螺环不稳定性对日冕物质抛射至关重要吗?

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作为主序星的太阳,其内部结构大体是稳定的.核心区的氢聚变反应为太阳提供了持续而比较恒定的能源,维持其 3.828×10^{26} W 的电磁辐射、 8.8×10^{24} W 的中微子辐射,以及往外输运的太阳风.然而,由于原初磁场^[1]以及太阳表面以下 0.3 倍半径范围内(即对流区)较差自转的存在,在发电机过程^[2]及磁扩散的共同作用下,对流区底部的磁场发生着周期性的变化.当其磁场强到一定程度,便会经由太阳表面而浮现到太阳大气中,并导致各种空间尺度和不同能量的爆发现象,如太阳耀斑、暗条爆发、日冕物质抛射等.其中,日冕物质抛射是尺度最大的剧烈爆发现象,质量高达 $10^{11} \sim 10^{13}$ kg 的物质携带着磁场以几十到 4000 km/s 的速度在行星际空间传播^[3,4].当它掠过地球时,会产生地磁扰动,强烈时严重影响人造卫星的正常运行、短波通讯、导航以及高纬度的电网.因此,对日冕物质抛射的触发及爆发机制的研究非常重要.这种研究不但对发生在其他恒星乃至吸积盘上的爆发过程有借鉴作用,也能够为预报地球周围的空间环境可能出现的灾害性扰动提供物理基础.国内很多研究组都在从事日冕物质抛射方面的研究工作^[5].

由于观测表明大多数日冕物质抛射源于日冕中暗条的爆发^[6]并伴随耀斑爆发,所以对日冕物质抛射的理论建模通常都会提及磁绳、暗条和耀斑^[7,8].在对日冕物质抛射的建模过程中,直到 20 世纪 90 年代初仍有不少人认为:只要爆发源区磁场的扭缠或剪切足够强,日冕物质抛射便可以在理想磁流体力学(即磁重联)的情况下爆发出去,并在其下方拉出电流片,而耀斑则是电流片形成后经由磁重联而得到的可有可无的后果.但是,1991 年, Aly^[9]和 Sturrock^[10]两人独立地发现:只要磁力线在日冕中是简单地连接(即磁力线不打结或不是自身封闭),在磁力线都固结在太阳表面的情况下,磁力线完全打开到无穷远处的状态其实对应的是磁能最高的状态.这就意味着,无论爆发源区磁场多么扭缠或剪切,它不可能不经过磁重联过程而爆发.此后,磁重联的作用逐渐被推上舞台中心^[11].

2005 年,德国学者认为,在托卡马克研究中提出来的螺环不稳定性(即 torus instability)对日冕物质抛射至关重要^[12]:只要背景水平磁场随高度衰减的速度(由衰减指数 $\frac{\partial \ln B_h}{\partial \ln r}$ 来表征,其中 B_h 代表磁场 B 的水平分量, r 代表径向

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距离)大于某个阈值,爆发就会发生.此后,螺环不稳定性被当作决定暗条爆发与否的重要参数.在过去的 14 年里,共有 510 余篇研究螺环不稳定性在日冕物质抛射爆发中的作用,其中 170 余篇由国内各天文台和各大大学发表,也就是说,中国学者在这方面贡献了约 1/3 的文章.因为螺环不稳定性(即磁重联)和二十世纪八九十年代研究得比较多的磁流体力学失衡(loss of equilibrium)机制本质一样^[13],所以,一方面,笔者觉得螺环不稳定性确实和其他触发机制一样,都是日冕物质抛射可能的触发机制之一;另外一方面,我又怀疑螺环不稳定性是否真的如那么多文章声称的那样起决定性作用,而且这方面的研究方法也有需要改进的地方.以下是我的个人观点.

(1) 螺环不稳定性只是各种触发机制的一种.源区磁场从其亚稳态过渡到爆发状态时,其触发机制可能是理想磁流体力学过程(如扭曲不稳定性、螺环不稳定性^[14]等),也可能是非理想磁流体力学过程(即磁重联)^[15-17].如文献[18]指出,似乎活动区暗条更容易被磁重联触发,而宁静区暗条更容易被理想磁流体不稳定性触发.文献[19]也表明,爆发的发生是多个磁系统相互作用导致的.

(2) 螺环不稳定性只可能是日冕物质抛射的触发机制,而不是爆发机制.正如文献[4]指出的那样,日冕物质抛射是否发生既有外因(如光球层剪切运动、新浮现流、背景磁场分布等),也有内因(如源区磁场的非势自由能、螺度等).螺环不稳定性作为一种触发机制,它可以使得暗条(或核心磁场)上升,并在暗条下方拉出电流片,但它自身无法让暗条爆发到行星际空间,因为这与 Aly-Sturrock 极限矛盾(除非该极限是错误的).换言之,即使从低日冕到行星际

空间背景磁场的衰减指数处处大于阈值,暗条也不可能因为螺环不稳定性而抛射到行星际空间.正如磁场失衡模型的研究工作所指出:磁绳的灾变发生后,磁绳在更高的位置存在一个新的平衡位置.从初始平衡位置跃迁到新的平衡位置是可能的,并伴随部分磁能的释放,但真正让暗条实现完全爆发,很可能还需要磁重联(或暗条物质回落).从这个意义上讲,我不是很赞同文献[20]把螺环不稳定性当作日冕物质抛射的爆发机制的说法.而且,我注意到很多文章在强调螺环不稳定性时,磁重联已经发生了.因此,我想强调的是,目前很多观测无法将理想磁流体力学不稳定性与磁重联的作用分割开.我们也许需要更大的望远镜和新的探测技术^[21]来提供高时空分辨率的多波段观测数据.

(3) 计算背景磁场衰减指数时最好考虑横向磁场衰减的梯度.很多文章在研究螺环不稳定性时计算的是背景横

向磁场沿着某个方向(主要是竖直方向)的衰减指数.由于暗条经常不是竖直向上抛射,因此比较好的方法是计算磁场的梯度场,即计算背景磁场每一个点的 $\frac{\partial B_{\parallel}}{\partial x}$ 和 $\frac{\partial B_{\parallel}}{\partial y}$,得到每一点的横向磁场衰减梯度^[22].这样做不但更为准确,也可以借此判断暗条爆发的方向,并与暗条实际抛射方向进行定量比较.

(4) 研究磁绳顶部处的背景磁场衰减指数可能是有问题的.在螺环不稳定性的理论推导过程中,磁场位形采用二维坐标,磁绳是自身封闭的.而在实际日冕中,磁绳是固结在太阳表面的.现在发表的大部分文章只关心磁绳顶部处的背景磁场衰减指数,然而对一个磁绳而言,其局部满足失衡条件并不等于整体会爆发.我们也许应该将磁绳更大范围处的背景磁场衰减指数纳入考虑范围.

致谢 国家自然科学基金(11533005, 11961131002)和江苏省 333 工程(BRA2017359)资助.

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Summary for “螺环不稳定性对日冕物质抛射至关重要吗?”

Is torus instability crucial for solar coronal mass ejections?

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Coronal mass ejections (CMEs) are the most violent eruptions in the solar atmosphere. What are the progenitors? How are the progenitors triggered to erupt? How are CMEs accelerated and how do they propagate in the interplanetary space? All these issues still remain elusive. In particular, a lot of efforts have been taken to the triggering mechanisms. From both theoretical and observational points of view, a CME progenitor can be triggered from a metastable state to eruption through either a resistive process, e.g., magnetic reconnection, or ideal magnetohydrodynamic (MHD) instabilities, e.g., kink and torus instabilities. About thirty years ago, it was once thought that CMEs can be due to an ideal MHD process, which opens up the initially closed magnetic loops, and the ensuing magnetic reconnection leads to a solar flare, which is dispensable for the CMEs. Considering the Aly-Sturrock constraint and the intimate correlation between CMEs and flares, it was then realized that magnetic reconnection may play a crucial role later. However, in the past fourteen years, there was an increasing trend to emphasize torus instability in CMEs, not only for their triggering, but also for the final eruption. On one hand, we believe that torus instability, as well as kink instability and magnetic reconnection, is one of the possible trigger mechanisms for CMEs; on the other hand, we are suspicious of some papers on how the torus instability was identified. Our main arguments are summarized as follows:

(1) Torus instability is only one of the trigger mechanisms. Other mechanisms may work as well, and sometimes several mechanisms may be at work simultaneously. Therefore, it is not surprising at all that a CME erupts while the criterion of torus instability is not satisfied.

(2) Torus instability can serve as a trigger mechanism, but presumably not a driven mechanism. Whether a CME can erupt or not depends on both external conditions, e.g., the background magnetic field, and internal conditions, e.g., the nonpotentiality of the core magnetic field in the source region and how fast the reconnection proceeds. Based on the Aly-Sturrock constraint, a line-tied flux rope can never erupt without reconnection or mass drainage even when the background magnetic field satisfies the criterion of torus instability everywhere from low corona all the way to the interplanetary space. When some papers claimed the key role of torus instability, magnetic reconnection was happening as well, which makes their conclusions unconvincing. So, it will be critical to distinguish resistive processes from ideal MHD instabilities in future studies.

(3) When studying the torus instability, it is better to calculate the 3-dimensional distribution of the decay index of the background magnetic field. Checking the decay index along one direction is not sufficient.

(4) When studying the torus instability, it might be meaningless to examine the decay index only at the apex of a flux rope. A local loss of equilibrium never means the catastrophe of a whole structure. We need to take in account the distribution of the decay index along the major part of the flux rope in the source region.

coronal mass ejections, magnetic reconnection, instabilities, magnetic field, magnetohydrodynamics

doi: 10.1360/TB-2019-0756