Flux Emergence Rates

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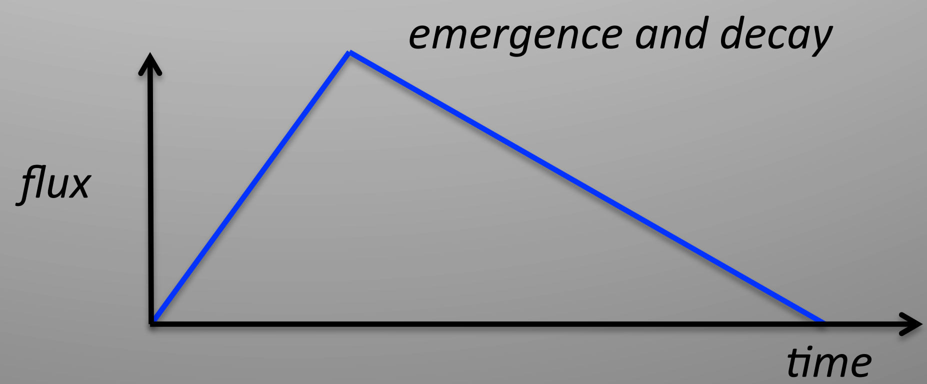
Many numerical simulations of flux emergence do not reproduce the observed characteristics of active region evolution.

Goal: Observe flux emergence rates, footpoint separation and other features of AR using HMI Sharp data to compare with simulations.

March 2015, Nordita Sunspot Workshop

Sunspot Emergence & Decay Rates



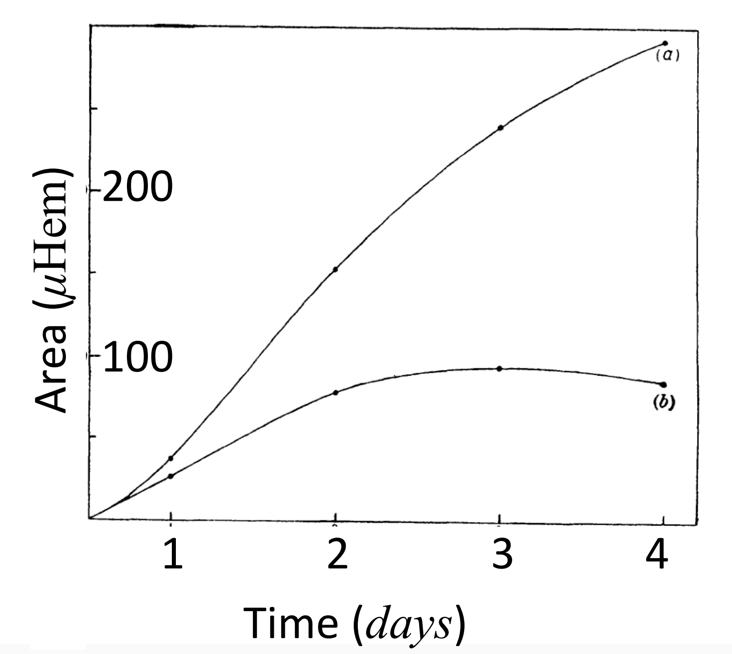
- There are many observational studies on sunspot emergence and decay.

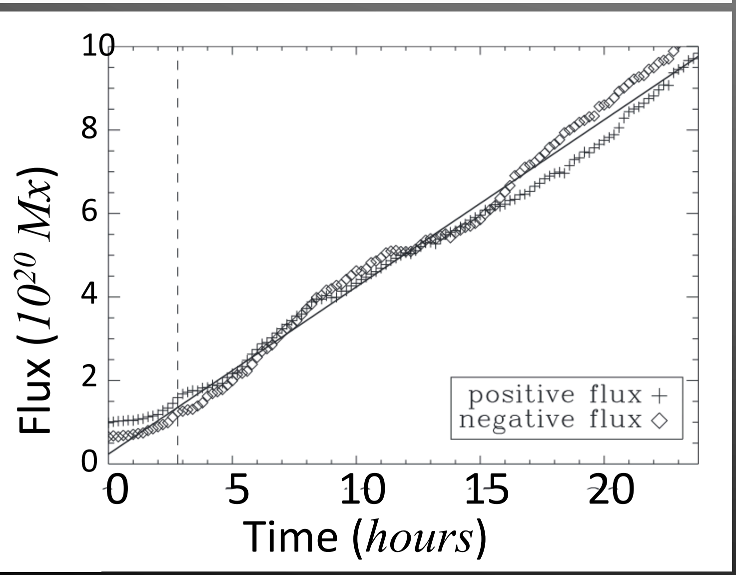
- Majority of studies are photometric (I_c) data and report values in μHem/ day (msh or MSH). More studies on decay than emergence.

- Photometric data tells us about spot formation and convection suppression rate. We need polarimetry to understand B flields. Also, simulations do not capture penumbra behavior well, so comparison with photometric studies not ideal.

- We use HMI Sharp data to study both photometric and magnetic emergence rates for 10 small to mid-size active regions. (+ 3 regions)

Sample Flux Emergence Rates (Mini Literature Review)

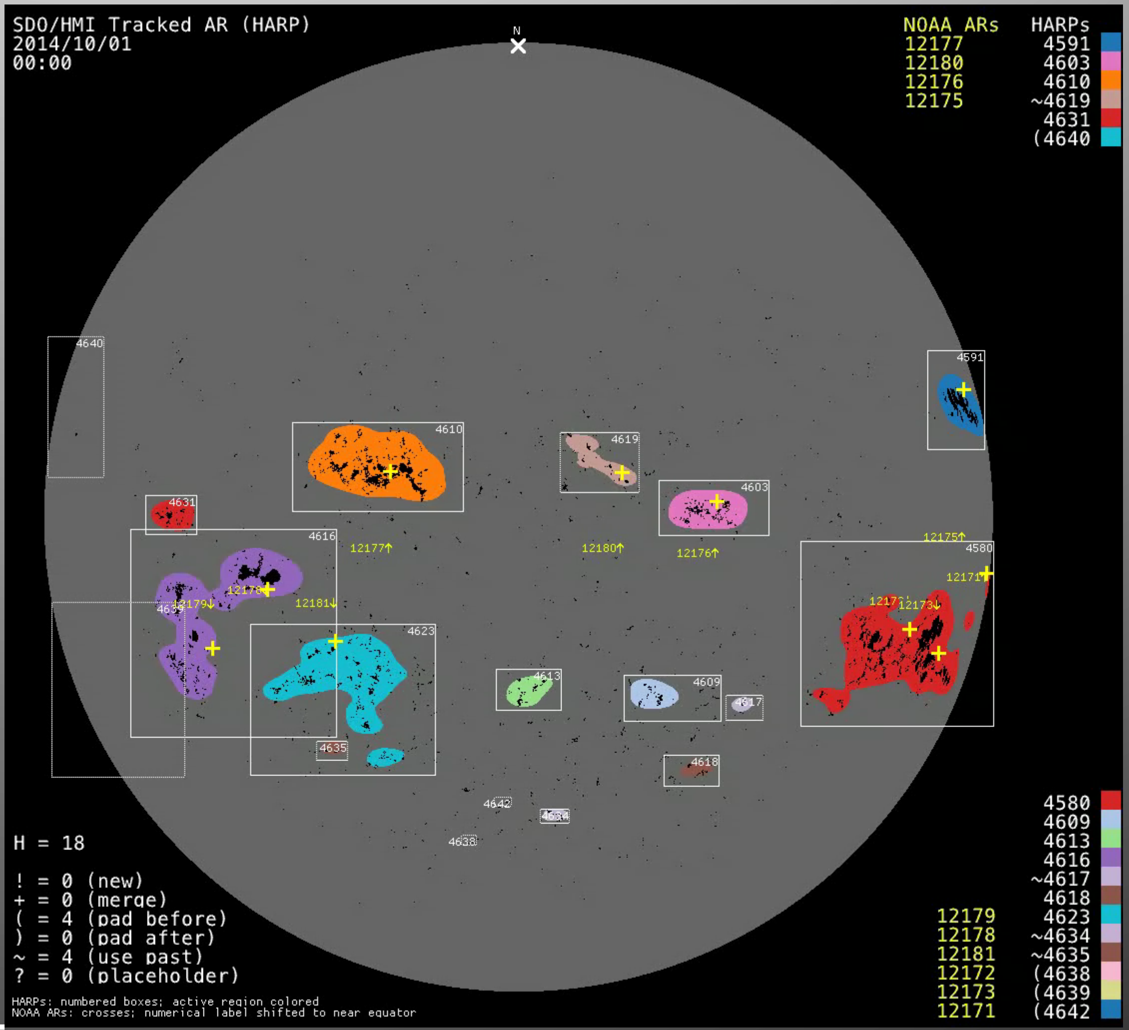




- Dobbie, 1939 (left) used data from Greenwich to study growth in (μHem/day) for large (75 msh/day) and small spots (25 msh/day). Photometric study.
- Dalla et al (2008) use GRBO data, report growth of ~40 msh/day Photometric study
- Murakozy, Baranyi, Ludmany (2014) nice study using Debrecan data Photometric study
- Centeno 2012 (left) used HMI, studied 2 regions for emergence. 4×10^{19} Mx/hr (peak flux 6×10^{21} Mx). Flux added by MDFs (moving dipolar features) between the 2 polarities after initial emergence. Magnetic study

Data

- Sharps (Space-weather HMI Active Region patches) are tracked, ME inverted ,azimuth dsiambiguated vector magnetic field data. Movies http://jsoc.stanford.edu/data/hmi/HARPs_movies/definitive/
- Sharp data, public Jan 2013 but available for entire mission for every active +more with 12 min cadence in 2 geometries– CEA (B_r) & unprojected
- Bobra et al 2014, Sun 2014, Hoeksema et al 2014 and Turmon et al, in prep.



- We examine 10 bipolar AR.
- They must emerge and begin decay on front side of disk, ~ small to mid-size ARs.
- Not using data within +/- 15 of limb.
- We use a noise threshold of 220 Mx cm^{-2} so that nothing below this value is considered.
    - *Last week, I added 3 AR to extend the range to larger and smaller flux areas.*

Flux Range Categories for Sunspots

Ephemeral Region: $3 \times 10^{18} - 1 \times 10^{20}$ Mx
Small AR Flux: $1 \times 10^{20} - 5 \times 10^{21}$ Mx
Mid-size AR: $6 \times 10^{21} - 4 \times 10^{22}$ Mx
Large AR flux: $\geq 4 \times 10^{22}$ Mx
Note: Penumbra forms $> 1 - 1.5 \times 10^{20}$ Mx

Our Sample Range:
2×10^{21} (low)
1×10^{22} (high)

(Added 2 large, 1 small)
(range then 3×10^{20}, 3×10^{22})

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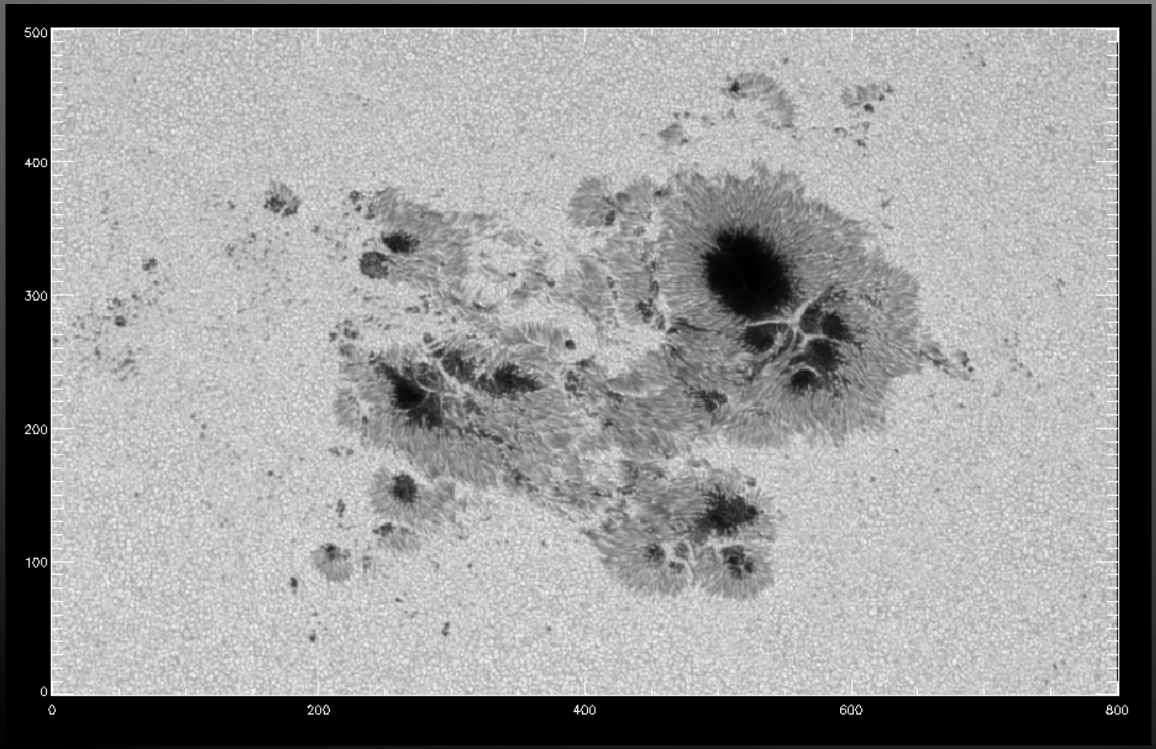
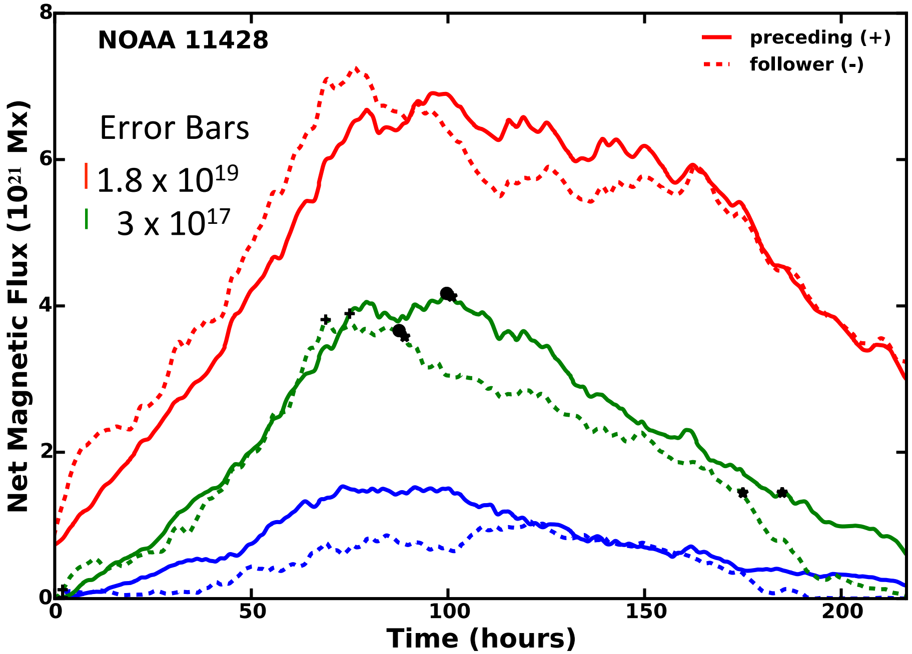
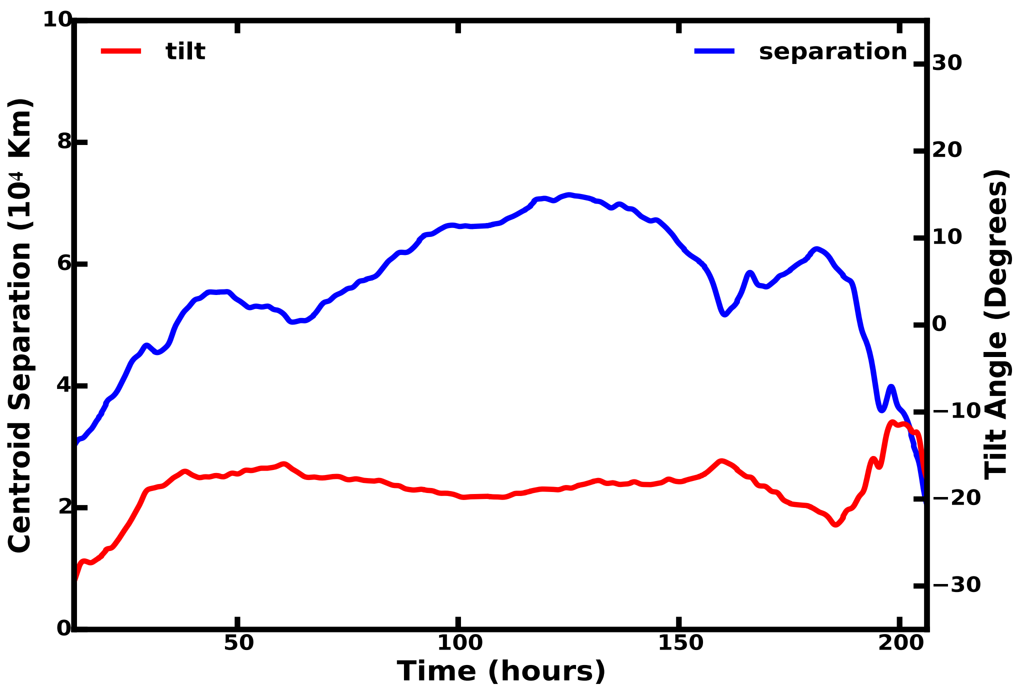
(Sources: Harvey & Martin 73, Zwaan 78, Schrijver & Zwaan 2000, Hagenaar 2001, Hagenaar et al 2003, Hagenaar, deRosa & Schrijver 2008, Leka & Skumanich 1998)



Fun fact: The monster spot AR 12192 (Harp 4698) that existed from Oct – Nov 2014 was a system containing flux upwards of 1×10^{23} Mx with an intensity contrast that indicates a temperature near 2000 K.

In the future, we hope to include larger regions in our study.





RESULTS…..*both photometric and magnetic*

Preceding (p) spot solid
Follower (f) spot – dotted

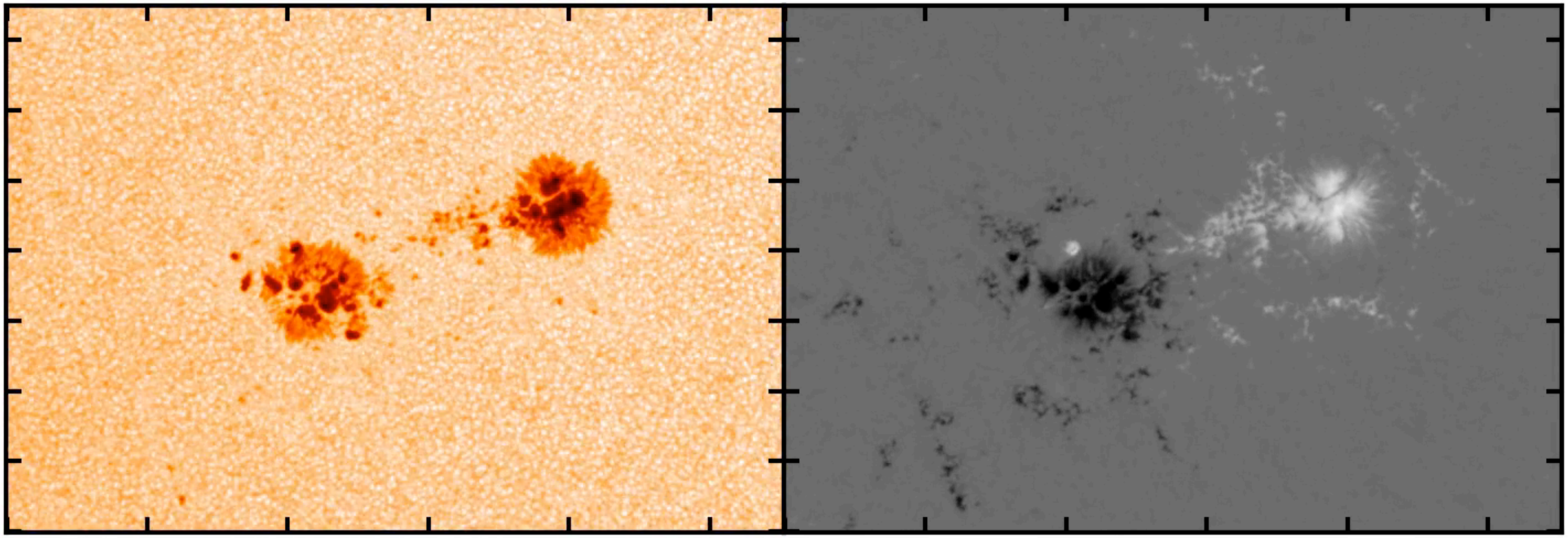
Total Flux in Region

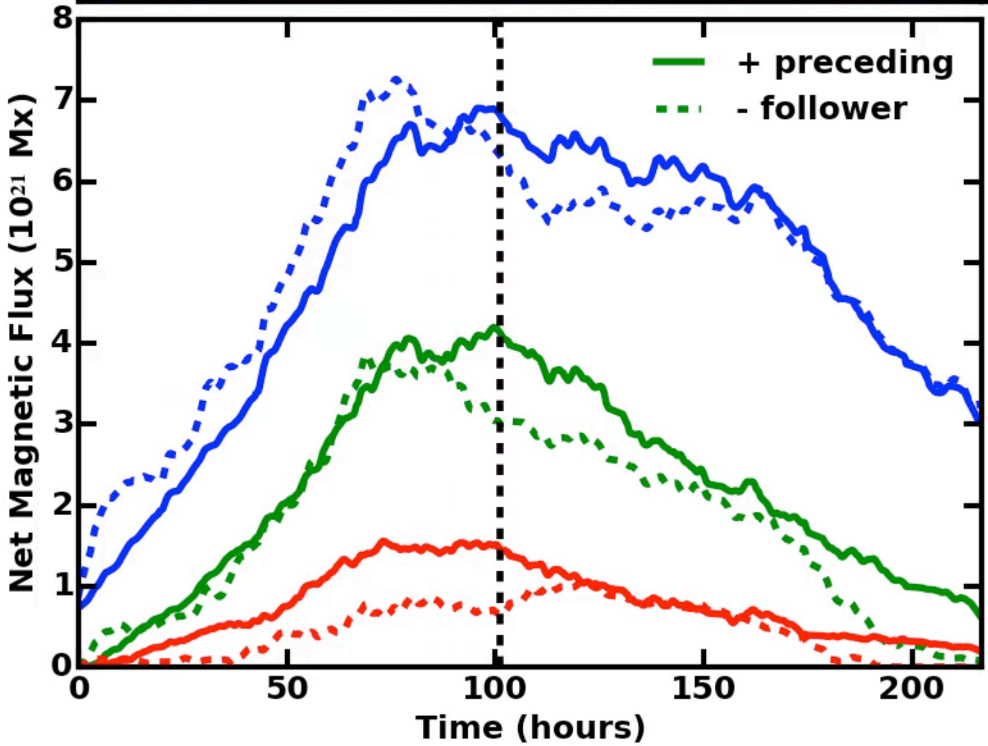
Flux in penumbra & umbra (< 85% Ic QS)

Flux within Umbra (pixels < 55% Ic QS)

Tilt, footpoint separation, # distinct umbra, flux and area

Determine time emergence begins & ends, decay begins & ends, length of plateaus.





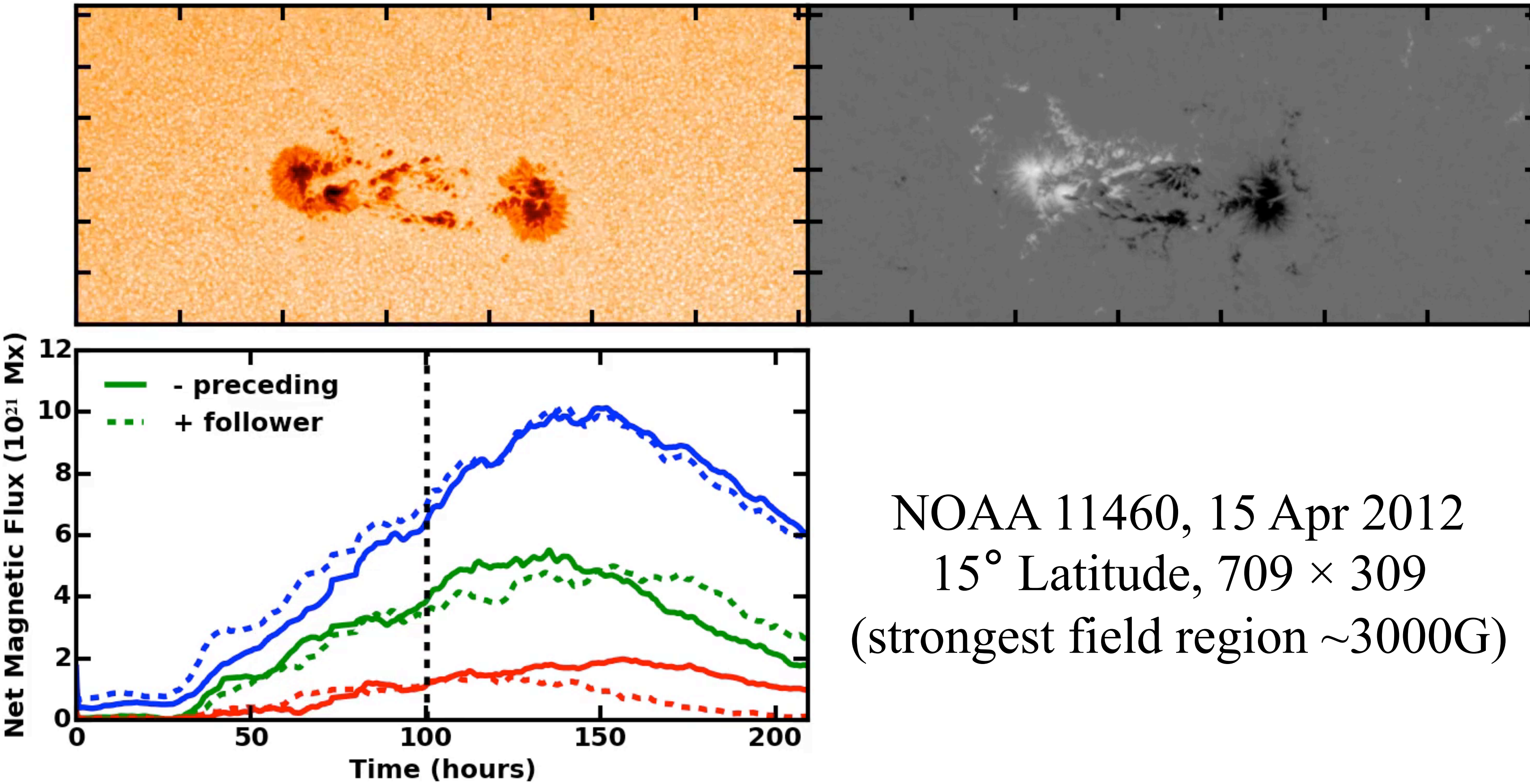
NOAA 11428, 2 Mar 2012

−17° Lat, 550 × 375 sharp_cea_720s

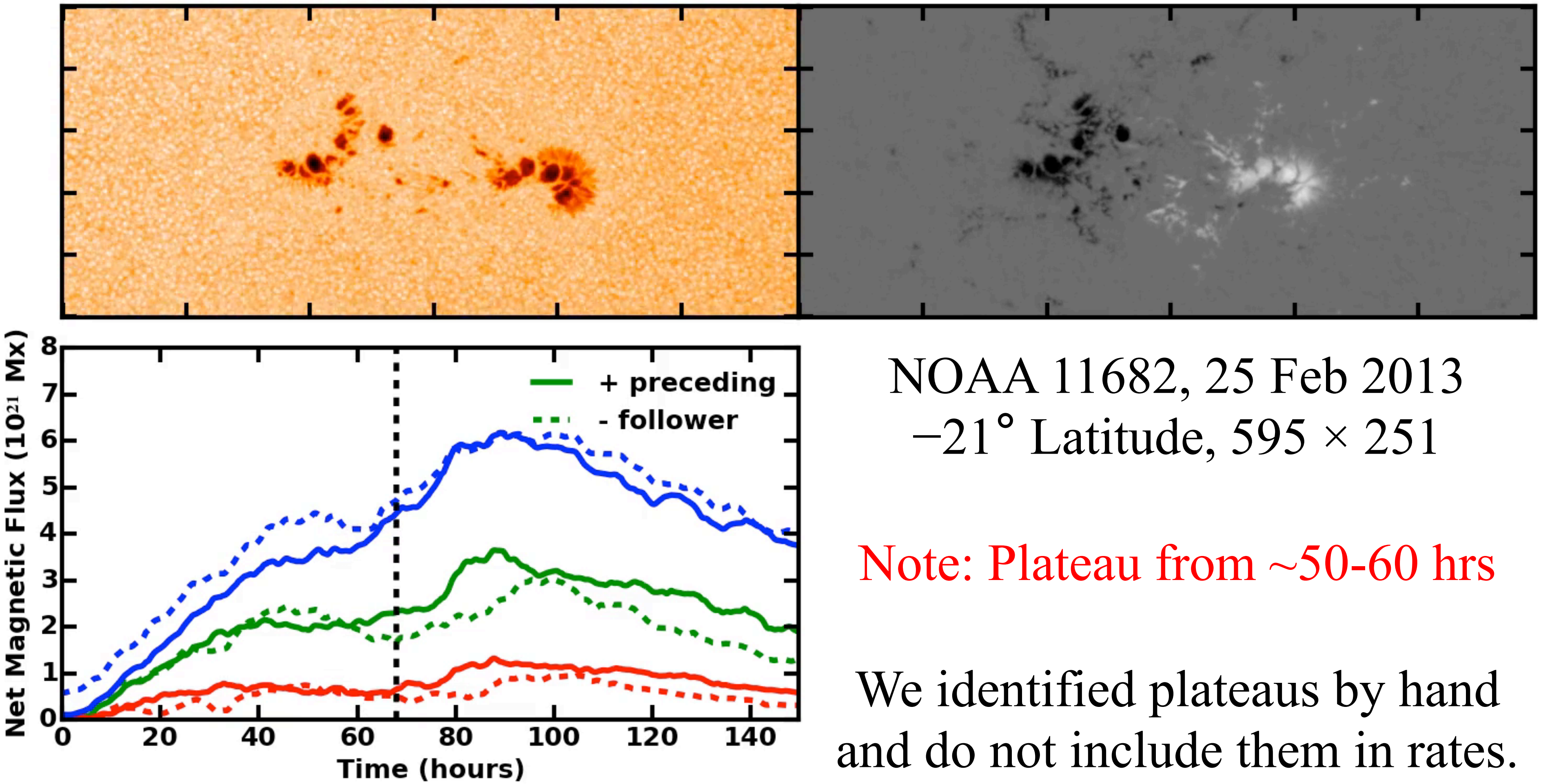
Emergence & Decay Rates in 10^{20} Mx/hr

(p) spot	.52, -.31
(f) spot	.51, -.24
(p) region	.87, -.39
(f) region	.92, -.32

I_c [10000, 65000], Br [2700 G, -1500]
Flux ($\times 10^{21}$ Mx) vs Time (hours) Gaussian Smoothed FWHM 20 h



NOAA 11460, 15 Apr 2012
15° Latitude, 709 × 309
(strongest field region ~3000G)



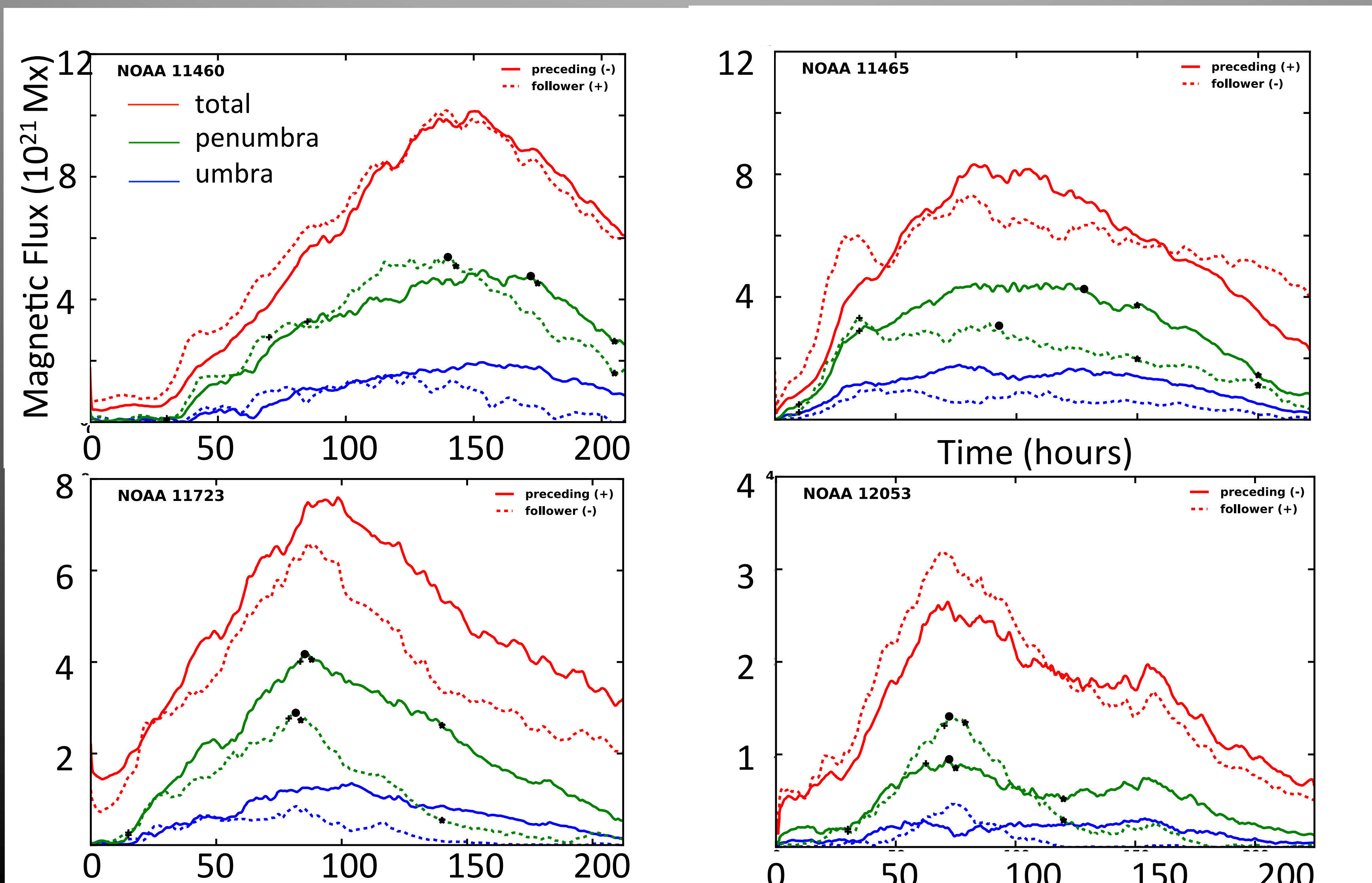
NOAA 11682, 25 Feb 2013
−21° Latitude, 595 × 251

Note: Plateau from ~50-60 hrs

We identified plateaus by hand and do not include them in rates.

p (f) spots are solid (dashed) lines respectively. Colors indicate total, penumbra and umbra. Note followers contain less flux by end.

Follower spots begin decay 19 hours, on average, earlier than preceding spots. They do not experience a plateau of stability.



rates of emergence and decay

NOAA	f_Φ	A_d	Φ_d	t_Φ	$\tau_{e\Phi}$	$\tau_{d\Phi}$
11141	0.54	45.0	11.3	48.0	0.68	-0.26
11184	0.59	175.9	–	–	1.09	–
11428	0.57	149.5	41.7	99.7	0.52	-0.31
11460	0.47	197.7	47.6	172.3	0.57	-0.62
11465	0.59	144.6	42.6	128.0	0.95	-0.44
11497	0.51	88.0	26.0	124.3	0.31	-0.36
11512	0.67	230.1	55.8	98.6	0.72	-0.27
11682	0.49	123.3	35.6	88.9	0.54	-0.26
11723	0.67	129.4	41.7	85.3	0.54	-0.27
12053	0.70	31.3	9.5	72.3	0.21	-0.07
Average	0.58	131.6	34.6	101.9	0.61	-0.32
Std Dev	0.08	63.1	15.9	36.0	0.27	0.15

NOAA	A_d	Φ_d	t_Φ	$\tau_{e\Phi}$	$\tau_{d\Phi}$
11141	49.1	9.2	44.7	0.50	-0.27
11184	117.7	31.0	33.5	0.92	-0.50
11428	147.0	36.6	87.6	0.51	-0.24
11460	178.3	53.8	139.9	0.64	-0.55
11465	87.8	30.6	92.8	1.22	-0.17
11497	100.2	26.5	124.9	0.48	-0.22
11512	137.8	29.7	56.5	0.58	-0.33
11628	–	30.7	99.6	0.52	-0.40
11723	92.7	28.9	81.7	0.38	-0.39
12053	45.4	14.1	72.3	0.28	-0.25
Average	106.2	29.1	83.3	0.60	-0.33
Std Dev	44.0	12.0	33.5	0.27	0.13

f_Φ = fraction of flux in p spot
A_d = Area in μHem
Φ_d = magnetic flux (10^{20} Mx)
t_Φ = time decay begins (hrs)
$\tau_{e\Phi}$ =emergence rate (10^{20} Mx/hr)
$\tau_{d\Phi}$ =decay rate (10^{20} Mx/hr)

Rates for Preceding

- Mean emergence rates were 0.61 x 10^{20} Mx /hr and decay rates were half that, 0.32 x 10^{20} Mx/hr.

and Following Spots

- Mean emergence rates were 0.6 x 10^{20} Mx /hr and decay rates were half that, 0.33 x 10^{20} Mx/h.

rates of emergence and decay

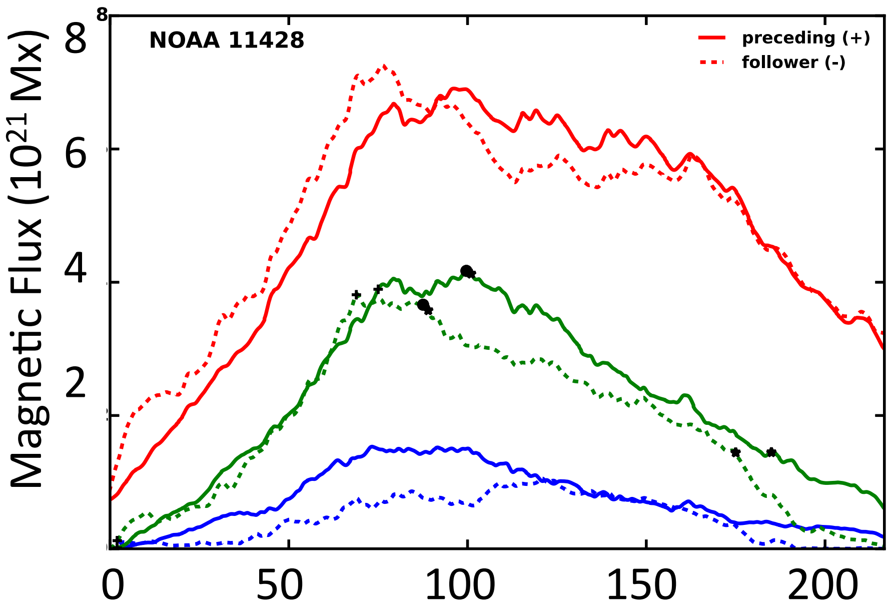
	Preceding Flux				Follower Flux			
NOAA	Φ_{max}	t_{max}	$\tau_{e\Phi}$	$\tau_{d\Phi}$	Φ_d	t_Φ	$\tau_{e\Phi}$	$\tau_{d\Phi}$
11141	21.7	48.8	1.02	-0.24	22.7	45.2	0.92	-0.27
11184	–	–	1.26	–	–	–	1.20	–
11428	69.0	99.7	0.75	-0.26	71.7	78.0	0.79	-0.15
11460	101.2	152.0	0.88	-0.79	101.3	140.8	0.77	-0.50
11465	79.5	111.9	1.40	-0.47	72.7	82.8	1.81	-0.14
11497	54.4	188.0	0.44	-0.39	49.0	135.8	0.61	-0.20
11512	82.2	95.0	0.91	-0.40	91.5	80.8	1.08	-0.45
11682	61.2	92.2	0.84	-0.44	61.1	104.4	0.86	-0.45
11723	75.9	98.8	0.73	-0.39	65.2	89.9	0.71	-0.59
12053	26.5	71.8	0.48	-0.14	31.4	72.8	0.43	-0.15
Average	61.6	106.5	0.87	-0.39	65.0	92.3	0.92	-0.32
Std Dev	25.3	41.4	0.30	0.18	25.0	30.5	0.38	0.18

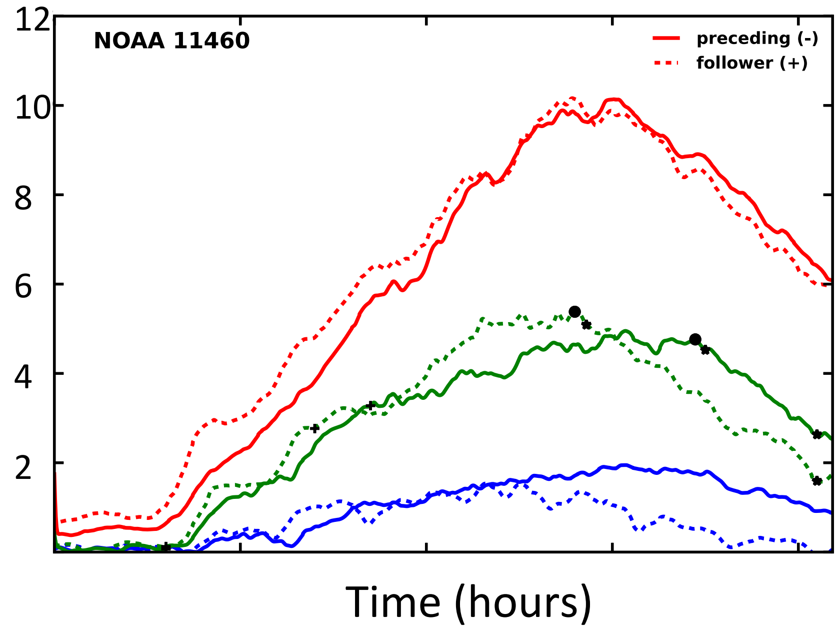
Φ_{max} = magnetic flux (10^{20} Mx)
t_{max} = time decay begins (hrs)
$\tau_{e\Phi}$ =emergence rate (10^{20} Mx/hr)
$\tau_{d\Phi}$ =decay rate (10^{20} Mx/hr)

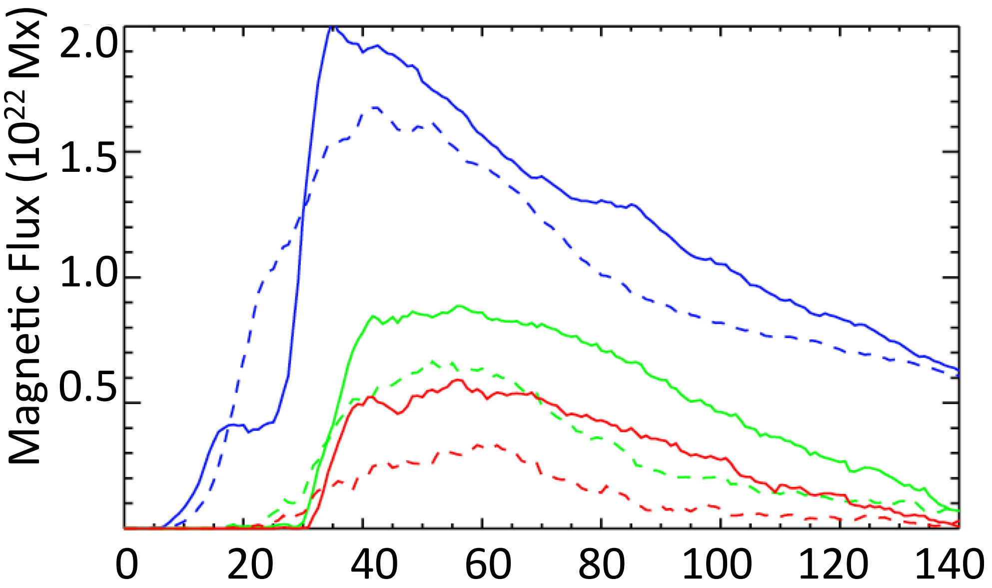
Rates for Preceding & Following Regions (Not Spots)

- Mean emergence rates were 0.61 x 10^{20} Mx /hr and decay rates were half that, 0.32 x 10^{20} Mx/hr.
- Mean emergence rates were 0.6 x 10^{20} Mx /hr and decay rates were half that, 0.33 x 10^{20} Mx/h.

Compare with Simulations





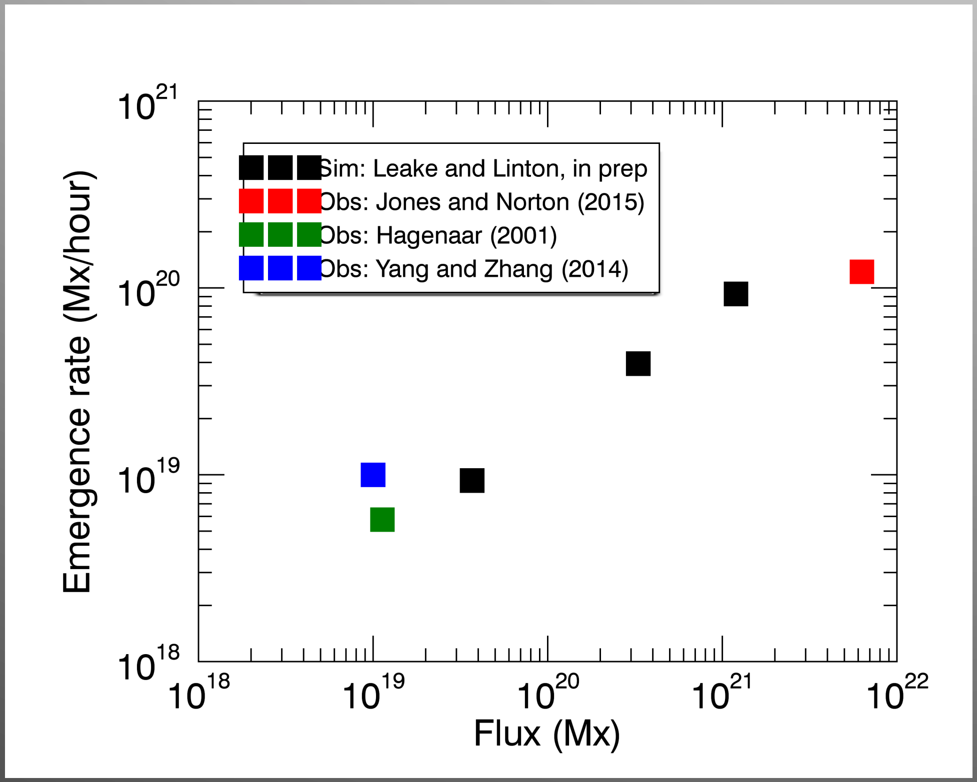


HMI observations, 2 AR in top panels.

Rempel & Cheung 2014 left
MURaM MHD code, domain size 147x74x16 Mm. Total flux of emerging loop is 1.7 x 10^{22} Mx. Includes convection. Rate is ~6.6 x 10^{20} Mx/hr.

Note different range of x-axis values.

Compare with Simulations

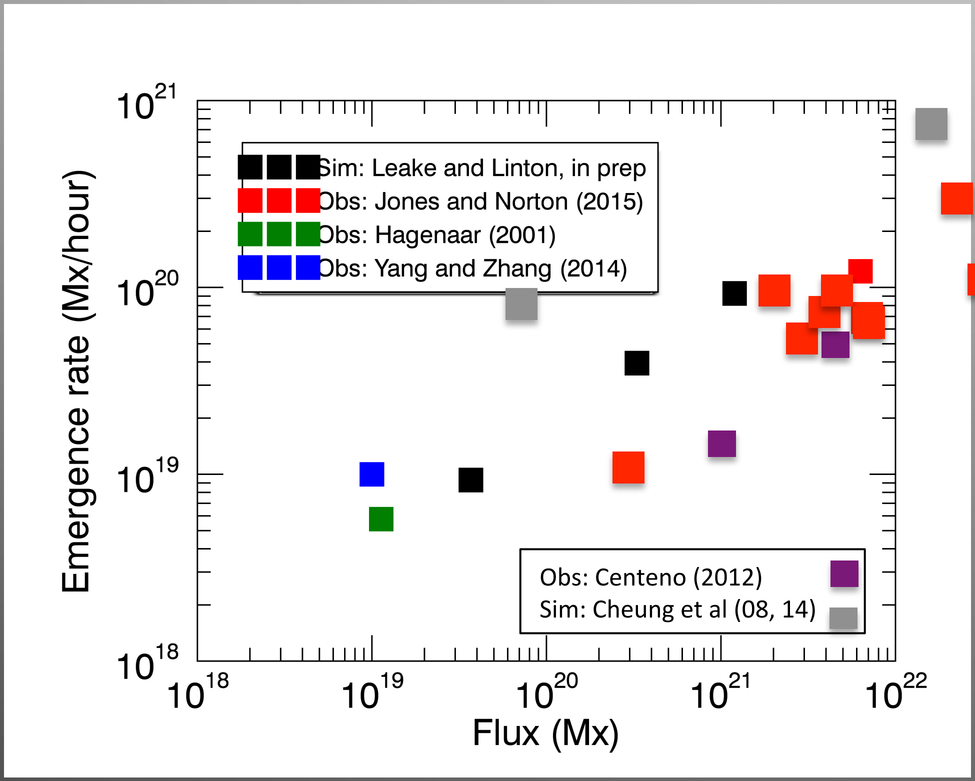


- Leake & Linton simulate flux emergence with Lare2.5D, a visco-resistive MHD code, range is -10 Mm to 100 Mm.
- Vary sub-surface initial field profiles, this varies AR flux values.
- Doesn't include convection but includes chromosphere and corona.
- Emergence rate ≈ 1/β. As flux increases, plasma beta decreases, emergence rate increases.

Simulations show emergence rate increases with increased flux.

NASA LWS Grant, PI Linton

Compare with Simulations



Extended flux range –add pts

- AR11158, peak flux 2 x 10^{22} Mx.
- emergence over 7 days:
  36 hours @ 0.6 x 10^{22} Mx/hr
  30 hours @ 3.0 x 10^{22} Mx
  5 days @ 0.78 x 10^{22} Mx

- AR12108, peak flux 3 x10^{22} Mx
- 8 days at 1 x 10^{20} Mx/hr

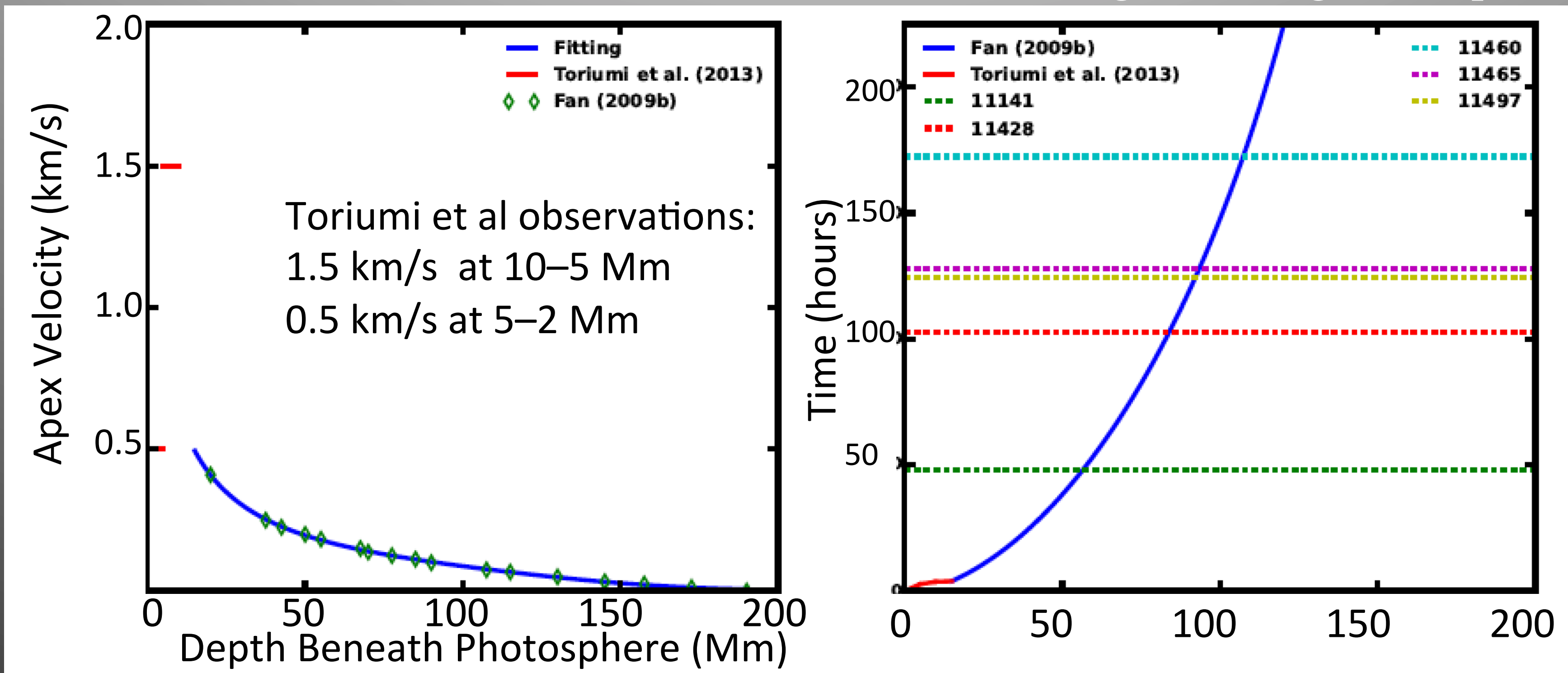
- Harp 4376 peak flux 3 x $10^{20,}$ 14 hrs @ 0.14 x 10^{20} Mx/hr

Observations show emergence rate increases with increased flux.

NASA LWS Grant, PI Linton

Aside: Subsurface Rise Times & Rise Rates

Using Fan 2009 simulations for a rising flux tube and Toriumi et al 2013 helioseismology observations, we estimate the time it takes for flux to emerge from a given depth.



5 Mm	5 hr	Rempel & Cheung (2014) simulations
50 Mm	40 hr	15 – 30 hrs for flux to rise last 15 Mm
100 Mm	145 hrs	Note: Takes ~1week to traverse top half of CZ
120 Mm	200 hrs (~8 days)	
150 Mm	425 hrs (~18 days)	
200 Mm	1900 hrs (~80 days)	Takes 2.5 months to traverse entire CZ

After rise through CZ, flux gets stuck at surface, needs MBI/MRT instability to emerge.

Aside: Footpoint Separations are ~72 Mm

			Point of De	
NOAA	θ_T	l_{max}	A_d	Φ_d
11141	12.5	94.5	98.1	20.6
11184	14.7	80.1	293.0	68.9
11428	-18.6	71.6	278.2	76.8
11460	6.3	80.2	366.6	98.1
11465	38.9	53.6	237.5	74.2
11497	-9.7	65.8	190.7	52.9
11512	-11.1	63.9	344.3	81.6
11682	0.9	71.5	232.1	64.0
11723	-18.7	74.2	240.9	69.4
12053	11.2	61.1	76.9	23.5
	Average	71.65	235.8	63.0
	Std Dev	11.6	94.4	24.6

l_{max} = footpoint separation in Mm
Θ_T = Tilt angle in degrees
A_d = Area in µHem
Φ_d = magnetic flux in $\times 10^{20}$ Mx

Why does the separation of the two polarities of a solar active region stops at the scales of ~100Mm? Fan, Living Review

In simulations, the flux is either line-tied at the bottom (emulating a connection to a deeper source), or allowed to move apart to the max. width of the simulation box.

The footpoint separation reaches a maximum after the onset of decay (~a day after) but in theory, there is no reason the footpoints should not continue to separate.

Conclusions

- Flux emergence rates increase with stronger flux regions.
- For regions with (0.2–1) x 10^{22} Mx, rates were 0.6 x 10^{20} Mx/hr for p & f spots. Decay rates are half the emergence.
- Surprised that p (f) spots show same rates. (f) finish emergence and start decay 19 hours earlier, on average, than p. Leaders (p) experience a plateau of stability after emergence that f spots do not.
- Simulations – both Lare2D (Leake & Linton and MURaM (Rempel & Cheung) – find flux emergence rates that are 2-10 times faster than the Sun.
- The umbra and penumbra are built simultaneously and proportionally to the flux emerging into the region. The # of umbra decreases over time (becomes more compact), but this is different than the flux emerging and then the spot assembling.