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太阳耀斑大气动力学的观测和模拟

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太阳耀斑是发生在太阳大气中的一种剧烈的活动现象, 发生的时标约为几分钟到几十分钟. 耀斑过程涉及能量释放、等离子体加热、粒子加速、物质运动、波动等现象. 耀斑爆发能够释放出大量的能量, 所发出的辐射基本覆盖了电磁波的所有波段. 耀斑发生通常还会伴随日冕物质抛射(CME), 从而对空间和地球环境造成影响.

目前我们对耀斑过程的理解还很不足(定量方面), 其中的一些关键问题仍待解决, 包括: 耀斑能量是在何时、何地被释放? 释放过程持续了多长时间? 能量释放/传输的主要形式是什么? 耀斑大气对能量释放又是如何响应的? 为此, 我们针对这些问题, 对耀斑大气等离子体的加热和动力学演化进行了详细的研究. 我们首先对耀斑的研究历史作了概述(第1章), 并介绍了相关的观测仪器(第2章)和计算模型(第3章), 然后用光谱数据分析了耀斑中的色球蒸发过程(第4章). 基于色球蒸发的研究结果, 我们进一步探究耀斑的加热过程. 我们采用由观测限制的加热函数对两个耀斑环进行了模拟(第5章), 得到的模拟结果与观测结果基本符合. 在此基础上, 我们又模拟了两套不同的耀斑环系统(第6章), 其中的加热时标有很大的不同, 由此产生了不同的动力学效应. 具体内容如下:

我们用Hinode/EIS的光谱数据研究了2007年1月16日耀斑的色球蒸发过程. 仔细分析了耀斑带上的3个点, 其中第1个点位于正的磁极区, 第2、3个点位于负的磁极区. 我们发现在耀斑脉冲相, 这3个点表现出不同的物质运动: 在第1个点处, 大多数谱线都呈现蓝移, 其中高温谱线的蓝移分量相对其静止分量占主导; 在第2个点处, 只能探测到较弱的向上运动(upflow), 相反, 高温谱线(形成温度为2.5~5.0 MK)都表现出显著的向下运动(downflow); 第3个点和第2个点的情况类似, 只是物质向下运动时出现多个速度分量. 第2、3个点处的向下运动可解释为色球压缩的证据. 这3个点表现出了不同的色球蒸发类型: 温和式色球蒸发和爆发式色球蒸发, 表明此耀斑区域可能存在着不同的加热机制.

我们随后用零维的EBTEL(基于焓的环的热演化)模型对耀斑加热的动力学过程进行了研究. 我们分析了2011年2月16日的一个M1.0级耀斑. 从EUV图像可以看出此耀斑由两个环系统组成, 在模拟中我们将其当作两个横截面积为$5''\times5''$的粗环. 从光变曲线来看, 先是UV 1600 Å波段(辐射主要来自环足点)出现快速增亮, 随后几个EUV波段的辐射也顺次增强. 这表明有能量快速沉积, 耀斑环对此产生响应. 我们运用最近提出的一个新方法, 即从快速上升的UV光变曲线得到耀斑环的加热函数, 再结合EBTEL模型来计算这两个粗环中等离子体的演化. 通过模型计算, 我们得到了各个EUV波段的辐射, 并与SDO/AIA和EIS观测的流量作了对比. 结果显示, 虽然EBTEL模型具有局限性, 但是从模型得到的光变曲线与观测的光变曲线符合得比较好: 它们表现出相同的走势, 绝对数值也在两倍范围之内. 此外, 我们还将模型计算的焓流速度与EIS测量的多普勒速度作了对比, 结果符合得也比较好. 这些事实表明, 这两个不同的耀斑环, 从足点的UV辐射显示了不同的加热函数, 再结合不同的环的长度, 最后表现出了不同的演化类型; 而这不同的演化类型在模拟和观测方面都得到了证实.

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我们用同样的方法分析和模拟了另一个C4.7级耀斑. 从AIA的图像我们辨认出了两套耀斑环系统: EIS的光谱观测显示, 这两套耀斑环的足点在脉冲相时表现出蓝移. 这两套环的演化和动力学过程非常不同: 第1套环的足点先是出现蓝移(∼10 km/s), 持续约25 min后转变为红移; 第2套环的足点出现较强的蓝移(∼20 km/s), 且持续了约1小时, 基本伴随耀斑的整个过程. 长时间的蓝移说明有持续的加热. 同时, AIA的UV 1600 Å观测显示, 第2套环的足点存在相隔15 min的两次增亮, 而第1套环的足点只有1次增亮. 我们用这两套环足点处的UV光变曲线构建加热函数, 结合EBTEL模型计算了环中等离子体的演化. 结果显示, 对于第1套环, 模型预测的EUV光变曲线与AIA的6个波段以及EIS的8条谱线的观测都比较符合, 模型计算的平均焓流速度与EIS测量的多普勒速度也比较一致; 但对于持续加热的第2套环来说, 模型预测的低温辐射与观测不甚相符, 另外, 模型没有完全重现出持续的蓝移. 模型与观测的差异, 一方面可能源于加热主要集中在耀斑环足点附近, 而这不能被EBTEL模型所模拟; 另一方面可能源于耀斑区存在未被分辨的、而加热率非常不同的耀斑环.

Observations and Modeling of Solar Flare Atmospheric Dynamics

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Solar flares are one of the most energetic events in solar atmosphere, which last minutes to tens of minutes. The eruption of a solar flare involves energy release, plasma heating, particle acceleration, mass flows, waves, etc. A solar flare releases a large amount of energy, and its emission spans a wide wavelength range. Solar flares are usually accompanied by coronal mass ejections (CMEs); therefore they could significantly affect the space environments between the Earth and the Sun.

At present, we do not fully understand the whole flare process. There are still many important questions to be resolved, such as when and where is the energy released? How long does the energy release last? What are the main ways of energy release? And how does the solar atmosphere respond to the energy release? To address these questions, we study in detail the flare heating and dynamic evolution. We first give a brief review of previous flare studies (Chapter 1), and introduce the observing instruments (Chapter 2) and the modeling method (Chapter 3) related to this thesis work. Then we use spectral data to investigate the chromospheric evaporation (Chapter 4). Based on the results, we further explore the flare heating problem. With observationally inferred heating functions, we model two flare loops, and compare the results with observations (Chapter 5). A consistency is achieved between modeling and observations. In addition, we model two different sets of flare loop systems with quite different heating profiles and dynamic evolutions (Chapter 6). The details are described as below.

Firstly, we investigate the chromospheric evaporation in the flare on 2007 January 16 using line profiles observed by the Extreme-ultraviolet (EUV) Imaging Spectrometer (EIS) on board Hinode. Three points with different magnetic polarities at flare ribbons are analyzed in detail. We find that the three points show different patterns of upflows and downflows in the impulsive phase of the flare. The spectral lines at the first point are mostly blueshifted, with the hotter lines showing a dominant blueshifted component over the stationary one. At the second point, however, only weak upflows are detected; instead,

notable downflows appear at high temperatures (up to 2.5–5.0 MK). The third point is similar to the second one except that it shows evidence of multi-component downflows. While the evaporated plasma falling back down as warm rain is a possible cause of the redshifts at the second and third points, the different patterns of chromospheric evaporation at the three points imply the existence of different heating mechanisms in the flaring region.

Then, we study the flare heating and dynamics using the "enthalpy-based thermal evolution of loops" (EBTEL) model. We analyze an M1.0 flare on 2011 February 16. This flare is composed of two distinctive loop systems observed in EUV images. The UV 1600 Å emission at the feet of these loops exhibits a rapid rise, followed by enhanced emission in different EUV channels observed by the Atmospheric Imaging Assembly (AIA) on board the Solar Dynamics Observatory (SDO). Such a behavior is indicative of impulsive energy deposit, and the subsequent response of overlying coronal loops. Using the method recently developed, we infer empirical heating functions from the rapid rise of the UV light curves for the two loop systems, respectively, treated as two big loops with cross-sectional area of $5''$ by $5''$, and compute the plasma evolution in the loops using the EBTEL model. We further compute the synthetic EUV light curves, which, with the limitation of the model, agree reasonably with the observed light curves obtained in multiple AIA channels and EIS lines: they show the same evolution trend, and their magnitudes are comparable within a factor of two. We also compare the computed mean enthalpy flow velocity with the Doppler shifts of EIS lines during the decay phase of the two loops. Our results suggest that the two different loops with different heating functions as inferred from their footpoint UV emission, combined with their different lengths as measured from imaging observations, give rise to different coronal plasma evolution patterns as revealed in both models and observations.

With the same method, we further analyze another C4.7 flare. From AIA imaging observations, we can identify two sets of loops in this event. EIS spectroscopic observations reveal blueshifts at the feet of both sets of loops during the impulsive phase. However, the dynamic evolutions of the two sets of loops are quite different. The first set of loops exhibits blueshifts ($\sim$10 km/s) for about 25 minutes followed by redshifts, while the second set shows stronger blueshifts ($\sim$20 km/s) which are maintained for about an hour. The long-lasting blueshifts in the second set of loops are indicative of continuous heating. The UV 1600 Å observation by AIA also shows that the feet of the loops brighten twice with 15 minutes apart. The first set of loops, on the other hand, brighten only once in the UV band. We construct heating functions of the two sets of loops using spatially resolved UV light curves at their footpoints, and model plasma evolution in these loops with the EBTEL model. The results show that, for the first set of loops, the synthetic EUV light curves from the model compare favorably with the observed light curves in six AIA channels and eight EIS spectral lines, and the computed mean enthalpy flow velocities also agree with the Doppler shifts measured in EIS lines. For the second set of loops modeled with twice-heating, there are some discrepancies between modeled and observed EUV light curves at low-temperature lines, and the model does not fully reproduce the prolonged blueshift signatures as observed. The prominent discrepancies between model and observations for the second set of loops may be caused by non-uniform heating localized especially at the loop footpoints which cannot be modeled by the 0D EBTEL model, or by unresolved fine flaring strands in the loops with quite different heating rates and profiles.