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Energy Release and Coronal Dynamics in Solar Flares: Insights from 2D and 3D Magnetic Reconnection Models

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While multi-wavelength observations of solar flares from various ground- and space-based platforms have provided crucial insights into the temporal, spatial, and spectral characteristics of near-simultaneous energetic and dynamic processes occurring across different layers of the solar atmosphere, several complex aspects of these observations remain poorly understood and continue to challenge solar physicists. Historically, the formation of parallel ribbons and the development of an overlying large post-flare arcade across the polarity inversion line (PIL) have served as key observational foundations for the standard 2D model of eruptive solar flares [1]. In this model, the immense and abrupt energy release during solar flares is attributed to large-scale magnetic reconnection occurring in a vertical current sheet, triggered by the eruptive expansion of a magnetic flux rope (MFR) in the solar corona. Notably, with the advent of X-ray imaging observations from Yohkoh in the 1990s, the detection of plasmoids led to a broader generalization of this classical reconnection scenario [2]. This gave rise to the unified model of solar flares—also known as the plasmoid-induced reconnection model—which extends the reconnection framework of the standard model to both eruptive and confined flares. In this unified model, plasmoid ejections trigger the inflow of magnetic fields into the current sheet, thereby promoting fast magnetic reconnection.

Contemporary observations have revealed significant departures from the classical flare scenario, marked by the identification of a new subclass known as circular ribbon flares [3]. In these events, one of the flare ribbons exhibits an almost completely closed, quasi-circular or quasi-ellipsoidal morphology. In the simplest configuration, the underlying photospheric magnetic field consists of a parasitic polarity embedded within an oppositely signed, larger-scale dipolar active region.

We present a series of complex circular ribbon flare events that not only display the characteristic circular ribbons but also exhibit additional features such as parallel ribbons, remote brightenings, and associated jet activity [4]. These diverse morphological signatures are interpreted within the framework of the topological structure associated with a three-dimensional magnetic null point. Furthermore, we report on more intricate cases of homologous quasi-circular ribbon flares, where observational evidence suggests the involvement of a more complex geometrical structure — the hyperbolic flux tube (HFT) — in the magnetic reconnection process [5].

Our analysis of these events offers valuable insights into the underlying magnetic conditions and reconnection dynamics that drive both eruptive and non-eruptive solar phenomena. These investigations also prompt a broader exploration of analogies in the onset mechanisms of solar jets, confined flares, and coronal mass ejections (CMEs), underscoring the critical role of complex magnetic topology in governing solar eruptive activity [6,7].

References

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