**Background for the McIntosh Archive (McA)**

## 1. Introduction

The McIntosh Archive (McA) consists of a set of hand-drawn solar Carrington maps created by Patrick McIntosh from 1964 to 2009. McIntosh used mainly Hα, He-I 10830Å and photospheric magnetic measurements from both ground-based and NASA satellite observations. Hα is the primary line of hydrogen and is formed in the chromosphere. With these, he traced polarity inversion lines (PILs), filaments, sunspots and plage and, later, coronal holes over a ~45-year period. This has yielded a unique record of synoptic maps of features associated with the large-scale solar magnetic field over four complete solar cycles.

The McIntosh maps were unique in that they traced the PILs (or neutral lines) that connected widely separated filaments, fibril patterns and active region corridors to disclose the large-scale pattern of the global magnetic field. In the 1960s, magnetographs were expensive, less reliable, and their magnetograms were not available on a routine basis. Another advantage of using Hα images was that PILs could be more accurately tracked through weak-field regions and near the solar poles (e.g., Fox et al., 1998; McIntosh 2003). Magnetograms were used to determine the overall dominant magnetic polarities and to show where their boundaries were. McIntosh (1979) and others showed that the large-scale Hα surface patterns matched well with the large-scale magnetic fields and their boundaries as measured on magnetographs.

Beginning in 1981, CHs were routinely added to the maps, primarily from ground-based He 10830Å images from National Solar Observatory (NSO) Kitt Peak Observatory and after 1992 from NSO's Sacramento Peak Solar Observatory. McIntosh also used 10830Å data to map coronal holes in 1978, but only for three rotations. We also added coronal hole data that became available in July 1974 when Kitt Peak began producing 10830Å images.

Many of the original hand-drawn McIntosh maps were published as Upper Atmosphere Geophysics (UAG) reports McIntosh (1975; May 1973–March 1974), McIntosh and Nolte (1975; October 1964-August 1965), and McIntosh (1979; 1964-1974). The maps were also routinely published in the Solar-Geophysical Data (SGD) Bulletins (the “Yellow books”). All of these reports are archived at the NOAA National Center for Environmental Information (NCEI).

McIntosh and various assistants generated these maps for each Carrington Rotation (CR) from 1964 to 2009, but with some gaps. Pat McIntosh is deceased, but his assistants coauthors I. Hewins and R. McFadden were trained by Pat in how to produce the maps and kept the boxes of maps and related materials. The first and foremost intent of the McA project was to preserve the entire archive. Under two NSF grants, this has been achieved by collecting and collating all of the material at the High Altitude Observatory (HAO) in Boulder, CO and completing scanning of all of the maps in a uniform manner.

This 45-year period covers four complete SCs, 20-23, or 600 CRs. The features on the maps include filaments, sunspots and active regions, large-scale positive and negative polarity regions, and CHs of each polarity. Scientists in France (Meudon Observatory), Russia, India (Kodaikanal

Solar Observatory) and China intermittently created similar maps in the 1970s and 1980s, but those efforts were short-lived and inconsistent with each other. The McA is distinctive in providing a consistent, long-term, reliable view of the evolution of the global solar magnetic field and feature data.

Part of the McIntosh archive now at HAO is an original atlas of Hα synoptic charts for SC 19 from 1955 to 1964. These were produced and published by V. Makarov and K. Sivaraman (1986) from Kodaikanal (India) Solar Observatory (KSO) Hα filtergrams, CaK spectroheliograms, and other data sources. Although the KSO SC 19 charts do not show active regions, plage, sunspots or CHs, the reliability and accuracy of the neutral lines and inferred magnetic polarities and their boundaries appear to be consistent with the McA maps. Therefore, these maps have been scanned and digitized (see SC19_kodaikanal_maps_2020.doc; URLs in Sec. 3), as part of the McA covering ~55 years from December 21, 1954 to August 13, 2009.

## 2. Previous Studies Using the Original McIntosh Maps

The McIntosh maps are a unique tool for studying the large-scale solar fields and polarity boundaries, because: (1) they clearly show the organization of the fields into long-lived, coherent features, (2) they have good spatial resolution to define polarity boundaries, and (3) the data are relatively consistent starting with SC 20 in 1964. A number of scientific discoveries have depended on using the McIntosh maps (e.g., McIntosh, 2003). For example using the maps, the latitudinal drift of polar crown filaments (PCFs), the evolution of polar CHs, and the reversal magnetic field at the poles (e.g., Webb et al., 1978; 1984) have been studied.

In one study, McIntosh (2003) traced the location of the maximum latitude for the PCFs on the synoptic maps over SCs 20-22, including the "secondary" PCF that appears at lower latitudes and replaces the "true" PCF after the solar magnetic field reverses. On each of the CR maps Pat McIntosh recorded the location of the maximum (polemost) latitudes of the primary and secondary polar crowns of filaments and concatenated them together to reveal the "rush-to-the-poles". Thus, for each CR/time plot there are 4 data points, the latitudes of the northern and southern hemisphere polar crown pairs. These features trace the final boundary between the old-cycle polarity, which reverses at the maximum of the cycle, and the new-cycle polarity that replaces it. This evolution occurs over at least 15 years (McIntosh, 1992). For each cycle, the polar-most (primary) crown begins the rush-to-the-poles in both hemispheres at about ~55° latitude. The replacement polar crown begins moving poleward at about the same time from ~40° latitude. The evolution of these features offers important hints about the Sun's interior fluid dynamics.

Time-series stack-plots of latitude zones of the maps help to identify and track large-scale solar features. These include active longitudes, CHs and polarity boundaries over SC time scales (e.g., McIntosh 2003; Gibson et al., 2017). Stacked over many CRs/years, these barber-pole patterns denote the varying rotation rates of the long-lived, large-scale patterns. These show how the polarities reverse during the SC and the difference in rotation rates between the poleward and equatorial zones. Decadal-long stack plots have established the evolution of polar crown gaps, polarity reversals and longitudinal drifts in patterns that circle the Sun over a cycle (McIntosh and Wilson, 1985; McIntosh et al., 1991; McIntosh 2003). Analysis of these patterns led to development of a model of emerging flux and surface evolution (McIntosh and Wilson, 1985; Wilson and McIntosh, 1991). McIntosh's maps have more recently been used to study the morphology and evolution of coronal cavities, as magnetic coronal mass ejection precursors (Gibson et al., 2010), and to study solar activity during the last prolonged minimum (Webb et al., 2011).

## 3. Implementation

The McA now consists of the preserved original data and electronic products produced by scanning and digitally processing the maps into a consistent, machine-readable format. A description and access to the archive is at: https://www2.hao.ucar.edu/mcintosh-archive/four-cycles-solar-synoptic-maps. It is also hosted at NOAA's National Centers for Environmental Information (NCEI) at: https://www.ngdc.noaa.gov/stp/space-weather/solar-data/solarimagery/composites/synoptic-maps/mc-intosh.

The maps are preserved in three formats: (1) Level0 GIF images which are direct scans of the original hand-drawn McIntosh maps; (2) Level1 GIF images which have been cropped, reoriented and scaled for consistency; (3) Level3 FITS format files and associated GIF images characterize the fully processed maps. The original maps were scanned and saved as Level0 GIFs in the Archive. These are read by an IDL routine (*levelone.pro*) which digitizes them in a consistent and reproducible manner. In particular, the code: (1) identifies the Carrington latitude/longitude boundaries of the scanned map, crops the space outside these boundaries, and rotates to ensure the maps have the same orientation; (2) resizes so that all maps have the same resolution; and (3) identifies latitude and longitude coordinates for each pixel. The maps are saved as Level1 GIF images in the archive, with metadata relating Level0 to Level1 preserved in intermediate data files, ultimately to become part of the Level3 FITS files (see below).

The Level1 GIFs are read into Photoshop and the filaments, filament channels, coronal holes (if present), sunspots, and plage groups are traced over with colors unique to each type of feature. This represents the primary human intervention to the process, and is a straightforward matter of identifying large dots as sunspots and plage areas, thick lines as filaments, hatched lines as CH boundaries, etc. A second IDL code (*leveltwo.pro*) reads the gif output of the Photoshop processing, replacing all pixels that do not possess the specific feature colors with white pixels, thus removing no-longer-needed information such as text and the original overplotted latitude-longitude grid. Five points of this initial grid are preserved (marked with an identifying color during the Photoshop session) as a means of quantifying any error potentially arising from a non-rectangular grid. A second Photoshop session is used to fill in CHs and quiet sun with colors defining their polarity. Since the initial session created continuous boundaries, this is a straightforward and reproducible step achieved simply by selecting the spaces within the boundaries and choosing a color based on the + and - symbols on the original maps.

The final IDL code (*levelthree.pro*) combines the metadata saved during the previous IDL steps of the digitization process with metadata entered into the spreadsheet record of the archive. The spreadsheet includes information such as data sources and cartographers for each map. The map data are now in the form of a uniform grid of numbers, each of which can be translated to a color that uniquely identifies the associated solar feature type. Further analysis examines quiet-sun pixels surrounding sunspots and plage to associate a signed polarity with them, resulting in further refinement of color/feature diversity. The map data, longitude-latitude data, a grid of polarity assigned to each pixel, and all metadata are then saved as the Level3 FITS files for the archive.

Finally, the IDL code calls a subroutine (*plotfinal.pro*) which creates standardized Level3 GIF images from the FITS files for a given CR number. This code can also be used to create customized GIFs from the FITS files if so desired. For a given CR, *plotfinal.pro* can produce up to 16 permutations of the (FITS) mapping variables that are output as "final" GIF files depending upon keyword settings. These are 8 with a heliographic grid and annotations and 8 with no grid and annotations. Other combinations include extensions of ±30° for -30° to 390° in solar longitude, or only 0°-360° in solar longitude; missing cream colored data poleward of ±70° in solar latitude, or missing cream colored with only CH boundaries, or CHs filled in with missing cream colored negative or positive polarity, or all colors filled in near the poles. The final file names reflect these combinations. Since all the final CR maps have the same color system and known scaling, features can be intercompared over many CRs, with time and as a function of solar cycle. We and others have also written codes to permit efficient searches of the map arrays.

A key feature of the final Level3 maps are the PILs that bound opposite-polarity photospheric magnetic fields. Solar features included on the maps include 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. These features are identified on the final archive maps using ten IDL colors (numbers) that allow digital sorting and searches for data analysis. In addition, missing data on a map are marked with a cream color, usually near the poles above 70°.

The *plotfinal.pro* code along with the processed maps in their final, searchable form are archived at the NOAA NCEI noted above. The archive is publicly available and the most recent version is accessible through the above HAO online site.

In addition, we have included comprehensive metadata in the Level3 FITS files that incorporate all the information needed to describe the original Level0 form of the maps. A separate metadata spreadsheet, containing information on data sources and cartographic notes, is maintained for all of the processed maps and is also available through the online sites. For each CR map the spreadsheet contains information about the McA data sources, the individual(s) responsible for map creation, and comments. The data types include filaments and other tracers of PILs, photospheric magnetic field polarities, CH boundaries, sunspots and plage. The data sources vary with time and include ground-based telescopes at various solar observatories, MDI images on the SOHO spacecraft, etc.

## 4. Recent Scientific Results

The two NSF grants have produced both innovative science as well as a public archive that is actively being utilized by the community. Some significant recent results include:

- There is a consistent long-term shift eastward in the position of equatorial CHs, completing a rotation every 2.5 years (Cranmer et al. 2017, Webb et al. 2018);
- The positions of low latitude CHs behave similarly to both sunspots and plage over a solar cycle and form a classic butterfly pattern (Hewins et al. 2020). The lifetimes of low-latitude CHs are usually less than one rotation but may extend to almost three years, and CHs do not in general rigidly rotate.
- The length of filaments has a solar cycle dependence, peaking at solar maximum (Mazumder et al 2018).
- Emery et al. (2020) studied the evolution of the median primary and secondary PILs and of the poleward CH boundary for SCs 19-23 using the McA. The primary and secondary PILs are ~14° apart, share common features in each hemisphere, and the CH boundaries are typically located ~16° poleward of the primary PIL. The PILs have peak periodicities of ~8 CR,~16 CR and ~25 CR, and the CH boundaries have ~10 CR and ~20 CR periods.

McA URLs:

https://www2.hao.ucar.edu/mcintosh-archive/four-cycles-solar-synoptic-maps

https://www.ngdc.noaa.gov/stp/space-weather/solar-data/solar-imagery/composites/synoptic-maps/mc-intosh

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