Downward catastrophe of solar magnetic flux ropes: another cause of flares?

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Abstract

Study about the evolutions of coronal magnetic flux ropes has important significance in understanding solar energetic activities. In previous studies, it is suggested that there exist a catastrophe, where the flux rope quickly jump upward from sticking to the solar surface to suspending in the corona. This catastrophe is believed to be an efficient mechanism for the solar eruptive activities, such as flares and coronal mass ejections. All the previous studies about the catastrophe, however, only discussed about the catastrophe with upward motions. In this paper, we mainly focus on the downward catastrophe, both its existence and properties. From the simulation in force free magnetic field under a partially open bipolar magnetic configuration, we found that, as well as the upward catastrophe, there was also a catastrophic loss of equilibrium where the flux rope fell back to the solar surface, indicating that this is a downward catastrophe. Although the moving directions are opposite, there are magnetic energies released by both the upward and downward catastrophe. This indicates that these two catastrophes are similar physical processes, and downward catastrophe could be an appropriate cause of energetic but non-eruptive activities, such as confined flares.

Basic principles

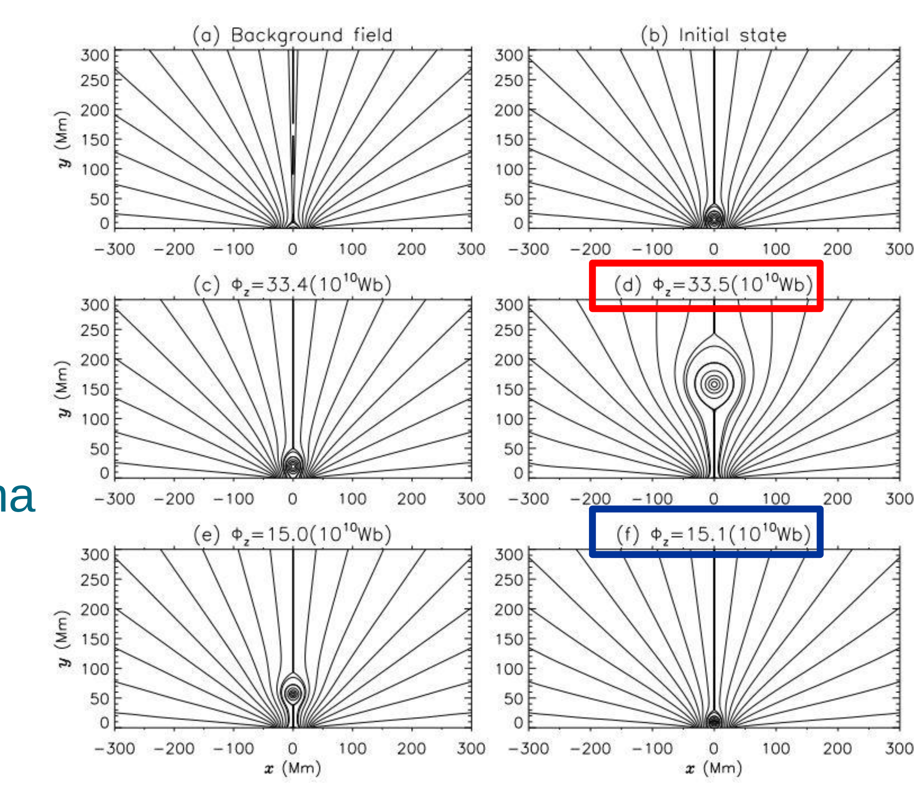
- Control parameters (**CP**)
  - Characteristic parameters describing the magnetic configuration
  - e.g. annular flux ψ_p and axial flux ψ_z of the flux rope
- Geometric parameters (**GP**)
  - e.g. height of the rope axis, length of the current sheet below the flux rope
  - Describing the equilibrium states of the flux rope
- We focus on the evolution of the ***equilibrium states*** (described by **GP**) of the flux rope versus varying **CP**
- A 2.5-Dimensional simulation, with $\frac{\partial}{\partial z} = 0$

What is catastrophe?

- Equilibrium states
  - The solutions of the force balance equation $F = 0$, vary with different **CP**
  - Might vanish for certain **CP** under certain magnetic configurations
- If there exists catastrophe:
  - After **CP** reaches a critical value, equilibrium states of the system will cease to exist in current configuration
  - The system will quickly evolves to a new magnetic configuration where exists equilibrium states, usually manifested as a sudden jump of **GP**
- Catastrophe: catastrophic loss of equilibrium states

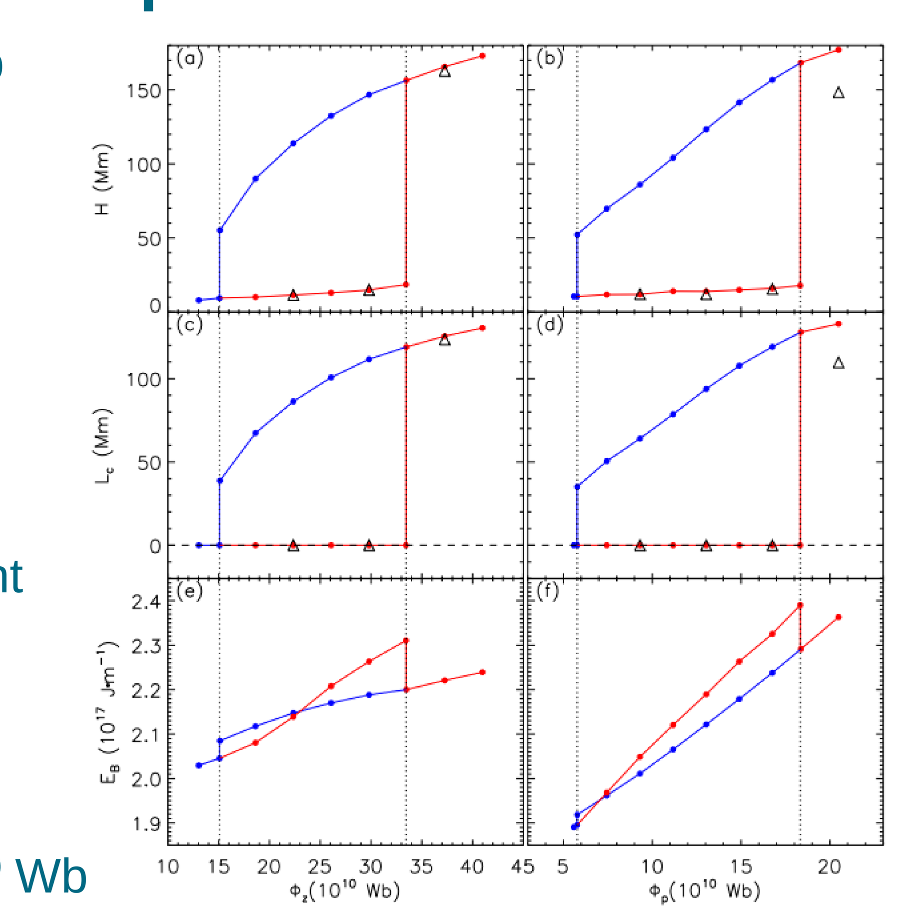
Background field

- Background magnetic fields:
  - Partially opened bipolar field
  - Two branches of equilibrium states
- Lower branch (**LB**):
  - The flux rope sticks to photosphere
- Upper branch (**UB**):
  - The flux rope suspends in the corona
- Relaxation method is utilized to obtain force-free solutions
- Catastrophes are manifested as jumps between **LB** and **UB**



Upward and downward catastrophes

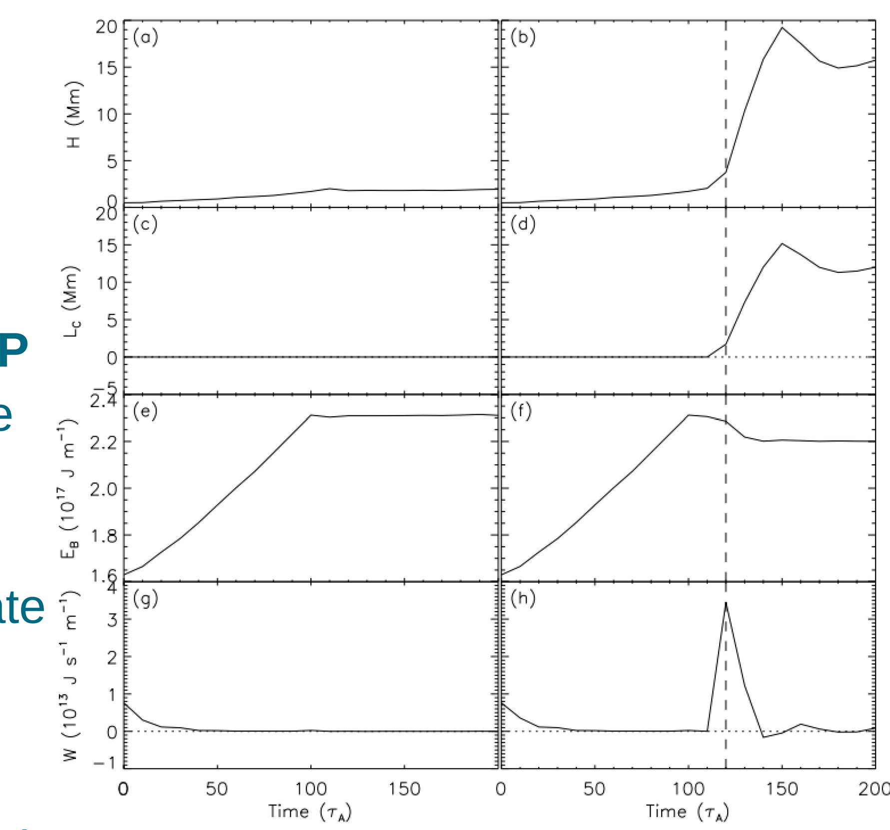
- The equations are solved by Multistep Implicit Scheme (Hu, 1989)
- Abscissa: **CP**
  - Left : axial flux ψ_z
  - Right : annular flux ψ_p
- Ordinate: **GP**
  - Describing the equilibrium states
  - Top: height of the rope axis
  - Middle: length of the vertical current sheet below the flux rope



- **Upward** catastrophe:
  - Correspond to the **RED** points
  - Catastrophic point (ψ_z): **33.5**$\times 10^{10}$ Wb
  - From **LB** to **UB**, Irreversible process
- **Downward** catastrophe of ψ_z :
  - Correspond to the **BLUE** points
  - Catastrophic point (ψ_z): **15.1**$\times 10^{10}$ Wb
  - From **UB** to **LB**, also irreversible
- Bottom: evolution of magnetic energies of the system
  - Magnetic energies are released
  - During both the upward and downward catastrophes

Work done by Ampere Force

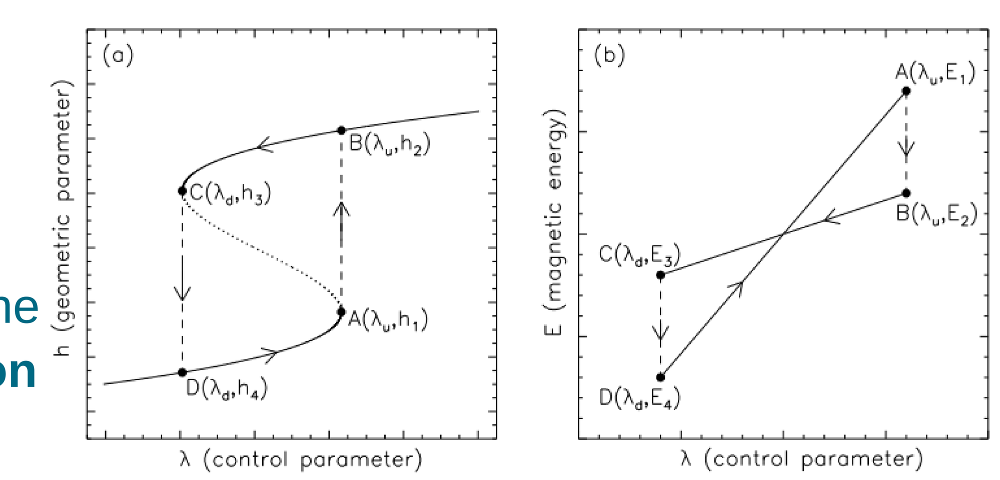
- A simulation step:
  - 0~100 τ_A: **CP** slowly and smoothly evolves to a certain value
  - 100~200 τ_A: The system evolves to ***equilibrium states*** with conserved **CP**
- Left: simulation step from the initial state to the state with $\psi_z = 33.4\times 10^{10}$ Wb (before upward catastrophe)
- Right: simulation step from the initial state to the state with $\psi_z = 33.5\times 10^{10}$ Wb (after upward catastrophe takes place)



- Reconnection is prohibited in the simulation
- In this simulation, the work done by Ampere Force (W, bottom panel) is the mechanism by which magnetic energies are released during catastrophes
- Downward catastrophe has similar results

Conclusion

- There exist two catastrophes
- The equilibrium states are multiple when **CP** is between the two catastrophic points
- These two catastrophes connect the two branches, forming a **circulation**



- Magnetic energies:
  - Stored with increasing **CP** ($D \rightarrow A$)
  - Released both with decreasing **CP** ($B \rightarrow C$)
  - Released during both the upward and downward catastrophes
  - The work done by Ampere Force is the mechanism for energies to release
- Work done by Ampere Force (W, bottom panel) should be the mechanism by which magnetic energies are released in the simulation
- Downward catastrophe is energetic (10^{23}~10^{24} J) but non-eruptive, from which we might infer that it could be another cause of confined flares

Appendix——Catastrophe model

- The large-scale catastrophe behaviors (a sudden jump of **GP**) are triggered by small-scale motions (reaching the critical **CP**)
- Magnetic energies are released by not only reconnection, but also the work done by Ampere Fore during catastrophe
- Upward catastrophe (time scale ~$v_A{}^{-1}$) could provide current sheet for fast reconnection, whose dissipative rate is rather large
- Downward catastrophe might be another cause of confined flares

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