New Astronomy 39 (2015) 25–35

Contents lists available at ScienceDirect

New Astronomy

journal homepage: www.elsevier.com/locate/newast

Detection of solar neutron events and their theoretical approach

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HIGHLIGHTS

- Here observational characteristics of 12 solar neutron events are presented.
- Different calculation methods of neutron energy spectrum are compared.
- It can be parameterized in the acceleration parameters and physical parameters of one specific solar neutron event.

ARTICLE INFO

Article history:
Received 25 July 2014
Received in revised form 18 December 2014
Accepted 29 December 2014
Available online 6 January 2015
Communicated by W. Soon

Keywords:
Flare
Particle emission
Neutron

ABSTRACT

Solar neutron events provide important opportunities to explore particle acceleration mechanisms using data from ground-based detectors and spacecrafts. Energetic neutrons carry crucial physics information of the acceleration site, such as energy spectrum, atmospheric elements of solar flare, scale height, convergence of the magnetic field and magnetohydrodynamic turbulence. Here 12 representative solar neutron events observed on the Earth, together with X and γ-ray observations from spacecrafts are presented. Theoretical approaches on solar neutrons that are carried out mainly through the Monte Carlo simulation are compared with the observation data, and the constraints of different theoretical models on the observations are to be summarized.

1. Introduction

Solar activities are intense explosions which accompany by producing high energy particles including solar protons, electrons and a small amount of neutrons. Neutrons are produced by collisions of ions in the solar photosphere, such as the interactions between the accelerated proton, heavy ion and the surrounding atmosphere as presented in Fig. 1. The processes include p–p reaction, α–α reaction, p–α reaction, p and α reaction with the surrounding heavy nuclei and their reverse reactions. Researches on the neutron and gamma rays can directly obtain the following information: the total number of accelerated particles, time evolution, angular distribution and their propagation in the flare atmosphere, etc. (Dorman, 2010; Hua et al., 2002; Murphy et al., 2012).

Theoretical researches on neutron escaping and eventually transferring to the Earth's surface were first put forward by Lingenfelter et al. (1965). Since then, Monte Carlo simulations have been developed to track a neutron until neutron was captured by hydrogen atoms in the solar atmosphere which emits 2.223 MeV neutron-capture line or escapes from the surface of the Sun (Hua and Lingenfelter, 1987a). Furthermore, they computed escaping-neutron angular distribution, energy spectrum and escaping-neutron spectrum near the Earth, considering the spiral angle of magnetic field in the solar flare loops and the magnetic mirror effect (Hua et al., 2002). The above calculations also include the relationship between the production of anisotropic neutrons, the height of the solar atmosphere, time evolution, angle and energy. Formula (1) and (2) express the neutron angular distribution and energy distribution, respectively (Hua et al., 2002).

$$\frac{d^2\sigma}{dE_n d\Omega_n} \propto exp[-(1-\mu_n)E_n/T_0], E_n < E_{max}, \quad (1)$$

where E_n is neutron energy, μ_n means cosine value of emitted neutron relative to the incident proton, and E_{max} is the maximal energy of neutron.

$$\frac{d\sigma}{dE_n^*} \propto (E_n^*)^\gamma exp^{-E_n^*/T_{evap}}, \quad (2)$$

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http://dx.doi.org/10.1016/j.newast.2014.12.010
1384-1076/

where E_n^* is neutron energy in the center of mass, T_{evap} is evaporation temperature with a value of 2.5 MeV, and $\gamma = 5/11$.

In addition, theoretical researches have also shown that time scale of neutron detected near the Earth is about 1166 s when neutron energy E_n is about 100 MeV (Hua et al., 2002). In the stationary reference frame of neutron, it takes about 1054 s to propagate from the Sun to the Earth. The average life span for the neutron decay is about 918 s, and it means that about 70 % neutron decays during the passage from the Sun to the Earth. High-energy neutrons are more likely to survive at 1 AU, and the corresponding angular distribution (its energy range is 100–1000 MeV) does not change essentially.

In observations, the detection methods of solar neutron can be divided into two types (Murphy et al., 2007): direct observation and indirect observation. Direct observations include the following cases: (i) Escaping-neutrons out of the solar atmosphere which reach the Earth can be directly captured by the Earth's orbit satellite. (ii) Ground-based neutron monitoring network can detect high-energy neutrons ($E > 200$ MeV). In addition, indirect observations include the following cases: (i) The escaping-neutrons, which decay into protons, can be detected in the space (Evenson et al., 1983). (ii) Neutrons on the Sun, which are captured by hydrogen atoms in the photosphere, can emit 2.223 MeV rays in space, and they can be detected by the γ -ray spectrometer. Because neutrons ($E < 100$ MeV) seriously attenuate during the propagation process of the Earth's atmosphere, they can not reach the Earth surface. Space exploration is the only method to detect neutrons ($E < 100$ MeV), while spacecraft and ground-based detector can detect neutron ($E > 100$ MeV) simultaneously.

2. The ground-based observational characteristics of solar neutron

2.1. Ground-level Enhancement (GLE) and solar neutron events

Solar energetic particle (SEP) with energy higher than 500 MeV are identified as Ground-level Enhancements Events (GLEs) (Andriopoulou et al., 2011). There are two types of the ground-level enhancements of solar cosmic ray intensity, i.e. proton ones caused by accelerated charged particles and unusual enhancements from solar neutron (Belov and Asipenka, 2009). They are both rapid rise of short duration in the counting rates of ground-based neutron monitors. Neutron-dominated enhancements are always connected with the observable flares which distribute uniformly on the Sun disk, while the solar origin of proton-dominated enhancement often concentrates at the western heliolongitudes. Their other differences are listed in Table 1. So far 71 Ground-level Enhancements Events (GLEs) have been identified, and the most recent event recorded on 17 May 2012 (GLE71) were analyzed separately (Papaioannou et al., 2014; Plainaki et al., 2014).

Because neutrons easily attenuate in the Earth's atmosphere, probability of capturing neutron is very low. Ground-level Enhancement (GLE) associated with solar activities which meet the following conditions can be confirmed as a solar neutron event. (i) We can eliminate that the enhancements are produced by high-energy ions, if the counts which are recorded by neutron monitors increase during the day and the other stations in the night without any enhancements. (ii) The time of counts recorded by the ground-based detectors is approaching to the corresponding emission time of hard X ray and γ ray in solar flare. (iii) The time of counts recorded by the ground-based detectors precedes the arrival time of solar proton events observed by GOES satellite, completely ruling out the interference from solar protons. (iv) The moments of counting enhancement recorded by the other solar neutron detectors (such as the solar neutron telescope and muon telescope) meet each other.

2.2. Characteristics of solar neutron events observed on the Earth

Table 2 shows the known observational features of 12 solar neutron events (1 case happened in solar cycle 21, and 4 cases occurred in solar cycle 22. The other 7 cases occurred in solar cycle 23). The observational characteristics include: (i) The soft X-ray magnitudes of solar neutron events that happened during solar cycle 21 and 22 were greater than X8 magnitude, while the soft

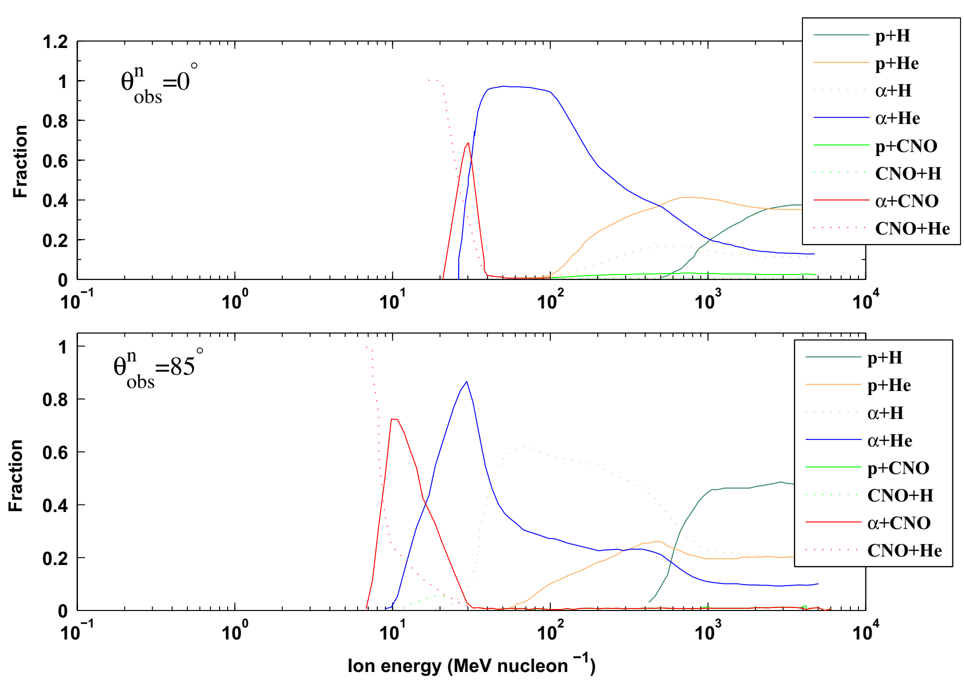

Fig. 1. Eight types of neutron-producing reactions which contribute to neutron production ($E > 30$ MeV). Top panel is for a disk flare and bottom panel is for a limb flare. CNO means all the nuclear species heavier than 4He.