Evolution of the critical torus instability height and CME likelihood in active regions

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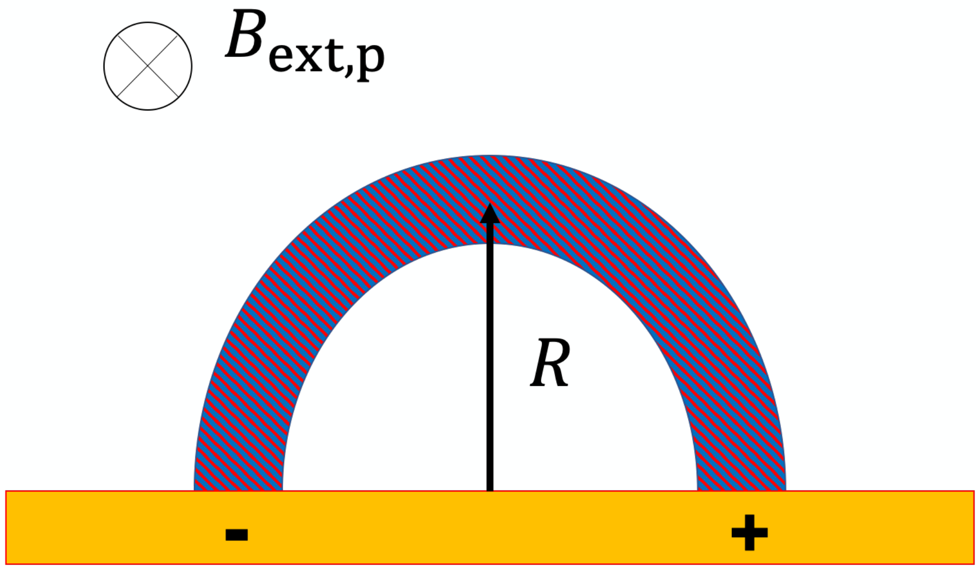
ESPM-16, 06/09/2021

CMEs and the torus instability

Coronal Mass Ejections (CMEs) drive extreme space weather, but we are unable to accurately predict them. What drives CMEs?



Magnetic flux ropes carry electric currents and expand via the hoop force. This can be balanced by the confining effect of an external poloidal magnetic field ($B_{\mathrm{ext,p}}$) e.g. tension from overlying loops.

Where $B_{\mathrm{ext,p}}$ drops off sufficiently rapidly in height, a perturbation will cause runaway expansion of a flux rope. This is the **torus instability** (Kliem & Török, 2006); a proposed driver of CMEs.

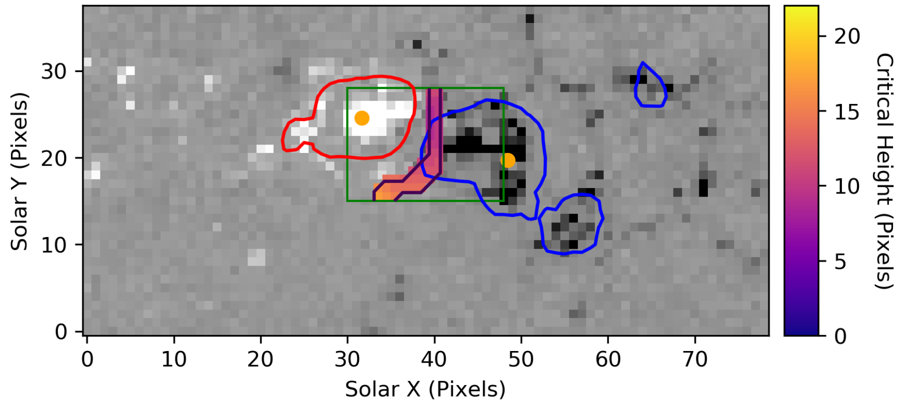
The **decay index**, n, quantifies how rapidly $B_{\mathrm{ext,p}}$ changes with varying radius, R, of a torus.

$$\boxed{n = -\frac{R}{B_{\mathrm{ext,p}}}\frac{dB_{\mathrm{ext,p}}}{dR}}$$

The critical value for instability in an arched flux rope is $n_{\mathrm{c}} = 1.5$.

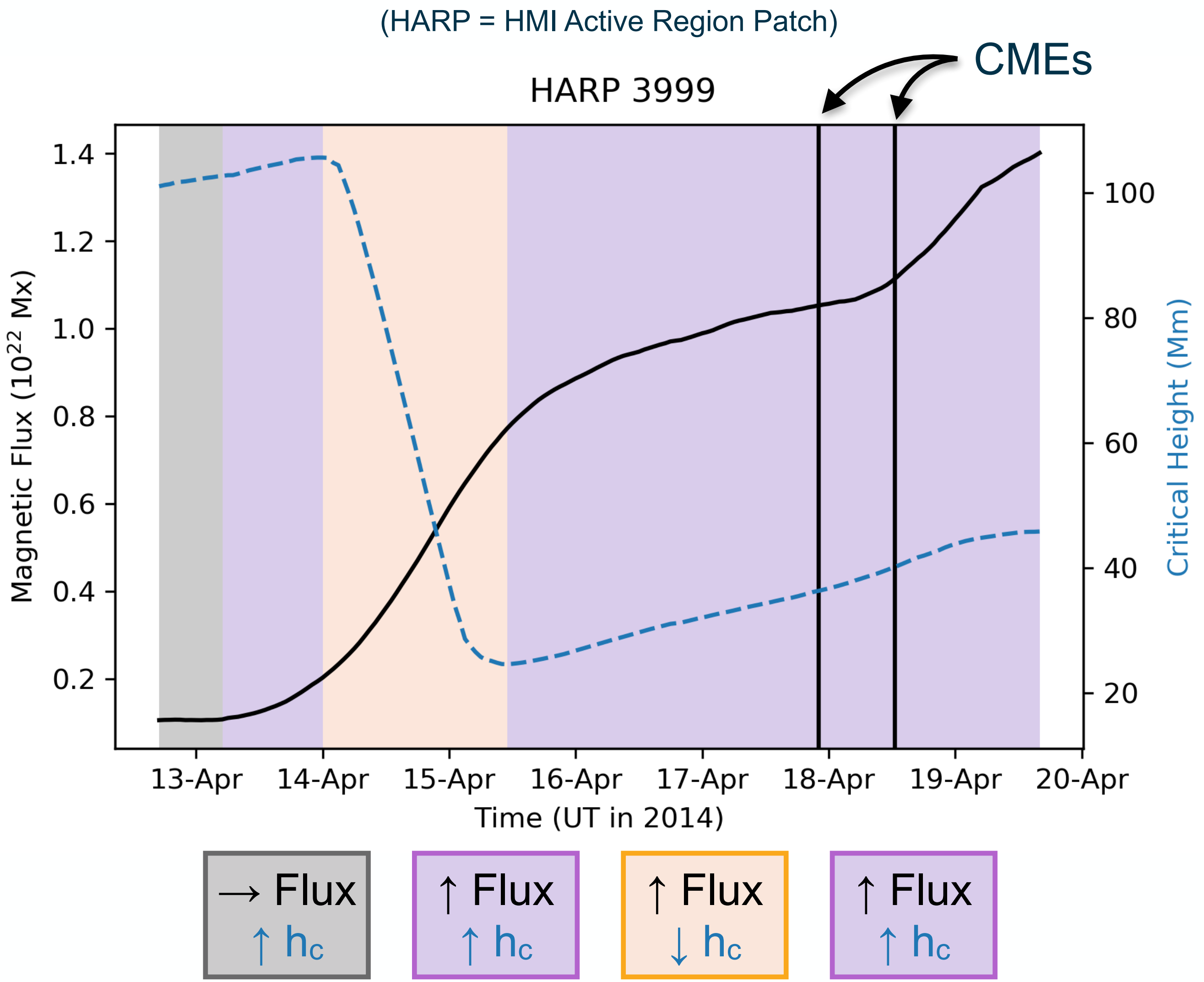
Evolution of critical height and magnetic flux

We model the B_{ext} of 43 active regions with potential field extrapolations at a cadence of 1 hour and calculate the **critical height,** $h_{\mathrm{c}} = h(n = 1.5)$, above central polarity inversion lines.



We identify **phases** of active region evolution as periods where the average critical height and unsigned magnetic flux are increasing or decreasing.

Do CMEs occur more often in certain phases?



Observations

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We total the number of hours and CMEs observed in each type of phase across the 43 active regions.

Number of Hours		Critical Height: Increasing	Critical Height: Decreasing
Flux	Increasing	2459	1286
Flux	Decreasing	1982	1129

Number of CMEs		Critical Height: Increasing	Critical Height: Decreasing
Flux	Increasing	21	14
Flux	Decreasing	5	9

Most CMEs per unit time when **magnetic flux is increasing and critical height is decreasing**.

Fewest CMEs per unit time when **magnetic flux is decreasing and critical height is increasing**.

Number of CMEs per 100 Hours		Critical Height: Increasing	Critical Height: Decreasing
Flux	Increasing	0.85	1.09
Flux	Decreasing	0.25	0.80

Critical height at CME onset

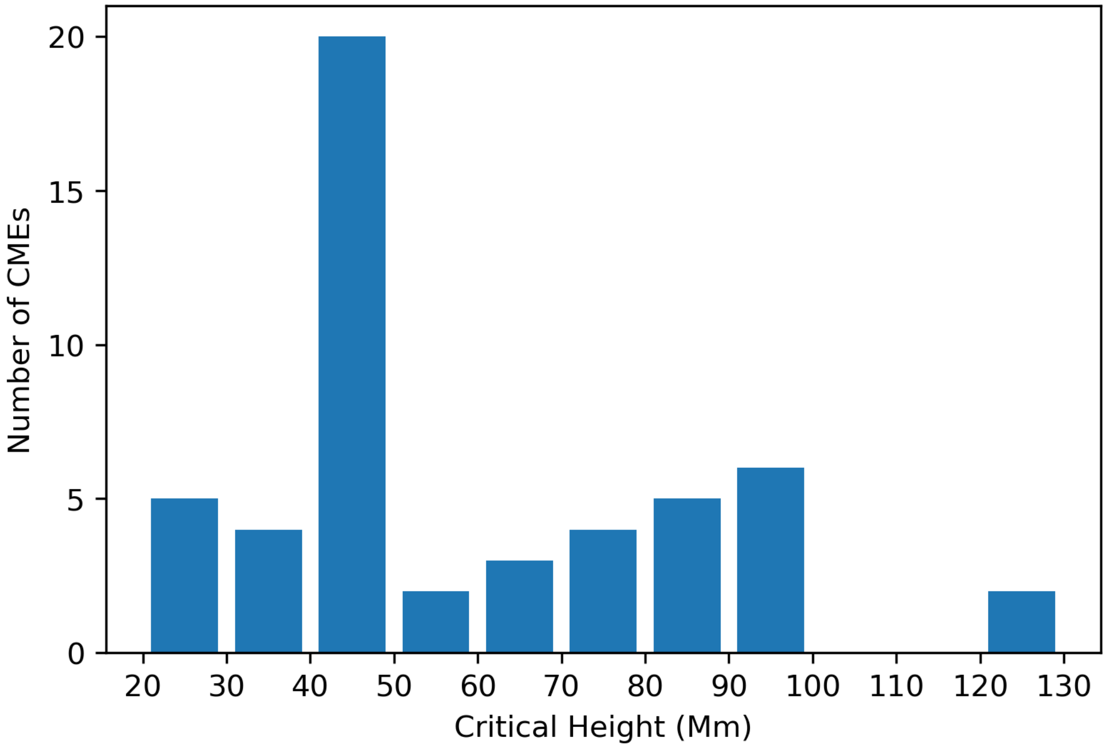
We record the critical height (h_c) from the modelled field that is closest to the onset time of each CME.

h_c is **most commonly between 40 and 50 Mm**.

Range: $24 - 126\ \mathrm{Mm}$

$\overline{h_c} = 59 \pm 25\ \mathrm{Mm}$

Median $h_c = 48\ \mathrm{Mm}$



$\overline{h_c} = 36.3 \pm 17.4\ \mathrm{Mm}$ (Wang et al. 2017, eruptive flares)

$\overline{h_c} = 20.9 \pm 9.5\ \mathrm{Mm}$ (Baumgartner et al. 2019, eruptive flares)

$\overline{h_c} = 58.0 \pm 33.6\ \mathrm{Mm}$ (Cheng et al. 2020, hot channel eruptions)

$\overline{h_c} = 118.3 \pm 47.4\ \mathrm{Mm}$ (Cheng et al. 2020, quiescent filament eruptions)

Critical height vs polarity separation

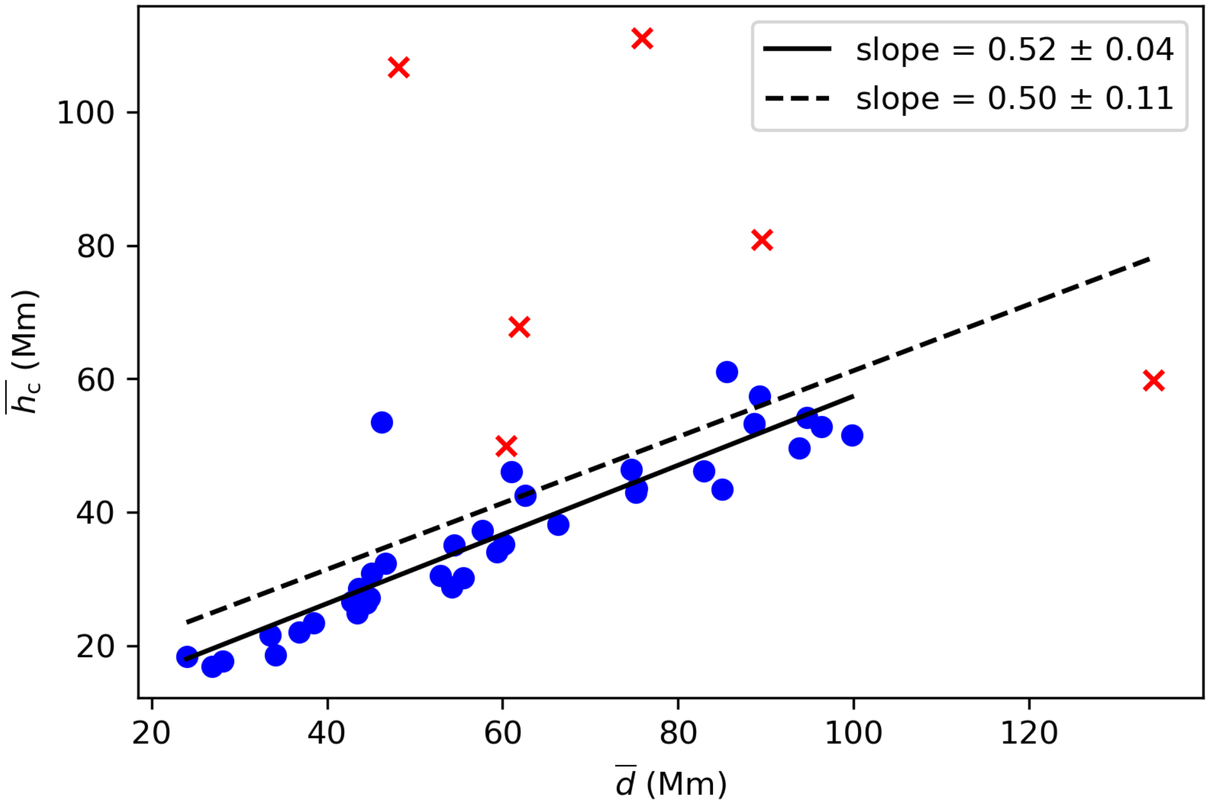
Previous studies found linear relationships between the critical height (h_c) and the separation of magnetic polarities (d) in active regions **at the times of flares**.

[Wang et al. (2017)]: $$\frac{h_c}{d} = 0.54$$

[Baumgartner et al. (2018)]: $$\frac{h_c}{d} = 0.4 \pm 0.1$$

We average h_c and d **over the observed life of each active region**. Fitting to 37 bipolar regions (where we quantify d most reliably), we find a slope of 0.52 ± 0.04.

We can use d as an observational proxy for h_c.



✕ = multipolar regions, ● = bipolar regions. Dashed line is fit to all regions, solid line is fit to only bipolar regions.

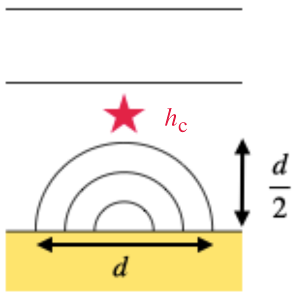
Conclusions

Highest CME rates when **magnetic flux is increasing and the critical torus instability height is decreasing** (**1.09** CMEs per 100 hours).

Lowest CME rates when **magnetic flux is decreasing and the critical torus instability height is increasing** (**0.25** CMEs per 100 hours).

CMEs occur commonly at critical heights (h_c) between 40 and 50 Mm, with a median of 48 Mm.

Extending previous studies, we find that $h_c \approx \frac{d}{2}$ **when averaged over the full lives of active regions** (d is the separation between magnetic polarities).



Forecasters and observation planners could **use h_c to identify regions that are more likely to produce CMEs**.

h_c can come from relatively fast potential field extrapolations, or from using d as an observational proxy.

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