博士学位论文摘要选登

太阳耀斑伽马射线计算及其观测

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耀斑加速粒子与太阳大气介质原子的核反应影响过程产生大量的伽马射线、中子、正电子以及π介子，这些辐射在许多耀斑中被观测到。产生耀斑伽马射线的主要机制是原子核共振和质子俘获中子和正负电子湮灭。核共振激发谱包括加速轻离子（质子和 α 粒子）与太阳大气重原子核碰撞产生的窄线和加速重核与周围大气的 H 、He 原子碰撞产生的宽线以及核连续谱（包括大量不可分辨的弱线、复合反应连续谱和非平衡反应连续谱）。

伽马射线是研究太阳耀斑高能粒子（尤其是质子和重核粒子）加速和传播最为直接的手段。通过伽马射线能谱分析，可以获得耀斑过程中加速粒子的成分、能量、角分布，以及太阳大气丰度等重要信息。TALYS 是一款高效的核反应模拟软件，它对核反应过程中所有信息（包括核反应截面）提供了完整的描述。我们利用 TALYS 计算得到核反应截面数据，开发了一套新的耀斑伽马射线谱计算程序。

这道程序使得伽马射线的计算更为完整和精确，同时对核连续谱成分有了更好的计算。

本论文前半部分该理论计算过程进行了详细讨论。此外，我们还详细计算了在不同条件下的伽马射线轮廓（以 4.438 MeV 线为例）。通过比较，我们发现，伽马射线轮廓特征（包括光谱宽度和线心位置）与加速离子能谱、加速离子角分布、太阳大气元素丰度以及耀斑位置等参数紧密相关。谱线轮廓观测和分析将有助于我们获取这些物理信息。

在论文后续部分，我们利用 GEANT4 模拟中子俘获线在太阳大气中的传输，并结合耀斑伽马射线能谱理论计算和 RHESSI 数据观测，分析研究康普顿散射效应对耀斑伽马射线能谱的影响。通过对 2005 年 1 月 20 日耀斑的分析，我们发现，该事件中中子俘获线形成区域平均密度约为 8 g cm⁻²，而在耀斑早期密度超过 15 g cm⁻²。如此高的密度意味着康普顿散射效应对中子俘获线的传播有明显作用。通过康普顿连续谱的校正，我们发现中子俘获线能量的演化规律（包括强度和峰值时间）与校正前相比发生明显改变，表明中子俘获线的康普顿散射在耀斑伽马射线谱中具有相应的贡献。

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The Calculation and Observation of Gamma-Rays from Solar Flares

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Nuclear reactions, due to the interactions of the flare-accelerated particles with the ambient solar atmosphere, produce a wealth of gamma-ray line, neutron, positron, and π-meson emissions. Such emissions have been observed in many solar flares. The principal mechanisms for the production of solar gamma-ray lines are nuclear deexcitation, neutron capture by proton, and positron-electron annihilation. The nuclear deexcitation spectrum consists of narrow lines resulting from the accelerated light-weight ions (protons and $\alpha$-particles) interacting with the ambient heavy nuclei, broad lines resulting from the accelerated heavy nuclei interacting with ambient H and He atoms, and nuclear continuum which includes a series of unresolved weak lines, compound continuum, and pre-equilibrium continuum.

The solar gamma-rays are the most direct diagnostic tool for studying the acceleration and transportation of energetic particles in solar flares, especially for protons and heavy ions. They provide a wealth of information about the nature of accelerated particles, as well as the physical properties of ambient medium. TALYS is an efficient code for simulating nuclear reactions, and it can provide detailed calculations for all the information, including cross sections. Based on TALYS, we develop a new program of gamma-ray production, which improves the completeness and accuracy of the previous calculations.

The theoretical frame of gamma-ray production in solar flares is treated in detail in the first half of the thesis. In addition, we take the 4.438 MeV line as an example to calculate the shapes of strong gamma-ray lines under different conditions. By comparison, we find that the shapes of gamma-ray lines (including Doppler width and shift) are closely related to the energy spectrum and angular distribution of accelerated ions, the solar atmospheric element abundance, and flare location, etc. As a result, the observation and analysis of spectral line shape will help us to obtain these physical parameters.

In the latter part of the thesis, we employ a Monte Carlo simulation toolkit named GEANT4 to simulate the transport of neutron capture line in the solar atmosphere, and study the effect of Compton scattering on the gamma-ray spectrum by combing the theoretical calculation with observational data. By analyzing the flare which occurred on 2005 January 20 (X7.1/2B), we find that the vertical depth for neutron capture on hydrogen is about 8 $\text{g} \cdot \text{cm}^{-2}$ on average and higher than 15 $\text{g} \cdot \text{cm}^{-2}$ during the early phase of the flare. It is suggested that Compton scattering has a significant effect on the propagation of the neutron capture lines, especially during the early phase of the flare. Furthermore, by using the Compton-scattered continuum to correct the neutron capture line flux, we also find that the time evolution, not only the intensity but also the peak time of the flux, can be changed considerably compared with the values before the correction. This result demonstrates that the Compton effect of 2.223 MeV photons plays a significant role in a gamma-ray spectrum.