Where do stars get their energy?

- Energy comes from a force. When a force is applied to something and it moves, energy is converted from the source which applies the force to the energy of movement of the object. All forms of energy can be interconverted except that motions that are disordered or random cannot be converted to ordered motions.

- Energy is equivalent to mass as discovered by Einstein:

  $$E = mc^2$$

  When an object is moving its mass is larger than when the object is at rest. This will have important consequences for the evolution of a black hole. For most situations, the increase in mass while in motion is too small to be important. However, for the system known as the Global Positioning System which relies on a network of satellites which have transmitter-receiver combinations on board, the effects of relativity must be taken into account or aircraft will crash.

- The constituent parts of matter – its atoms and molecules made up of nuclei and electrons – can undergo changes in which some of the mass in the nuclei is converted to energy. This can produce nuclear power. The energy is useful, some of the products are also radioactive and these cause the nuclear power plants to have a bad reputation.

Particles and Forces

In order to understand energy for a star we have to describe the way matter is constructed and the way its constituent parts can interact.

- The fundamental particles we will encounter are:
  - Photons
  - Electrons
  - Neutrinos
  - Protons
  - Neutrons
- These particles produced forces on one another by four different mechanisms:
  - Gravity
  - Weak forces
  - Electromagnetism
  - Strong forces
- Most particles have anti-particles:
  - The positron is the anti-particle for an electron.
  - The anti-proton is the anti-particle for proton.
  - The hydrogen atom consists of a proton and an electron. An anti-hydrogen atom consists of an anti-proton and a positron.
  - The anti-neutrino is the antiparticle of the neutrino.
- Particles and their anti-particles can annihilate each other to produce energy usually in the form of photons but possibly in the form of a neutrino and anti-neutrino.

Families of particles

The basic building blocks of matter: **protons, neutrons, electrons, neutrinos** and others are known as a group as **elementary particles**. As we dig deeper into the nature of matter we discover new ways that particles can be taken apart. A rock or piece of metal can be subdivided until it becomes a number of molecules. The molecules can be subdivided into individual atoms. Each atom can be subdivided into its electrons and nucleus. The nucleus can be subdivided into its protons and neutrons. This much is perhaps reasonably familiar. Particle physicists have learned that the nuclei can be further subdivided into what are known as quarks with there being three to a nucleon. The quarks have properties which are known as color and strangeness and depending on how the three are put together they can form either a proton or a neutron. There are other particles which go by such names as gluons and and vector bosons. The particles in the nucleus are known as **hadrons** and they all have large masses.

The second group of elementary particles are the electrons, positrons, neutrinos and anti-neutrinos. There are two other types of particle related to the electron but having a higher mass and other somewhat different properties known as the mu meson and the tau meson. They are related to the electron in somewhat the same way as the neutron is related to the proton although the mass difference is much greater between the two types of meson and the electron. Collectively these lighter particles are known as **leptons**.

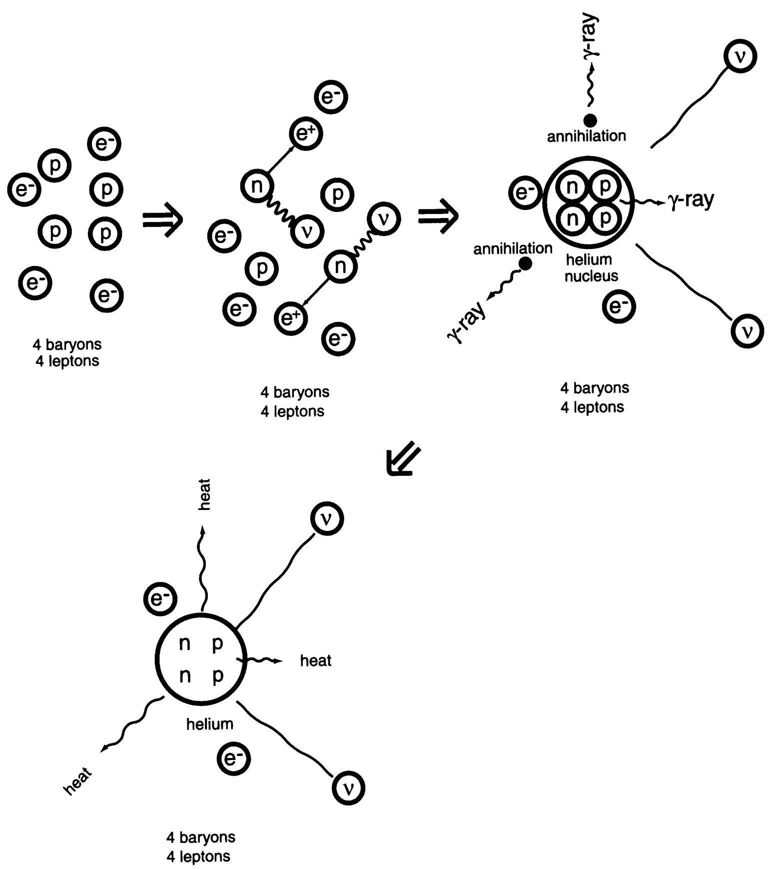
Of all these elementary particles, the one we most need to bring into the picture is the **neutrino**. These particles have no rest mass and interact by what is known as the weak force. The hadrons in the nucleus interact by what is called the strong force and the difference between these two types of force is tremendous. Because of the weakness of this force, the neutrinos, once formed, almost do not interact with anything. This is bad because it makes them difficult to detect; this is good because they can come to us from the centers of stars.

Nuclear reactions

- Each nucleus of matter has a number of neutrons and protons.
- The number of protons determines what element this nucleus will be.
- The number of neutrons adds to the number of protons to determine the mass of the nucleus. Two nuclei with the same number of protons but a different number of neutrons are called **isotopes**.
  - A nucleus with one proton is Hydrogen.
  - A nucleus with two protons is Helium.
  - A nucleus with six protons is Carbon.
  - A nucleus with eight protons is Oxygen.
  - A nucleus with twenty-six protons is Iron.
- Pairs of nuclei can join together in a fusion reaction to form a new nucleus which is the sum of the two parts.
- Protons can be converted to neutrons by the emission of a positron or the capture of an electron. This requires the weak force and is slow compared to the fusion reactions.
- The energy of a nucleus depends in detail on the number of protons and neutrons. Some nuclear reactions release energy, others require energy.

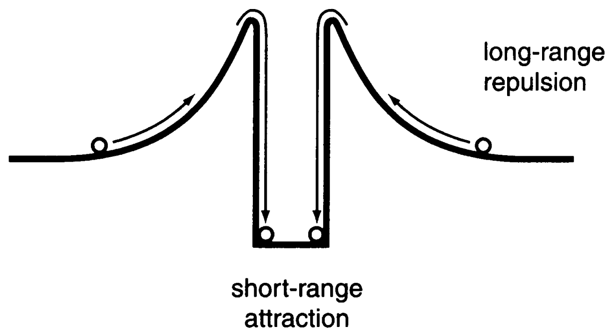
Hydrogen burning

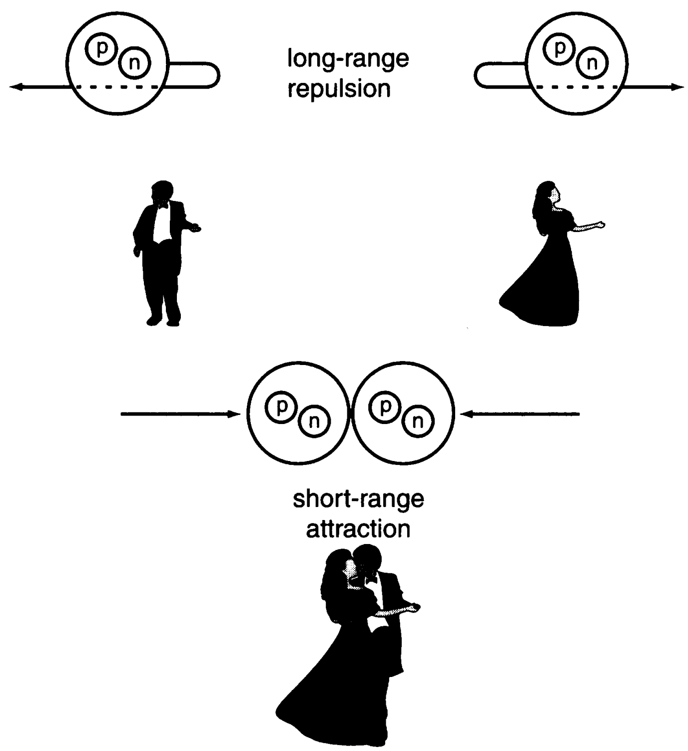
Every visible star loses energy to space by emitting electronmagnetic radiation into space. The process most important in replenishing this lost energy is the nuclear transformation of lighter elements into heavier elements through fusion reactions. The reactions which provide the greatest energy return are those which convert hydrogen into helium. This is shown schematically below:



The upper left figure shows four hydrogen atoms with their four protons and four electrons. They are not bound together but the electrical forces keep them in more or less the same part of the star. The second figure shows the conversion of two of the protons to neutrons with the emission of positrons. In order to keep a constant number of leptons, two neutrinos must be emitted as well since each positron counts as a negative lepton and each neutrino counts as a positive lepton and the algebraic sum of the created leptons must remain zero. The positrons annihilate an equal number of electrons and create some electromagnetic radiation shown as gamma rays. Finally, the four nucleons are joined together to form a single helium nucleus.

Attraction – repulsion in fusion reactions

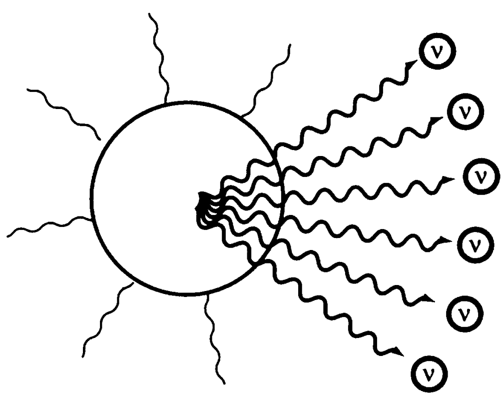


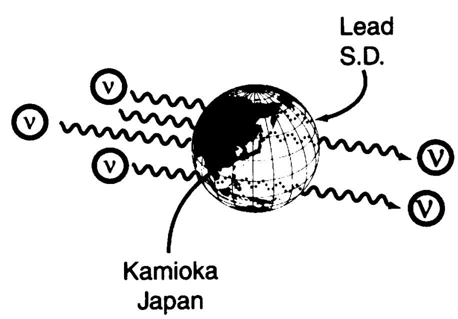


Each nucleus has a postive charge associated with its protons. When two positively charge nuclei approach, the electrical charges repel each other and the two nuclei tend to bounce off. Occasionally they are aimed exactly at each other with enough energy to overcome the repulsion. When this happens, they can get close enough for the strong force to be felt and they then are snapped together into a single joint nucleus.

Solar Neutrinos

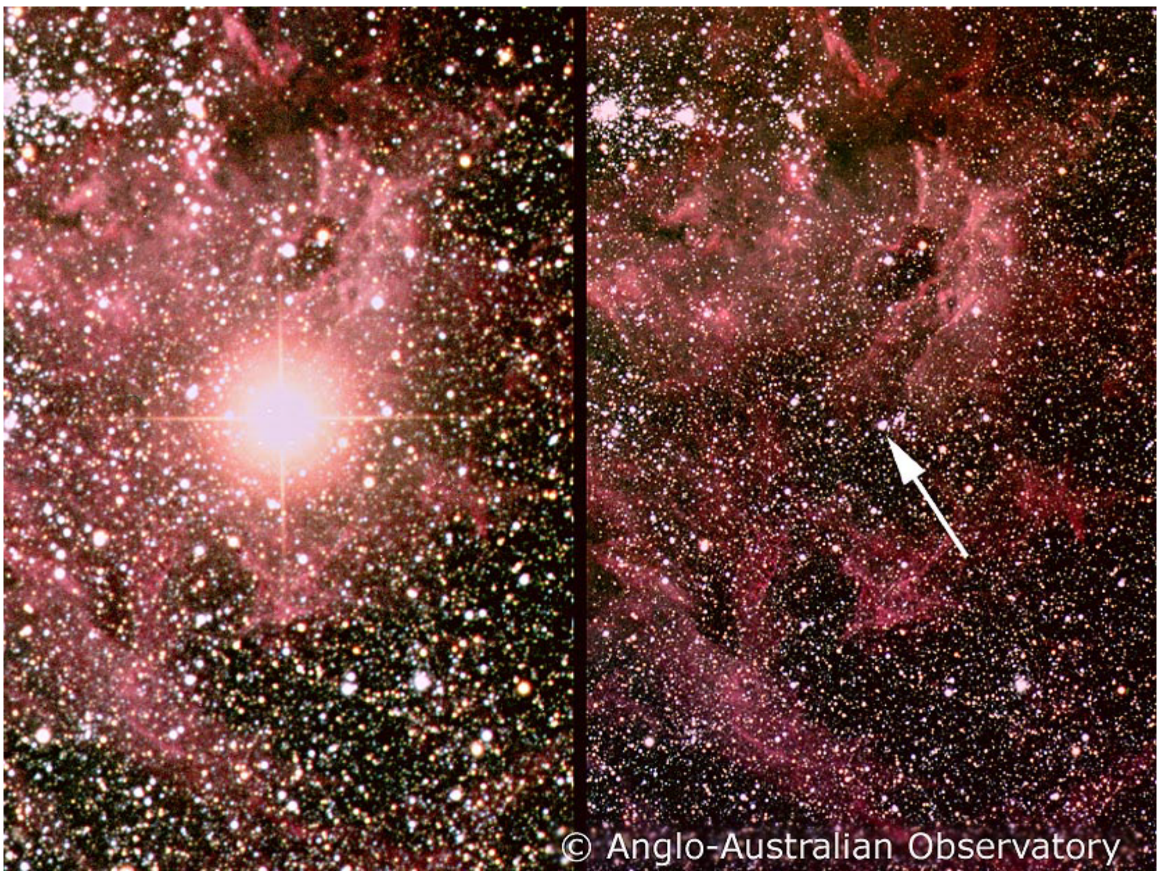
The conversion of hydrogen into helium must be occurring inside main sequence stars like the sun. Therefore, the sun must be producing a steady stream of neutrinos. These can be detected because, although the reaction probability is small, it is not zero. With enough matter and adequately sensitive instruments, they can be detected. When a neutrino bounces off an electron, it gives the electron a major fraction of its energy. Since the electron has a small mass, this causes it to move near the speed of light. When it does this inside a tank of water, it is moving faster than the speed of light inside the tank because the water slows down the speed of light. This causes the generation of the light equivalent of a sonic boom call Cherenkov radiation which can be detected.





Neutrinos come from supernovae

The high densities and temperatures associated with supernovae produce neutrinos which were detected in the same systems used for the solar neutrino detection. The figure below shows the important supernove designated as SN1987a. This occurred in the Large Magellanic Cloud and produced a cluster of detected events in the system which preceeded the SuperKamiokanda system which was known as Kamiokanda. It was also detected in a system called IMB which was in operation in the US.



These photographs are from the Anglo-Australian Telescope and have been prepared by David Malin.