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Neutrinos from Stars

Stars represent an important source of astrophysical neutrinos, and the study of stellar neutrinos is an important branch of neutrino astronomy. In this chapter we shall first introduce the basic theory of stellar evolution and then describe the basic properties of stellar neutrinos. To be explicit, we shall concentrate on the neutrinos generated from thermal nuclear reactions in the solar core. The production processes, experimental detection and flavor conversions of solar neutrinos will be discussed in detail.

6.1 Stellar Evolution in a Nutshell

Although there does not exist a complete theory of star formation, it is commonly believed that stars were formed from the clouds of the primordial gases bounded by the gravity. A star can in general be defined as an astrophysical object bounded by the gravity of itself and radiating energy from its internal thermal nuclear reactions (Prialnik, 2000). In this section we outline the quantities describing a star and the equations governing its evolution.

6.1.1 Distance, Luminosity and Mass

The Sun is a typical main-sequence star best known to us. Let us first summarize the observational characteristics of the Sun so as to get a ballpark feeling of the main-sequence stars, which represent a long and static period in the evolution of stars. The average distance between the Sun and the Earth is defined as an astronomical unit: 1 AU = 1.496 × 10^{13} cm. The total mass of the Sun is $M_\odot = 1.989 \times 10^{33}$ g, and its radius is $R_\odot = 6.955 \times 10^{10}$ cm. In comparison, the mass and radius of the Earth are $M_\oplus = 5.974 \times 10^{27}$ g and $R_\oplus = 6.378 \times 10^8$ cm. Note that $R_\odot$ (or AU) serves as a standard scale in determining the distances of planets (or stars) from the Earth within (or beyond) the solar system. A common method for the distance determination is the stellar parallax (Prialnik, 2000; Carroll and Ostlie, 2007).
parallax is one half of the angle between the lines of sight of a star from two different positions of the observers. By a measurement of the parallax \( p \), the distance of a star from the solar system can be determined as 
\[
d = (1 \text{ AU}) / \tan p \approx (1 \text{ AU}) / p, \tag{6.1}
\]
where \( p \) is assumed to be very small and its unit is radian. In view of 1 radian \( = 57.2958^\circ \), one may define the distance unit as parallax second (i.e., parsec or pc for short). Then an astrophysical distance can be written as 
\[
d = (1/p) \text{ pc with 1 pc} = 3.086 \times 10^{18} \text{ cm},
\]
where the unit of \( p \) is arc second. Another conventional unit is light year (i.e., ly for short), defined as the distance travelled by the light in a Julian year. Namely, 
\[
1 \text{ ly} = 9.461 \times 10^{17} \text{ cm and then 1 pc} \approx 3.262 \text{ ly}. 
\]
The stellar parallax is always smaller than 1”. For instance, Proxima Centauri (the nearest star other than the Sun) has a parallax angle \( \sim 0.77'' \) (Carroll and Ostlie, 2007). The Earth’s atmosphere makes a ground-based telescope difficult to reach a precision better than 0.03”, implying that it is impossible to measure a distance farther than 30 pc. To overcome such an obstacle, the European Space Agency launched the satellite Hipparcos in 1989. This mission was able to measure the parallax angles with an accuracy in the range \((0.7 \sim 0.9) \times 10^{-3}\) arc seconds for more than \(10^5\) stars (Perrymann et al., 1997).

The observation of a star is to measure its apparent luminosity \( l \), which depends on the absolute luminosity \( L \) and the distance \( d \). The values of \( L \) and \( l \) characterize the energies emitted from the star per second and received by the detector per second per square centimeter, respectively. If the energy released by a star is isotropic and not absorbed on the way to the detector, we have 
\[
l = L/(4\pi d^2). \tag{6.2}
\]
Historically, the apparent magnitude \( m \) is used to describe the brightness of stars. The Greek astronomer Hipparchus was the first to assign \( m = 1 \) to the brightest star and \( m = 6 \) to the dimmest one in the sky (Krisiunas, 2001). It was later realized that the human eye actually responded to a difference in the logarithm of the brightness. For instance, a difference of 5 magnitudes corresponds to a factor of 100 in brightness; i.e., one magnitude difference is equivalent to a factor of \(10^{1/5}\) in the apparent luminosity. One may therefore obtain 
\[
l \propto 10^{-2m/5},
\]
implying
\[
\frac{l_2}{l_1} = 10^{2(m_1-m_2)/5}. \tag{6.3}
\]
The absolute magnitude \( M \) is defined as the apparent magnitude that a star would have if it were located at 10 pc from the Earth. So one may express the distance of a star in terms of its apparent and absolute magnitudes:
\[
d = 10^{(m-M+5)/5}, \tag{6.4}
\]
where \( d \) is measured in parsecs, and \( m - M = 5 \log[d/(10 \text{ pc})] \) is called the star’s radius modulus. The absolute luminosity of the Sun is \( L_\odot = 3.839 \times 10^{33} \text{ erg s}^{-1} \). The apparent luminosity of the Sun can then be given by
\[
l_\odot - \frac{L_\odot}{4\pi(1 \text{ AU})^2} = 1.365 \times 10^6 \text{ erg cm}^{-2} \text{ s}^{-1}, \tag{6.5}
\]