

太阳耀斑光谱诊断和辐射动力学过程研究

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太阳耀斑是太阳大气中最为剧烈的活动现象之一,涉及到很多复杂的物理过程,包括快速的能量释放、等离子体的不稳定性、高能粒子的加速和传播、耀斑大气辐射和动力学变化、物质的运动和抛射现象等.耀斑伴随各个波段的辐射增强,耀斑的高能粒子和辐射输出是空间灾害性天气的主要扰动源.因此,对耀斑辐射过程的研究具有重要的理论和应用意义.

通过观测分析与理论模拟相结合,论文对耀斑的光谱特征和辐射机制进行了一些探讨,特别是注重非热过程的诊断和白光耀斑的起源,其主要研究内容如下:

(1) 研究了利用不同色球谱线来诊断耀斑大气加热过程的方法.基于 4 个不同的半经验模型,利用非局部热动平衡计算并考虑不同强度的非热电子束轰击情况,得到了 $H\alpha$ 和 $CaII$ 8542 Å 谱线轮廓,鉴于它们对热和非热过程的不同反应,我们利用它们的强度组合来诊断耀斑的加热过程.结合南京大学太阳塔对 2001 年 10 月 19 日一个 X 级耀斑的观测,我们定量地给出了耀斑爆发过程中各种加热效应的情况.结果表明位于耀斑带外边缘的非热效应比内侧要明显,而内边缘的温度相对高一些.另一方面,在耀斑的上升相,非热效应增加明显;而在衰减相,非热效应快速减弱,但大气的温度仍然保持在一个较高的状态.对该耀斑两个核块的分析结果表明其非热电子束流量分别约达到了 $10^{10} \text{ erg}\cdot\text{cm}^{-2}\cdot\text{s}^{-1}$ 和 $10^{11} \text{ erg}\cdot\text{cm}^{-2}\cdot\text{s}^{-1}$.

(2) 利用辐射动力学模型来计算白光连续谱的增强.一般认为白光耀斑起源于太阳大气的色球低层或光球高层.特别是最近一些观测探测到了 $1.56 \mu\text{m}$ 处的辐射增强,该波段的连续谱通常认为产生于太阳大气很低的层次,可以低至光球层以下几十公里.通过辐射动力学模型的计算,我们研究了非热电子束轰击对连续谱的影响.非热粒子束流量对于连续谱增强的作用是很显著的,特别是当流量约超过 $10^{10} \text{ erg}\cdot\text{cm}^{-2}\cdot\text{s}^{-1}$ 的时候.电子束的低端截止能量也能对连续谱有很大的影响.当加大低端截止能量的时候,连续谱也会增强.另外,非热电子束的谱指数也影响到连续谱的增强.连续谱的相对增强还依赖于日心角的变化.当耀斑位置从日心变化到日面边缘时,相对增强甚至可以有量级的变化.我们的理论结果可以解释除 $1.56 \mu\text{m}$ 之外观测到的各波段白光辐射的增强.在这个过程中,辐射加热的贡献非常显著.

(3) 通过辐射动力学模型来探讨周期性非热电子束轰击下 $H\alpha$ 谱线的响应情况.在周期性粒子束轰击下, $H\alpha$ 谱线各部分均有响应,且响应的周期跟粒子束的周期一致.谱线线心和线翼对周期性粒子束轰击有不同的时间响应,体现在不同的相位延迟上.线心部分的相位延迟最小.蓝翼和红翼的响应不一致,蓝翼与非热粒子束之间的相位差较小,而红翼的相位差比较大.线心和线翼的变化的相位差可以用不同的形成高度来解释.因为线心形成在较高层,对非热电子束的响应较快.但蓝翼和红翼的差别似乎不能完全用形成高度来解释,一种可能的原因是宏观速度场改变了蓝翼和红翼的吸收和发射过程.谱线各部分对短周期振荡粒子束的不同响应对我们利用光学谱线来诊断耀斑加热过程具有重要的意义.

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(4) 利用 RHESSI 高时间分辨率的资料来探测耀斑爆发过程中的短时标尖峰事件. 我们给出了硬 X 射线尖峰事件的初步统计特性. 大约 20% 的尖峰事件能够在 100 keV 以上的高能段被探测到. 主要的统计特性总结如下: (i) 无论是脉冲式耀斑还是缓变事件都可能产生尖峰事件, 而且具有几乎相同的概率. 大约 90% 的尖峰事件出现在耀斑的上升相, 超过 60% 的尖峰事件出现在耀斑的峰值附近. (ii) 尖峰事件的持续时间变化范围为 0.2~2 s, 其平均值大约为 1.3 s, 并且不依赖于能段的选择. 与耀斑不同, 尖峰事件具有几乎对称的轮廓, 上升相和衰减相持续的时间并没有明显的差别. (iii) 在一些最强的尖峰事件中, 有 2/3 的尖峰事件相对于缓变的背景具有更硬的谱. 另外高能时延的尖峰事件相比低能时延的尖峰事件来说, 趋向于具有更硬的 X 射线谱.

Spectral Diagnostics and Radiative Hydrodynamics of Solar Flares

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Solar flares are one of the most significant active phenomena in the solar atmosphere. It is involved in very complicated physical processes, including energy release, plasma instability, acceleration and propagation of energetic particles, radiation and dynamics of the flaring atmosphere, mass motions and ejections, and so on. Enhanced radiation during flares spans virtually the entire electromagnetic spectrum originating from different layers of the solar atmosphere. High energetic particles and strong radiations that are produced during the flare eruptions play a major role in space weather. Therefore, it is very important and necessary to study the mechanisms of solar flares.

In this thesis, combined with ground and space observations, the theoretical calculations are used to study the spectral features and radiation mechanisms of solar flares. In particular, our research is concentrated on the diagnostics of non-thermal processes and origin of the white-light flares. The main contents are described as follows:

(1) Different chromospheric lines are used to diagnose the heating mechanisms in flares. We calculate the H α and Ca II 8542 Å line profiles based on four different atmospheric models, including the effects of non-thermal electron beams with various energy fluxes. These two lines have different responses to the thermal and non-thermal effects, and can be used to diagnose the thermal and non-thermal heating processes. We apply our method to an X-class flare occurred on 2001 October 19 and find that the non-thermal effects at the outer edge of the flare ribbon are more notable than that at the inner edge, while the temperature at the inner edge seems higher. On the other hand, the results show that non-thermal effects increase rapidly in the rise phase and decrease quickly in the decay phase, but the atmospheric temperature can still keep relatively high for some time after getting to its maximum. For the two kernels that we analyze, the maximum energy fluxes of the electron beams are approximately 10^{10} erg·cm $^{-2}$ ·s $^{-1}$ and 10^{11} erg·cm $^{-2}$ ·s $^{-1}$, respectively. However, the atmospheric temperatures are not so high, i.e., lower than or slightly higher than that of the weak flare model F1 at the two kernels. We discuss the implications of the results for the two-ribbon flare models.

(2) The white-light emission in solar flares is studied by radiative hydrodynamic simulations. It is believed that solar white-light flares (WLFs) originate from the lower chromosphere and upper photosphere. In particular, some recently observed WLFs show a very large continuum enhancement at $1.56 \mu\text{m}$ where the opacity reaches its minimum. Therefore, it is important to make clear how the energy is transferred to the lower layers responsible for the production of WLFs. Based on radiative hydrodynamic simulations, we study the role of non-thermal electron beams in increasing the continuum emission. We vary the parameters of the electron beams and disk positions and compare the results with observations. The electron beam heated model can explain most of the observational white-light enhancements.

(3) The effect of periodic non-thermal electron beam on chromospheric lines is studied. Heated by the periodic non-thermal electrons, the $\text{H}\alpha$ line center and wings show the same periodicity as the injected electrons. The line center and wings have different time delays compared to the bombarded electron beam. The line center has a relatively small phase difference. The red and blue wings also show different time delays. The blue wing shows a smaller phase difference compared to the red wing. The phase differences between the line center and wings can be explained by their different formation layers. However, the phase difference between the red and blue wings can not be fully explained in this manner. A possible explanation is that the macroscopic velocity field changes the emission and absorption features at the red and blue wings. The above results provide useful information for diagnosing the heating processes by using the fine time structures observed in chromospheric lines.

(4) A statistical study of RHESSI hard X-ray spikes is made. The spikes refer to fine time structures on time scales of seconds to milliseconds in hard X-ray time profiles during solar flares. We get a preliminary statistical result of temporal and spectral properties of hard X-ray spikes. About one fifth of the spikes can be detected in photon energies higher than 100 keV. Some main properties of the spikes are as follows: (i) Spikes are produced in both impulsive flares and long-duration flares with nearly the same occurrence rates. 90% of the spikes occur during the rise phase of the flares, and about 70% occur around the peaks of the flares. (ii) The durations of the spikes vary from 0.2 s to 2 s, with an average being 1.3 s, which is independent of photon energies. The spikes exhibit symmetric time profiles with no significant difference between the rise and decay phases. (iii) Among the most energetic spikes, about two thirds of them have harder count spectra than their underlying slow-varying components. There is also a weak indication that spikes exhibiting time lags in high-energy emissions tend to have harder spectra than spikes with time lags in low-energy emissions.