亮点

从磁绳的日面足迹揭示日冕物质抛射内部磁通量的演化特征

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摘要 作为太阳大气中最剧烈的大尺度爆发性磁活动, 日冕物质抛射是引发近地灾害性空间天气的首要驱动源. 时至今日, 在爆发过程中, 日冕物质抛射内部轴向磁通量的详细演化特征尚不明确. 近期, 国内太阳物理学者提出了一种优化的识别方法, 成功提取并研究了日冕物质抛射主体磁绳结构在太阳表面的足迹及其完整变化信息, 发现爆发磁绳的轴向磁通具有先快速增大, 随后逐渐减小的演化特征, 且与伴生耀斑的能量释放过程具有很好的时间对应性. 这一研究定量地给出了日冕物质抛射爆发过程中内部磁场参量的变化规律, 对理解日冕物质抛射的三维爆发过程有着重要的意义.

关键词 太阳活动, 日冕物质抛射, 太阳耀斑

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日冕物质抛射是太阳大气中频繁发生的大规模物质喷射现象, 每次抛射能够快速向行星际空间释放大量的磁化等离子体(10^7 – 10^{10} t)和能量(10^{29} – 10^{32} erg), 并可能强烈扰动与人类高科技活动密切相关的地球空间环境, 引发灾害性空间天气^[1]. 日冕物质抛射经常与太阳耀斑相伴发生, 两者均由太阳磁场演化所驱动, 被解释为同一能量释放过程的两种不同表现形式^[2,3].

在标准太阳爆发理论框架下^[2,3], 日冕物质抛射的主体结构由扎根于太阳光球的扭缠磁力线构成, 通常被形象地描述为磁绳^[4,5]. 磁绳的形成过程可能与太阳大气中磁场能量与磁场螺度的持续累积过程密切相

关^[4–6]. 磁绳的整体磁通量由环向磁通和轴向磁通两部分构成, 其中轴向磁通是研究磁绳起源的重要物理参量, 其变化影响着日冕物质抛射的后续演化. 然而, 在真实的观测中, 想要测量爆发磁绳的轴向磁通变化却并不容易.

鉴于日冕磁场测量的困难^[7–9], 不少科学家意识到如果能够认证爆发磁绳的日面足点并准确识别出其几何截面, 那么便有望结合可靠的光球磁场测量^[10]实现对日冕物质抛射内部磁绳轴向磁通变化的定量测定^[11–13]. 根据现有太阳爆发理论, 太阳物理学家通常利用以下两种方式来确定爆发磁绳的足点区域: (1) 利用

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色球双带耀斑尽头的钩状结构认证磁绳足点区域范围. 一方面, 数值模拟^[14,15]预言磁绳的足点多扎根于磁场准分界面足印包围的范围内, 而准分界面足印在观测中被发现与色球双带耀斑具有很好的空间对应性^[16]. 另一方面, 观测工作也直接表明爆发磁绳的足点的确经常被耀斑带的钩状尽头包围^[17]. 因此, 人们通常认为耀斑带尽头的钩状部分包围的区域就对应着磁绳足点区域^[13-17]. (2) 利用双子日冕暗化区认证磁绳的足点区域. 日冕物质抛射发生时, 爆发磁绳会发生快速的拉伸与膨胀, 导致低日冕中物质密度下降, 形成辐射强度下降的日冕暗化区^[18-20]. 其中, 成对出现在极性反转线两侧的双子暗区, 也被建议当作指示爆发磁绳足点区域的特征结构^[18,21,22].

在实际的观测应用中, 采用以上两种方法均会遇到一些棘手的问题. 如第一种方法, 在许多耀斑事件中其色球耀斑带尽头的钩状结构往往并不是闭合的, 特别在耀斑上升相这种情形更加显著, 因而在钩状结构开口处难以确定磁绳足点区域的边界. 在第二种方法中, 双子暗化区缺少明确的物理边界, 需要基于其变暗程度人为设定阈值限定其边界. 由于以上方法的局限性, 要准确地识别出爆发磁绳足点区域在爆发期间的完整变化信息亟需更加合理的新方法.

为解决这一问题, 南京大学Xing等人^[23]近期提出了一种新的磁绳足点区域识别方法. 这一识别方法同时考虑色球耀斑带尽头的钩状结构和双子暗化区, 以区域生长和形态学梯度算子更加合理地确定了对应于磁绳足点区域日冕暗区的范围, 而且能够普遍适用于耀斑带钩状结构部分封闭或半封闭的情况. 凭借这一优化的方法, 他们准确提取并定量研究了4个典型日冕物质抛射事件爆发阶段的磁绳轴向磁通的完整演化

信息, 发现其磁绳轴向磁通在爆发过程中均呈现出先快速增加, 后逐渐减小的演化特征, 与对应耀斑的软X射线流量具有基本类似的变化趋势. 特别地, 轴向磁通的快速增加过程都发生于耀斑脉冲相, 意味着磁绳轴向磁通的增加与耀斑主要能量释放过程直接相关. 这一结果对于理解日冕物质抛射内部磁通的演化特征有着重要的科学意义.

近期, 法国太阳物理学者Aulanier和Dudík^[24]利用磁流体力学数值模拟研究了磁绳三维爆发过程涉及的磁场拓扑变化, 发现存在三类磁重联过程: 背景磁场间的重联、磁绳内部磁场间的重联, 以及磁绳与背景磁场的重联. 其中, 第一类重联可能同时增加磁绳的轴向与环向通量; 第二类重联能同时引发磁绳环向磁通增加和轴向磁通的减少; 第三类重联虽不会引起磁绳轴向磁通的变化, 但能导致磁绳足点位置的迁移^[25-27]. 结合此项三维模拟进展, 上述的观测研究^[23]发现的磁绳轴向通量的先增加后减少的演化特征, 有可能分别对应了背景场之间的重联过程和磁绳内部的重联过程. 需要指出的是, 观测表明第三类重联经常在日冕物质抛射现象中发生^[25-28], 它在引发磁绳足点空间位置迁移的同时, 还会驱动双带耀斑尽头的钩状结构发生复杂的往返运动^[22,24]. 对于此类磁绳足点迁移事件, 是否仍能利用双带耀斑尽头的钩状结构和双子暗化区准确地认证爆发磁绳的足点区域有待进一步确认^[24,25].

爆发磁绳的环向与轴向磁通的比值反映了磁绳的扭缠程度, 在日冕物质抛射的演化中发挥着重要的作用^[4,5]. 想要全面了解日冕物质抛射爆发期间磁绳内部的轴向与环向磁场通量的演化规律, 不仅需要进一步结合行星际磁场的原位探测等重要手段^[11-13], 同时还必须开展观测数据驱动的磁流体力学模拟研究^[29,30].

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Evolution of the toroidal flux of solar coronal mass ejections derived by tracing their on-disk footpoints

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As the most violent large-scale explosive phenomenon in the solar atmosphere, coronal mass ejections (CMEs) are the main source of disastrous space weather in our solar-terrestrial environment. Detailed evolution of the toroidal magnetic flux inside CME flux ropes is still poorly understood. Recently, researchers from Nanjing University developed a new method to achieve a better identification of the footpoint regions of erupting CME flux ropes. Applying this new method, they successfully obtained and further quantitatively investigated the evolution of toroidal flux of four erupting flux ropes. They found that the toroidal flux of CME flux ropes experiences a rapid increasing phase followed by a decreasing phase. Such a two-phase evolution of toroidal flux is generally synchronous with the energy release process in CME-associated solar flares. This study provides a quantitative assessment of the variation of the toroidal flux of CME flux ropes during their eruptions, which is of vital significance for understanding the three-dimensional nature of CMEs.

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