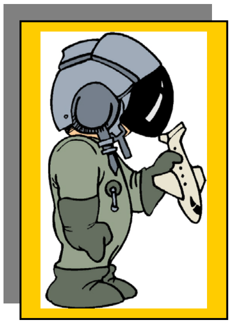
GENESIS SEARCH FOR ORIGINS Education

The Sun and Solar Wind: A Search for the Beginning

Models in Science

STUDENT TEXT

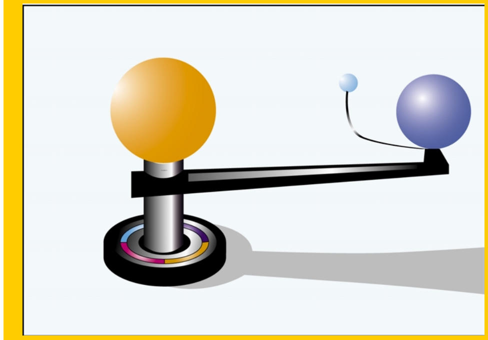


Most children like to play with models, including model cars, tinker toys, model houses, and so on. Likewise, most scientists interact with models. However, their model interaction is out of necessity (and maybe a bit of their childhood left in them!), as the forging of new science is frequently dependent on the development of models. When you think about it, it is easy to understand the importance of models in science. Many times the objects of a scientist's attention are too small to be observed directly, or they may be inaccessible for direct visual study, as would be the case for the center of the Earth or the surface of a distant galactic object. Other topics of study, such as gravity, magnetism, or energy, can be studied through their effects on matter. But gravity, magnetism, and energy cannot be seen directly, so they too are modeled. You may think of additional reasons why it would be necessary for scientists to develop models as they probe the secrets of nature.

Types of Models

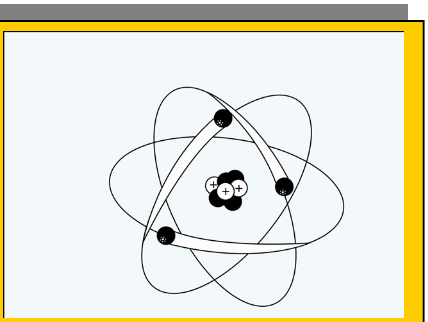
The models that scientists develop take many different forms. In some cases they are actual physical constructions. A good example of this kind of model would be one that represents the Earth, moon, and sun as small wooden spheres that are mechanically moved in such a way as to illustrate the phases of the moon, eclipses, and so forth (see Figure 1). Other models may be nothing more than mental images that are developed in an effort to picture something unseen. A good example would be the Bohr solar system model of the atom that is often used by beginning chemistry students. In this model the nucleus is imagined to be like the sun and the electrons are visualized as whirling around the nucleus analogous to the planets orbiting the sun (see Figure 2). Other models are mathematical in nature and depend on algebraic or other kinds of statements to describe a phenomenon or object. Rays of light are good examples (see Figure 3), as these can be treated as waves and equations can be developed that describe the properties of waves in great detail.

Figure 1



Physical Model of Sun, Moon, and Earth

Figure 2



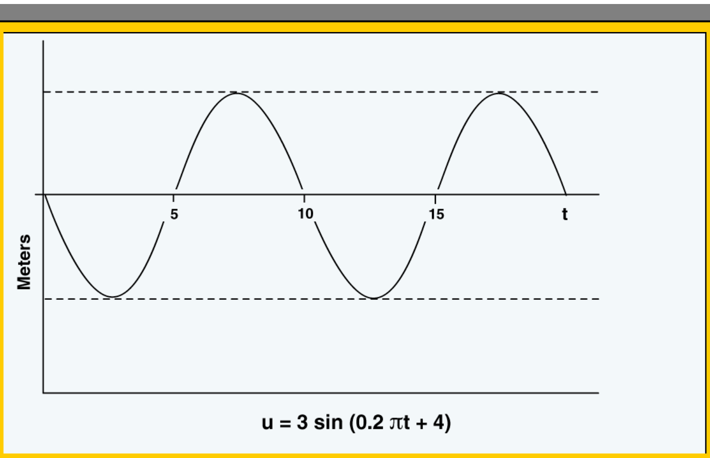
Mental Image of Atom

Models usually evolve and are improved as scientific advances are made. Not infrequently, a model is thrown out completely based on new findings that prove it to be misleading or fatally incorrect. It is also the case that different models often are used to describe the same thing, and the choice of models depends on the goal of the scientific investigation or perhaps the scientific sophistication of the individual conducting the work. A good example once again is models of the atom. The solar system model is adequate for many purposes, but a highly mathematical model based on the field of quantum mechanics is necessary for rationalizing other aspects of an atom's behavior. In a fundamental way, models are developed in an effort to explain how things work in nature.

Model Development and Use

So how are models developed? Basically they are conceived by making physical observations on a system of interest to establish facts. Scientists then combine these facts with appropriate laws or scientific principles and assumptions to give a "picture" that mimics the behavior of the system to the greatest possible extent. It is on the basis of such models that science makes many of its most important advances, because such models provide a vehicle for making predictions about the behavior of a system. These predictions can be tested later as new measurements, technology, or theory are brought to bear on the subject. The new measurements may result in modification and refinement of the model, although certain issues may remain unresolved by the model for years. Nevertheless, the goal always is to continue to develop the model in such a way as to move it ever closer to a true description of a natural phenomenon.

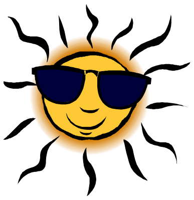
Figure 3



Mathematical Model

It has been necessary to model objects in the solar system. Recent history has changed this to a certain degree, since missions have been sent to the moon and Mars that provide opportunity for direct visual inspection of, at least, part of the surface of these neighbors. Clearly these missions, along with others, have changed and improved the existing models of the moon, Mars, and other objects in the solar system. This is the nature of science.

Modeling the Sun



The sun is an object that certainly must be modeled. It is enormous in diameter, distant, hot, gaseous, and unlikely to be visited up close and personal at any time in the near future. Hence it has been necessary to make observations over the years and develop a model to try to explain how it works. What has evolved is usually called the Standard Solar Model, which basically is a mathematical model. And as stated by the astrophysicist John Bahcall [see article references], "The Standard Model is the result of the best physics and input parameters that are available at the time the model is constructed," (s*ee handout, "Standard Model of the Sun").*

The fundamental facts about the sun that are well enough established for us to rely on them with a high degree of certainty are its shape (spherical), diameter, mass, luminosity (energy output), and age. Of these, the age is the least established. Other less important facts are known, but they do not materially affect the development of the basic model.

The major scientific principles and assumptions employed by the Standard Solar Model are:

(1) the sun originated from a primordial cloud of (mostly) hydrogen and some helium gas and that the fraction of helium has increased steadily over the life of the sun;

(2) the sun currently is in a steady state, meaning that it is neither expanding nor contracting;

(3) there is a core where hydrogen is undergoing nuclear fusion to make helium and this is the primary source of the sun's energy; and,

(4) energy produced in the core is transferred outward by radiation until it gets to the opaque convection zone, where energy transfer is more efficient by convection.

Energy transfer by conduction is not considered important and is not a part of the model. The principal uncertainties of the model are:

(1) the chemical composition of the primordial gas (the hydrogen/helium ratio); and

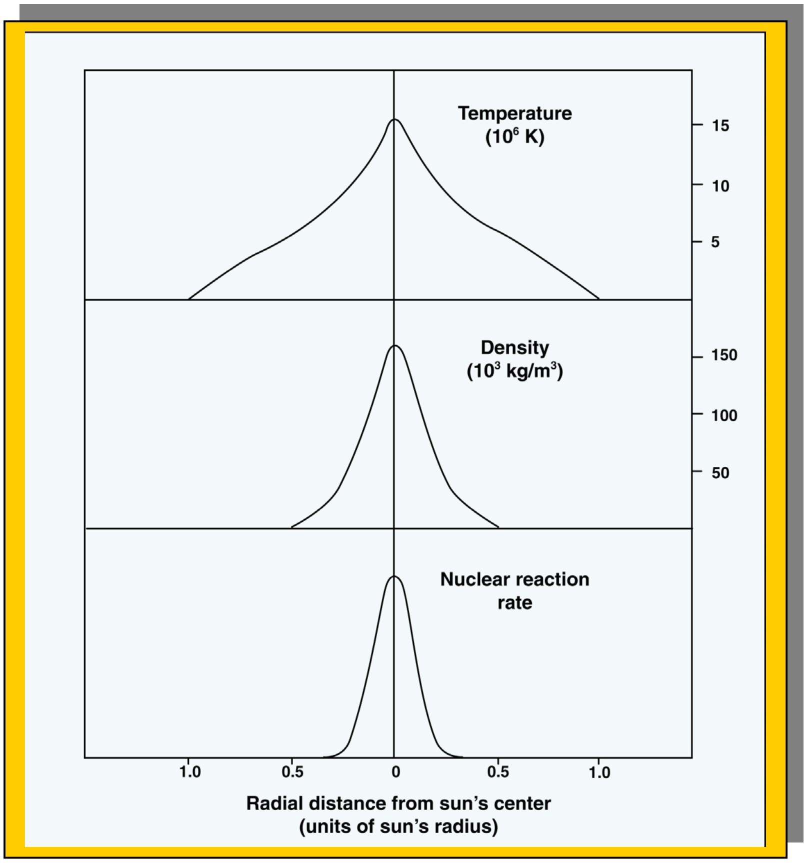
(2) the details of energy transfer in the convective zone.

Various well-known physical laws are necessary for developing the model, including some aspects of the Kinetic Molecular Theory of Gases and thermodynamics.

The Model is Calculated

Armed with the above parameters and other information gleaned from experiments conducted here on Earth (such as studies of nuclear fusion), trained specialists are able to calculate a model of the sun. This model can then be used to predict other properties of the sun. Over the past 25 years or so, literally hundreds of changes have been made in the Standard Solar Model in an effort to obtain increasingly good numerical agreement between the model and the observed sun.

Figure 4



A recent calculation by Bahcall predicts a temperature and density at the center of the core of 15,600,000 °K and 148,000 kg/m^3, respectively. A sketch of the principal zones of the solar interior based on this calculation shows many features in common with other drawings and artists' renditions of the solar interior that have been published over the years. However, Bahcall's picture also is quantitative and some of his findings are summarized graphically in Figure 4 where the variations of temperature, pressure, and density are shown as a function of distance from the sun's center. Among other things, it is seen that in his model the convection zone begins about 0.7 of the way out from the sun's center, and the temperature at that point has fallen to around 1,000,000 °K.

The Model is Tested

But are these calculated results regarding the interior of the sun correct? How confident are we that the temperature at the beginning of the convection zone is around 1,000,000 °K? In other words, how can we test the Standard Solar Model? Our confidence level is determined by the extent to which the model provides numerical and other information that is in good agreement with the observed sun. Two of the most important tests of current interest are: 1) **neutrino** production and their detection here on Earth; and, 2) measurements of subtle seismic activities within the solar interior by monitoring oscillations in the sun's photosphere. This is the new science of helioseismology.

Using New Techniques

As indicated elsewhere, the solar energy output in the Standard Solar Model is provided mostly by nuclear fusion reactions involving protons. In Appendix A, you will see that in the first fusion step, mysterious particles called neutrinos are produced. These particles, having no charge and little mass, should be bombarding the Earth at the rate of 6 x 10^{14} neutrinos per second for every square meter of surface according to the Standard Solar Model. Detecting these neutrinos experimentally with an instrument would provide a good check of the correctness of one of the assumptions of the Standard Solar Model.

Neutrinos

Neutrinos, they are very small.
They have no charge and have no mass
And do not interact at all.
The Earth is just a silly ball
To them, through which they simply pass,
Like dust maids down a drafty hall.

J. Updike: Cosmic Gall. Originally published in : The New Yorker, 17 December 1960, p. 36. Reproduced in J. Updike: Telephone Poles and Other Poems, Alfred A. Knopf, New York 1979, p. 5 and in J. Updike: Collected poems 1953-1993, Alfred A. Knopf, New York 1993, p 315.

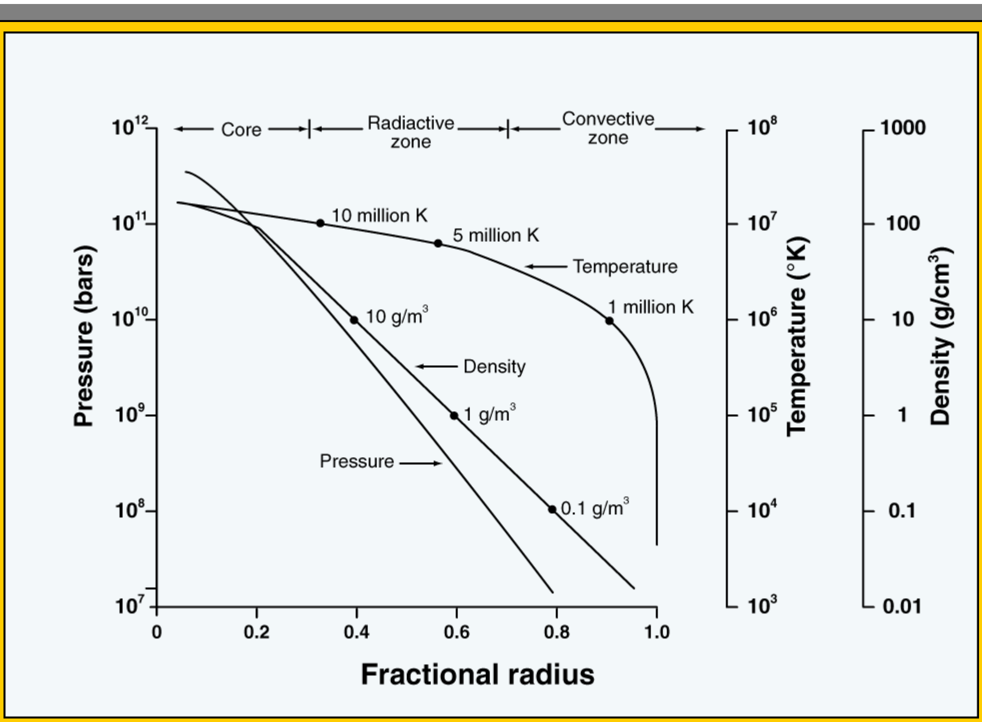
Unfortunately, neutrinos are very difficult to observe. The first efforts to detect them involved a very large experiment placed 1.5 km underground in the Homestake Gold Mine in the Black Hills of South Dakota. Why underground? Largely to shield the experiment from the effects of cosmic rays that would make interpretations of the results more difficult. The neutrino detector is a vessel containing 400,000 liters of perchloroethylene, C_2Cl_4, which also has been used as a dry-cleaning agent. This substance was chosen for its high chlorine content, since it had previously been established that sufficiently energetic neutrinos have a slight possibility of interacting with chlorine-37 nuclei and converting them to argon-37. If argon-37 is detected, it is evidence of the impact of a neutrino on chlorine-37.

More About Neutrinos

The neutrinos produced in the primary fusion reaction (proton-proton chain) are not energetic enough to transmute chlorine-37 into argon-37. It actually was more energetic neutrinos that are thought to be produced by minor secondary fusion reactions in the sun's core that were being sought by the scientists in the Homestake Mine. Suffice it to say that neutrinos were detected by the experiment, thus offering some confirmation of the correctness of the Standard Solar Model. However, as is often the case in science, there were new questions raised by the experiment. Fewer neutrinos than were predicted were actually detected. This "solar neutrino problem" has continued to confound astrophysicists for the past 30 years. Is there something about neutrinos that we do not know? Is modification of the Standard Solar Model required? The current view is that something in the nature of neutrinos causes the discrepancy and that the Standard Solar Model is still valid. New experiments are being set up to detect neutrinos from the proton-proton chain itself. Perhaps these experiments will provide definitive answers to the neutrino problem.

Helioseismolgy - Applying Old Techniques in New Ways

Figure 5

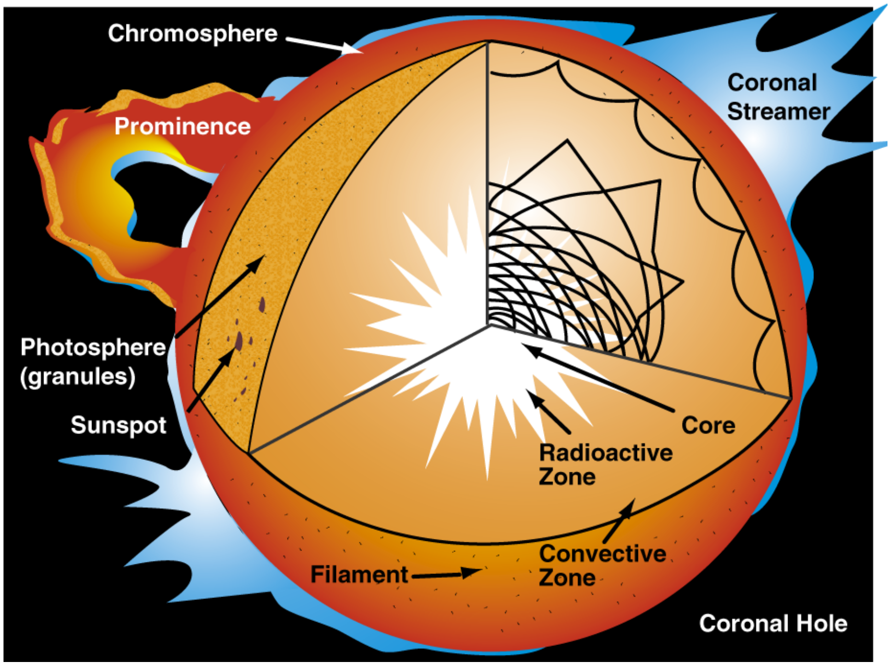


Adapted from: K.R. Lang, "Sun, Earth and Sky", Springer-Verlag, New York, 1995. p 21.

Now let's turn briefly to helioseismology and see how these studies add support to the Standard Solar Model. Helioseismology is the study of oscillations of the sun's photosphere that result from seismic events within the interior. More specifically, the surface motions are due to sound (or pressure) waves arising inside the sun. Thus, it is clear that study of the photospheric oscillations may provide information about the interior and, consequently, about the correctness of the Standard Solar Model.

The experimental basis for helioseismology is the **Doppler effect**. Small displacements in the wavelengths of absorption lines associated with the photospheric spectrum can be used to calculate velocities of the photospheric medium from which the spectrum is obtained. In other words, small inward and outward motions of the photosphere on the order of 0.5 km/s can be observed experimentally in this fashion. Now, since the Standard Solar Model provides estimates of the temperature profile of the sun, it is possible to calculate the expected speed of sound waves traversing the interior. This, in turn, makes it possible to make predictions about photospheric oscillations and to compare these predictions based on the Standard Solar Model with the observed oscillations. This field is in its infancy and astrophysicists are excited about the possibilities for learning much important information about the sun through application of this technique. The results obtained so far confirm the essential correctness of the Standard Solar Model.

Figure 6



Standard Model of the Sun

At this point you should be totally convinced of the importance of and necessity for models in science. It clearly would be impossible to begin to understand our immense solar system without the construction of models.

Figure 7

Data Table of Sun's Properties

Sun			
	Radius	6.9598×10^{10} cm	
	Mass	1.989×10^{33} grams	
	Luminosity	3.854×10^{33} erg s^{-1} (3.854×10^{23} kW)	
	Age	4.55×10^{9} years	
	Volume	1.412×10^{33} cm^3	
	Mean density	1.409 g cm^{-3}	
	Mean distance from Earth	1.4959787×10^{13} cm	
	Composition	by number	91% H, 9% He, 0.1% other
		by mass	71% H, 27% He, 2% other
Core			
	Temperature	1.577×10^{7} °Kelvins	
	Density	151.3 g cm^{-3}	
	Pressure	2.334×10^{11} bars	
Convection zone			
	Radius	0.713 x radius of sun	
	Temperature at base	2.12 to 2.33×10^{6} °Kelvins	
Photosphere			
	Temperature	5780 Kelvins	
	Pressure	10^{-4} bars	
Corona			
	Temperature	2 to 3×10^{6} °Kelvins	