The Sun Also Warms

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Recent discoveries that shed light on the possible influence of the Sun on the climate of the Earth owe to experiments and instruments born of high technology and launched into space. They have provided us with new ideas about the nature of changes in Sun's light, its charged particle emissions, and how they both affect the Earth.

Changes of the Sun's light and particles interact in many different ways with the Earth's environment that extends outward to the near space surrounding Earth. The latest surprising developments in the study of the Sun-climate connection suggest that the Sun notably influences the temperature of the Earth, through both changes in the Sun's light and its wind of charged-particles.

Dynamic Sun - At the 15 million-degree K heart of the Sun, sunlight is created by nuclear fusion of hydrogen into helium. This process should continue fairly steadily for the next and last 5 billion years of the Sun's 10-billion year hydrogen-fusing phase. But in the outer shell of the Sun, about one-third its radius deep, a remarkable process occurs. The shifting motions of hot gas just below the surface twist the magnetic field there. The twisted magnetic field rises to the surface of the Sun, where it appears in features like sunspots (Figure 1). They are small regions on the surface of the Sun that are about 2000 K cooler, and so appear darker in contrast, than the surrounding quiet Sun. Sunspots are threads of intense magnetic fields, up to 10,000 times stronger than the Earth's magnetic field that pulls at a compass needle. The number of sunspots seen on the surface of the Sun, hence, the Sun's total surface magnetism, varies with a periodicity of approximately 11 years (Figure 2).

The Sun's surface magnetic field also changes on many other time scales - from as short as seconds to billions of years. The Sun's changing magnetism has several consequences, some only recently learned. For example, the surprise of the last 20 years is the observed fact that the total light, or brightness, of the Sun also changes in step with the magnetic cycle. That means the Sun is a variable star brightening and fading in light every 11 years. The Sun brightens when the magnetism strengthens, e.g., at the peak of the 11-year sunspot cycle.

Along with the better-known changes in magnetism and light of the Sun occur variations in the streams of charge particles flowing from the Sun. The charged particles, or ions, are fast-moving protons and electrons - the constituents of atoms. Recall that if an apple were magnified to the size of the Earth, the atoms of the apple would then be the size of an actual apple. If an atom were magnified to the size of a large lecture room, the nucleus of an atom, or a proton in the case of a hydrogen atom, would be smaller than the period at the end of this sentence.

But as tiny as the ions are, they travel at speeds of 500 km/sec (about 1 million miles per hour), fill the solar system and interact with the matter in it. Some particles hit and modify the atmosphere of the Earth, and can cause beautiful and benign phenomena like aurorae. More serious consequences of the Sun's varying wind of ions to a young space-faring civilization are changes in the upper air, causing satellite orbits to drift or erode, or damaging satellite electronics and interrupting operations.

Figure 3 shows other examples of the Sun's magnetic phenomena. The bright splashes on the image represent gas in the outer atmosphere of the Sun called the corona at a temperature of two million degrees K.

The closed magnetic loop regions are heated by the magnetic field to high temperature. Sunspots are hidden beneath the loops of magnetic field that thread up from the surface, rise into the Sun's outer atmosphere and arch downward to be anchored again below the surface. In contrast, coronal holes are areas of open magnetic field where particles stream away from the Sun at high speed. Both the coronal holes (open magnetic areas) and sunspots (closed areas) vary in surface coverage every 11 years, but opposite because the closed or open magnetic fields tend to crowd each other out. That is, when sunspots are numerous the surface area covered with coronal holes is small and as sunspots decline in number the area coverage by coronal holes expands.

Sun's brightness change and global climate change - Observations of the Sun's change in total light made by NASA satellites since 1978 show that the Sun brightens and fades in its total energy output in step with the 11-year magnetic cycle. The amplitude of brightness change over a cycle seems too small to cause significant global temperature change on Earth.[2] But hypothetical brightness changes of a few tenths percent sustained over decades, longer than the Sun has been observed by satellite, could drive terrestrial temperature to change significantly. That would be the simplest way for the Sun to cause global climate change.

The climate record indicates a solar influence of this kind. An example is the record of the Sun's magnetism, which is a proxy for solar brightness change, whose direct measurements extend back only to 1978, and reconstructed land temperatures of the Northern Hemisphere over 250 years (Figure 4). The two curves are highly correlated over several centuries.[3] Those changes in the Sun's magnetism are presumed to indicate changes in the Sun's brightness.

Assuming that the Sun's magnetic change represents the Sun's changing brightness, [4] computer simulations [5] of the climate suggest that an increase of no more than 0.5% in the Sun's brightness could produce observed global average temperature changes of about 0.5 C over the last 100 years. How believable is a brightness change of the Sun of 0.5% over 100 years? An independent estimate has been made through a unique program of observations of surface magnetism and brightness changes in sunlike stars - those close in mass and age to the Sun. An analysis of those data yields an estimate of brightness change as large as several tenths per cent over decades. That is similar to the change inferred for the Sun for several decades to centuries.[6]

Additional evidence points to the Sun's signature in the climate record over millennia. Every few centuries the Sun's magnetism weakens to low levels that sustain for several decades. An example is the magnetic low from ca. 1640 - 1720, called the Maunder Minimum, when sunspots were rarely seen (see Figure 2). The Maunder Minimum occurred within a several-centuries-long period of relatively cool temperatures and severe climate called the Little Ice Age.

Records of the Sun's magnetism over millennia reveal that the Maunder Minimum is not unusual. Periods of low solar magnetism appear approximately every several centuries. Long records of the Sun's magnetism are based on measurements of the isotopes radiocarbon, 14C, from tree growth rings and 10Be from ice cores. Why do the isotope records contain information on magnetic changes of the Sun? Begin with the fact that those isotopes are produced in the air by cosmic rays. Cosmic rays are energetic particles traveling through the Galaxy near the speed of light. The amount of cosmic rays hitting the Earth's atmosphere, hence the amount of 14C and 10Be formed, is modulated by changes in the Sun's magnetism. In the air, 14C may combine with oxygen to form a carbon dioxide molecule and be incorporated in a tree growth ring through photosynthesis; 10Be may precipitate into an ice layer of the ice sheets at high latitudes.

The isotope records indicate that the Sun's magnetism of the 17th century was low then and for every few centuries before that, with occasional prevailing magnetic maxima. During periods of weak magnetism, the Sun should dim compared to the average or magnetically high intervals, when the Sun should brighten.

Tree growth records from Scandinavia and ice core records from Greenland covering the last 10,000 years show that 17 out of 19 coolings line up with lows in the Sun's magnetism.[7]

Charged particle flows and climate change - The simple idea of the changing total light of the Sun as an influence on the Earth's climate is incomplete. As mentioned, not only the light and magnetic field of the Sun but also the flow of charged particles hitting the Earth's atmosphere varies every 11 years, and probably on longer time scales.

Figure 5 shows a possible link between the effects of the Sun's charged particles hitting the Earth's atmosphere and the Earth's temperature. The temperature of the lower troposphere measured by Microwave Sounder Units (MSUs) aboard NOAA-NASA satellites has been recorded since 1979.[8] Along with the MSU temperature curve is plotted the changing area of the Sun covered by the coronal holes the open magnetic field regions, from which high-speed particles flow. The changing flow of high-speed particles from the Sun, represented by the increase and decrease of the Sun's surface area covered by coronal holes, corresponds well with the warming and cooling of the lower troposphere.

Four things should be noted: First, the two curves disagree at several times. Much of the disagreement is caused by internal changes of the climate, for example, the occurrence of large volcanic eruptions (Mt. Pinatubo caused a large cooling beginning around June 1991), and El Niño warmings (1997-98) and La Niña coolings (1988-89). Second, note that an 11-year variation in tropospheric temperature, which we argue is a signature of solar change, has an amplitude comparable to that of the El Niño and La Niña events.

Third, the curve of changing area covered by coronal holes is inverted. That means that at times of highest particle flows from the Sun, the troposphere is coolest. That fact leads to a possible explanation of this correlation, described below.

Fourth, a source of charged particles besides the Sun is the Galaxy. The skeletons of many dead massive stars thread the Galaxy. A massive star ends its brief life in an energetic supernova explosion (Figure 6). During a supernova explosion, a star brightens by a factor of 100 million in a fraction of a second, temporarily outshining the combined light of all the 100 billion stars in the Galaxy. The terrific energies of the Galaxy-wide rain of cosmic rays owe to a continuing series of supernova explosions that started early in the Galaxy's life some 15 billion years ago.

The maelstrom of cosmic rays helps make the near-space environment of Earth a malebolge modulated by the Sun's varying magnetic field. The flux of cosmic rays peaks when the Sun's overall magnetic field is weak - i.e., at the same time the flow of fast particles from the coronal holes reaches maximum strength. At present there is no way to distinguish which source of extraterrestrial ions - either the Sun or the Galaxy - explains the correlation with lower tropospheric temperature. Perhaps both the Sun and Galaxy contribute to changing the tropospheric temperature.

Two physical effects may explain the correlation. First, an increase in the wind of particles - either from the Sun or Galaxy - temporarily raises the propensity to form terrestrial clouds and so increases the Earth's cloud coverage. Depending on the type of cloud formed, the air temperature may vary in response.

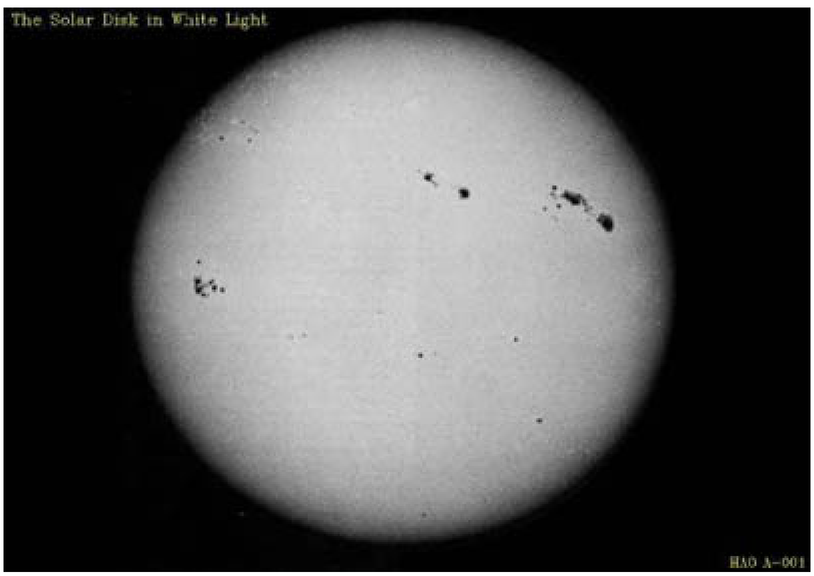
Can empirical support be found for that idea? First, satellites have measured the changing cloud coverage of Earth for clouds grouped by altitude: high clouds (above 7 km), middle clouds (3-7 km), and low clouds (below 3 km). The records of cloud coverage are shown in Figure 7 along with an estimate of the cosmic ray flux hitting the atmosphere. Surprisingly, a good correlation is seen for cosmic ray flux and changing cloud coverage[9], but only for low clouds.[10] At times of low solar magnetism the cosmic ray flux increases, and the coverage by low clouds expands. Exactly how that correlation between cosmic ray flux and cloud cover would relate to lower tropospheric temperature changes is still puzzling. Matters under serious study include the type of cloud being modulated and the aspect of the theory of clouds that would link cloud cover variations to tropospheric temperature change.

Independent support for a link between changes in cosmic rays and clouds comes from further out in the solar system. There the planet Neptune brightens and fades every 11 years.[11] Neptune's whitish methane clouds either brighten or increase in surface coverage when the cosmic ray flux is intense, because those are the times when the Sun's magnetic field is weak.[12]

An alternate, or additional explanation for the correlation between extraterrestrial charged particle fluxes and the temperature of the lower-troposphere is that the varying flux of ions, modulated by the Sun's changing magnetic fields, may affect the chemistry and dynamics of the stratosphere (especially nitrogen oxide and nitrogen dioxide [NO, NO2] and ozone). In turn, those stratospheric changes may impact the air currents and temperature of the troposphere below.

Implications - Understanding of the possible effects of the changing Sun on climate change is still evolving. [13] The idea that the total energy output of the Sun changes is one of the simplest mechanism for the Sun's possible effect on climate change. However, the Sun's output comes in many wavelengths. The Sun also emits energetic ions. Both types of output vary in time, space and frequency. The components of the Earth's atmosphere and surface respond differently to the many aspects of the Sun's diverse energy outflows, possibly in ways that are yet unknown. But the characteristic signature of the Sun's variability from years to centuries is present in some climate data, especially as revealed by new instruments in space. Understanding natural factors of climate variability, like the variable Sun, is key to studying the impacts of human dimensions of climate change.

Figures



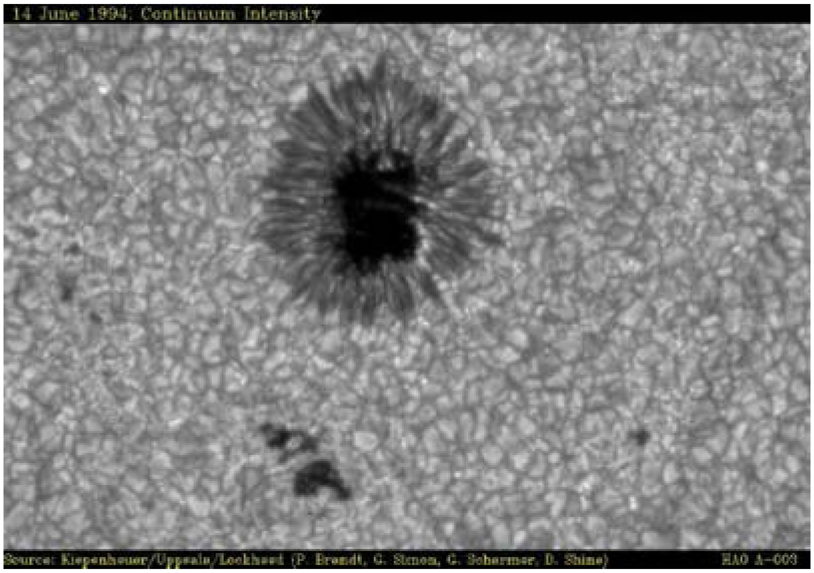


Figure 1 – Sunspots dot the gaseous disk of the sun in white light (upper panel). An individual sunspot, an area of strong magnetic field, seen close up (lower panel) has a dark, inner portion, called the umbra. For this sunspot the Earth world barely cover the umbra. The gas of the surrounding quite Sun, nearly absent of strong magnetic field, is mottled with a pattern of fluid motion called granulation. (Images courtesy of P.Charbonneau and O. R. White at High Altitude Observatory, www.hao.ucar.edu/public/slides).

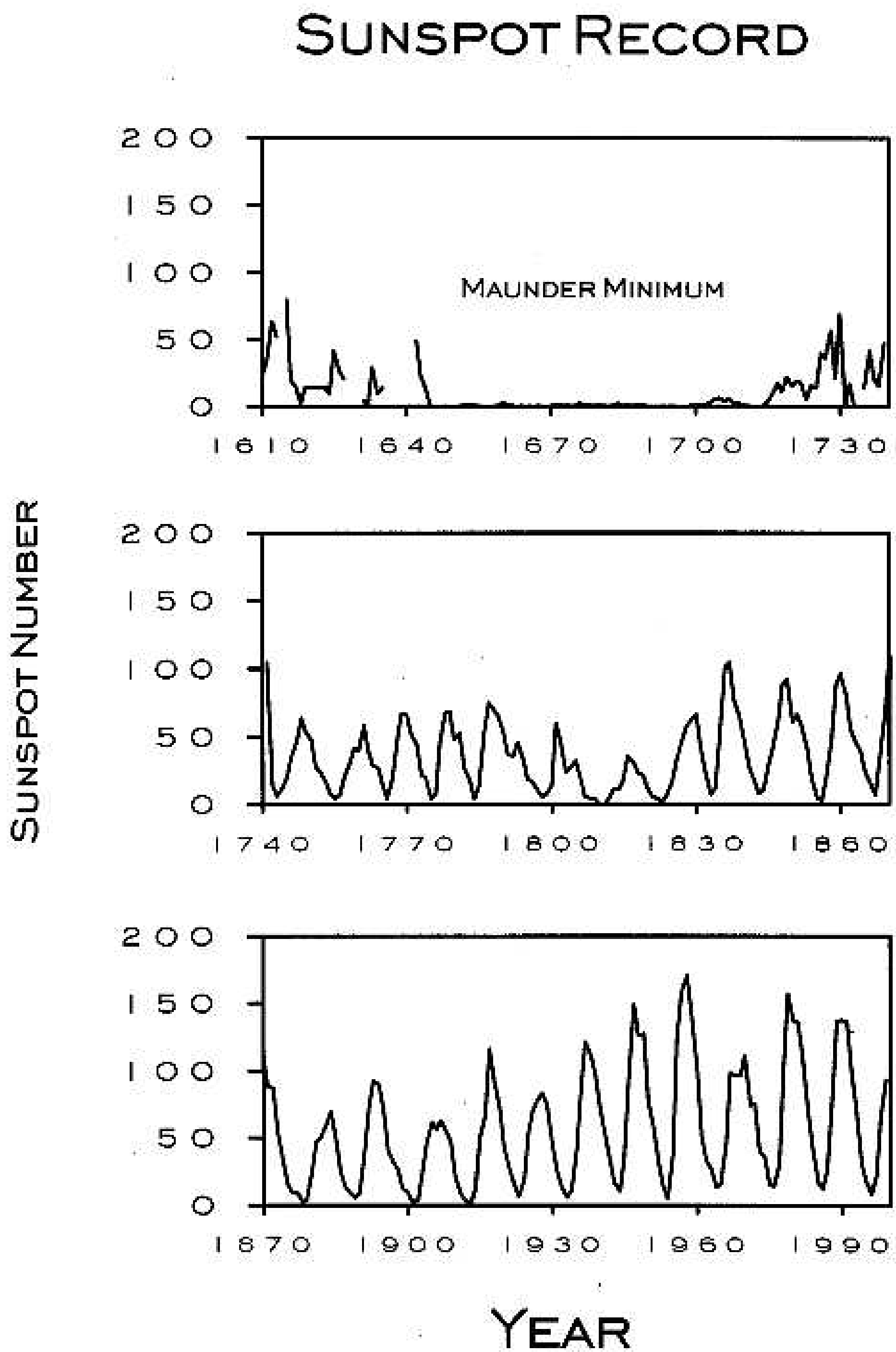


Figure 2 – The record of annually-averaged sunspot number. Note the approximate 11-year cycle in the Sun's surface magnetism and the magnetic low period when sunspots were rare, ca. 1640-1720, called the Maunder Minimum.

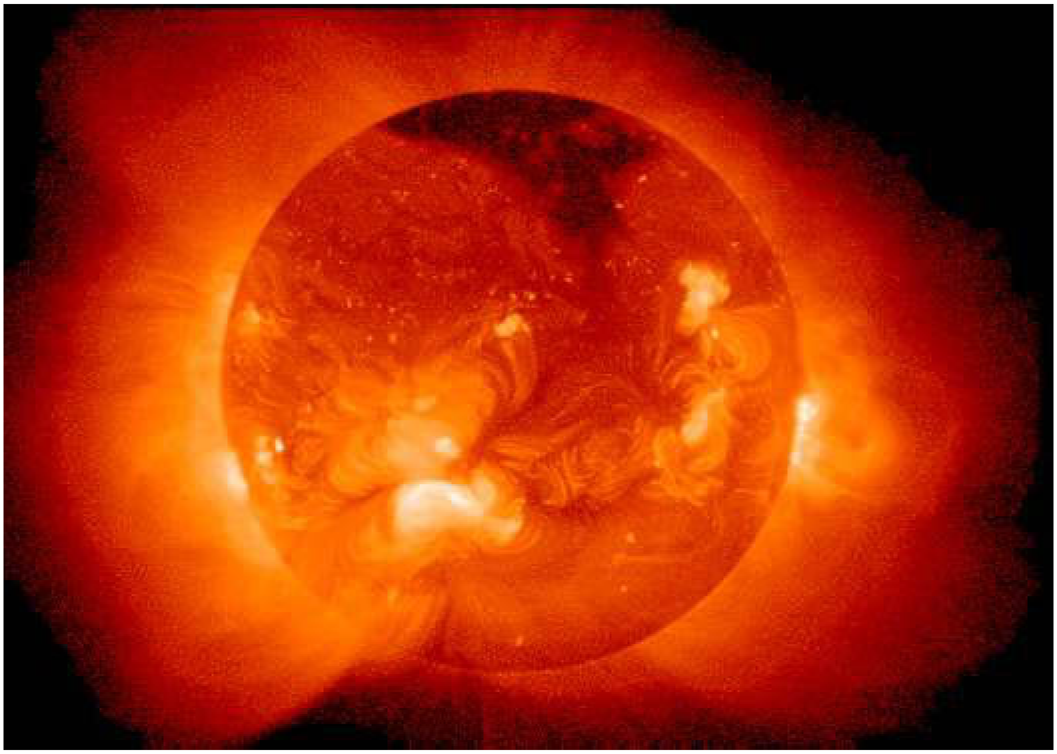


Figure 3 – An image of the Sun taken in soft x-ray wavelengths on May 8, 1992 by the YOHKOH satellite. The bright features indicate gas at several million degrees K in the hot, rarefied gas of the outer layer of the Sun called the corona. Darker areas, especially near the poles, are called coronal holes. In them, the opened shape of the magnetic field allows the heated gas to stream into the solar system (image courtesy of YOHKOH Archive Center).

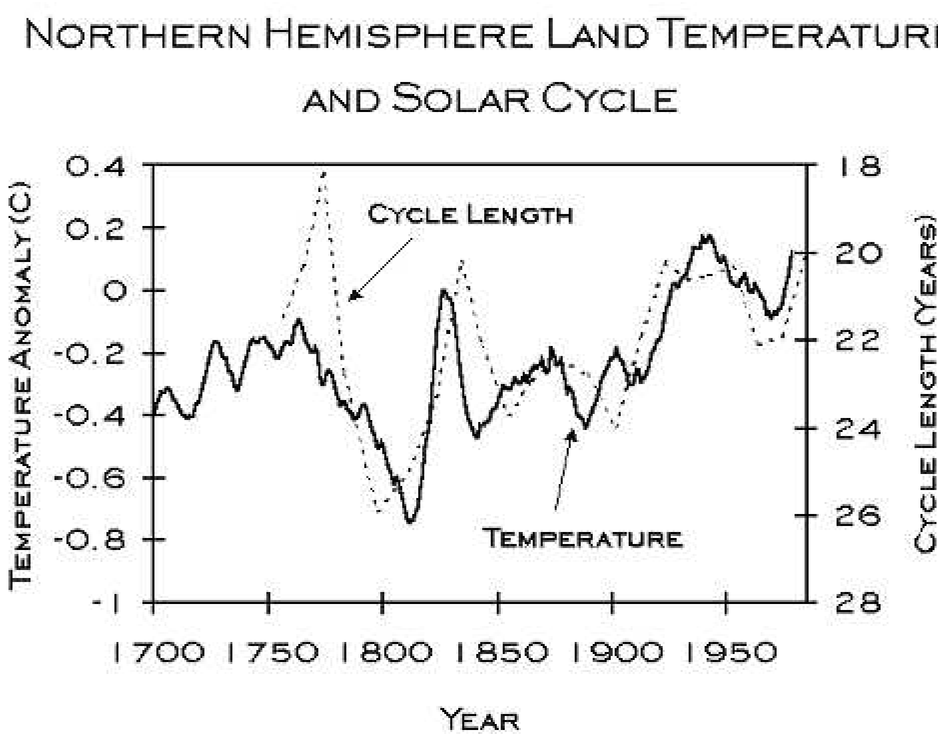


Figure 4 – Changes in the Sun's magnetism (the length of the 22-year, or polarity cycle, dotted line) and changes in Northern Hemisphere land temperatures (solid line). Shorter magnetic cycles are more intense, which suggests a brighter Sun (Baliunas and Soon 1995).

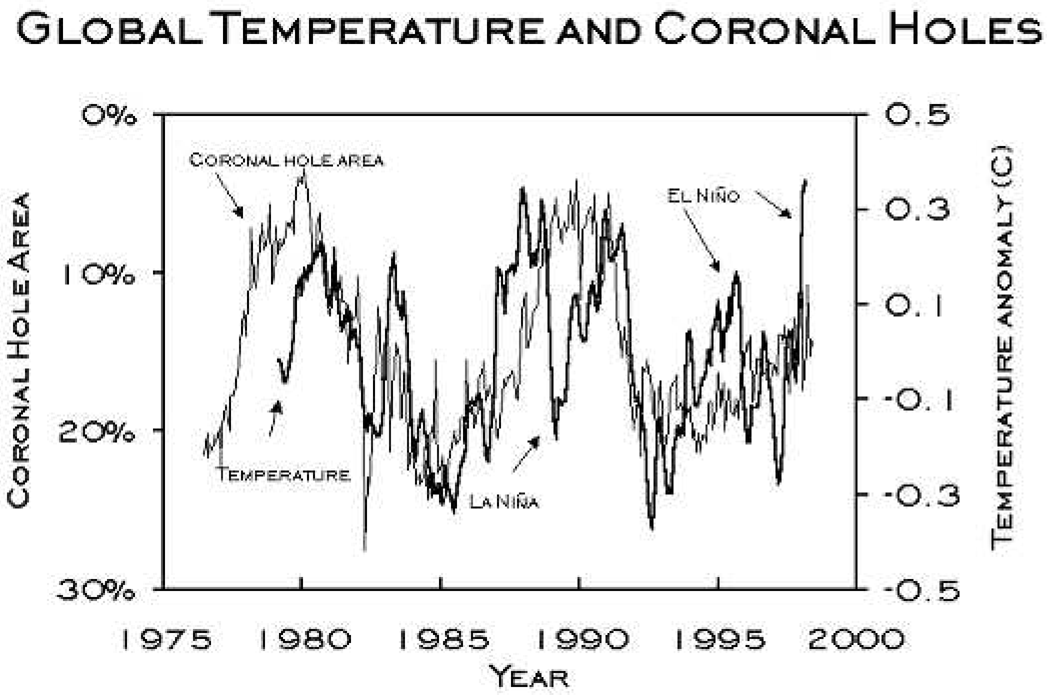


Figure 5 – The percent of the Sun's surface area covered by coronal holes (regions of open magnetic field carrying fast-moving charged particles from the Sun) and the globally-averaged satellite temperature record of the lower troposphere. The two curves are strongly correlated, except when internal changes of the Earth's climate are present, e.g., strong El Niño events or volcanic eruptions, as labeled. The cause of the 11-year modulation in the temperature record may be either fast particles from the Sun or high-energy cosmic rays from the Galaxy or both.

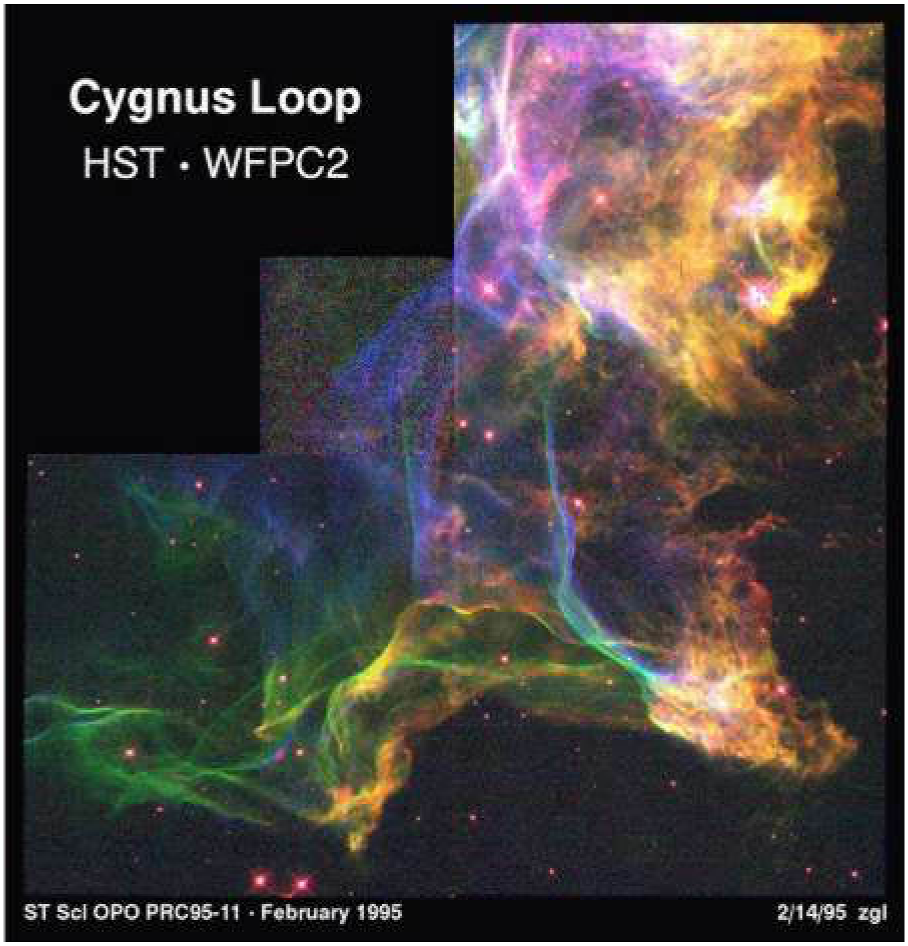


Figure 6 – The source of cosmic rays that hit the Earth is the supernovae scattered throughout the Galaxy. One example is a star in the direction of the constellation Cygnus 2,500 light years away exploded 15,000 years ago. This image from Hubble Space Telescope shows a segment of the remnant gas and dust. The shockwave of the explosion travels at 40 million miles per hour and interacts with surrounding matter to make cosmic rays that move nearly at the speed of light. (Image courtesy of Space Telescope Science Institute operated by AURA/STScI).

Sun-Galaxy-Climate Link?

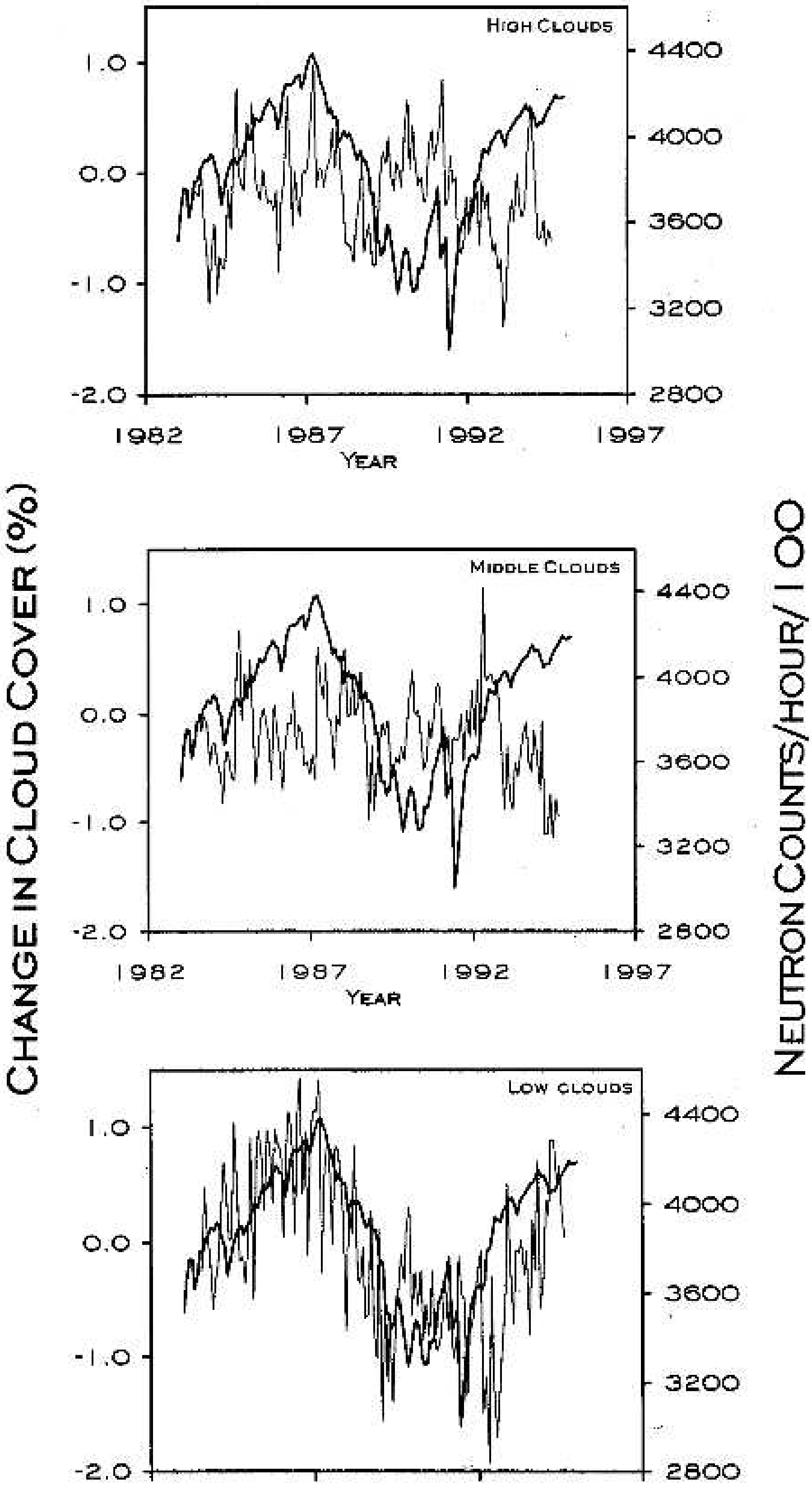


Figure 7 – The percent change in cloud cover of the Earth measured by the International Satellite Cloud Climatology Project (ISCCP) satellite for high (top panel), middle (middle panel), and low (bottom panel) clouds is plotted with the neutron flux measured on Earth.[14] The neutron flux is a proxy of the cosmic ray flux in the atmosphere because cosmic rays hit the Earth's air molecules and make neutrons. The flux of cosmic rays, and hence, neutrons, is modulated by the Sun's 11-year magnetic cycle. A strong correlation is seen only for low clouds. (This updated figure was first shown by E. Friis-Christensen [through his personal communication with N. Marsh and H. Svensmark] in a March 6, 2000 NASA Sun-Climate Research Workshop in Tucson, Arizona.)

Notes

[1] R. P. Feynman, R. B. Leighton, and M. Sands, 1966, The Feynman Lectures on Physics, Vol. 1.

[2] Over the cycle, the full range of brightness change is at most 0.14%. Such changes seem insufficient in amplitude and time scale to cause a temperature response of the climate system that is larger than 0.1 C over the period of observations.

[3] Northern Hemisphere land temperatures (from B. S. Groveman and H. E. Landsberg 1979, Geophysical Research Letters, 6, 767; P. D. Jones et al. 1986, Journal of Climate and Applied Meteorology, 25, 161) are shown because the global surface records do not reach back so far (S. Baliunas and W. H. Soon, 1995, Astrophysical Journal, 450, 896); first reported in a shorter temperature record by E. Friis-Christensen and K. Lassen 1991, Science, 254, 698; K. Lassen and E. Friis-Christensen, 1995, Journal of Atmospheric and Terrestrial Physics, 57, 835).

[4] It assumes that one knows the mechanism of solar change (i.e., total brightness), and the response of the climate to such change. Neither is known! Some wavelengths of sunlight may be more important than others in affecting the climate. For example, the solar ultraviolet irradiance may make changes in the chemistry in the stratosphere and troposphere (J. D. Haigh, 1996, Science, 272, 981); visible-wavelength irradiance changes may affect the lower atmosphere and sea surface (W. B. White, J. Lean, D. R. Cayan and M. D. Dettinger, 1997, Journal of Geophysical Research, 102, 3255). Both portions of the solar irradiance spectrum may combine to influence the dynamics of planetary-scale waves and Hadley circulation. In addition, brightness changes have been considered here independent of wavelength. Then, too, the Sun's surface magnetism and wind modulate the galactic cosmic rays impinging on the geomagnetic field, and so the electrical (B. A. Tinsley, 1997, Eos, 78, No. 33, 341) and chemical (J. W. Chamberlain, 1977, Journal of Atmospheric Science, 34, 737) properties of the upper atmosphere. In turn, cloud microphysics and cloud coverage may change (H. Svensmark & E. Friis-Christensen 1997, Journal of Atmospheric & Terrestrial Physics, 59, 1225). See also W. Soon et al., 2000, New Astronomy, 4, 573.

[5] Further details can be found in E. Posmentier (1994, Nonlinear Processes in Geophysics, 1, 26) and W. H. Soon et al. (1996, Astrophysical Journal, 472, 891); the latter contains a diagnostic comparison of the model results to the observations.

[6] S. L. Baliunas and W. H. Soon, 1995, Astrophysical Journal, 450, 896. Also, a recent analysis (R. Willson, 1997, Science, 277, 1963) finds a baseline change in irradiance between the solar minima in 1986 and 1996. Over a century, that base change would be about 0.4%.

[7] W. Karlén and J. Kuylenstierna, 1996, Holocene, 6, 359; W. Karlén 1998, Ambio, 27, 270.

[8] The MSU temperature record of J. Christy and R. Spencer is described on the website http://www.ghcc.msfc.nasa.gov/temperature/. The data are available at ftp://wind.atmos.uah.edu/msu.

[9] H. Svensmark and E. Friis-Christansen (1997, Journal of Atmospheric Solar-Terrestrial Physics, 59, 1225)

first demonstrated such an idea. Although several issues remain unresolved (T. S. Jorgensen and A. W. Hansen, 2000, Journal of Atmospheric Solar-Terrestrial Physics 62, 73; and W. Soon et al., 2000, New Astronomy, 4, 563) the updated information here supports the idea of an influence of extra-terrestrial charged particles on terrestrial clouds.

[10] Recall that the flux of cosmic rays, like the flux of fast-moving ions from the Sun, is modulated by the Sun's 11-year cycle of magnetism. Also remember that either cosmic rays or the Sun's ions, may be implicated in cloud changes.

[11] J. I. Moses, M. Allen and Y. L. Yung, 1989, Geophysical Research Letters, 16, 1489; G. W. Lockwood, D. T. Thompson, B. L. Lutz and E. S. Howell, 1991, Astrophysical Journal, 368, 287. See also S. Baliunas and W. Soon, 1998, World Climate Report, 3, (No. 15), 10.

[12] In the case of Neptune, its distance from the Sun means the Sun's influence should be weaker than at the Earth. Neptune's cloud changes may thus owe to changes in cosmic ray flux.

[13] W. Soon et al. 2000, New Astronomy, 4, 563.

[14] Neutron-count data were provided courtesy of C. Lopate; University of Chicago. Cloud data courtesy of G. Campbell, Cooperative Institute for Research in the Atmosphere/Colorado State University (CIRA/CSU).

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