

# Magnetic field measurements and MMFs using the IR Fe line at 1564.8nm

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## Overview

Over 30 years of observations and theories comprise the study of moving magnetic features (MMFs). MMFs, which often occur in opposite polarity pairs, migrate radially outwards through the sunspot moat at speeds of about 1 km/s. Magnetogram images and maps of the magnetic field vector using the IR Fe line at 1564.8 nm have penumbral magnetic features that appear to move radially outwards at similar velocities and azimuth angles as those of MMFs in the moat, something not predicted by preceding work. We use polar time slice images to measure the radial velocities of both types of features in an attempt to determine the validity of this relationship, as well as to evaluate its implications for our understanding of sunspot magnetic fields.

## MMFs and BPs: Previous work

When Hale discovered magnetic fields in spots, he effectively introduced magnetohydrodynamics into solar physics. The study of solar magnetic fields has since become an important component of solar physics. Sunspots are the best observable features in the intermittent solar magnetic field. A typical sunspot consists of an umbra that is dark in continuum, cooled by its strong vertical magnetic field. The umbra is surrounded by a brighter penumbra, where the magnetic field flares out, reaching a near-horizontal inclination. During its decay, the penumbra is often surrounded by a moat, an annular zone extending to about 20 Mm and lacking a stationary magnetic field. (Zwaan)

Magnetic flux in a sunspot is contained in narrow filaments called flux tubes. These flux tubes, while below the current limit of telescope resolution, are the key to the fine structure dynamics of the sunspot magnetic field. Therefore, our ideas of small magnetic features, such as MMFs and bright points, are as much theory as observation, and continue to be studied with increasing interest.

In 1971 Vrabec noted the systematic outward streaming of small (<1') magnetic knots of both polarities within annular areas surrounding several sunspots. Harvey and Harvey (1973) termed these knots 'moving magnetic features' (MMFs) in what was the first real, systematic study of these phenomena. MMFs aren't visible in continuum movies, so H73 studied the MMFs using time series of magnetograms and H $\alpha$  filtergrams. They found that MMFs appear only around sunspots which possess a moat. Like their predecessors, Sheeley and Vrabec, H73 found that MMF's first appear at the

outer penumbral boundary and travel in near-radial directions at speeds of  $\sim 1$  km/s, until they vanish or reach the network. They estimate the flux of individual features at  $6 \times 10^{17}$  to  $8 \times 10^{19}$  Mx. While MMFs tend to appear in opposite-polarity pairs, and may carry 2-10 times the flux of the parent sunspot, the rate net flux carried away from the sunspot in MMFs is of the same magnitude of the decay rate of sunspot flux.

While moat MMFs have repeatedly been observed, reports on temporal variations in the sunspot penumbra are far less common. Bovelet and Weihr looked at flow in both the moat and penumbra by measuring the motions of G-band bright points. In 1969 Sheeley noted in his spectroheliograms BPs moving outwards from sunspots at speeds of  $\sim 1$  km/s. Some of these BPs were cospatial with the magnetic field concentrations. Bovelet and Weihr studied the moat flow by looking at a large population of BPs that were cospatial with magnetic field concentrations. To track the BPs over their lifetime, they used an algorithm called multiple level tracking. MLT was capable of tracking 1426 isolated BPs by separating and extending each recognised feature into a realistic shape, and using that shape to determine flux and exact position from the moment each feature reached an intensity threshold, until the moment it sank back below that threshold. They were then able to determine the magnitude and angular offset from radial of the velocity of each BP. Their measurements had a large random component, but showed an overall systematic outward radial drift of  $.3$  km/s. They found these speeds to be at a maximum at the outer penumbral boundary, decreasing to nearly zero at  $\sim 20$  Mm, which they took to be the extent of the moat.

Bovelet and Weihr also studied  $\sim 275$  bright structures within the penumbra. Unlike the BPs in the moat, the Penumbral Bright Structures possess both inward and outward velocities, with the outward velocities concentrated in the outer penumbra. They also studied Penumbral Dark Structures, which are located primarily in the outer penumbra and move predominantly outwards. They believe that some of the moat 'drift' might persist in the outer area of the penumbra, causing this outward motion.

Another study that observed inward and outward motions in the penumbra was done by Lites et al in 1997. They found that at low frequencies in maps of fluctuations in continuum intensity, magnetic field strength, and field inclination, distinct features moving radially inward can be seen in the inner penumbra. In the outer penumbra and surrounding quiet sun, distinct outward-moving features are visible. They believed these features to be signatures of the convective interchange of magnetic flux tubes in the sunspot.

## Data

The data I worked with are spectropolarimetry scans taken in June of 2002 at the McMath-Pierce telescope on Kitt Peak. The camera used was the

CSUN-NSO infrared camera, using a 256x256 pixel detector. The observers made polarized, east-west scans of the spectrograph over the active region NOAA 10008, a sunspot located just southeast of disk center. Sixteen scans were taken from 17:38 to 21:59 UT at a 15 minute cadence. Two of these scans were eventually thrown out because they were corrupted. The magnetic field measurements were made using the instrument -corrected Fe line 1564.8nm. As far as we could find, nobody has yet studied sunspot magnetic fields using this line: however, it is ideal for studying moving magnetic features for a variety of reasons.

The data were analyzed by measuring the Zeeman splitting of the line, which is directly proportional to the strength of the field causing the splitting, allowing us to directly measure that field strength. The pattern and amount of splitting is also a property of the magnetic the spectral line used, namely the wavelength and a property of the transition known as the g-factor. Our IR Fe I line at 1564.8 nm has a longer wavelength than any optical choice, as well as a very high g factor, making it an excellent choice for magnetic field study.

Besides our choice of line, our data has the benefit of a long data-collecting period of 4.5 hours of data. The slow .2-2 km/s speeds of the type of features we are looking at require a long period of observation for measurable results. These features also have a lifetime of ~4 hours, so an observational period of this length is preferable. The combined benefits of the line choice, full vector measurements, and long observation period make this data uniquely good for studying the sunspot magnetic fields.

Despite these attributes, our data was difficult to analyze because of seeing. MMFs, on the scale of only ~1', require high resolution. However, in our data, atmospheric turbulence causes image motion and degradation that severely limit resolution. Turbulence in the atmosphere is compounded by turbulence that builds up inside the telescope tube as it is heated by the sun. This problem can be minimized by evacuation of the tube or by adaptive optics. Other telescopes, like the DOT on the Canary Islands, take advantage of the location's steady, cool breeze to remove turbulence between the mirror and detection apparatus. Our data were taken without benefit of any of these devices. Additionally, the slow speed of scanning means seeing can change drastically over the course of a single frame.

## Analysis

Carl Henney created maps of continuum intensity, magnetic field strength, mf inclination to the line of sight, and asymouth angle of the transverse field by applying a least-squares fit to the magnetic field components at every pixel. The line of sight magnetic field strength map map shows a double umbra. The northward umbra is darker in continuum, about .45 times quiet sun intensity, and has a stronger magnetic field ~2800 G, than the southern umbra

( $I=.55 q_{\text{sun}}$ , field=2300G). Also visible is the penumbra, cooler than quiet sun, but with a weaker magnetic field (1200-1400G). In inclination, the umbra is dark, as it's inclination to vertical is near zero. In contrast, the penumbra shows an inclination of about 90 degrees.

These inclination maps also reveal another interesting phenomenon: 'wiggles', or regions of less inclination to vertical. In contrast to the near-horizontal inclination of the rest of the penumbra, these regions possess field inclinations of 40-60 degrees to the line of sight. Time sequences show that these features are dynamic on the period of observation, moving radially outward through the penumbra. Our goal was to look at the velocities and azimuth locations of these features, and explore the possible relationship between these features and the MMFs of the moat.

The line fitting method used to make the magnetic field maps does not work well on the weaker field outside the spot. Therefore, a different and simpler method was used to study motions in the moat area: we created a time series of magnetograms by differencing the line wings of the Fe 1564.8 nm Stokes V spectra, effectively integrating over that line. After shifting the images so that the spot center was aligned between frames, and removing two bad frames, we were left with a time series of 14 magnetograms spaced over the 4.5 hour period.

Our goal with the magnetogram images was to find the velocities of the radially moving MMFs, with hopes of later comparing these velocities to those of the penumbral inclination 'wiggles'. Measuring the radial velocities was made difficult by atmospheric seeing, which often blurred some of the features in a frame. Therefore, automated methods of feature tracking, like MLT developed by Bovelet and Weihr, were not applicable.

My first attempt to identify and track MMFs was to visually and manually track moat features over the course of the 14 good frames, and use the positional changes to calculate the radial velocities of the MMFs. This revealed an average outward velocity of  $\sim .25$  km/s, with directions varying only to about 20 degrees of radial. However, the paths of these features could not be visualized in time slice diagrams produced along the direction of motion of each feature.

Next we attempted to use a technique of local correlation tracking, similar to the method November and Simon used for proper-motion measurements of solar granulation. Local correlation tracking corrects for atmospheric geometric distortions in a time series by cross correlating small segments of the images in time. We attempted a two-fold purpose with local correlation tracking: we hoped to remove large-scale atmospheric shifts, as well as uncover the organized radial shift due to moat flow. To do this, we adapted our software to output shift values, and plotted them to a vector field. The result was noisy and lacked any organization: we realized that the program, when lacking a real correlation, would output a false and often large shift value. To improve our correlations, we tried adapted versions of several other correlation programs, none of which provided a clear visualization of the moat flow. We

attempted to again adapt the software to use only well-correlated shifts, once again resulting in a disorganized shift field. Our ultimate conclusion was that while local correlation works well for images of the quality of November and Simon, our significantly larger noise levels made use of LCT impossible.

Our final attempt at MMF identification and tracking was to revert to using time slice diagrams. However, this time, we approached it by imaging the sunspot in polar coordinates. The goal of time slices is to image in one spatial dimension and a time dimension. In polar coordinates, radial motion becomes spatially one dimensional. By creating time slices over the range of azimuthal angles, I identified nearly 40 MMFs in the magnetograms. We measured the motion of each feature in space and time to find the radial velocity ( $dr/dt$ ) and then map these velocities to the spots. We also repeated the time slice procedure to look for moving features in the maps of magnetic field inclination. This method revealed an additional 10 moving features.

## Results

The MMFs in the magnetograms had a variety of velocities, from .18 to 2.51 km/s. These results were consistent with previous work, including Ryutova's observations that MMFs possess a wide velocity range. The median velocity was about .4 km/s. As Zhang and Solanki found, we also noticed that the MMFs appear to cluster at particular azimuths around the sunspot. The majority of the features were members of opposite polarity pairs.

The most unexpected result from the magnetogram studies was that several of the MMFs identified moved within the penumbra. Nearly half of the 38 magnetic features from the time slices were first discovered moving outwards through the outer penumbra, lying in contradiction to the strict outer-penumbra starting boundary previously supposed for MMFs. These features appear to move radially outwards in lanes between more vertical field concentrations. Their velocities remain relatively constant as they pass through the outer penumbral boundary into the moat, and there is no azimuthal or velocity distinction between the penumbral-start MMFs and the moat-start MMFs. Additionally, the 10 features we tracked in the inclination maps of the magnetic field move radially outwards at similar velocities to the MMFs, in the range of .18-1.7 km/s. These features appeared to cluster at the same azimuth angles as the MMFs, suggesting that the types of features are related. Our discovery of these two new features in the penumbra has an important impact on our understanding of the structure and formation of these features.

## Models

Harvey and Harvey first proposed that MMFs are the mechanism of the slow decay of sunspots, and this idea has been adopted by a variety of later works. While most sunspots decay fast by fragmentation, many larger spots- the ones surrounded by moat cells- decay gradually. Across the moats of such spots

stream MMFs of both polarities, with the total rate of flux removal in MMFs indicative of the decay rate of the sunspot.

Because of the significant role of MMFs in sunspot dynamics, it is important to try to understand the MMF in the context of the sunspot environment. Features on the scale of single flux tubes are beyond our resolution capabilities, so we have been forced to settle for models of MMFs, which take into account observations and what we know about the magnetic and convective properties of a sunspot.

Three types of MMFs have been observed around sunspots. According to Thomas et al, Type I MMFs, the most commonly observed, are opposite-polarity pairs. Type II MMFs are single magnetic elements with the same polarity of the sunspot, moving outward across the moat with speeds similar to those of Type I MMFs. Type III MMFs are single magnetic elements with polarity opposite that of the sunspot. These MMFs move rapidly outward through the moat. Types I and III MMFs are only seen around sunspots with penumbrae, while a penumbra is not a requisite for type II MMFs. Most models tend to either omit talk of Type II and III MMFs, or attribute them to opposite-polarity pairs in which one member is not visible. The main focus of MMF models is on Type I MMFs. While most theories conclude that MMF pairs are the footpoints of a small part of a magnetic field line that loops through the solar surface, the cause and nature of these U loops differs greatly between models.

Harvey and Harvey first proposed that a series of MMF's is actually the repeated emergence of a sub-photospheric sunspot field line. Ryutova adopted this intuitive picture, citing the wide range of flow velocities observed in 'near sunspot' regions as the cause of flux tube deformation and the generation of a stable kink. This 'kink' may then evolve into a traveling MMF or series of MMFs. Each flux tube has its own range of critical flow velocities which may cause it to deform. The exchange of energy and momentum between magnetic flux and outer motions result in the onset of nonlinear shear stabilities which lead to the observed macroscopic effects on the flux tubes.

Ryutova also actually claims to see the flux tube emerging, its ends becoming a pair of opposite-polarity MMFs. In accordance with these observations, Spruit et al present a second model of rising loops. The properties of active regions produce U-loops: flux tubes having two ends at the photosphere but otherwise still embedded in the convection zone. Once a U loop develops, the bottom of the flux tube becomes magnetically buoyant and rises. As it rises, the flux tube expands, and field strength drops, becoming controlled by convection on top of the convection zone. At the surface, the large loop is fragmented into a series of closed loops, the footpoints of which are the members of an opposite polarity MMF pair. Flow in the moat cell grabs the top part of the rising loops and carries them radially outward.

Unlike Spruit's the rising U loop model, Zhang and Solanki propose that MMFs are formed when the field lines in a small part of the magnetic

canopy dip down to produce a 'falling' U-loop. They begin their scenario with a packet of dense, outward-flowing Evershed gas in the penumbra. The vertical field gradient of the penumbra provides a force that resists the gravitational force. At the outer penumbral edge, this supporting force disappears, and sufficiently massive and dense gas can no longer be supported by the flux tube field. Therefore, the gas sinks, taking the magnetic field with it, causing a U loop to be created near the penumbral edge, with gravity and magnetic tension working to submerge and push up the flux tube, respectively.

Thomas and Weiss explain the production of MMFs through the interaction of the magnetic field with turbulent, compressible convection in the solar granules and supergranules. In their model, granules grab flux tubes, with their associated outflows of gas, from the sunspot penumbra and pull them under the surface of the sun. They are then carried outwards by a large supergranule, ~30 Mm in diameter, that is centered on and stabilized by the sunspot. Occasionally, a submerged flux tube surfaces, producing outward-moving magnetic loops.

Unlike other theorists, Thomas et al do not dismiss single polarity MMFs. Type I MMFs, along with Type III MMFs rely on the near- horizontal flux tubes of the penumbra, and correspond to deeply submerged flux tubes. Type II MMFs correspond to vertical flux tubes stripped off of the sunspot umbra and carried outwards.

## Conclusions

These three models all predict MMFs, predominantly in opposite - polarity pairs. However, none of the theories or observations thus far have observed an MMF manifestation in the moat. As Shang and Solanki said, the MMF tend to first appear at a distance of 1000 - 5000 km from the outer boundary of the sunspot. However, we note MMFs in the penumbra, as well as magnetic inclination features in the penumbra that seem to be correlated with MMFs.

If we look at our penumbral features, it is most likely they are not related to the PBS or PDS observed by Bovelet and Wehr, as the speeds and predominant directions of these features differ from our observations. The velocities and azimuth angles of our penumbral features are more comparable to the velocities and clustering azimuth angles of the MMFs we measured in the moat.

Most of the theories thus far either don't address or completely disregard a possible penumbral MMF manifestation, probably because no such manifestation has yet been reported. These theories also depend, to varying degrees, on the environmental change between the penumbra and moat, and this dependence allows us to eliminate some theories based on our observations. For example, the justification of Zhang and Solanki that the lack of magnetic field in the moat is what causes the MMFs to form, lies in direct contradiction to our

observations of the moving penumbral magnetic features. More analysis must be done to relate these features to the other models. However, it is clear that the discovery of penumbral MMFs forces us to reevaluate how and where MMFs are formed. Further study is necessary to confirm our results and to provide more evidence towards the relationship between the penumbral and moat features. Accordingly, we have repeated the observations of June 2002 this summer, using a better camera and the McMath's adaptive optics bench. Hopefully, analysis of this new data will help solve the mystery of the dynamics of MMFs.

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