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On the Aly-Sturrock Paradox – A Puzzle of Magnetic Field Opening

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During a coronal mass ejection (CME), a closed pre-eruption magnetic field structure is distended outward and apparently opens up, at least in the coronagraph field of view. Because the time-scale of the CME field opening is considered to be shorter than the energy build-up time-scale of the eruption, the pre-eruption closed field must have more energy than the post-eruption open field. However, as far as force-free fields are concerned, such an energy ordering is allegedly forbidden according to the Aly-Sturrock theorem [1, 2]. The theorem states that the least upper bound of the energy of all closed force-free fields, which have the same boundary-normal field (B_n) distribution and are mutually accessible by continuous footpoint displacements conserving B_n in ideal MHD, is the energy of the corresponding open field. Even if we admit that the seemingly open configuration may extend only to a finite distance from the sun, this theorem allows a very tight energy budget for CMEs and eruptive flares. We will examine the proof procedure of the theorem by Aly and Sturrock and discuss in what situations the theorem can be validated. Particular attention is given to the limiting procedure in the energy-increasing sequence from the potential field to the open field. Counter-examples of the Aly-Sturrock theorem will be presented, which involve entwining multiple flux systems. An MHD simulation result supporting this argument will also be presented.

References

1. J. J. Aly, Astrophys. J., 375, L61–L64 (1991).
2. P. A. Sturrock, Astrophys. J., 380, 655-659 (1991).