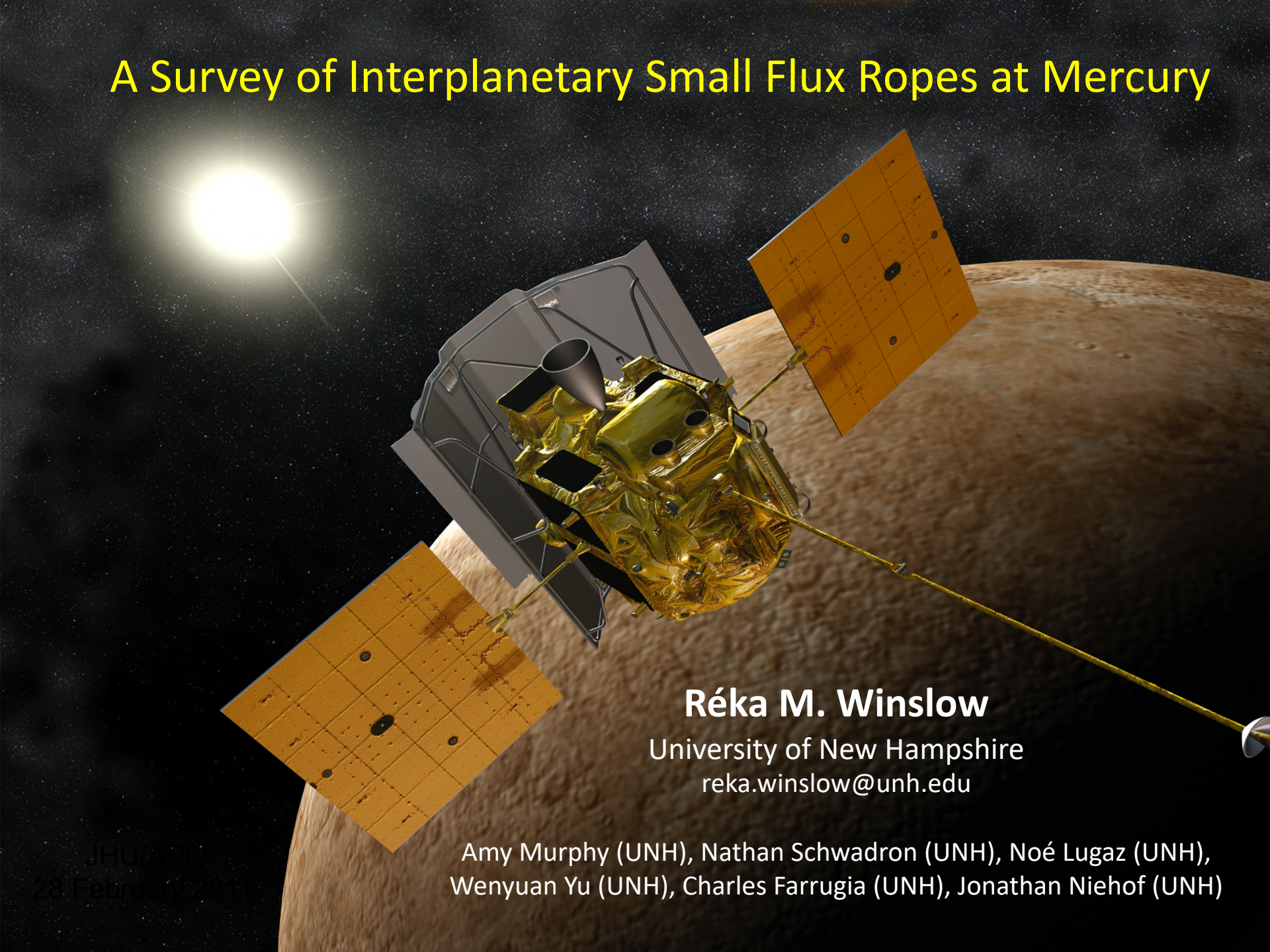
A Survey of Interplanetary Small Flux Ropes at Mercury



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Intro and motivation

(Murphy, Winslow et al. 2020, ApJ - in production)

- Small flux ropes (SFRs) are interplanetary twisted magnetic flux ropes with durations of a few minutes to a few hours. Their field structure is similar to that of magnetic clouds, but they have different plasma properties *(Moldwin et al., 1995)*.

- There is some evidence that SFRs can trigger geomagnetic substorms *(Feng et al., 2010)*, and that they may accelerate energetic particles *(Le Roux et al., 2018)*. Thus, understanding the origin of SFRs and how they evolve as they move through the heliosphere may help with space weather prediction.

- We built a catalog of SFRs observed between 0.31 and 0.47 AU from MESSENGER from 2011-2015.

- Except for recent Parker Solar Probe results *(Zhao et al., 2020)*, only one other study has looked at SFRs observed at < 0.95 AU *(Cartwright & Moldwin, 2010)*, and they found only 13 SFRs. Our work adds to the list of SFRs observed in the inner heliosphere.

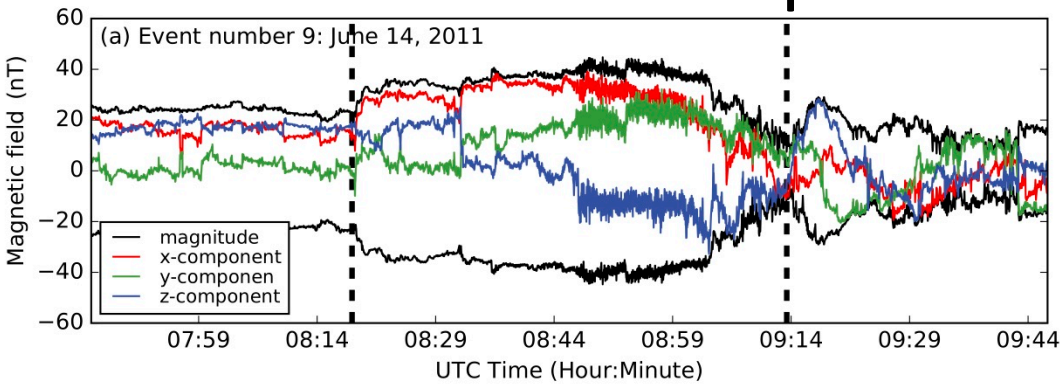
SFR identification

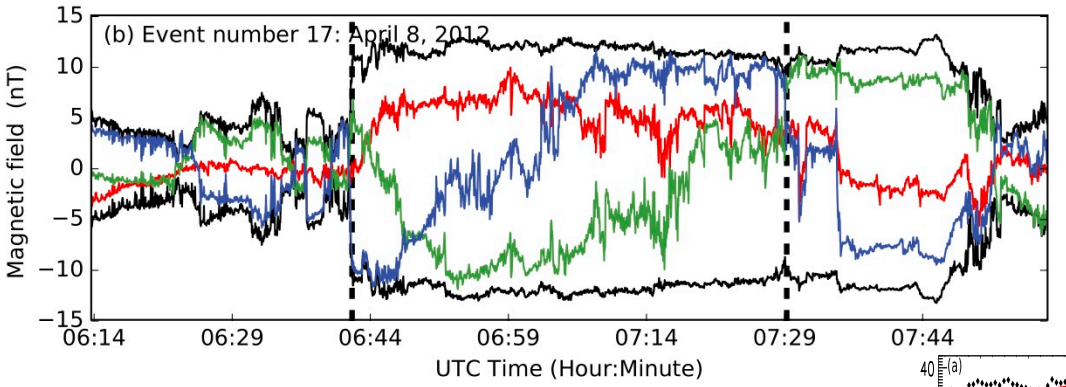
- Used only magnetic field data due to lack of continuous solar wind data from MESSENGER *(e.g., Gershman et al. 2012)*.

- Strict set of criteria used to visually identify SFRs and minimize the inherent uncertainties in using magnetic field data alone.
  - Combination of visual and automatic detection methods is likely to yield more complete databases without false detections; however, given that we do not have plasma data, automatic detection methods would have complicated the situation by including Alfvén waves.

- Criteria used:
  - average field magnitude at least 1.3 times IMF on either side of the event,
  - a gradual change in polarity in one magnetic field component (not B_R to exclude the heliospheric current sheet),
  - duration between 2 minutes and 4 hr,
  - minimum variance analysis ratio > 2,
  - well-fit by force-free constant α flux rope model.

Example SFR events

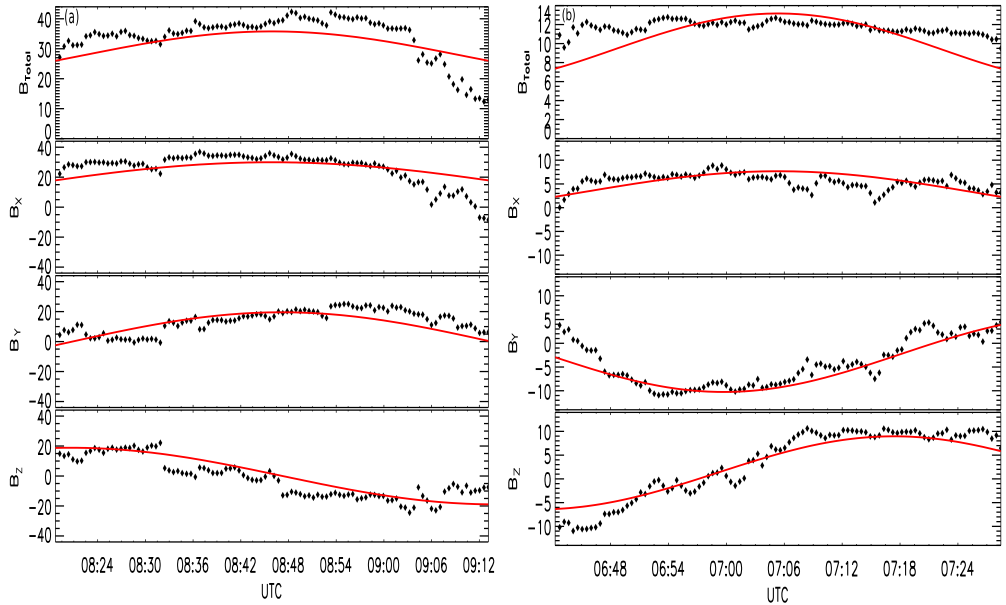




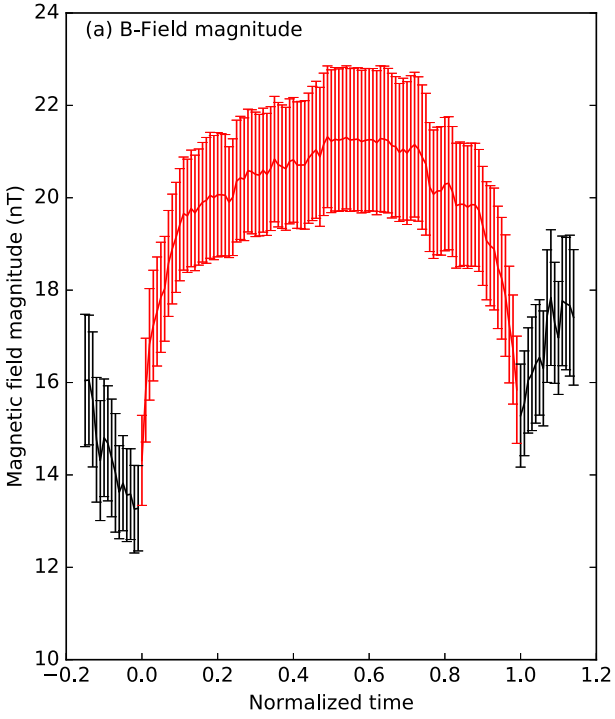
Catalog consists of 48 SFRs that met these criteria; events are available as supplemental table to the *Murphy, Winslow, et al. 2020* paper.

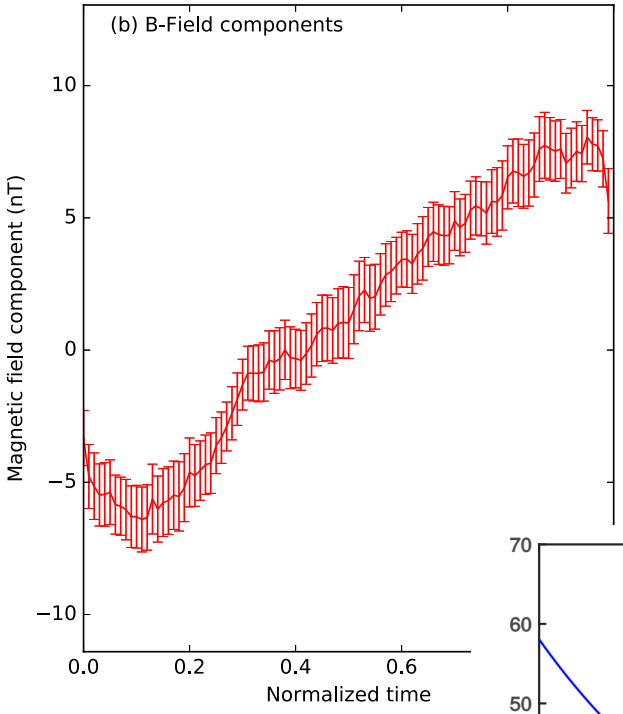
2 example SFRs in MESSENGER IMF data are shown (all far from Mercury magnetospheric passage).

Force-free flux rope fits to the magnetic field for the same 2 events.



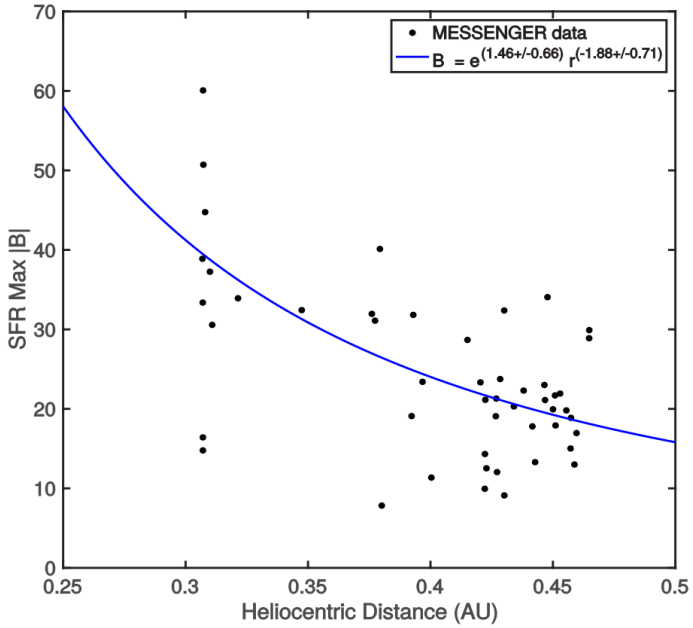
Average profile of SFRs at Mercury



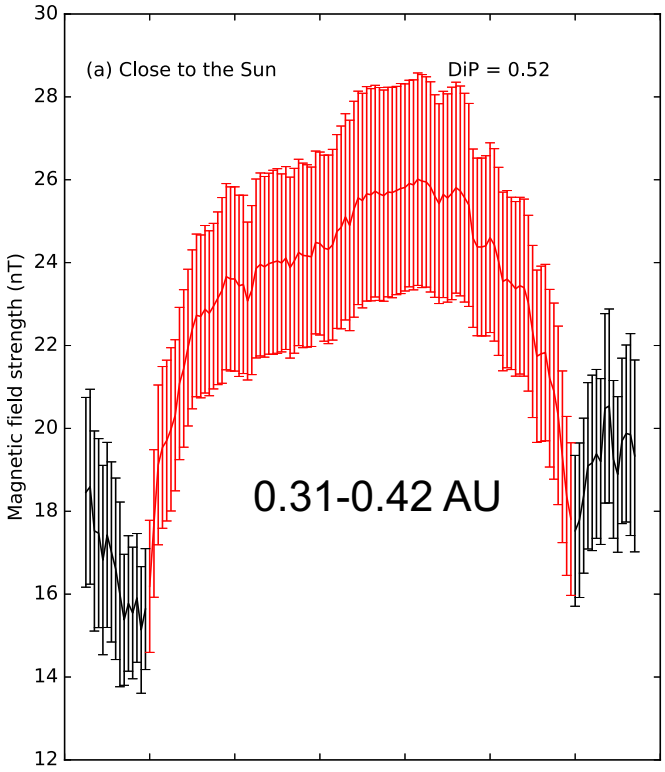


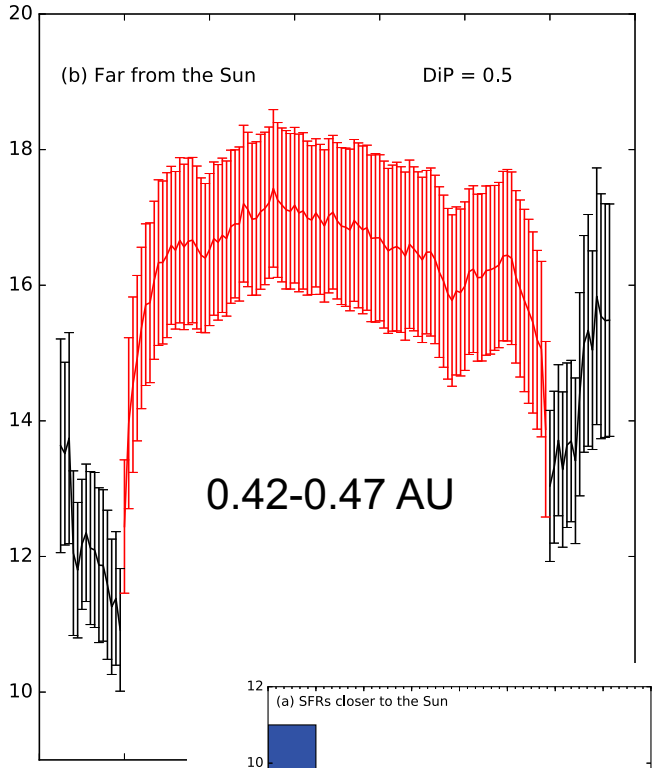
Conducted superposed epoch analysis on the magnetic field magnitude and the field component with the observed rotation, to derive average field profile of SFRs at Mercury.

Observed decrease in the magnetic field strength with distance ($\sim r^{-1.9}$) is indication that these structures are expanding in the solar wind.



Proximity to the Sun

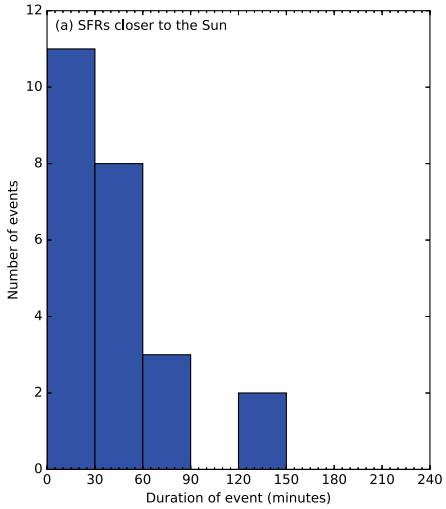


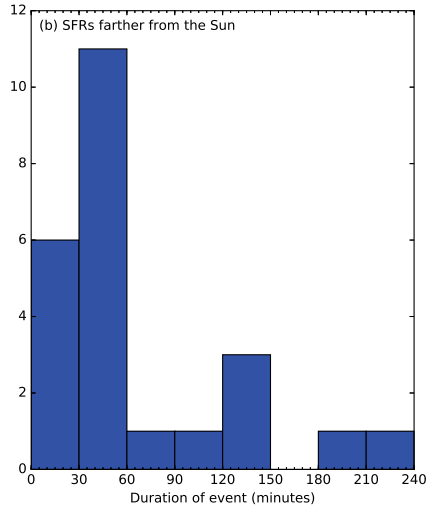


Distortion parameter (DiP) of *Nieves-Chinchilla et al. (2018)* is larger for SFRs closer to the Sun, which is a statistically significant result.

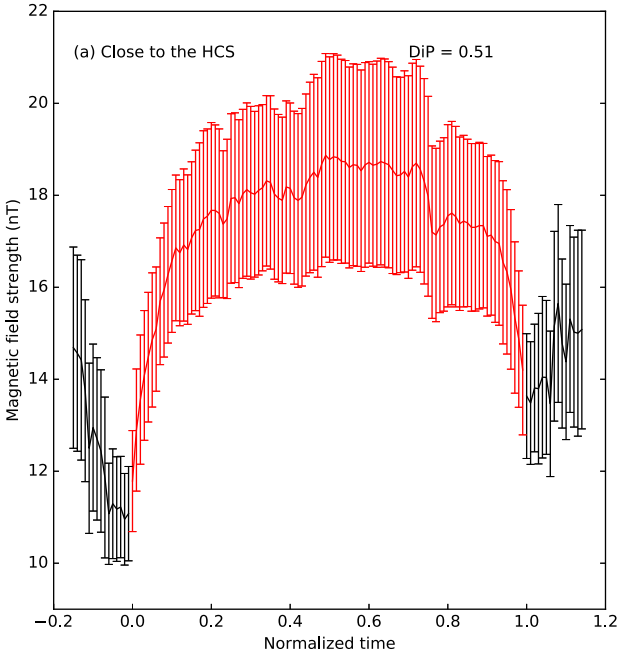
SFRs farther from the Sun (at 0.42–0.47 au) have a more symmetric profile than the SFRs closer to the Sun (at 0.31–0.42 au).

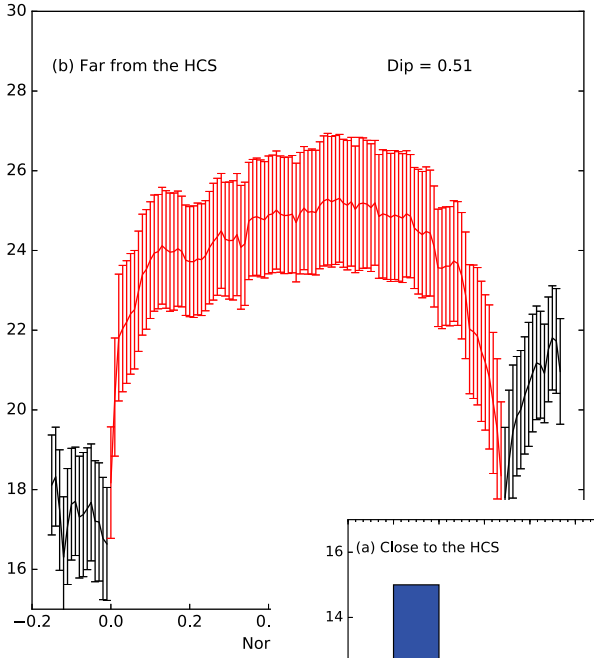
Change in symmetry with increasing heliocentric distance suggests that on average the SFRs may originate closer to the Sun and expand toward equilibrium as they move out.





Proximity to the heliospheric current sheet (HCS)

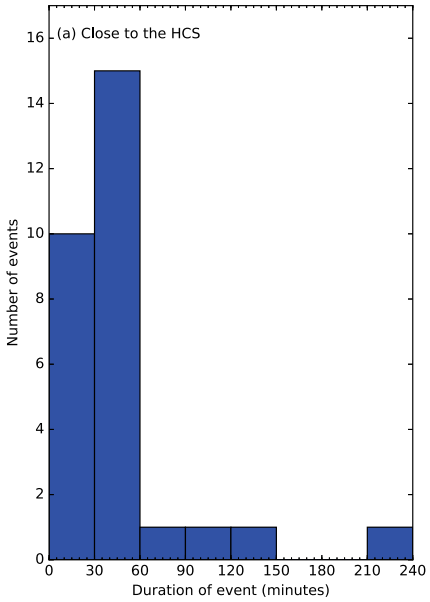


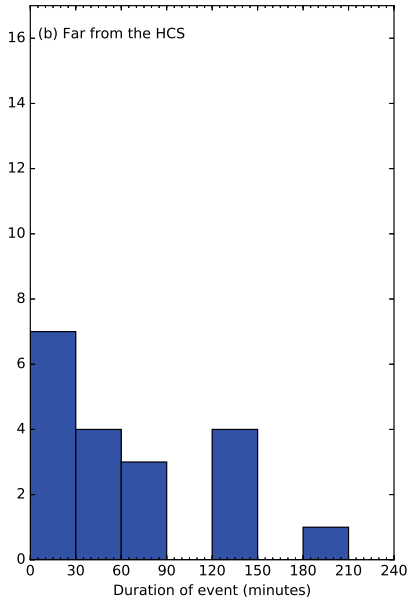


Average profile fairly symmetric both near and far from HCS.

Defined near HCS to be within 6 hrs of a current sheet crossing or MESSENGER skimming the HCS.

60% of our SFRs are within 6 hrs of the HCS (i.e. close to the HCS).





Main Results

Our results suggest that there are 2 different populations of SFRs in our catalog (likely formed through separate processes):

1. SFRs that are found near the HCS and are observed to mostly occur in clusters within minutes to hours of each other, i.e., likely formed through a quasi-periodic formation process near the HCS.
   - Occur more frequently and are of shorter duration than ones far from the HCS.
   - Likely formed near the HCS either at the Sun or in the innermost heliosphere.
   - Their radial size and periodicity is in agreement with the periodic density structures (PDSs) described in *Viall et al. (2008).*

2. SFRs that are found far away from the HCS and are observed to always occur as isolated events, i.e., they do not occur clustered in time.
   - Likely formed away from the HCS, possibly at the Sun as small CMEs, as hypothesized by *Feng et al. (2007, 2008).*

The SFRs observed at Mercury are expanding as they propagate with the solar wind, as deduced from the SFR durations, the magnetic field strength fall-off with distance, and the fact that the average SFR profile is more symmetric farther from the Sun.