THE HISTORY OF SUNLIGHT

WHAT DOES ASTRONOMY HAVE TO DO WITH GEOLOGY?

Everything. The Earth’s evolution is a sidelight to the Sun’s, and has been ever since the solar system’s formation was triggered by a nearby star’s explosion 4.6 Ga ago. The Earth is a concentration of the heaviest, least volatile products of nuclear fusion in stars. The planet’s operation basically consists of the stellar-powered reprocessing of extinct stars’ relatively rare heavy-element leftovers, some 99.98% of the power now coming from sunlight and virtually all the rest from nuclear and gravitational potential energy laid up by stars that went extinct before the Sun began to shine.

Changes in the Earth’s sunlight dose (i.e. insolation) have been among the most important influences on the planet’s operation and evolution. The second class (“How has the Earth Remained Habitable?”) touched on the single largest, longest-term change: the relatively huge increase in the Sun’s luminosity from 75-80% of its present value in the 4.5 Ga since it first began to shine as a main-sequence star. Here we will see how this increase has come about and how the controlling factor may contribute to the Sun’s variability on shorter time scales.

GETTING ORIENTED

Where Are We in Space? In the Milky Way, one galaxy among millions in the universe, thousands in the Local Supercluster, and tens in the Local Group; in the midst of a wave of star formation on one of this spiral galaxy’s arms, about 30,000 light-years from the galaxy’s center and revolving around it once in about 250 Ma (the so-called galactic year); about 8 light-minutes from a middle-aged star of about average mass.

Where Are We in Time? Roughly 10-15 Ga after the Big Bang, moving outward at about 0.2% of the speed of light; about 4.6 Ga after the formation of the solar system and of our planet.

HOW STARS WORK

Astronomers comparatively study stars at different stages in their evolution to obtain the time perspective necessary for testing astrophysical models of stellar evolution. Our time perspective on the solar system’s early evolution comes mainly from such theories.

---

1 As you remember, Earth scientists find it convenient to denote thousands of years in ka’s (kiloans), millions in Ma’s (megans), and billions in Ga’s (gigans).

2 Better estimates of the age of the universe await astronomers’ resolution of a controversy over two inconsistent measurements of the Hubble Constant, $H_0$, in Hubbles Law, an empirical description of the ongoing expansion of the universe:

$$\text{Galaxy’s Speed Relative to Us} = H_0 \cdot \text{Galaxy’s Distance} \quad (6.1)$$

Recognizing the Distance = Velocity $\times$ Time formula in disguise, one recognizes $H_0$ as one over the apparent age of the universe (i.e. one over the age that the universe would have if it always had been expanding at the present net rate). Until recently, it had been believed that the actual expansion rate must have been decreasing in consequence of galaxies’ mutual gravitational attraction, so that the actual age of the universe would be less than $1/H_0 - (2/3)/H_0$ according to the standard (or Einstein-de Sitter) model. However, in 1998, two independent groups of astrophysicists reported measurements demonstrating that the rate of expansion is slowly increasing — a finding so unexpected, and with such profound implications for fundamental physics, that the editors of Science voted it the Breakthrough of the Year (J. Glanz, Science 282, 2157-2158 (1998)). Cosmologists are still trying to work out how the rules of game have changed for dating the Big Bang.
Stellar Temperature, Luminosity, and Mass — When stars’ absolute luminosities (i.e. a star’s energy emission per unit time; the excitance of the star’s photosphere times the photosphere’s effective area) are plotted against their temperatures as black-body radiators in a Hertzsprung-Russell diagram, most stars fall along a linear trend called the main sequence — a trend that, as explained below, amounts almost literally to Stefan’s Law (Class 2)

\[
\text{Excitance} \propto (\text{Absolute Temperature})^4
\]  

(2.1)
as written in the stars.

Nuclear Fusion, Stellar Power, and Element Building — The dominant energy-producing reaction in main-sequence stars, referred to as hydrogen burning, is the fusion of hydrogen \([^1\text{H}]\) into helium \([^4\text{He}]\) by the net reaction

\[
4 \, ^1\text{H} \rightarrow ^4\text{He} + \text{energy equalling 0.7\% of the four hydrogen atoms’ mass}
\]

The main reaction in red giants is helium burning, conversion of \(4\text{He}\) into carbon \([^{12}\text{C}]\) by a similar process. Elements as heavy as iron are produced through additional fusion reactions in Red Giants. Still heavier elements — and all the geologically important radioactive isotopes — are produced mainly in supernovae.

Why the Sun’s Luminosity Has Increased Through Time — As explained below, a main-sequence star’s luminosity depends on the mass of the star and on number of atoms within it (or, alternatively, on the mean atomic mass \(= \text{star’s mass ÷ number of atoms}\)):

\[
\text{Star’s Luminosity} \propto (\text{Star’s Mass})^3 \cdot (\text{Mean Atomic Mass})^4
\]

\[
\propto (\text{Star’s Mass})^7 \div (\text{Number of Atoms})^4
\]

(6.1a)
(6.1b)

For the Sun, as for any main-sequence star, the main reason for the luminosity increase with time is the increase in mean atomic mass accompanying the four-to-one conversion of hydrogen atoms into helium atoms. Fusion consumes a very small fraction amount of a main-sequence star’s mass into energy. Only the hydrogen in the star’s core, perhaps a tenth of the star’s initial supply, is used up. The decrease in luminosity accompanying the decrease in mass is negligible in comparison to the increase due to the increased mean atomic mass.

Main-sequence stars can be thought of as stable, hydrogen-burning, hot-air balloons in which thermal pressure (which keeps the star inflated) and gravitational pressure (which holds the star together) are in stable, self-regulating equilibrium. The condition for equilibrium is that the thermal pressure equals the gravitational pressure at the star’s center. The key relation (6.1) follows from this balance of pressures:

\[
\text{Thermal Pressure} \propto \frac{\text{Number of Atoms} \cdot \text{Central Temperature}}{\text{Star’s Volume}}
\]

\[
\propto \frac{\text{Star’s Mass} \cdot \text{Central Temperature}}{\text{Mean Atomic Mass} \cdot \text{Star’s Volume}}
\]

\[
\text{Gravitational Pressure} \propto \frac{\text{Star’s Mass} \cdot \text{Star’s Density}}{\text{Star’s Radius}}
\]

(6.2a)
(6.2b)
(6.3)

Equating the two pressures gives this relation for the star’s central temperature, which, it develops, is related to the star’s luminosity by way of Stefan’s Law:

\[
\text{Central Temperature} \propto \frac{\text{Star’s Mass} \cdot \text{Mean Atomic Mass}}{\text{Star’s Radius}}
\]

(6.4)
Radiant energy escapes from a star just as it does from the Earth’s atmosphere: by atoms’ emission, absorption, and reemission of light. Unlike the Earth, however, a star is essentially all atmosphere. The star’s central temperature corresponds to the Earth’s surface temperature; the star’s “surface temperature” (actually the temperature of its photosphere) corresponds to the Earth’s effective temperature. Just as in the Earth’s atmosphere, the excitance increases linearly from the star’s center upward to its photosphere in proportion to the number of atoms an outgoing quantum of light would encounter (i.e. the gas column’s optical thickness):

\[
\text{Central Excitance} \propto \text{Surface Excitance} \cdot \text{Star’s Density} \cdot \text{Star’s Radius} \quad (6.5)
\]

One combines (6.2)-(6.5) with Stefan’s Law (2.1) to find the star’s surface excitance, which one multiplies by the star’s surface area to find the star’s luminosity as given in (6.1).

**Stars’ Evolutionary Pathways** — The basic stages are protostar (gas and dust cloud), pre-main-sequence star (or PMS star) (glowing, gravitationally heated ball; hydrogen fusion sputtering to life; thermal and gravitational pressures equilibrating), main-sequence star, and aftermath (variable, depending on stellar mass).

**Stars of solar mass**: After about 10 Ga on the main sequence, the star explodes to become a helium-burning red giant and ends up eventually as a white dwarf. Fusion produces elements no heavier than carbon in any abundance.

**Stars more than about 10 times as massive**: After as little as 100 ka, the main-sequence star explode as a supernova as it gravitationally collapse into a neutron star or, if massive enough, a black hole. Red giant and supergiant stars this massive produce elements as heavy as iron. Supernovae generate a profusion of isotopes, including all the heavier ones and a distinctive profusion of radioactive ones.

Relatively distant supernovae have been suggested as possible causes of mass extinctions.

**Star formation**: Stars form in large groups within clouds of gas and dust. In many instances, passage of a supernova’s shock wave initiates the cloud’s gravitational collapse and fragmentation into protostars. Star groups tend to disperse within roughly 10 Ma.

Roughly 85% of stars like the Sun end up revolving around companions. We probably owe our existence to the absence of a stellar companion, for its gravitational influence most likely would have rendered a long-lasting solar system impossible.

**THE HISTORY OF SUNLIGHT**

**Overall Trend for the Sun’s Main-Sequence Phase** — Details of the nuclear physics (specifically, details on how rates of fusion reactions depend on temperatures in the Sun’s core) lead to the conclusion that (i) the Sun’s luminosity should have increased steadily to about 1.3 times its zero-age main-sequence (ZAMS) level as a result of the buildup of helium in its core, and (ii) that the Sun’s main-sequence phase should continue for another 5 Ga, more or less, until the hydrogen in its core is exhausted (altogether perhaps 10% of the Sun’s ZAMS hydrogen supply) and the Sun implodes to become a red giant.

Our simple-minded model gives a quick-and-dirty check on the predicted change in the luminosity. If the Sun is halfway through its main-sequence phase and some 5% of its ZAMS hydrogen has been converted into helium, then, according to (6.1), the Sun’s present luminosity relative to its ZAMS value should be
Present Luminosity
ZAMS Luminosity = \left[ \frac{\text{Present Mass}}{\text{ZAMS Mass}} \right] \cdot \left[ \frac{\text{ZAMS Number of Atoms}}{\text{Present Number of Atoms}} \right]^{4}

\approx \left[ \frac{100\% - 0.7\% \text{ of } 5\%}{100\%} \right]^{7} \cdot \left[ \frac{100\%}{100\% - 5\% + 5\%} \right]^{4}

\approx (0.9997)^{7} \cdot (1.039)^{4} \approx (0.998) \cdot (1.2) \approx 1.2 \quad \text{... not bad!}

One notable uncertainty about the Sun concerns the so-called solar neutrino problem: the most generally accepted model of the star’s operation predicts that the flux of neutrinos from hydrogen burning ought to be about twice the observed value, suggesting that the model is flawed, that the instruments are faulty, or some combination to the two. Various solar physicists have claimed that one or another minor modification to the model makes is all that is needed to make the problem go away. Among the possibilities invoked is that Sun in effect goes “putt, putt, putt” like a gasoline engine because it takes a while for the helium “exhaust fumes” from each very-many-years-long pulse of hydrogen burning in the Sun’s core to be replaced by a fresh shot of hydrogen “gasoline” from the surrounding region.

The Sun as a Variable Star — The Sun is not a variable star in astronomers’ sense of the term, but its luminosity does vary slightly with the 11-year sunspot cycle in a manner reminiscent of flare stars. For years, scientists have noted hints of a corresponding cyclicity in climate, tree-rings, and animal populations, especially at high latitudes and in biologically stressful situations. A current “hot topic” in meteorological and climatological research is how the solar wind blown off in sunspot-related solar flares might interact with the upper atmosphere so as to influence weather and climate closer to the ground.

**STUDY QUESTIONS**

0. Continuing Questions: How has the Earth’s energy budget changed? What is the source of the energy in sunlight? … the energy that drives sea-floor spreading, continental drift, and mountain building?

1. Why has the Sun gotten brighter as the Earth has gotten older? How could the Earth have remained continuously habitable for at least 3.5 billion years — and what does it mean that the Earth evidently has been continuously inhabited for that period of time?

2. How old is the universe? Our galaxy, the Milky Way? The Sun? The Earth?

3. Why is it important to know about stars and their evolution in order to understand the Earth’s operation?

4. Suppose the Sun were 50 times more massive than it is, or about as massive as a star can get. How would the solar system’s history differ from what it has been? Could such a star have developed within a few light-years of the Sun since life arose?

---

3 There are a few hidden assumptions behind this result; for instance, that the Sun’s loss of mass to the solar wind has been negligible (which is consistent with the current rate of loss, ~10^{-14} solar masses per year).

4 By “variable star” astronomers ordinarily mean one of several types of star whose luminosity varies much more than the Sun’s.

5 A flare star is a variable main-sequence star barely massive enough to sustain hydrogen burning which characteristically undergoes order-of-magnitude luminosity fluctuations in connection with its starspot cycles (the equivalent of the Sun’s sunspot cycle).