Rush the Poles: What is going on around 55° Latitude?

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Summary. *The poles of the Sun present a number of tantalizing mysteries. Presently, limited by their line-of-sight viewing angle to the more sensitive spectroscopic (and spectropolarimetric) measurements, they are amenable to other methods of remote sensing, primarily using features and patterns visible in narrow- and broad-band imaging from the ecliptic. The purpose of this white paper is to highlight an ensemble of the latter observations and reveal that the regions around 55° latitude present a scientific target of a magnitude similar to tracing the source of the Nile, or water on other planets…* ***Is 55° the seat of the Sun's dynamo processes - where the magnetic field that shapes and drives the heliosphere originates?*** *Critical spectroscopic access to this region and measurement of the underlying structures and flow patterns requires long-duration, continuous observing periods at high latitude - at the Sun's poles. We are not advocating for a particular mission concept with this white paper. Instead, we want to highlight the breakthrough science that would be enabled from these sustained vantage points and solar sail technology.* ***Advances in communication, solar sail, and instrument miniaturization technology will undoubtedly accelerate access to the science we highlight below.***

Much like the hostile environment of the Earth's polar regions played in limiting their (successful) exploration until risk was reduced by a mix of human guile and technology, the polar regions of the Sun present a gravitational challenge that requires the same mix to overcome. We anticipate that the payoff for the latter exploration will be significant for a range of scientific endeavors, most notably the origin of the Sun's magnetic activity patterns.

In this white paper we will assume that a dedicated mission to study the Sun's polar environment is under consideration, but lacks specific scientific targets - such is the norm with largely uncharted spaces.

The infographic presented over the page is designed to highlight a specific scientific target that requires sustained long-duration observations of the Sun's polar region - *is the region around 55° latitude the seat of the Sun's dynamo?*

The presently fashionable slate of numerical models that describe the self-sustaining generation of the Sun's magnetic field ("dynamo"), and hence its activity patterns, depend fundamentally on a *continuous* meridional circulation - from equator to pole and back again at the base of the Sun's convection zone (e.g., Charbonneau 2010). Further, this class of models derive stresses required to form and emerge the global-scale toroidal field from the rotational profile of the solar interior in the zonal direction [perpendicular to the rotation axis]. As such, these models imply the presence of an inflow [or vortex] at the Sun's poles which has yet to be detected and heavily leverage a continuously varying rotational profile from equator to pole. Finally, these models all use the long-duration availability of the sunspot record as a benchmark for which to identify success.

Over the course of the last decade, observational work has revealed a number of patterns that appear to contradict some of the fundamental considerations of the dynamo models (McIntosh et al. 2014). This work re-established and extended patterns that had been cataloged and reported in the late 1980s as the "extended solar cycle" (Wilson et al. 1987).

Wilson and colleagues, worked independently for nearly a decade before they combined their analyses, recognized that the global-scale morphology of the corona (from the green line coronagraphic record), an pattern of excess super-differential rotation in the photosphere (visible as the 'torsional oscillation'), and groupings of (small) ephemeral bipolar active regions formed a pattern that extended the conventional picture of solar activity (cf. the Maunder (1904) butterfly diagram of sunspots) back nearly a decade earlier and to much higher latitudes (compare to the central row of the infographic below).

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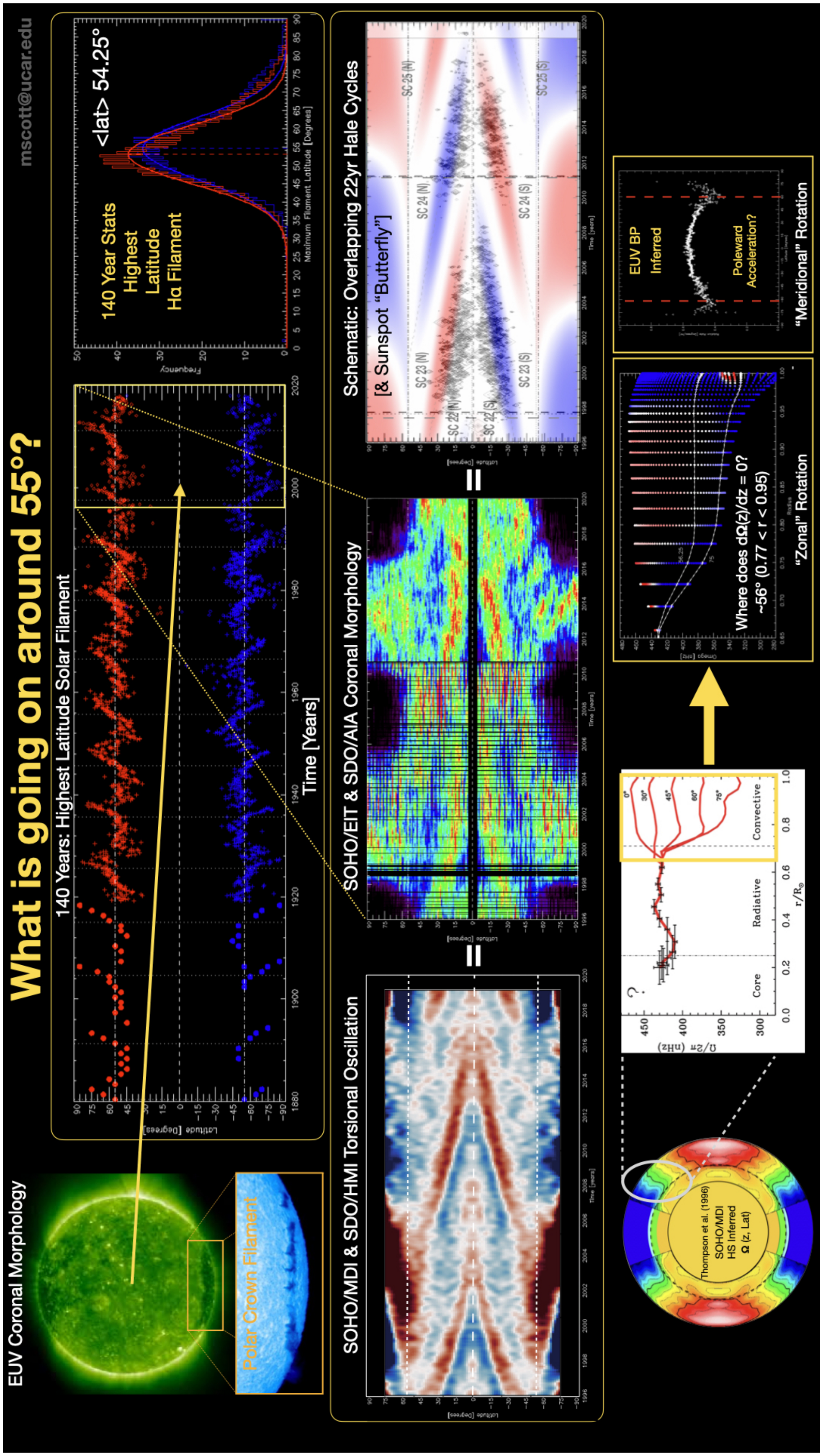
What is going on around 55°?
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EUV Coronal Morphology
Polar Crown Filament
140 Years: Highest Latitude Solar Filament
Time [Years]
140 Year Stats
Highest
Latitude
Hα Filament
<lat> 54.25°
SOHO/MDI & SDO/HMI Torsional Oscillation
SOHO/EIT & SDO/AIA Coronal Morphology
Schematic: Overlapping 22yr Hale Cycles
[& Sunspot "Butterfly"]
Thompson et al. (1996)
SOHO/MDI
HS Inferred
Ω (z, Lat)
Core
Radiative
Convective
Where does dΩ(z)/dz = 0?
~56° (0.77 < r < 0.95)
"Zonal" Rotation
EUV BP
Inferred
Poleward
Acceleration?
"Meridional" Rotation

McIntosh et al. (2014), and subsequent work **(**McIntosh et al. 2019**)**, established that the diagnostics initially identified by Wilson trace out the variation of Sun's 22-year magnetic polarity (or Hale) cycle. They then postulated that the sunspot butterfly pattern and its modulation in amplitude were a direct result of the intra- and inter-hemispheric interactions of the Hale Cycle's toroidal magnetic bands as they overlap in latitude and time. They identified that these bands have their origins at about 55° latitude and that approximately every 22 years a new system departs on a ~20 year journey to a point where it cancels with its oppositely polarized counterpart in the other hemisphere. *In short, the toroidal bands that become the sunspot forming bands (see infographic) appear to have their origin around 55°, some decade or more before they ever form sunspots.*

The progression of the Sun's highest latitude filaments offers some illuminating context, although not necessarily new (Lockyer 1931, Bocchino 1933), to the previous paragraph. Referring to the top row of the infographic and using the 140 year long Hα photographic record, we see that 55° is the (almost) persistent latitude of the polar crown filament and that they basically divide the polar and equatorial regions. The roughly periodic poleward excursions, known as the "rush to the poles" (Altrock 1997), are part and parcel of the Sun's polar reversal process and start concurrently with the cancellation of the previous Hale Cycle at the Sun's equator (McIntosh et al. 2019). *Recall that filaments require two physical properties to be sustained, the presence of a magnetic neutral line, and a convergent/divergent flow.* Similarly, we note from studies of global scale coronal morphology (e.g., Altrock 1997, McIntosh et al. 2014), that 55° is the limiting latitude of the polar coronal holes.

The long temporal baseline points to 55° being a physically important, almost geometrically stable, latitude. One where persistent shear flows can exist, possibly contradicting the presence of a persistent meridional flow from equator to pole that is required to sustain classes of dynamo models, as if the presence of the Hale Cycle bands and their combination to modulate sunspot production have not already undermined those assumptions.

Finally, from a helioseismic perspective, the iconic investigation of Thompson et al. (1996) revealed the internal structure of the Sun's rotation rate (bottom row of infographic). We are drawn to the near constant radial profile of the (zonal) rotation rate near 55°. Mapping out the gradient of the rotation rate with depth reveals that it is almost identically zero between 0.7 and 0.95 solar radii at a latitude of ~56°, is this a coincidence? This behavior appears to also satisfy the conditions set for Parker's "dynamo wave" solution (Parker 1955) - can Parker's hypothesis explain the myriad patterns exhibited by the Hale Cycle? Finally, tracking the evolution of readily observable features from the ecliptic reveals flow patterns above 55° indicative of an strong polarward component of the flow - supporting the presence of a polar vortex (McIntosh 2020). In short we point to potential breakthroughs in understanding how our star works.

Long duration, high latitude, observations are required to extract information about the (deep-seated) flows in the vicinity of 55° (or above). Holding station at high latitudes will not be absolutely necessary, but long orbital periods may be required to keep relevant latitudes in the field of view as continuously as possible. We envision that solar sail technology could/should play a vital role in the positioning and station keeping of the observing platform(s). A more detailed review of the flow characteristics - as can be best accomplished with present data - will be required to refine the observational requirements and constraints.

References

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