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Preserving a Unique Archive for Long-Term Solar Variability Studies

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Key Points:

- The goal is to preserve and digitize the McIntosh Archive created by Patrick McIntosh from 1964 to 2009
- The Archive is a unique 45 year record of the evolution of the solar magnetic field
- The maps use chromospheric and photospheric magnetic measurements to trace neutral lines, filaments, sunspots, and plage and coronal holes

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Abstract The McIntosh Archive consists of hand-drawn solar Carrington maps created by Patrick McIntosh from 1964 to 2009, using Hα, He 10830 Å, and photospheric magnetic measurements to trace polarity inversion lines, filaments, sunspots, and plage and coronal holes, yielding a unique 45 year record of the evolution of the solar magnetic field. We discuss our efforts to preserve and digitize this archive.

The solar dynamo that produces the solar activity cycle visible at the surface is thought to arise from inductive flows within the solar interior (Charbonneau, 2010). Surface features may thus be intimately controlled by the magnetic field at various depths and are manifested in the evolution of large-scale features like coronal holes (CHs), filaments, polarity boundaries, and active regions and sunspots. Overall, these motions give clues to the internal fluid dynamics of the Sun and its dynamo processes over solar cycle (SC) time scales.

The Sun reveals at least two characteristic migrations of surface features (see, e.g., Hathaway, 2015). The first is the equatorward movement of sunspots, which is a key aspect of the 11 year cycle. The second is the poleward movement of high-latitude filaments/prominences, the so-called "rush to the poles," which is a tracer of the solar polarity reversal process and the onset of the 22 year magnetic cycle. Zonal flows such as the torsional oscillations have been associated with both of these migrations. Observations of small-scale magnetic features, such as bright points, sunspots, and CH centers (McIntosh et al., 2014), as well as helioseismic studies of the zonal flows (Howe, 2016) provide support for an extended period of solar activity, for example, from 17 to 22 years long (Cliver, 2014).

The rush-to-the-poles phenomenon observed in both solar filaments and in coronal emission and the zonal flows may be fundamental to the polarity reversal and the subsequent development of the polar fields (Babcock, 1961; Leighton, 1964, 1969). The polar field strength at solar minimum, either measured directly or deduced from the number of observed polar faculae, has been used to predict the peak sunspot number of the following cycle (Muñoz-Jaramillo et al., 2013). Thus, observations of the evolution of these features over long, SC time scales are fundamental for understanding the solar dynamo and its effects at the surface.

To pursue such studies, Patrick McIntosh in 1964 (SC 20) began creating hand-drawn synoptic maps of solar activity, based on daily Hα imaging measurements (Figure 1). These synoptic maps were unique because they traced the polarity inversion lines (PILs) connecting widely separated filaments, fibril patterns, and corridors within active areas to reveal the large-scale organization of the solar magnetic field. At the time, magnetographs were expensive and the resultant magnetograms not routinely available. Another advantage of Hα measurements was that PILs could be more precisely determined in weak field regions and near the poles of the Sun (Fox et al., 1998; McIntosh, 2003). It has been shown that the large-scale Hα patterns on the surface match well the large-scale magnetic fields measured with magnetographs (e.g., McIntosh, 1979).

CHs were added to the maps starting in 1978, primarily using ground-based He-I 10830 Å images from NSO-Kitt Peak. Magnetograms were used, when available, to determine the overall dominant polarity and to show where the polarities changed. Some of the original hand-drawn McIntosh maps were published as Upper Atmosphere Geophysics (UAG) reports in McIntosh (1975), McIntosh and Nolte (1975), and McIntosh (1979). Versions of the maps were also routinely published in the Solar-Geophysical Data Bulletins (the "Yellow books") in the Prompt monthly reports.

McIntosh and his assistants created these synoptic maps for each Carrington Rotation (CR) during the interval 1964–2009, with the exception of a 2-year period from July 1974 to July 1976. Thus, the synoptic maps cover

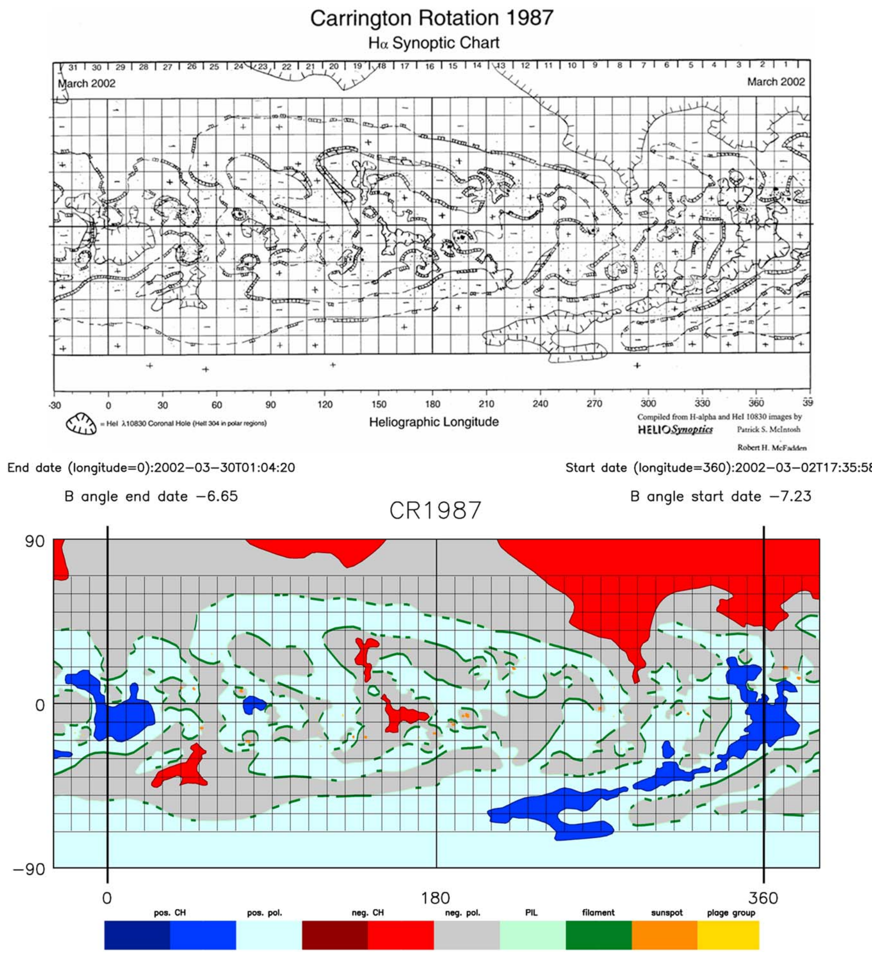

Figure 1. 0(top) Scanned copy (Level0) of an original synoptic map from March 2002 created by Pat McIntosh. (bottom) Processed colorized map (Level3) from the new McIntosh archive with negative (gray) and positive (light blue) polarity magnetic fields, negative (red) and positive (dark blue) CHs, filaments (green), and PILs (black).

~45 years or ~570 CRs, or nearly four complete SCs. The features on the maps include filaments, large-scale positive and negative polarity regions, CHs of each polarity, sunspots, and active regions (Figure 1, top). The McIntosh map collection is unique, providing a consistent view of the evolution of the global solar field.

Although Pat McIntosh is now deceased, Ian Hewins and Robert McFadden were trained in the mapping by Pat from 2000 to 2010. With NSF support, the original data have been preserved and organized by scanning and digitally processing the maps into a consistent, machine-readable format. The result is an archive, which we call the McIntosh Archive (McA) that may be utilized by scientists and the public for years to come. This work has been performed at Boston College and the NCAR/High Altitude Observatory (HAO) in Boulder, CO. A website describing and providing access to the archive can be found at https://www2.hao.ucar.edu/mcintosh-archive/four-cycles-solar-synoptic-maps.

The maps are preserved in three formats:

1. Level0 gif images are direct scans of the original hand-drawn McIntosh maps.
2. Level1 gif images have been cropped, oriented, and scaled for consistency, as described below.

- The Level0 and Level1 data sets have been completed for all of the original maps, 1964–2009.

3. Level3 FITS format files and associated gif images represent the fully processed maps, as described below.

- Presently more than half of the ~570 CR maps have been completed as Level3, starting in SC 20, 1967 through to the start of SC 24 in 2009 but with long gaps in SCs 20, 21, and 22.

The processing consists of using Photoshop and Interactive Data Language (IDL) to convert the maps to a standard size based on number of pixels in width (heliolongitude) and height (heliolatitude), to remove any unnecessary notes, marks, or symbols, and to colorize the maps. The final Level3 maps key on PILs, or "neutral" lines, which form the boundary between opposite-polarity photospheric magnetic fields. Solar features included on the maps are the following: CHs having positive polarity magnetic field and their boundaries, positive magnetic fields, CHs having negative polarity magnetic field and their boundaries, negative magnetic fields, PILs, filaments, sunspots, and plage groups. The final archive maps have these features identified by 10 IDL colors (numbers) which permit digital sorting for data analysis purposes. In addition, missing data are identified as yellow (usually in the polar regions above 70°).

We have written an IDL code, *plotfinal.pro* that makes plots from the Level3 files (e.g., Figure 1, bottom), as well as other codes to permit efficient searches of the map arrays. These codes are publicly available with the processed maps archived at the NOAA's National Centers for Environmental Information (NCEI) in their final, searchable form at https://www.ngdc.noaa.gov/stp/space-weather/solar-data/solar-imagery/composites/synoptic-maps/mc-intosh/ (and accessible through the Web page above). A metadata spreadsheet is maintained for all processed maps and contains information such as data sources and cartographic notes.

The archive for SC 23, from 1996 to 2009, is complete and currently being analyzed (e.g., Gibson et al., 2017). Our future processing tasks include bringing the remaining McIntosh maps to Level3 and completing or creating the approximately 110 maps or CR periods that are incomplete or missing from the original archive. In addition, we plan to scan and process an original atlas of 132 Hα synoptic charts for SC 19 (1955–1964) that were produced by V. Makarov and K. Sivaraman and are available at HAO. These were produced using Kodaikanal (India) Solar Observatory (KSO) Hα filtergrams and CaK spectroheliograms and published in Makarov and Sivaraman (1986). These will be compared to recently reprocessed Kodaikanal data (Chatterjee et al., 2017; K. Tlatova and A. Tlatov, 1917, private communication).

A variety of historic scientific discoveries have depended on the use of the synoptic maps (see McIntosh, 2003, for a review). For example, the maps have been used to describe the drift of polar crown filaments (PCFs) to higher and lower latitudes, the disappearance and reappearance of polar CHs, and the reversal of the polar magnetic field (e.g., Webb et al., 1984). The PCFs and their PILs trace the final boundary between the old-cycle polarity, which will reverse at cycle maximum, and the new-cycle polarity which replaces it, an evolution that takes about 15 years. These motions and their evolution provide important clues about the fluid dynamics of the Sun and its dynamo processes. More recently, McIntosh's maps have also been used to study the morphology and global context of coronal cavities, as part of a study of the nature of coronal mass ejection magnetic precursors (Gibson et al., 2010), and the global context of solar activity during the last solar minimum (Thompson et al., 2011; Webb et al., 2011).

The Hα synoptic maps have proven to be unique tools for studying the structure and evolution of the large-scale solar fields and polarity boundaries, because (1) they have excellent spatial resolution for defining polarity boundaries, (2) the organization of the fields into long-lived, coherent features is clear, and (3) the data are relatively homogeneous back to the start of cycle 20 in 1964 (McIntosh & Wilson, 1985). Time series zonal "stack plots" of the maps are invaluable in identifying and tracking large-scale features, including polarity boundaries, CHs, and active longitudes, over SC time scales (e.g., Gibson et al., 2017; McIntosh, 2003). An atlas of stack plots of the Hα synoptic charts covering two full SCs, from 1966 to 1987, was published by NOAA (McIntosh et al., 1991). Decadal stack plots have demonstrated the evolution of gaps in the polar crown, polarity reversals, and longitudinal pattern drifts that circle the Sun over a cycle (McIntosh, 2003; McIntosh & Wilson, 1985). Their analysis led to the development of a model of flux emergence and surface evolution (McIntosh & Wilson, 1985; Wilson & McIntosh, 1991).

The overall science objective is to utilize the completed McA maps to investigate long-term solar variability over SC periods. Our analysis work emphasizes understanding the SC variation of the toroidal and poloidal components of the magnetic field, its connection to the dynamo and dynamo models, the sources and evolution of active regions, CHs, filaments, and how the rotation rates of the various solar features vary over these cycles.

A scientific study uniquely enabled by the McA is to follow the evolution of solar magnetic features as functions of time across many maps, such as with time series plots over SC time scales, that is, "butterfly" plots. For the McA maps we can plot the latitude-longitude locations of specific colored (numbered) regions on each

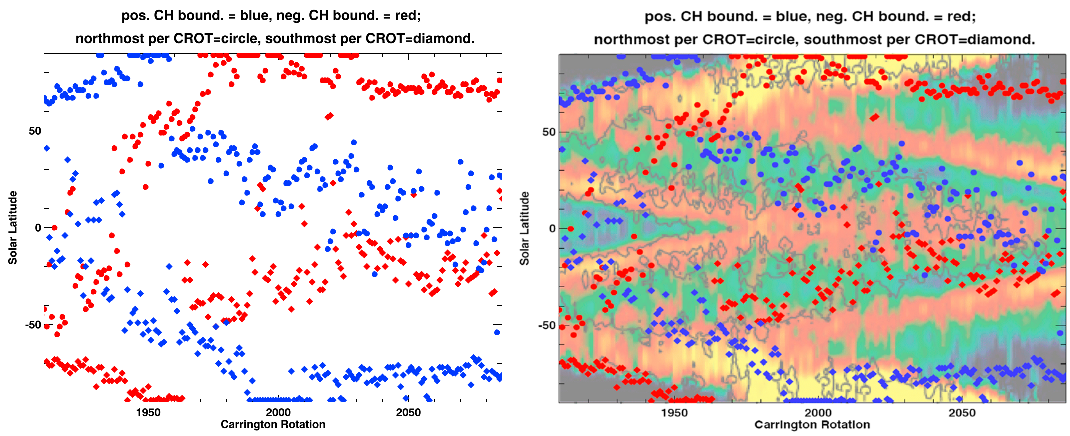

Figure 2. (left) The poleward most CH boundaries per CR for SC 23. (Filled circles diamonds) indicate the most northward (southward) extensions of CH boundaries for each CR. Red and blue indicate magnetic polarity. (right) This same plot overlaid on a plot of the zonal flows (torsional oscillations) of the near-surface (0.99 $R_\odot$) magnetic field from the National Solar Observatory (NS) Global Oscillation Network Group (GONG), Solar and Heliospheric Observatory (SOHO) Michelson Doppler Imager (MDI), and Solar Dynamics Observatory (SDO) Helioseismic and Magnetic Imager (HMI) data, covering the period from the beginning of the GONG observations in 1995 to the present (from Howe, 2016; prepared by R. Komm). This shows that the poleward and equatorward magnetic flows over SC 23 match CH locations very well.

map and concatenate them together to form butterfly plots of specific features over SC time scales (see examples in Gibson et al., 2017).

The McA maps enable studies of the SC variation of both closed and open magnetic structures as never before and eventually will cover five contiguous SCs, 19–23. As an example, Figure 2a plots the poleward most CH boundaries per CR for SC 23. It also shows the poleward migration and what may be two populations of CHs, polar CHs and low-latitude CHs that follow the sunspot/plage butterfly pattern. Analyses of small-scale magnetic features, such as EUV bright points, magnetic regions of influence, g-nodes, torsional oscillations (Figure 2b) with sunspots and CH centers, have recently been made (e.g., Bilenko & Tavastsherna, 2016; Karna et al., 2015; McIntosh et al., 2014). The activity bands of these features emerge around 55° north and south latitudes and take 18–19 years to reach the equator. Our maps show a pattern of polar and low-latitude CHs with opposite polarities separated by the PCFs, which tend to demark this important 55° latitude zone.

Acknowledgments
We dedicate this article to Patrick McIntosh who passed away in October 2016 (Hewins et al., 2017). Pat should be considered one of the founding Fathers of what we now call Space Weather, because of his pioneering work in forecasting research starting at the Space Environment Laboratory at the National Oceanic and Atmospheric Administration (NOAA) in Boulder. The work of the authors was supported by National Science Foundation RAPID grant 1540544. The National Center for Atmospheric Research (NCAR) is supported by the National Science Foundation. The repository for the data discussed here is available at https://www.ngdc.noaa.gov/stp/space-weather/solar-data/solar-imagery/composites/synoptic-maps/mc-intosh/ (McIntosh, 1964).

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