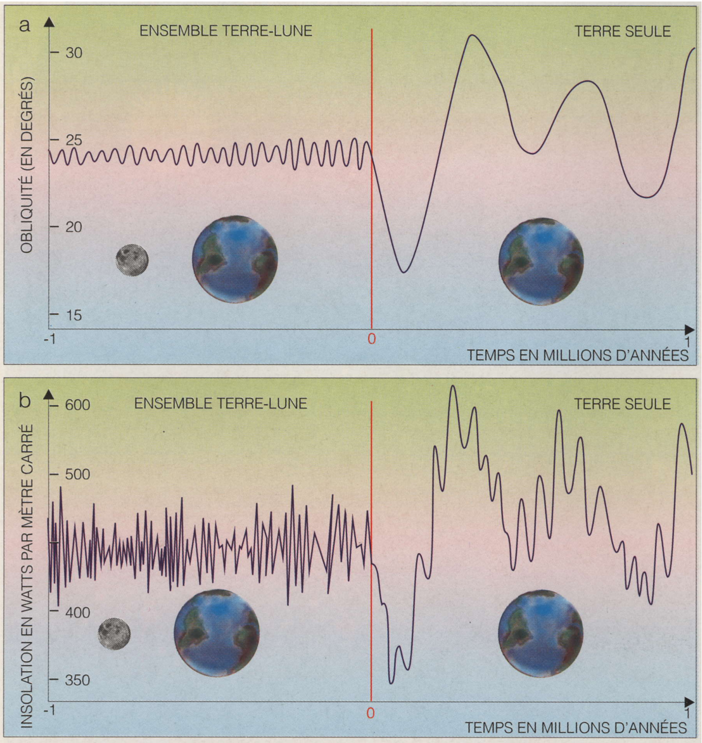

Figure 3: In this numerical simulation, the Moon is removed abruptly at our present date ($t = 0$). Under the influence of planetary perturbations, and in the presence of the Moon, the Earth's obliquity is not fixed, but undergoes small variations (± 1.3 degrees) about its mean value (23.3 degrees) (a). These small variations are enough to induce changes of nearly 20 percent in the insolation received on Earth at 65 degrees north lattitude (b), and, according to Milankovich's theory, are the cause of the ice ages. After removing the Moon, variations in terrestrial obliquity over a period of one million years are significantly increased.

precession would decrease from its present value of 50.47 to around 15.6 seconds per year, thus approaching the Earth's orbital frequencies and their attending resonances. In 1982, W. Ward studied this problem using a simplified model, and concluded that removing the Moon would induce variations in terrestrial obliquity on the order of those of Mars. But the Moon's absence would also mean a higher rotational speed for the Earth, which would increase the size of its equatorial bulge. According to Ward, the resulting increase in solar torque on the larger bulge would offset the absence of torque due to the Moon, leading in the end to obliquity variations comparable to those observed now.

At the Bureau of Longitudes in Paris, we recently studied this problem using a much more accurate model of terrestrial motion. We made use of calculations of the orbital motion of the Earth and the other planets that I carried out earlier over a model time period of some 400 million years. It was these calculations that I used in 1989 to show that the orbital motion of the solar system, and more especially of the inner planets (Mercury, Venus, Earth, and Mars), is chaotic. It was therefore possible to study numerically, over very long time periods, variations in the Earth's orientation due to its orbital variations. We first of all simulated an abrupt disappearance of the Moon, then observed the behavior of the Earth's obliquity over one million years. This is a relatively short time, not long enough, for example, for effects arising from the chaotic nature of the orbital motion to be detected. Nevertheless, variations on the order of ± 15 degrees in the Earth's obliquity were observed, and the resulting variations in insolation at 65 degrees north lattitude were much more significant than before. If, as advanced in Milankovich's theory, the variations in insolation at high lattitudes are responsible for periods of glaciation, it is very likely that the variations depicted in Figure 3 would induce still more significant temperature changes on the Earth's surface.

Our goal is however not to rid ourselves of the Moon, but to understand the possible evolution of the Earth had the Moon not existed, which naturally leads us to inquire about the Moon's origins.

The Origin of the Moon

The Moon confronts us with a number of astronomical problems. Its mass, 1/81 that of the Earth, is very large for a planetary satellite, and in that respect is unique in the solar system. Only Jupiter, Saturn, and Neptune possess satellites of comparable mass, yet those planets are respectively 318, 95, and 17 times as massive as the Earth. The formation of the Moon thus poses a distinct problem, for which a number of different scenarios have been proposed.

In the fission scenario, centrifugal forces of a rapidly rotating Earth (2–3 hours) tore off a large portion of its mantle to form the Moon. This model has been very nearly abandoned, in part because it is difficult to account for such a high initial rotation speed for the Earth, in part because of the Earth's and Moon's noticeably different chemical compositions, and especially because the Moon does not lie close to the Earth's equatorial plane, but instead only 5 degrees from its orbital plane.

The Moon might have been formed at the same stage as the Earth, through the accretion of material in orbit around it. This would explain the Moon's nearness to the plane of the ecliptic, but not the marked difference in chemical composition.

In the capture hypothesis, the Moon was formed in some neighboring part of space, then captured by the Earth's gravitational field. Two modes of capture have been proposed: "soft" capture, and "hard" capture. Hard capture entails a violent collision between the Earth and some massive body, with the subsequent accretion of the resulting debris forming the Moon. The problem with these scenarios—the latter currently enjoying the most favor—is their low probability of occurrence. Skepticism concerning a capture scenario adheres to the "principle of mediocrity," which requires that observed events be generic rather than exceptional.

Though the Moon's origin remains enigmatic and subject to varied speculation, it is nevertheless possible to retrace its history to a very distant past.

The Moon's Past History

The Moon exerts a force of attraction on the Earth which we observe daily through the phenomenon of tides. Since the Earth rotates more rapidly on its axis (once daily) than the Moon revolves around the Earth (about once every 28 days), the tides move over the Earth's surface, and this motion is accompanied by a dissipation of energy.

This in turn leads to a slowing of the Earth's rotational speed (a lengthening of the day by 0.002 seconds per century), and an increase of the Moon's mean distance from the Earth of about 3.5 centimeters per year. Several million years ago, the Earth rotated noticeably more rapidly on its axis, and the Moon was noticeably closer.

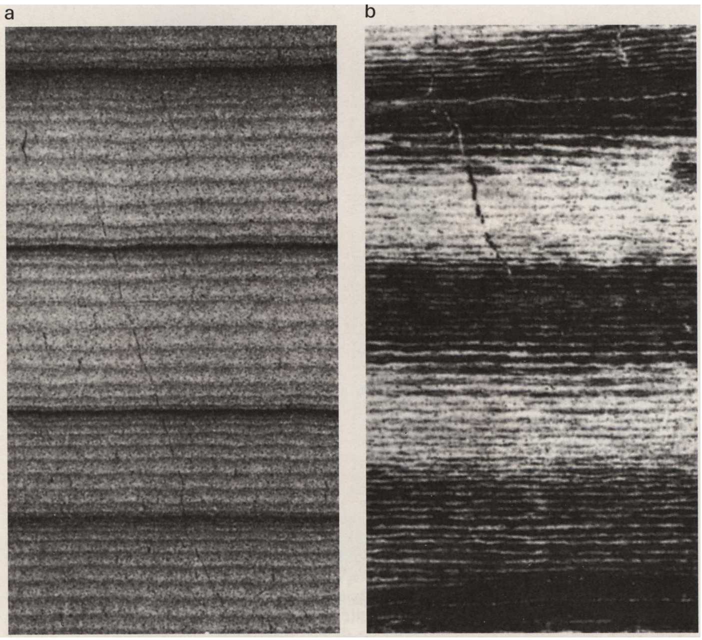

Figure 4: Sedimentary layers studied in Australia by G. Williams. (a) 650 million years ago, these layers were formed through successive deposits in an estuary of dark clay and light sand by the tides. Assuming the length of the year has remained constant, it is possible to deduce from these records the length of the day and the distance between the Earth and Moon in the distant past. (b) Dating back 2.5 billion years, these layers probably also reflect the tidal effects of the Moon.

The rate of slowing is not constant, and evidence of its variation may be found in records of past tidal cycles, such as coral reefs and certain shell fossils. But it was by analyzing sedimentary deposits that the Australian geologist G. Williams found that the length of the day 2.5 billion years ago was about 20 hours, while the Moon was some 348,000 km from Earth (compared with 384,000 km currently). To find these values, Williams analyzed deposits that were successively brought into an estuary by the sea through the action of tides. The annual cycle of these tides allowed him to estimate the time scale of these deposits, under the reasonable assumption that the length of the year has not appreciably changed over time. The Moon was thus present at this early epoch. More tenuous fossil records seem to indicate that the Moon was present still earlier, as far back as 3.8 billion years ago. If the Moon was indeed captured, its capture apparently occurred during an early phase of the solar system's development.

The Moonless Earth

As we saw earlier, if the Moon were not present, the Earth's rotational speed would be somewhat higher, since it would not have been slowed through the dissipative effects of lunar tides. By extrapolating the values found previously by Williams, the Earth's primordial rotational speed may be estimated at about 1.6 times its present value, corresponding to a day of about 15 hours in length. At the Bureau of Longitudes, Frédéric Joutel, Philippe Robutel and I began with this hypothesis and studied possible variations in the Earth's obliquity. To do this, we used a new method for analyzing the stability of motion: the method of frequency analysis.

Ordinarily, for each value of the Earth's initial obliquity, we obtain a speed of precession of its axis of rotation. If the motion is stable, this precession speed changes continuously with the initial obliquity. On the other hand, if the motion is chaotic, or unstable, the speed of precession is no longer uniquely defined, and depends strongly on minor differences in the initial conditions. A graph of the speed of precession as a function of the initial obliquity therefore indicates the stability of subsequent obliquities (see Figure 5). This analysis shows a vast chaotic zone extending from 0 up to about 85 degrees initial obliquity. Whatever the Earth's initial obliquity in this range, in the absence of the Moon, the Earth's subsequent obliquity would be subject to strong oscillations, nearly ranging over the whole chaotic zone in the space of a few million years.

In Figure 5, we present the minimum, mean, and maximum values attained by the Earth's obliquity over an 18 million year period, for various initial obliquity values. On such a short time interval, the obliquity does not range over the entire chaotic zone in the examples considered, but our analysis shows that the full extent of the chaotic zone may be attained over longer time periods. In the absence of the Moon, the Earth would undergo variations in its obliquity of sufficient magnitude so as to drastically alter its surface climate. It should be pointed out that with an obliquity of 85 degrees, the Earth's axis of rotation would very nearly lie in its orbital plane, as is the case with Uranus. The whole planet would then be subject, as the polar zones are now, to days and nights of several months duration. At the poles, the Sun would remain high in the sky for long periods, and, although no climate simulations have yet been carried out for the Earth in this tilted configuration, it is likely that such a drastic redistribution of insolation would cause significant changes in the Earth's atmosphere.

Of course, in choosing a primordial rotational speed of 15 hours for the Earth, we made what seemed to be the most reasonable choice, but other scenarios of lunar formation could lead to different primordial rotational speeds. Since all of these are highly speculative, we also chose to study the stability of the Earth's obliquity in the absence of the Moon

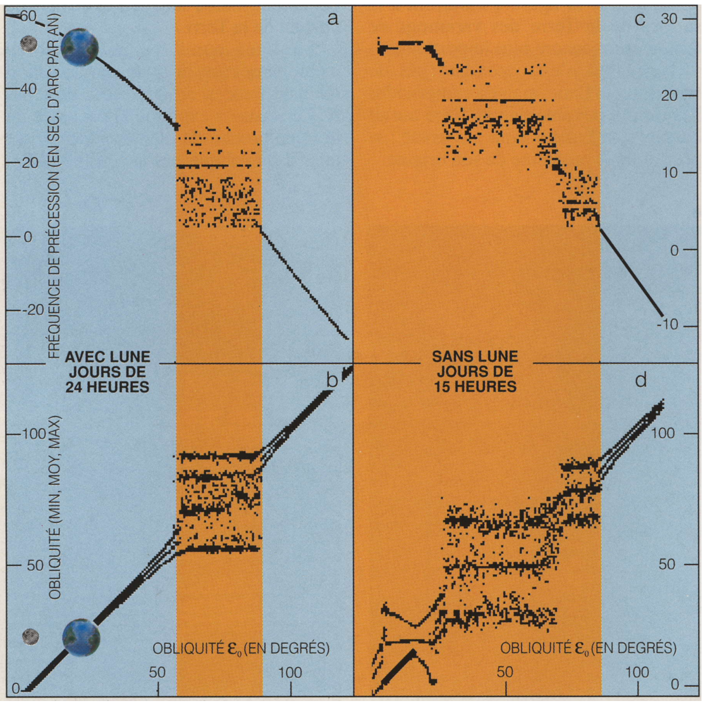

Figure 5: Each point in these figures corresponds to a simulation of the Earth's motion over 18 million years (a,b) with, and (c,d) without the Moon. The minimum, mean, and maximum obliquity values attained over this interval are shown in (b) and (d) as a function of the initial obliquity. If the motion is stable, the frequency of precession p varies continuously as a function of the initial obliquity (e). In this regular zone (which includes the present conditions of the Earth) the variations of the Earth's obliquity are slight, as in the blue zones of Figures (a) and (c). By contrast, in the red zone of Figure (a), the frequency of precession is not well defined; the obliquity is chaotic, and may vary by 60 to 90 degrees over a few million years. Without the Moon, and for a terrestrial rotation period of 15 hours, the chaotic zone (in red) extends from 0 to nearly 90 degrees (c). During a period of 18 million years, the obliquity does not range over the entirety of this zone (d), but no obstacle prevents it from doing so over longer periods.

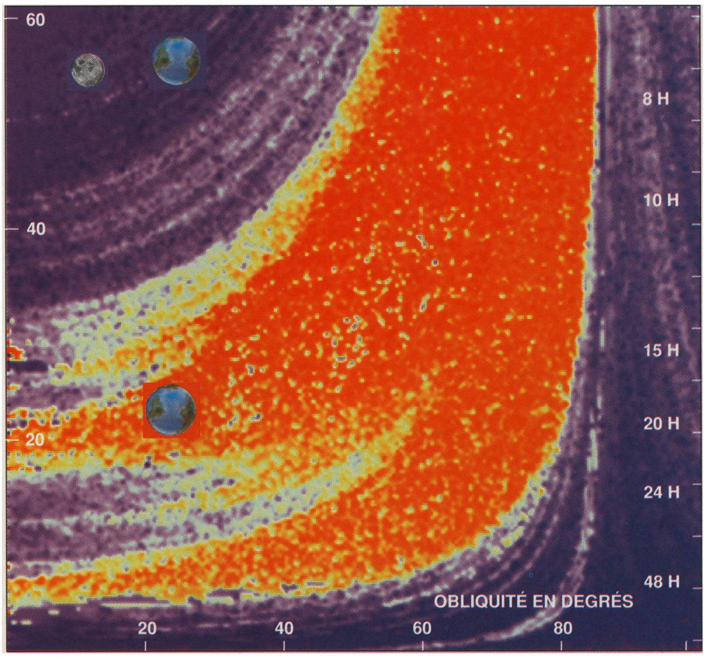

Figure 6: Analysis of the stability of the Earth's obliquity (in the absence of the Moon), for all values of length of day, and all initial obliquities. The stable motions correspond to the blue zone, and the strongly chaotic motions to the red and orange zone. In the stable zone, where the current position of the Earth-Moon system may be found, variations of the Earth's obliquity are very slight. On the other hand, in the chaotic red zone, the obliquity may trace out an entire horizontal line segment over several million years. For a rotational speed of 20 hours, for example, the Earth's obliquity without the Moon may range from 0 to nearly 85 degrees.

for all possible values of primordial rotational speeds of the Earth. We found that for all rotation periods between 12 and 48 hours, there is a very large chaotic zone of terrestrial obliquity, ranging from nearly 0 to more than 80 degrees. It is therefore legitimate to say that the Moon acts as a climatic regulator for the Earth, assuring relative climatic stability through the ages. This naturally leads us to look at the corresponding situation in the case of the other planets.

The Chaotic Obliquity of the Planets

In much the same way as described above for the Earth, we studied the stability of the axial orientation of all the principal planets of the solar system. Mercury and Venus are special cases, since—no doubt because of solar tides acting over time—their rotational speeds are now very slow. Venus also possesses a trait that has long intrigued astronomers: it does not rotate in the same direction as the other planets, or in other words, it is upside down. Until now, most astronomers considering this fact had concluded that Venus was formed upside down—or at least with its rotational axis in its orbital plane, since then dissipative effects arising from solar tides, core-mantle interactions, or from atmospheric tidal forces due to the Sun could bring it into an upside down position.

We have shown instead that, even if Venus started with a rotational speed similar to the Earth's, and in the same direction, the presence of a large chaotic zone in its obliquity could subject it to severe tilting, bringing its rotational axis very nearly into its orbital plane. The dissipative effects just described could then bring it into its present position, where ultimately it might stabilize as its rotation slowed further.

The situation for Mercury is slightly different. As is the case for Venus, we do not know Mercury's primordial rotational period, but it is enough to assume it was shorter than 300 hours to assure that, in the course of its history, Mercury underwent strongly chaotic variations in its obliquity, ranging from 0 to 90 degrees in the space of a few million years. As with Venus, the continued effects of tides could then slow its rotation, causing it to right itself and end up in its present position.

Mars is far from the Sun, and its satellites Phobos and Deimos have masses far too small to slow its rotation, so that its present rotational period of 24 hours 37 minutes is close to its primordial rotational period. Mars' equator is inclined 25 degrees with respect to its orbital plane, and its speed of precession, 7.26 seconds per year, is close to certain frequencies of motion of its orbit. Moreover, variations in the inclination of Mars' orbit are considerably stronger than those of the Earth. It follows that variations in its obliquity over a period of one million years are also much stronger than the Earth's, and G. Ward has found obliquity variations on the order of ± 10 degrees about a mean value of 25 degrees. These variations bring about strong climatic changes on Mars' surface, and certain surface structures seem to bear witness to these changes.

Our recent computations provide also evidence that the motion of Mars' rotational axis is chaotic. This has two consequences. First, as is also the case for the orbital motion of the inner planets, it is not possible to predict the orientation of Mars' axis for periods longer than a few million years.

But more important, the obliquity of Mars is subject to much larger variations than those predicted by Ward, ranging between about 0 and 60 degrees in less than 50 million years. Models of the past climates of Mars should be reviewed in light of these new results. The existence of this large chaotic zone in the orientation motion of Mars also removes a constraint from models of solar system formation, since Mars' obliquity cannot be considered primordial.

The Formation of the Solar System

Since the work of Safronov in 1960, models of solar system formation admit the existence of a very massive initial solar nebula. Because of gravitational instabilities, part of this nebula condensed to form the Sun. The rest of the nebula condensed into small bodies, or planetoids. The planets were then formed out of the larger planetoids by way of collisional accretion of smaller planetoids. A large part of the remaining planetoid mass was then ejected from the solar system. Safronov showed that if accretion took place in the presence of many small planetesimals, the planets would all rotate in the same direction with very nearly zero obliquity. To account for the considerable variation in the observed obliquities of the planets, Safronov was required to introduce a so-called "stochastic component" in the accretion mechanism; this entails a final phase in which planets suffer a number of random collisions with planetoids large enough to account for the observed obliquities. Our recent results show that all the obliquities of the inner planets may be accounted for by the action of secular perturbations of the planets, complemented, in the case of Mercury and Venus, by the dissipative effects described earlier.

We also show that the obliquities of the outer planets are essentially stable, as are their orbital motions. We are unable to account in this way for the large obliquity of Uranus (98 degrees). It is however possible to envisage for Uranus a scenario similar to that proposed for Venus, in an early stage of the solar system formation, in the context of Safronov's hypothesis of a massive primordial solar system.

Possibility of Extraterrestrial Life

On October 12, 1992, NASA inaugurated a vast program called SETI (Search for Extra Terrestrial Intelligence) to search for signals arriving from possible advanced civilizations. Over the next ten years this program will use radio telescopes to search over a large portion of the radio frequency spectrum for signals of extraterrestrial origin. Because the sky is so vast, some 800 stars of solar type at distances less than 80 light years from Earth have been singled out for special attention. These will each be watched for about 20 hours, the seemingly minimum time during which something is likely to be detected, at least from a strong source of the type that might be anticipated to come from one of these possible extra-solar systems.

A fundamental principle underlies any such project: our situation on Earth is not extraordinary, and should therefore be repeated many times in our galaxy, in any number of varied forms. Yet, for a given star in our galaxy, we are unable to quantify the likelihood of the appearance of organized life similar to that on our planet.

Even without reference to the appearance of life itself, nor to the conditions that could lead to the development of a civilization that might wish to communicate using radio waves, we presently have no idea of the probability of a Sun-like star possessing a planetary entourage. In spite of frequent announcements of the discovery of extra-solar planets, no such object has yet been observed directly, and only the observations of (likely) proto-planetary disks of the Beta-Pictoris type are convincing.

However, almost all estimates of the probability of extraterrestrial life seem to agree on one point: in any planetary system, the planet located neither too close nor too far from its sun may allow the development of organized life as we know it on Earth. In fact, simulations carried out by Michael Hart in 1978 showed that outside a thin "zone of habitability," runaway greenhouse effect of the atmosphere could lead to situations of the type observed on Venus if the Earth were only 5 percent closer to the sun, while if the Earth were somewhat further from the sun, it would experience runaway glaciation.

Our calculations show that this is not the case, that the evolution of life on Earth is probably intimately linked with an event that seems unlikely in current models of the formation of planetary systems: a planet located in the zone of habitability is able to sufficiently stabilize its long-term insolation variations through the presence of a massive Moon-like satellite. Of course, it should be possible to find other particular circumstances leading to long-term climatic stability for a planet, but it should be stressed that these situations are probably uncommon. The probability of the existence, in a planetary system, of planets with stable climates comparable to our own must no doubt be reexamined and reduced by several orders of magnitude, as is the case for the probability of success of NASA's SETI project.

Remaining Questions

Using the orbital motions of the planets of the solar system, we have shown that the Earth very likely owes its climatic stability to the presence of the Moon. It should also be pointed out that if our existence is intimately tied to that of the Moon, it is possible to accept a scenario for the formation of the Moon of such small probability of occurrence that we would ordinarily reject it in confining ourselves to generic situations. Theories of the formation of the Moon would then need to be reconsidered in this light.

In addition, the orbital motion of the planets and of the Earth itself is chaotic. This does not seem to induce major changes in its orbital parameters over a few hundred million years, but in other planetary systems, this may not be the case, and orbital instabilities alone may induce strong climatic changes, or even the ejection from the planetary system of the one planet initially residing in the zone of habitability. Only a deeper understanding of the global dynamics of planetary systems will allow us to respond, at least partly, to such questions.

We are also far from understanding the mechanisms of formation of planetary systems. One of the great difficulties confronting us is that we possess only one example of a planetary system, namely our own. The discovery of another would be a boon to understanding the history of our solar system, even if no form of life existed in the other system.

Finally, the climatic changes on the surface of a planet arising from significant changes in its orbit or orientation are still not well understood, and it can only be hoped that an increased understanding of atmospheric dynamics will allow these changes to be successfully simulated by computers.

These various problems, though encompassing disparate subfields of astronomy, together make up a vast research program; but efforts toward their resolution will doubtless lead us to a better understanding of the origins of the solar system and of the appearance of life on Earth.

Translated by H.S. Dumas

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