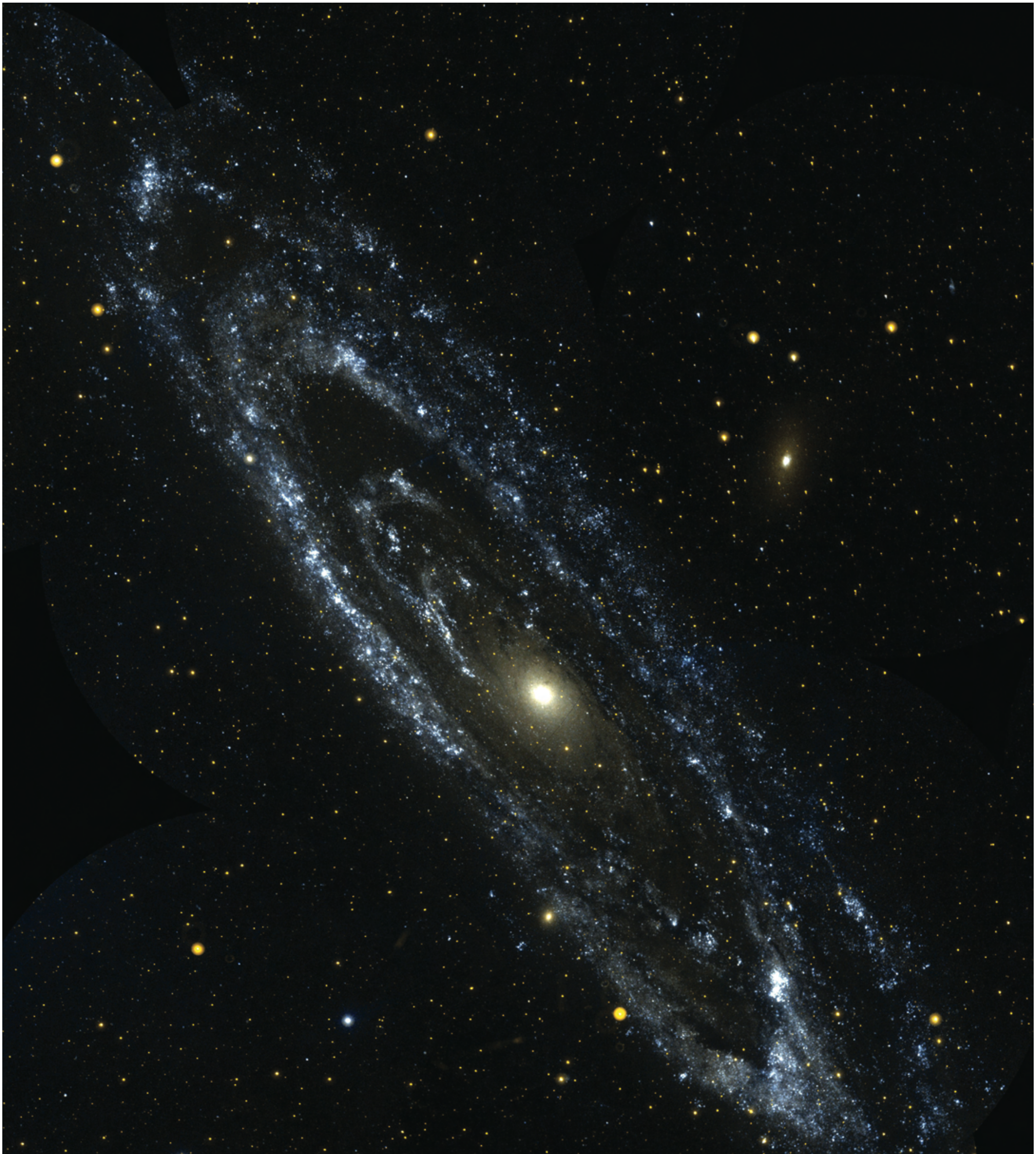

The Great Andromeda Nebula, a vast collection of stars some 2 million light years away. Although each of the stars in the central core and spiral arms of that faraway galaxy is much like our own star, the Sun, we see most of them blurred together by great distance, and through a speckled foreground of countless other, much nearer stars which belong to own spiral-shaped galaxy, the Milky Way.

AN OVERVIEW

The Stars Around Us

In a world of warmth and light and living things we soon forget that we are surrounded by a vast universe that is cold and dark and deadly dangerous, just beyond our door. On a starry night, when we look out into the darkness that lies around us, the view can be misleading in yet another way: for the brightness and sheer number of stars, and their chance groupings into familiar constellations, make them seem much nearer to each other, and to us, than in truth they are. And every one of them— each twinkling, like a diamond in the sky—is a white-hot sun, much like our own.

The nearest stars in our own galaxy—the Milky Way—are more than a million times farther away from us than our star, the Sun. We could make a telephone call to the Moon and expect to wait but a few seconds between pieces of a conversation, or but a few hours in calling any planet in our solar system. But one placed to the nearest star would impose a mandatory wait of almost nine years between a question asked and the answer received. And though the radio waves that carry our phone messages travel at the unimaginable speed of 670 million miles per hour, calls placed to the celestial area codes of most of the other stars in the sky would exact truly big-time roaming charges, with conversational exchanges separated by unavoidable pauses of hundreds to thousands to millions of years.

Yet these vast and lonely reaches of interstellar space are neither vacant nor ever still. There are about 30 atoms—mostly hydrogen and helium—in each cubic foot of interstellar (or interplanetary) space, and many more than this in the vicinity of the Sun and the planets. In addition, there are also occasional molecules and dust grains. Moreover, were we to look closely at any sampled volume, however small and wherever it is, we would find it heavily trafficked: continually crossed and criss-crossed by high-speed, atomic particles from the Sun or the cosmos that are ever passing through.

Many of these itinerant transients are the accelerated protons and electrons and atomic nuclei that are flung outward continually into space from the overheated atmospheres of our own Sun and countless other stars: the omnipresent effluent

Technical or semi-technical words introduced in the text are printed in blue generally where they first appear in the text. They are then defined in alphabetical order in the Glossary, starting on page 263.

of solar and stellar winds. Others—the so-called cosmic rays, which are often more energetic and hence more lethal—are atomic particles of the same kinds that were expelled much more forcefully from catastrophic stellar and galactic explosions of long ago and far away.

Our Dependence on the Sun

The Earth, warmed and illumined by a benign and nearby star—and insulated and protected from a surrounding environment that is entirely hostile to life—remains a most unusual island in the middle of a dark and stormy sea.

Life itself is possible only because of the Sun and our nearness to this strong and unfailing source of light and heat and energy. From it, and for free, we receive in endless supply not only light and heat, but a steady stream of countless other gifts and essentials. Among them are the blue of the sky, the clouds, rain and snow, trees and flowers and tumbling streams, the replenishment of the oxygen we breathe, and all of the food we eat.

The Sun is the source of all the energy that human beings have ever used in burning wood, and in burning coal, oil, gasoline and natural gas: for these fossil fuels are but repositories of solar energy from ages past, captured through photosynthesis in the leaves of plants from long ago. All the energy we derive from wind and water power comes also from the Sun. For it is heat from the Sun that drives the winds, and heat from the Sun that keeps the rivers flowing by evaporating surface water from the seas, to fall again as rain on inland watersheds.

Can there be any wonder that the Sun was so widely revered and sanctified by early peoples everywhere? Or that hymns still sung in churches today so often draw on solar similes?

Break forth o beauteous heavenly Light, and usher in the morning
Come, quickly come, and let Thy glory shine, gilding our
darksome heaven with rays divine

The Sun's Inconstancy

Yet the Sun is neither constant nor entirely beneficent. As a variable, magnetic star, the Sun is ever changing and in many ways: most often through violent explosions and eruptions of colossal scale. The glowing, gaseous surface that appears so perfectly white and still from far away is in reality a roaring, roiling arena of continual conflict and eruption.

Even the sunbeams that stream outward in such bounty are not entirely benign: for with them come solar gamma rays, x-rays, ultraviolet radiation, and highly energetic atomic particles, all of which are potentially lethal for living things. Were it not for shielding by ozone, atomic oxygen and nitrogen in the upper atmosphere—and the armor of the arching lines of force of the Earth's magnetic field—damaging short-wave radiation and atomic particles from the Sun would have long ago extinguished life on Earth. Sunlight allowed life to take hold on the planet, but it is these invisible shields, high above our heads, that have permitted it to continue and evolve.

Most of the Sun's short-wave radiation is kept from reaching the surface of the Earth and the oceans: absorbed by atoms and molecules of air as it streams downward through the atmosphere. The absorbers of gamma rays and x-rays and far ultraviolet radiation are chiefly atoms and molecules of oxygen and nitrogen that populate the thin and highly rarefied air in the upper atmosphere, as far as 100 miles above the surface.

But the bulk of the Sun's damaging ultraviolet radiation gets through these first lines of defense and penetrates further, until with as little as five miles to go before it reaches the surface, it is finally stopped. There in the stratosphere and upper troposphere, it is largely absorbed and blocked by molecules of ozone: a trace gas present in so meager a supply that were all of it compressed to the density of ordinary air at the surface of the Earth it would be much thinner than a window pane.

The recurring streams of atomic *particles* that flow continually outward in heated winds from the Sun—or in violent bursts when parts of the Sun erupt and explode—are blocked by other means. Incoming atomic particles, regardless of their electrical charge, are fast depleted in number by repeated collisions with atoms and molecules in the air, from the moment they enter the Earth's atmosphere.

Most of those that carry a + or – electric charge—including protons and electrons and ions of helium and lithium and boron and almost all the other elements—are repelled or captured before they can enter the upper atmosphere of the Earth. In this case the shielding—which is most protective at lower latitudes—is provided by the arched lines of magnetic force that tower high above the surface of the planet, and all around it, providing a wrap-around magnetic bumper, rooted in the planet's internal magnetic field. Undeterred by this magnetic barrier are high-energy galactic cosmic rays, whose energies per particle are so great that they pass right through it and on down into the upper atmosphere.

Intruders From Afar

Interstellar particles from a host of other, more distant stars also thread the solar system, as do the considerably more energetic particles that arrive as cosmic rays from unseen stellar and galactic explosions elsewhere in the universe. Charged galactic cosmic rays of sufficient energy per particle can overpower the defenses of our own magnetosphere to spend their prodigious energies in collisions with atoms and molecules of air in the upper atmosphere. Many of these, however, are repulsed by the Sun before they reach the near vicinity of the Earth, as though shooed away by a protective mother hen.

The degree of cosmic ray protection we receive from the Sun depends upon magnetic conditions on the surface of the star, which wax and wane in a cycle of about eleven years. In the peak years of the cycle, when the extended realm of the Sun (the heliosphere) is more disturbed, more alien particles are turned away. In the valley years, at the minima of the solar cycle, there are fewer disturbances in the heliosphere, and more cosmic rays intrude into the solar system.

The last maximum of solar activity was reached in 2001. Today, as solar activity has fallen to an apparent minimum in the 11-year cycle, the traffic of galactic cosmic rays in the near-Earth environment is especially heavy. A few years from now, when solar activity begins another climb—toward an expected sunspot maximum in about 2013—the number of cosmic rays that reach the Earth will again be diminished by about 15 percent.

What Gets By

Neither the magnetosphere nor the atmosphere is 100% successful in blocking all that the Sun (or other more distant sources) sends in our direction. Usable heat and light are allowed to pass, almost unchecked, as we would have them do. As noted below, some of the Sun's ultraviolet radiation, though depleted, also makes its way to the ground.

Some of the charged solar particles that approach the Earth still find their way into the upper atmosphere and magnetosphere. Most are caught and temporarily stored within closed field lines of the Earth's magnetic field, but these, too can work their way, in time, into the upper atmosphere.

When these and other energetic particles collide with atoms of air about 100 miles above the surface, they provoke atoms of oxygen and nitrogen and certain molecules to emit light in pure colors of green or red or blue. When conditions are right, we can witness the intrusion of these escapees from either the Sun or the Earth's magnetospheric holding cell as brightly painted streaks of light in the northern and southern sky: the transitory and ethereal displays of the aurora borealis and aurora australis.

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Nor are all the harmful rays of sunlight blocked from reaching the ground. A fraction of the damaging solar ultraviolet radiation that pours down unremittingly on the dayside of the Earth slips by the stratospheric ozone shield, to continue downward as potentially-damaging, shorter-wavelength UV-A and UV-B radiation.

The number of UV-A and UV-B rays that make it to the surface of the Earth depends on the variable thickness and density of the stratospheric ozone layer; on the distance the ultraviolet rays must travel through the remaining air that lies beneath it; and on the clarity of the sky. It depends as well on how much the Sun itself has generated, for solar ultraviolet radiation varies from day to day and year to year, in step with changes on the surface of the Sun. But on any day, a much greater fraction of damaging solar ultraviolet rays will reach the ground (1) at high elevations (as in the Rocky Mountain west); (2) where the Sun most often shines (as in southern Arizona); and (3) at lower latitudes (as in Florida, Hawaii, or Australia) where sunlight passes more vertically through the air and hence along a shorter path to reach the surface.

Voyages of Discovery in an Age of Exploration

The story of how we came to know all that happens just beyond the protective walls of our atmosphere and magnetosphere is a tale of recent exploration. As is that of how the near-Earth environment, and the walls themselves, are shaped and battered by a highly variable Sun. While much had been learned about both the Sun and the Earth, the space between them was, before the second half of the last century, largely *terra incognita*: a void sketched in with theory and supposition, much like the early maps of the known world that were drawn before the epic voyages of Columbus and Magellan.

Although rocket-launched probes had briefly sampled the nearer reaches of the upper atmosphere in the late 1940s, it was about the time when NASA was established, in 1958, that longer and farther voyages of exploration at last began.

The first of these were lofted into low-Earth orbits but several hundred miles above the ground, to circle the planet at the ragged upper edges of our atmosphere. Here only the last vestiges of air remain; the sky is no longer blue; and the atmospheric pressure is reduced to less than a millionth of a millionth of what we are accustomed to at the surface of the planet.

Others ventured further, into and beyond the Earth's extended magnetosphere, charting for the first time its form and content and asymmetry. Immediately encountered in these early explorations were the Earth's radiation belts: largely unexpected swarms of captured electrons and protons and other charged particles, entrapped by the Earth's magnetic field and held there, as in a magnetic cage.

The shape of the Earth's magnetic field was found to be not the simple curved lines of force like those traced out by iron filings above the poles of a bar magnet, but a dynamic, distorted and distended structure: compressed flat on the Sun-facing side by the persistent pressure of the solar wind, and stretched out by the solar wind on the other side to well beyond the orbit of the Moon.

Further explorations into near-Earth space identified, at last, the solar sources and ensuing chain of events responsible for the disturbances, called geomagnetic storms, that had been detected and recorded by magnetic instrumentation on the surface of the Earth since the middle 1800s.

Polar aurorae—the occasional displays of colored light in the nighttime sky that had been described in lore and legend for at least 2000 years—were seen in their entirety from the vantage point of space. Observed from above, what had appeared from below as curtains of colored light were revealed in their entirety as full rings of varying diameter, centered on the Earth's magnetic poles.

There, much like a pair of neon signs, glowing circles of light define the zones near the two poles of the planet where electrons and protons most easily find their way down into the Earth's upper atmosphere. And there—hundreds of miles high—they spend their energies in aerial collisions with atoms of oxygen and nitrogen. Some of these energetic particles come directly into the atmosphere from the Sun; others from a cache of stored particles—some captured earlier from the Sun, others from our own ionosphere—that are sequestered in the Earth's magnetotail.

A New Appreciation

In these voyages of discovery much was learned of the true nature of the Sun, the real character of the near-Earth environment, and the form and functions of the magnetosphere and the upper and middle atmosphere. But the truly New World that was found in all these explorations was surely that of the winds of charged particles that blow outward without respite from the Sun, in all directions, including our own. At times these blow but briskly. At others, they come far faster, driven by Krakatoan eruptions on the Sun that tear whole parts of the star away and send them hurtling through the realm of the planets.

The principal legacies of this new age of discovery are a better definition and more enlightened awareness of the very real effects of solar variations on the planet on which we dwell: the realities that accompany the benefits of living with a star. We suspected that the Sun's total radiation varied: we now know it does and by how much. And we have found that near-Earth space—just beyond our door—is a place of tempestuous and often violent weather: not the familiar weather of wind and rain and sleet and snow, but the space weather of variable solar radiation, streams of energetic atomic particles and imbedded magnetic fields, driven by the volatile moods of a near-by star.

The Consequences

Among the down-to-Earth consequences of an inconstant Sun are the impacts of known or suspected variations in the Sun's output of radiation and particles on the climate of the Earth, and the effects of these changes in enhancing or ameliorating the present global heating which is driven principally by increasing greenhouse gases.

As important—societally, economically, and in terms of national security—are the impacts of solar storms and eruptions on communications of all kinds, from telephone to television; on navigational and other geographic positioning systems; on the health and safety of passengers and crews in high-altitude jet-aircraft flights that cross polar and sub-polar regions; on the operation and integrity of electric power grids; on electronic devices of all kinds carried on civil and military spacecraft; and on the safety of astronauts.

What is more and more apparent is that with technological advances and greater sophistication in much of what we do, we lean more and more heavily on systems that are exposed and vulnerable to changes on the Sun and in the near environment of the Earth. Particularly vulnerable are manned space flights, and most particularly those that venture beyond the protective shields of the Earth's atmosphere and magnetosphere; as on envisioned voyages to distant Mars, on shorter travels to and from the Moon, and in connection with the inhabited lunar colony that is now in early planning stages.

Truly essential in all of these impacted areas of everyday life and space exploration is the ability to forecast space weather, day by day and in advance, tailored to specific needs. The accuracy and utility of such forecasts lean heavily on two essentials: (1) a thorough knowledge of the Sun-Earth system; and (2) the availability of an ongoing stream of round-the-clock space weather data.

To meet this challenge, some twenty-six spacecraft are today in orbit around the Earth or the Sun—or on further voyages of discovery, far from home—to explore, patrol and monitor the complex, coupled Sun-Earth system. Their purpose is to track, understand and ultimately predict the major changes on the Sun and in near-Earth space that affect space weather and human endeavor. Together, they make up an ongoing fleet of modern spacecraft, designed and operated to complement each other, and to work together as an ongoing System Observatory in near-Earth space.

An Interconnected System

Our knowledge of the Sun-Earth System has been acquired through the years on a piece-by-piece basis, through the efforts of generations of men and women in many countries. But in these early efforts, the focus was most often on the exploration and study of isolated parts of the larger whole: the Sun, the Earth's magnetosphere, ionosphere or upper atmosphere, and ultimately, with the Age of Space, the nature and dynamics of the interplanetary medium that fills the void between the Earth and its distant Sun.

With new understanding came specialization and ultimately the emergence of whole new fields of study including solar physics, aeronomy, atmospheric physics and chemistry, and space, cosmic ray, magnetospheric, and ionospheric physics. But as was always known, these are all connected together, like links in a chain.

Advances made in recent years regarding the essential interdependence of these elements of the chain, and the pressing need to forecast the impacts on the modern world of solar-driven changes in this system have called for a more holistic approach. And the emergence of the all-encompassing science of heliophysics: the study of an interconnected system, extending from the soil beneath our feet to the white-hot surface of the Sun, and including all that lies between. The ultimate goal is an analytical working model of the coupled Sun-Earth system: a chain of interacting links that can replicate the impacts of solar events on the Earth and human endeavor.

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The intrinsic interconnectedness of almost everything, including the Earth and all things in it, is a common theme today, though not at all a new one. "Pull up any part of Nature," said John Muir in the early 1900s, "and you will find its roots entangled with all the rest."

The same truth may have been expressed most eloquently a few years earlier by the mystic poet Francis Thompson, in London, in 1893:

All things by immortal power, near or far,
hiddenly, to each other linkéd are;
that thou canst not stir a flower
without troubling of a star.

We know as well, today, that what happens on our own star—93 million miles away—can perturb the Earth and trouble our own lives and well-being.