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This Restless Globe

A Look at the Motions of the Earth in Space and How They Are Changing

by Donald V. Etz

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Our restless globe and its companion. While heading out for its rendezvous with Jupiter, a camera on NASA's Galileo spacecraft snapped this 1992 image of Earth and its Moon. The terminator, or line between night and day, is clearly visible on the two worlds. Image courtesy of NASA.

The Greek philosopher Heraclitus of Ephesus, said 2500 years ago that the perceptible world is always changing.

Heraclitus was not mainstream, of course. Among his contemporaries were philosophers like Zeno of Elea, who used his famous paradoxes to argue that change and motion are logically impossible. And Aristotle, much admired in ancient Greece and Rome, and the ultimate authority in medieval Europe, declared "...the earth does not move..."

We today know that Heraclitus was right, Aristotle was wrong, and Zeno...was a philosopher. Everything in the heavens moves, from the Earth on which we ride to the stars in the most distant galaxies. As James B. Kaler has pointed out in The Ever-Changing Sky: "The astronomer quickly learns that nothing is truly stationary. There are no fixed reference frames..."

The Earth's motions in space establish our basic units of time measurement and the yearly cycle of the seasons. Over the centuries of human civilization, these motions and their changes have prompted some of the earliest and most enduring scientific endeavors. Over the few thousands of millions of years of Earth history, they appear to have markedly affected its climate.

To bring it all together, and to dispel some misconceptions, we will take a look at the major motions of the Earth and the more important ways they are changing.

The Major Motions of the Earth

Rotation and Revolution: Days and Years

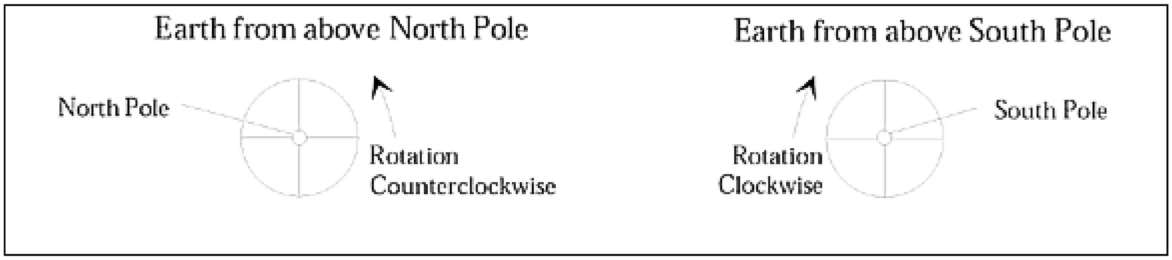

Figure 1. Earth's rotation as viewed from above the north and south geographic poles. Illustration courtesy of author.

The Earth rotates eastward on its axis-counterclockwise, viewed from above the North Pole; clockwise, viewed from above the South Pole-to give us our days (see Figure 1). The plane of the Earth's rotation (the equator), extended to the background of stars, is called the celestial equator. The axis of its rotation can be extended to mark the celestial poles in the background of stars, north to a point about 1° from Alpha Ursa Minoris (Polaris), and south to a point about 1° from Sigma Octantis (a fairly dim star sometimes called Polaris Australe).

The Earth revolves around the Sun-also counterclockwise viewed from above the North Pole, clockwise viewed from the South Pole-to give us our years (see Figure 2). The plane of the Earth's orbit is called the ecliptic (where eclipses happen). This plane passes through the 12 so-called zodiacal, or animal-form constellations, plus often-overlooked Ophiuchus. The ecliptic's axis currently extends north to the north ecliptic pole, a point in Draco, and south to a point in Dorado we call the south ecliptic pole.

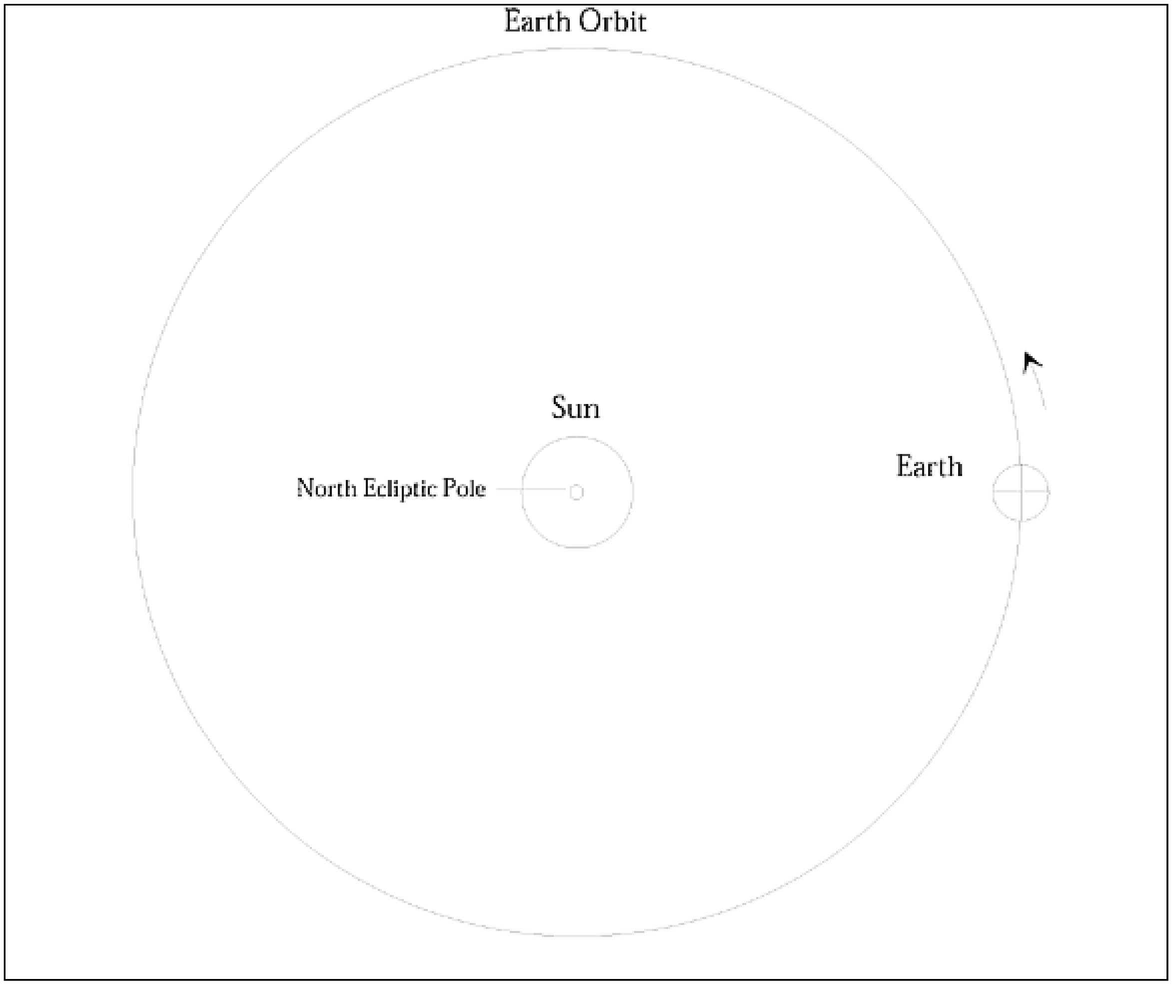

Figure 2. Earth's orbit as viewed from the north ecliptic pole. Illustration courtesy of author.

The Earth's direction of revolution probably arose from the rotation of the early nebula from which the Solar System formed, and its direction of rotation perhaps from the impacts of other large (proto)planetary bodies as the Earth grew.

Obliquity: Seasons

The celestial equator is currently tilted about 23.44° in relation to the ecliptic (Figure 3). This angle is called the obliquity of the ecliptic. The reason for this particular obliquity is not clear. A value close to it was probably established very early in the history of the Solar System. However, some writers suggest that it was originally much greater.

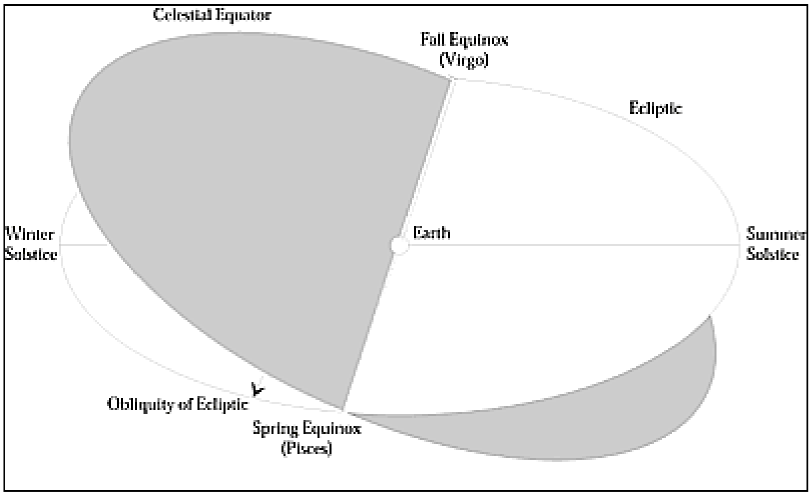

Figure 3. The celestial equator and the ecliptic. Illustration courtesy of author.

The celestial equatorial plane and the ecliptic currently intersect in Pisces, not far from the border with Aquarius, and in Virgo, not far from the border with Leo. The Sun in its apparent yearly progress along the ecliptic reaches the Pisces intersection at the Spring equinox on 21 March and the Virgo intersection at the Autumn equinox on 23 September. This annual variation gives us our seasons, opposite in the northern and southern hemispheres. The Sun shines more directly on the northern latitudes in the Spring and Summer, when it is north of the celestial equator, and on the southern latitudes in the Fall and Winter, when it is south of the celestial equator.

Eccentricity

The Earth's orbit around the Sun is not a perfect circle, but slightly "stretched" into an ellipse (Figure 4). Its eccentricity is currently about 0.0167, which means that the Earth-Sun distance varies about 1.67% of the mean distance. The Sun is not at the center of the ellipse, but at one of its two geometric focal points, each currently about 2.5 million km from the center. Hence, the Earth-Sun distance varies some 5 million km throughout the year. The Earth is closest to the Sun -- at perihelion -- about 2 January, when the Sun is in the middle of Sagittarius, and farthest from the Sun -- at aphelion -- about 4 July, when the Sun is in the middle of Gemini.

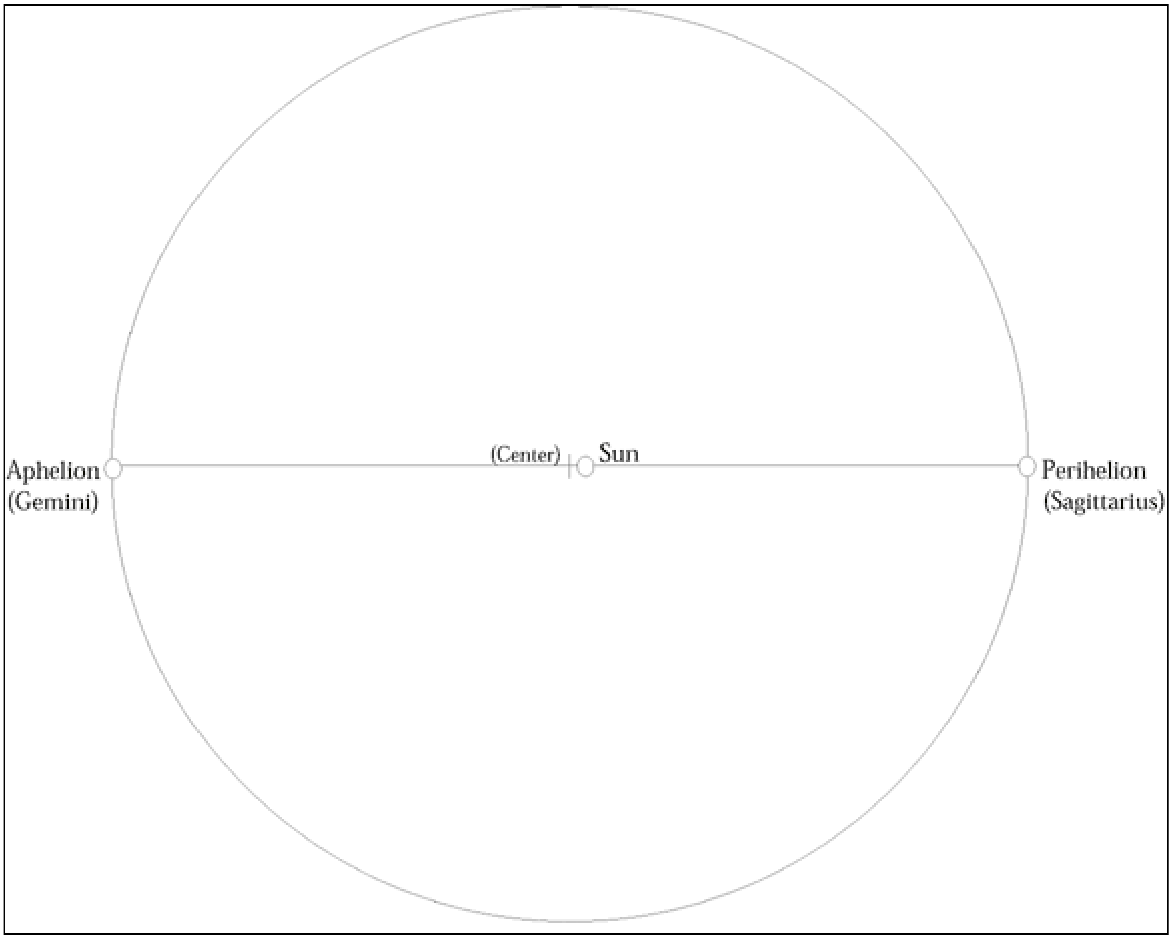

Figure 4. The small eccentricity of the Earth's orbit. Illustration courtesy of author.

Because the difference in distances is small, this eccentricity does not have a significant effect on the Earth's climate. However, it does affect the duration of the seasons, since the Earth takes longer to cover the more distant segments of its orbit. Currently, summer is for us in the North our longest season (93.65 days) and winter our shortest (88.99 days).

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How These Motions Are Changing

These terrestrial motions are not stable, but changing. The changes are important to us, since they affect our time reckoning, our climate, and our understanding of the Earth's past.

The Day

The Earth's rate of rotation is decreasing, so that the length of the day is increasing. Tides raised on the Earth, primarily by the Moon, cause the Earth's rotation to decelerate. In accordance with the principle of conservation of angular momentum, the Moon's orbit is correspondingly receding from the Earth (see Figure 5).

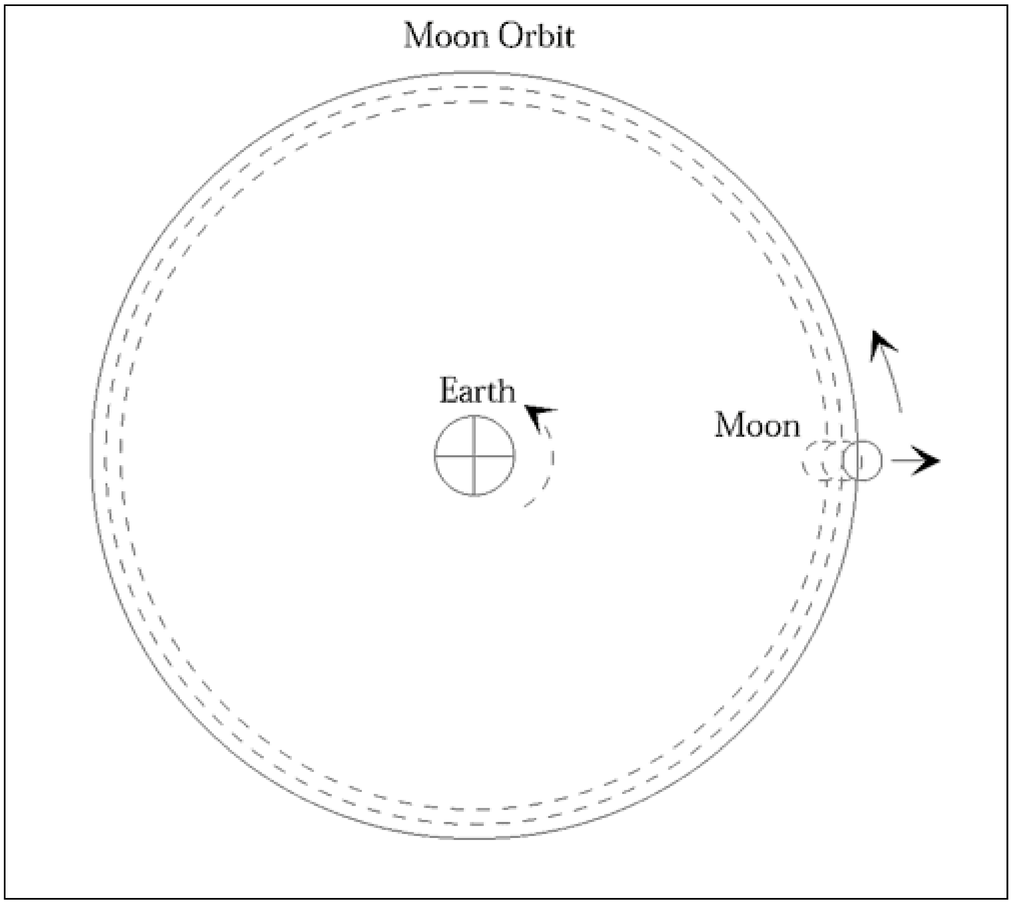

Figure 5. The Moon recedes and the Earth's rotation slows. Illustration courtesy of author.

Records of solar and lunar eclipses over the past 2500 years indicate that the tidal effect, about 2.3 milliseconds per century, is partially opposed by a factor which reduces the increase in the length of the day to about 1.7 milliseconds per century. This countereffect is probably caused by the recovery of the Earth's shape from the distortion of the last ice age, when the polar latitudes were depressed by the weight of the ice caps. In the long run, the effect should vary with the growth and shrinking of the ice caps. It has been suggested that today the tidal effect is also being slightly reduced by the growing number of huge water reservoirs on Earth, particularly in the northern hemisphere.

Sediments preserved in rock record daily tidal changes, and also changes in step with the phases of the Moon, during earlier geological periods. These records have enabled scientists to determine that some 900 million years ago, assuming the length of the year has not changed significantly, the day was only about 18 modern hours long, and there were about 480 days in the year.

The Year

Currently, the sidereal year -- the time it takes the Sun to return to the ecliptic longitude of a given fixed star-is about 365.2564 solar days. The sidereal year appears to be increasing slightly, about 0.01 second per century. This increase may not mean that the Earth's orbital motion is slowing down. Instead, the orbit may be increasing in size, which increases the period of revolution. The change is very small. If constant, it would amount to an increase of less than one day in one billion years.

The Orientation of the Earth in Space

The orientation in space of the Earth and its orbit is gradually changing, in several ways.

The Invariable Plane

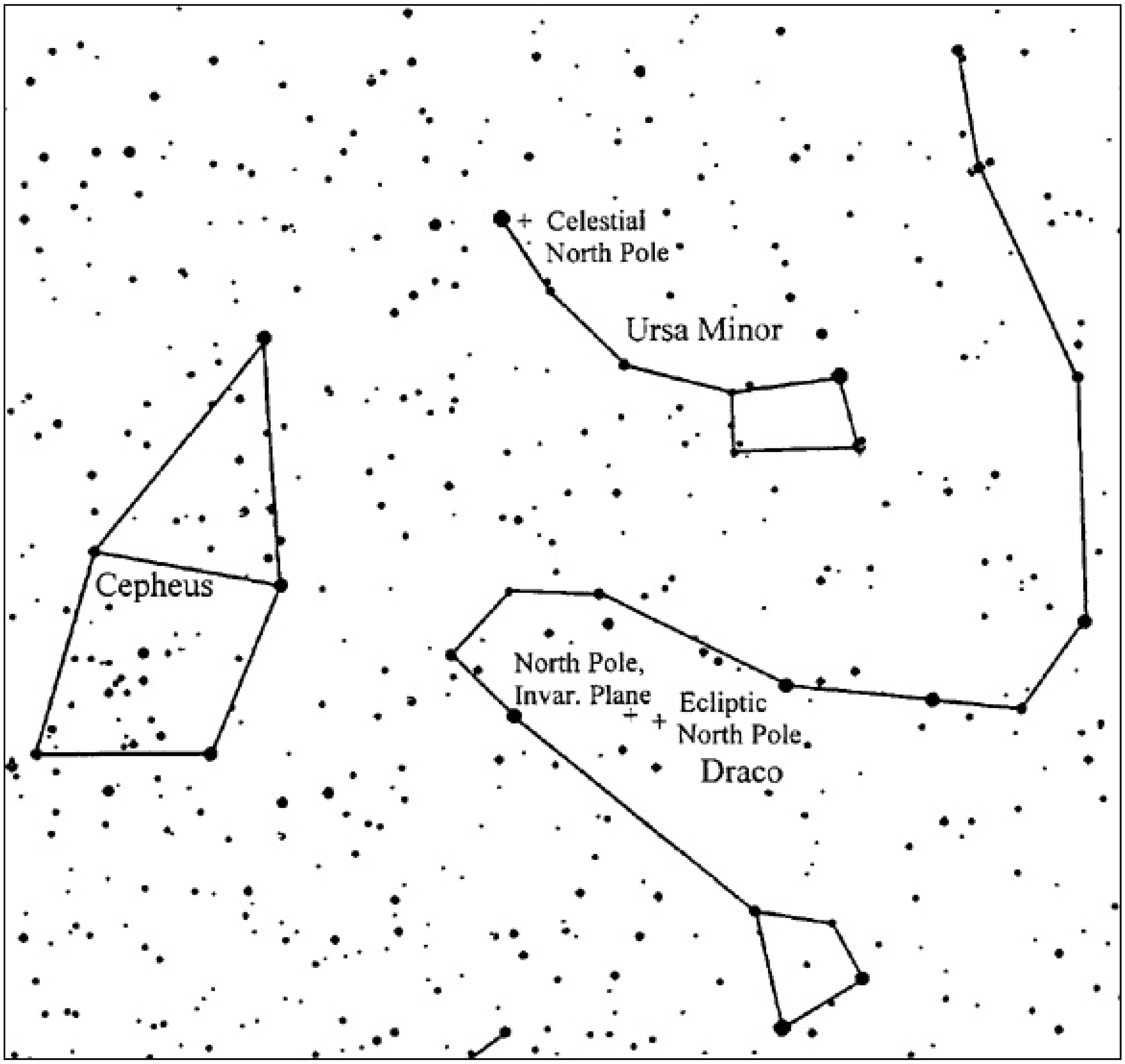

Figure 6. The current location of the celestial north pole, the ecliptic north pole, and the north pole of the invariable plane in the northern sky. Illustration courtesy of author.

To consider how this is happening, we need a reasonably stable frame of reference. For this, we can use the so-called invariable plane of the Solar System. The invariable plane is formally defined as "the plane through the center of mass of the solar system perpendicular to the angular momentum vector of the solar system." It represents the total angular momentum of all Solar System objects, insofar as their elements are known. It is not absolutely invariable but for most practical purposes can be considered so. The north pole of the invariable plane lies in Draco, its south pole in Mensa. The ecliptic is currently only about 1.58° from the invariable plane (Figure 6).

Precession of the Earth's Axis

The rotation of the Earth on its axis causes it to bulge at the equator and flatten at the poles. The gravitational force exerted on the equatorial bulge, almost entirely by the Moon and Sun, attempts to align the Earth's equator more closely with the ecliptic, but the rate of the Earth's rotation tends to maintain its obliquity. Instead, this gravitational force causes the Earth's axis of rotation to precess slowly. The poles describe an arc clockwise (opposite the direction of the Earth's rotation and revolution) as viewed from above the Earth's North Pole, looking down, but counterclockwise as viewed from the Earth's surface, looking up at the northern stars (Figure 7). The Earth behaves like a top spinning too slowly to remain stationary against the forces acting on it. The celestial equator rotates like a plate wobbling on top of a pole in a juggler's act.

This motion is called lunisolar precession. It tends to shift the intersection of the celestial equator and the ecliptic westward along the ecliptic, through the zodiacal constellations. The celestial poles take about 26,000 years to complete one cycle of precession. In the Pyramid Age, about 2500 BC, the North Celestial Pole (NCP) was in Draco, near the star Thuban. About 2000 years from now the NCP will enter the constellation Cepheus.

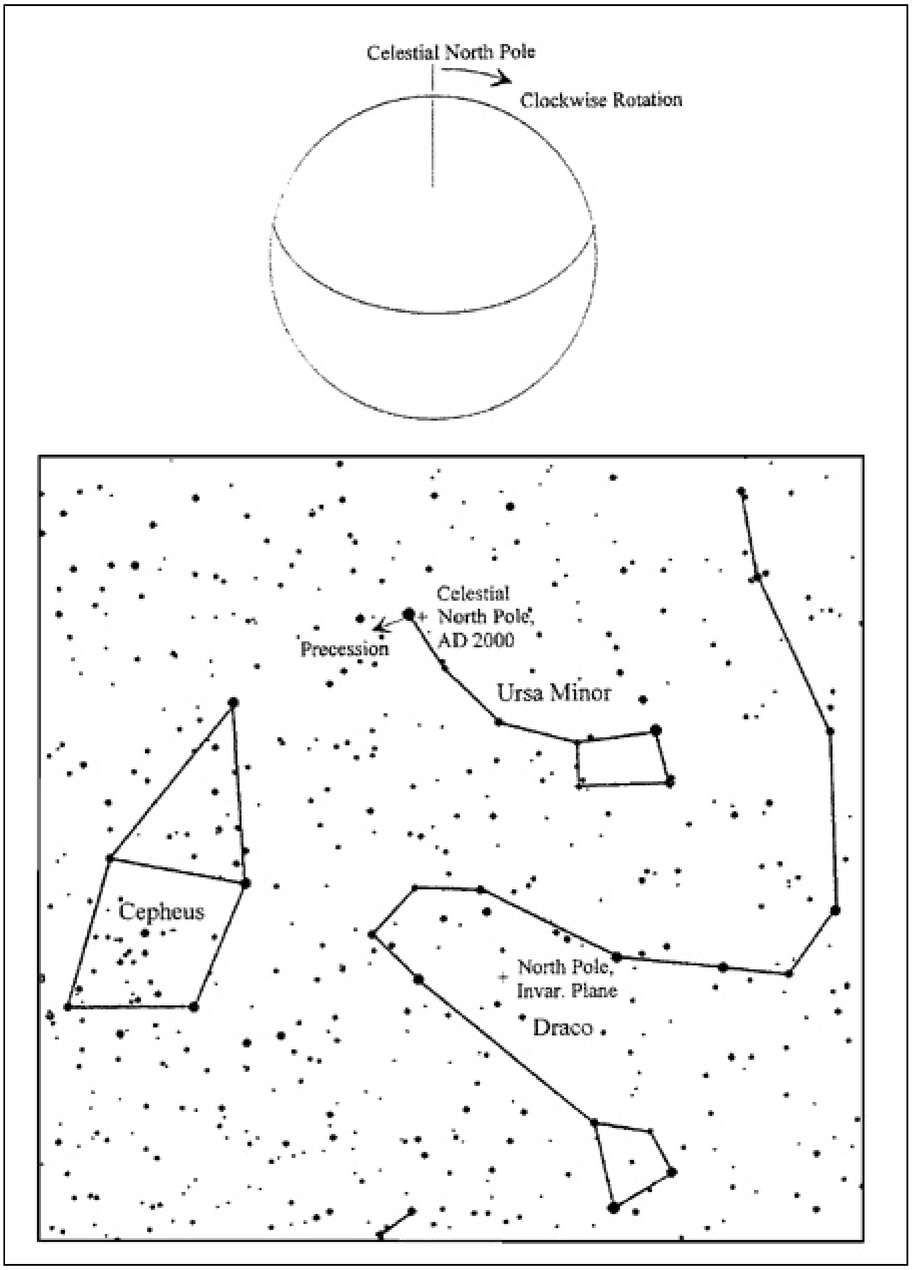

Figure 7. The precession of the celestial north pole, viewed from above the north pole and against the background of northern stars. Illustration courtesy of author.

The path of the poles is not a circle, but a loop or spiral. This time around, the NCP has come very close to Polaris, but the next time it is expected to pass about 3° from that star. This changes the angle between the celestial and ecliptic poles slightly, contributing to changes in the obliquity of the ecliptic.

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Precession of the Ecliptic

The relation of the celestial equator and poles to the ecliptic and its poles is complicated by the fact that the ecliptic is not stationary. The gravitational force of the Solar System planets, especially Jupiter and Venus, causes the ecliptic to precess, wobbling as its poles describe an arc counterclockwise in space, around the poles of the invariable plane. The ecliptic is like a second wobbly plate atop the same juggler's pole. However, it wobbles much less -- it precesses much more slowly than the celestial equator, and its poles describe a much smaller arc (see Figure 8).

This motion is called planetary precession. It tends to shift the ecliptic westward along the celestial equator, counteracting a small part of the effect of lunisolar precession. The path of the ecliptic poles, like that of the celestial poles, is not a circle in space but a loop or spiral.

The Combined Effects

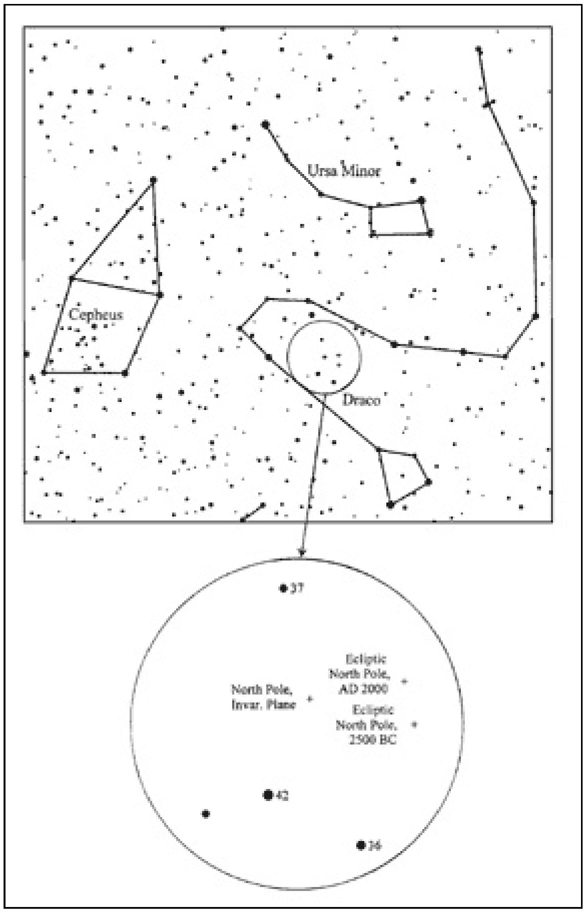

Figure 8. The precession of the ecliptic north pole through the background of stars. Illustration courtesy of author.

The effects of these changes, in combination, are general precession, the observed precession of the equinoxes westward along the ecliptic, and a change in the obliquity of the ecliptic (its inclination in relation to the celestial equator) and its inclination in relation to the invariable plane.

The Precession of the Equinoxes

Today the equinoxes are in Pisces and Virgo, and the celestial poles in Ursa Minor and Octans. In the Pyramid Age, the equinoxes were in Taurus, not far from the border with Aries, and Scorpius, along the border with Libra (Figure 9). Because the equinoxes precess, moving westward along the ecliptic opposite the apparent eastward progress of the Sun during the year, they advance to meet the Sun. The Sun returns to an equinoctial point in less time than it takes to return to a fixed star. This gives us two different astronomical measures for the year: the return of the Sun to the Spring equinoctial point (tropical year, about 365.2422 days), and its return to the longitude of a fixed star (sidereal year, about 365.2564 days). For most human affairs, we are more interested in the tropical year, because it is in step with the seasons. Neither astronomical year consists of a whole number of days, but human calendars do. Hence, calendar-makers have struggled for several thousand years to determine exactly how long the year is, and to devise systems for allocating the fractional day.

The rate of general precession is currently about 50.29 arcseconds per year. At this rate, the equinoxes would make one revolution in about 25,770 years. However, the rate has been increasing slightly, decreasing the tropical year even more.

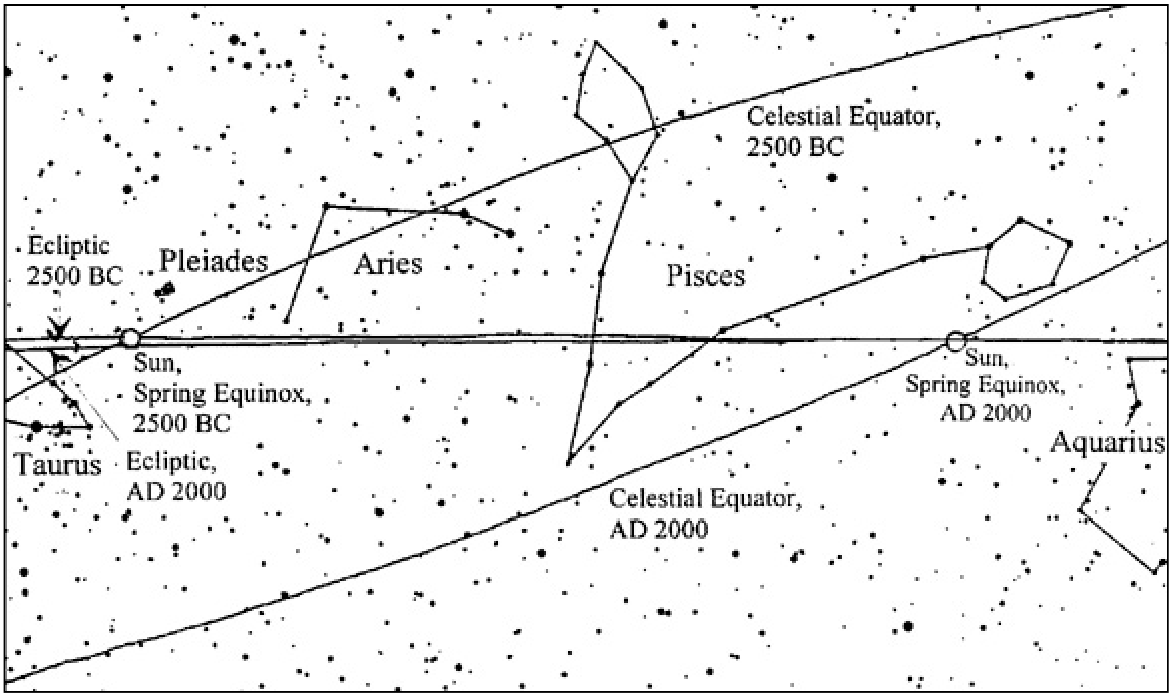

Figure 9. The precession of the equinoxes, 2500 BC to AD 2000. Illustration courtesy of author.

A Decrease in Obliquity

Planetary gravitational influences are also the primary factor in changing the obliquity of the ecliptic. Today, it is about 23.44°, as mentioned. In the Pyramid Age, it was about 24.02°. It has been decreasing from a peak of about 24° some 8,000 years ago toward a low of about 22° some 13,000 years hence. The obliquity goes through cycles of varying amplitudes with a period of about 41,000 years. The rate varies-currently it is about 0.47 arcseconds per year.

A Decrease in Inclination

The inclination of the ecliptic in relation to the invariable plane also goes through cycles of varying amplitude, with a period of about 100,000 years. It is currently 1.58°, as noted, and decreasing. Its last maximum, about 30,000 years ago, was about 2.6°, and it is expected to decrease to a minimum of about 0.8° in about

20,000 years. The greater the inclination of the ecliptic, the greater the extremes of the Earth's travels north and south in relation to the Sun.

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The Earth's Orbit

The shape and orientation of the Earth's orbit around the Sun are also changing, under the influence of the other planets.

The Orbital Eccentricity

The eccentricity of the Earth's orbital ellipse is currently decreasing from a peak of about 0.02 some 14,000 years ago toward a low of about 0.003 some 25,000 years from now (Figure 10). It passes through cycles of varying amplitudes with a period of about 95,000 years. During the ice ages, the peak eccentricity reached 0.05-0.06. At that time, the difference between perihelion and aphelion distances was about 16 million km.

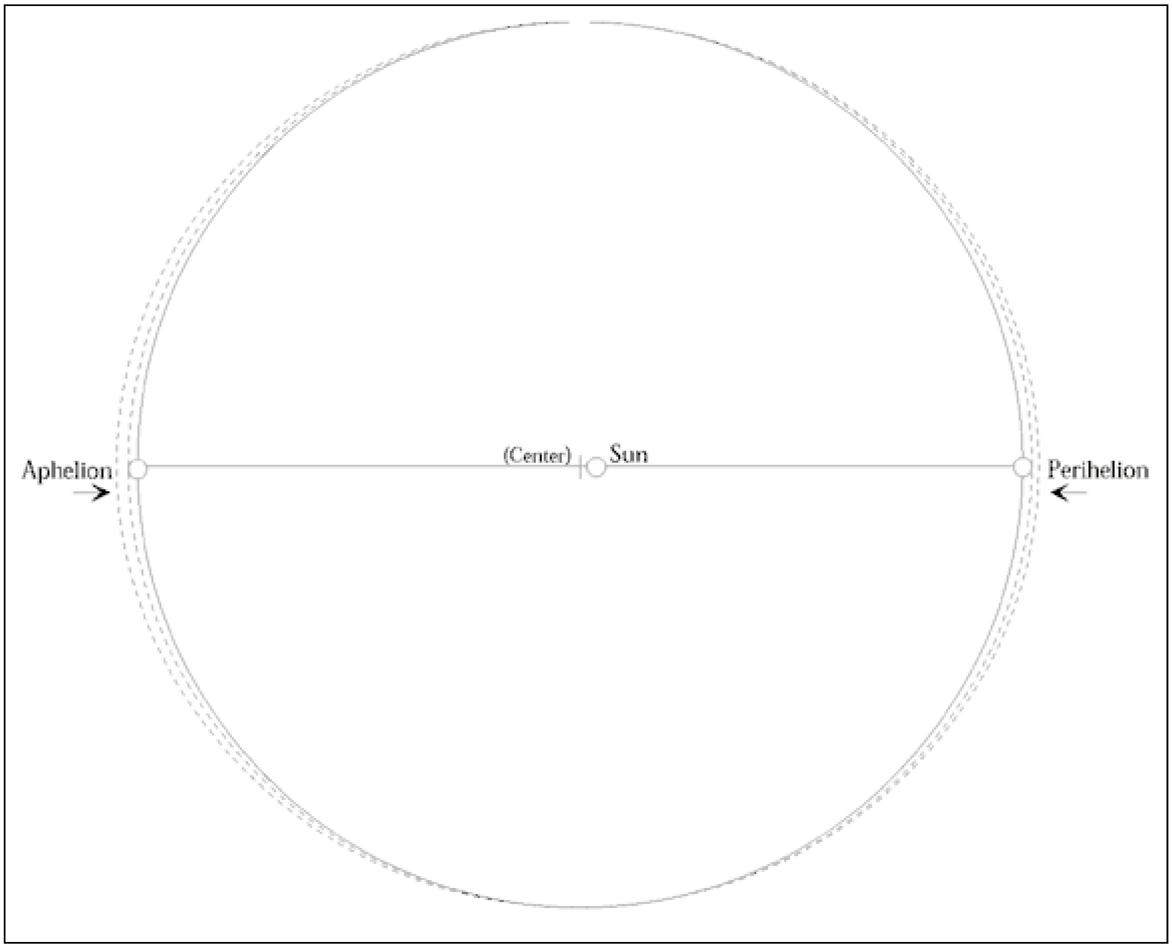

Figure 10. The shrinking eccentricity of the Earth's orbit. Illustration courtesy of author.

The Longitude of Perihelion

The perihelion and aphelion are precessing, advancing eastward along the ecliptic about 11 arcseconds per year in relation to the fixed stars. This is the difference in arcseconds between the sidereal year and the anomalistic year. At this rate, they will take about 114,000 years to make a complete revolution.

The perihelion is currently in the middle of Sagittarius. In the Pyramid Age, it was near the western edge of Sagittarius, its border with Ophiuchus (Figure 11). It and the Spring equinox, advancing westward about 50 arcseconds per year, move about 1 arcminute per year in relation to each other. At this rate, the time between coincidences of the perihelion and equinox is about 21,000 years. This interval, rather than the sidereal movement of the perihelion, is sometimes called the precession of the perihelion. It has been confused with the precession of the equinoxes. The perihelion and Spring equinox last coincided about 16,500 years ago, almost on the border of Ophiuchus and Scorpius. They will next coincide in about 4,500 years in Sagittarius, near the border of Capricornus (see Figure 12).

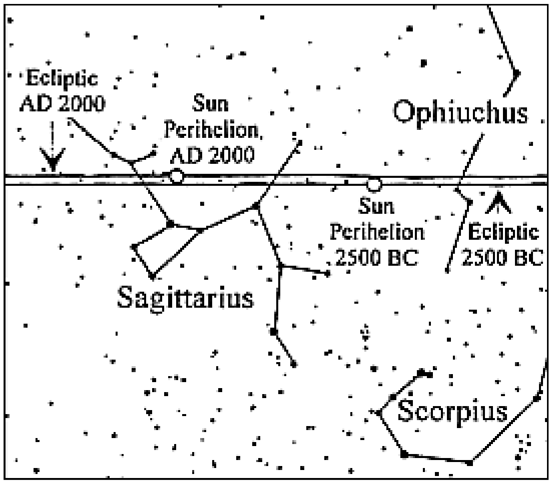

Figure 11. The precession of the perihelion of the Earth's orbit, 2500 BC to AD 2000. Illustration courtesy of author.

The change in eccentricity, plus the changing relation between the perihelion and aphelion of the Earth's orbit and the equinoxes and solstices, change the duration of the seasons. Today, Summer is the longest season and Winter the shortest. In the Pyramid Age, Spring was the longest and Autumn the shortest.

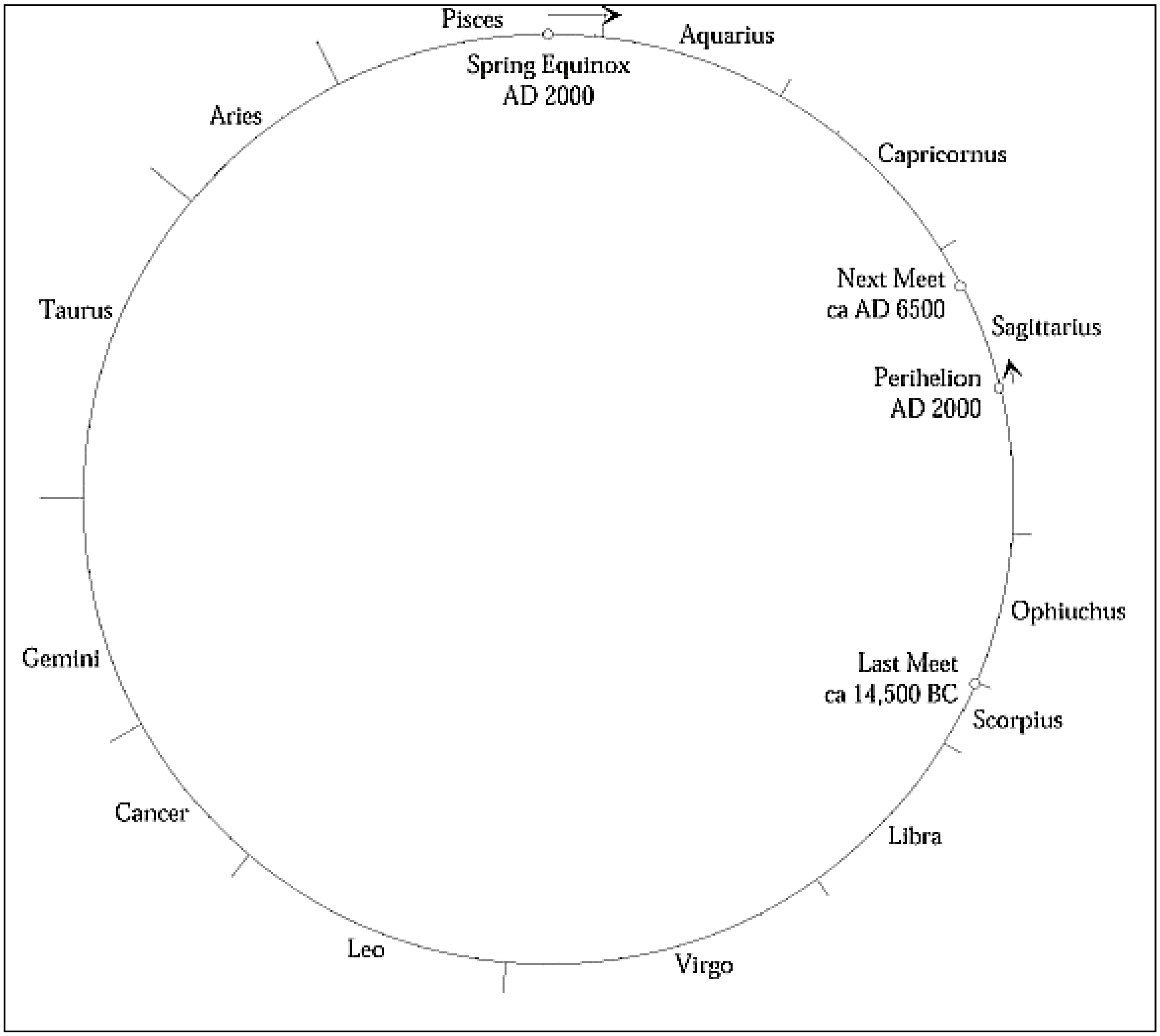

Figure 12. The combined precessions of the equinoxes and perihelion. Illustration courtesy of author.

Precession in Human History

None of the changes in the Earth's motions that we have considered are apparent to the unaided eye. Even a lifetime of observing would not necessarily reveal them. But some astronomical positions and events preserved in "social memory" -- either oral teaching or documents -- for several generations may provide clues to the astute observer that something in the heavens is changing. (Then it may have been necessary to overcome human inertia and ideology to convince others of the changes.)

The most rapid change is lunisolar precession, which affects the positions of the stars and the precession of the equinoxes. This change can be detected, over a century or two, in several ways: stars moving closer to or farther from the poles, stars rising farther north or south, and stars rising heliacally (just before the Sun) or culminating around sunset later in the year.

To observers as far south as the Nile delta, the seven main stars of Ursa Major were fully circumpolar in the northern sky from the 4th millennium BC to the birth of Christ. However, in the 3rd millennium, they began to move away from the NCP. They also rotated, the eastern end today's Big Dipper moving south faster than the western. Alkaid, the star at the Dipper's eastern tip, moved south most rapidly. This change should have been detectable to observers armed with records going back several generations. A document from ancient Egypt suggests that it was. The Book of Day and Night (12th century BC) speaks of binding the Leg (their name for Ursa Major) to mooring posts, as though seeking to keep it from moving farther from the NCP.

One of the brightest stars to change its position significantly at rising was Arcturus (Alpha Boötes). In the 2000 years following the Pyramid Age, it shifted southward along the horizon about 0.7° in azimuth per century. Natural or artificial alignments used to mark its rising would gradually have become useless.

The equinoxes and solstices shift even more rapidly -- about 1.4° per century. Since these events were observed by people responsible for the calendar, their changes were likely to be noticed. The ancient Chinese apparently keyed their earliest calendars to the culmination of certain stars such as Antares at sunset on these dates. Because of precession, they found it necessary to revise this system every few centuries.

Hipparchus of Nicaea (2nd century BC) is the first known astronomer to have made careful observations and compared them with those of earlier astronomers to conclude that the fixed stars appear to be moving slowly in the same general direction as the Sun. Confirmed by Ptolemy (2nd century AD), this understanding became common in medieval Europe and the Near East, although a few astronomers believed that the motion periodically reversed itself. The Chinese astronomer Yü Hsi (4th century AD) was the first known in east Asia to take official note of precession.

The Motions of the Earth and the Climate

Many climatologists have looked to the changing motions of the Earth to explain the recurring ice ages of the Pleistocene geological epoch, which began an estimated 1.7 million years ago. The prevailing theory holds that the changing obliquity of the ecliptic (41,000-year cycle) and a combination of the changing eccentricity of the Earth's orbit (about 100,000-year cycle) and the relative movement of the perihelion and the spring equinox (complex cycle, averaging about 21,000 years) account for the cycles of glaciation. These changes affect the seasonal and latitudinal distribution of sunlight on the Earth's surface, and this presumably causes the ice ages, although the mechanism is not fully understood. The 100,000-year cycle of glaciation has been difficult to relate to the eccentricity cycle.

A competing theory, recently revived and redefined, holds that a major climatic factor in the last one million years is the changing inclination of the Earth's orbit with respect to the invariable plane (a 100,000-year cycle). Around maximum, this inclination is thought to dip the Earth's orbit low enough that a dust cloud between the Earth and the Sun reduces the amount of sunlight reaching the Earth and triggers a glacial cycle.

Conclusion

Our knowledge of the Earth's motions has come far from the theology of medieval and early modern Europe, which took literally Psalm 104:5, and cited it against Galileo.

"He set the earth on its foundations;
it can never be moved." (NIV)

The Earth does move, and its motions vary in ways that the early Copernicans could not have predicted or detected. The changes are responsible for changes in the length of the day and the year, and for changes in the relative durations of the seasons. They may be responsible for the ice ages. Knowledge of these motions and their changes is useful not only to astronomers but also to historians and climatologists-indeed, to any profession concerned with the changing behavior of the Earth and with records of it in history and geology.

Donald V. Etz is a retired technical writer and a non-retired amateur astronomer and historian who lives in Dayton, Ohio. He gives lectures on astronomical subjects to his local astronomical society and other organizations and has published a couple of articles on these subjects. His particular astronomical interests are the history of astronomy and the behavior of the Solar System. His particular non-astronomical interests are his grandchildren and church activities. His email address is donetzday@worldnet.att.net.