Magnetic Flux Emergence Rates of Sunspots: Observations Compared to Simulations

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Abstract

- We report an easily measured quantity − the magnetic flux emergence rate of sunspots as observed with HMI on SDO − hoping the value can better inform us of how flux emerges into the solar atmosphere.
- A trend is seen; larger flux regions emerge faster than smaller ones. Rates ($d\Phi/dt$) scale with total peak flux as a power law $d\Phi/dt \approx \Phi_{max}^{0.36}$.
- These rates are put into context with previously observed & simulated rates.
- This may assist in constraining the choice of boundary and initial conditions in simulations that demonstrate that rates increase when a flux tube has higher buoyancy & twist, or is in the presence of a strong convective upflow.

Our Criteria to Select the Active Regions

- Must emerge and begin decay on front side of disk. These are small to mid-size ARs. No data within +/- 15 of limb.
- A threshold of 575 Mx cm^{-2} is applied; nothing below this is considered in order to minimize the 24 hr periodicities in HMI data due to orbital velocity.

Examples of Active Region Flux Ranges:

Ephemeral:	$3 \times 10^{18} - 1 \times 10^{20}$ Mx
Small AR:	$1 \times 10^{20} - 5 \times 10^{21}$ Mx
Mid-size AR:	$6 \times 10^{21} - 4 \times 10^{22}$ Mx
Large AR:	$\geq 4 \times 10^{22}$ Mx

The 10 sunspots have a range of 2 x 10^{21} (low) – 1 x 10^{22} Mx (high)

NOAA 11428, 2−11 Mar 2012, −17° Lat, 12 min cadence, 550×375 pixel

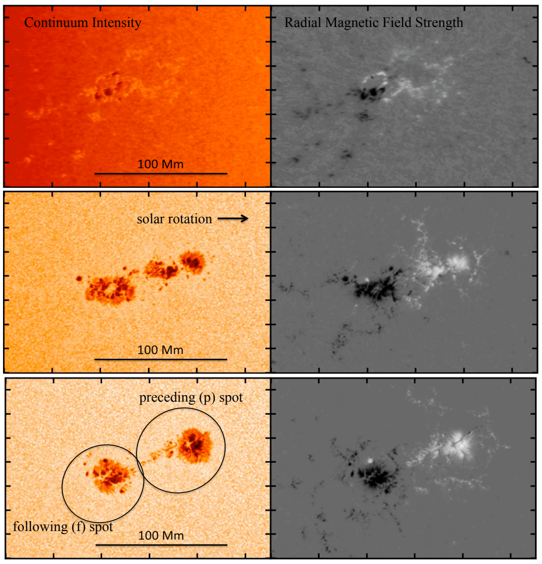

Fig 1. Snapshots of Flux Emerging

t = 2 hours

t = 50 hours

t = 60 hours

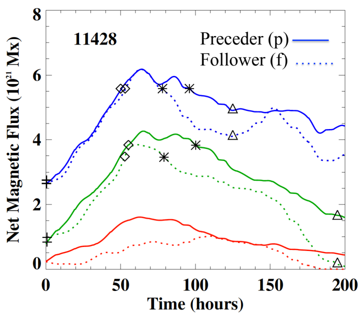

Fig 2. Observed Flux vs. Time

Flux in entire region/patch

Flux in penumbra & umbra

Flux in umbra only

Emergence begins (+) & ends (◇)
decay begins (*) & ends (△).

Rate of emergence & decay preceder flux, umbra + penumbra

$\tau_e = d\phi/dt = 4.6 \times 10^{19}$ Mx hr^{-1}

$\tau_d = d\phi/dt = -2.3 \times 10^{19}$ Mx hr^{-1}

Table 1: Sunspot Results (umbra & penumbra) **Region Results** (all flux in region)

p spot	ϕ_{max}	3.9×10^{21} Mx	p polarity	ϕ_{max}	6.0×10^{21} Mx
Emergence	τ_e	6.8×10^{19} Mx hr^{-1}	Emergence	τ_e	7.1×10^{19} Mx hr^{-1}
Decay	τ_d	-1.9×10^{19} Mx hr^{-1}	Decay	τ_d	-2.7×10^{19} Mx hr^{-1}
f spot	ϕ_{max}	3.3×10^{21} Mx	f polarity	ϕ_{max}	5.7×10^{21} Mx
Emergence	τ_e	4.9×10^{19} Mx hr^{-1}	Emergence	τ_e	7.1×10^{19} Mx hr^{-1}
Decay	τ_d	-3.4×10^{19} Mx hr^{-1}	Decay	τ_d	-3.7×10^{19} Mx hr^{-1}

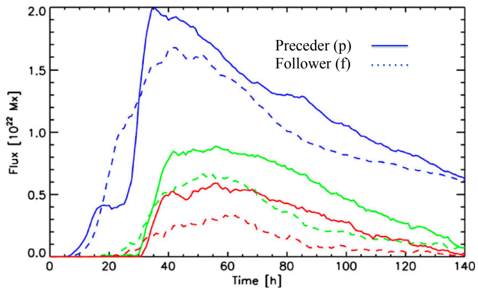

Fig 3. Simulated Flux vs Time

Results from a simulation by Rempel & Cheung (2014) of an emerging sunspot. The blue, green and red lines denote similar quantities of total flux, flux in penumbra and umbra, and flux in umbra for both p and f spot as in Fig 2. Note that the simulation shows flux emerge faster and on a shorter timescale than what is observed.

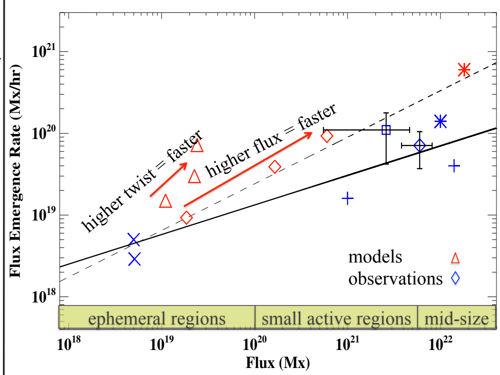

Fig 4. Observed & Simulated Rates

Results from this study (◇), compared with rates reported in the literature as observed by HMI(+) & other instru-ments (×, *, □). Also plotted are simulations by Rempel & Cheung 2014 (*) as well as other studies (◇, △). Solid line shows fit of observations apart from those of Otsuji et al. 2011 using Hinode SOT data, shown by dashed line. Simulated rates are, on average, higher than observed.

Conclusions

- Signed flux emergence rates for sunspots average 3.6 x 10^{19} Mx per hour.
- The average rate of each region was 7.1 x 10^{19} Mx per hour. Stronger flux regions emerged faster. The rate scales as a power law as a function of peak flux.
- There is considerable scatter in the emergence rates. Flux emergence depends on many factors including buoyancy, twist of flux tubes, nearby flow rate.
- Decay rates are half the emergence rates (i.e., sunspots emerge fast and decay slow), and rates are in good agreement with the rate at which moving magnetic features are expected to carry away magnetic flux.
- There is much less scatter in decay rates. Sunspots may all decay in a similar way.
- Simulations provide rates that are somewhat faster than the rates observed and timescales that are much shorter than observed.
- Twist and flows are positively correlated with emergence rate and it may be that velocities in some simulations are too high, ie. non-solar.

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