SP11A-05

Moving Magnetic Features Inside the Penumbra of NOAO 10008

S Luszcz (Cornell University), MJ Penn (NSO), S. A. Jaeggli (U. Hawaii), C.J. Henney (NSO)

Abstract: 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 outward through the sunspot moat at speeds of about 1 km s^{-1}. A sequence of sixteen scans of the active region NOAO 10008 were taken using the NSO-CSUN IR camera at the NSO McMath-Pierce Solar Telescope on 24 June 2002 17:38-21:59. Using the Fe I absorption line at 1564.8nm, magnetogram images and maps of the magnetic field vector were produced, revealing magnetic features within the penumbra that appear to move radially outward at similar velocities and azimuth angles as those of MMFs in the moat. Some features are observed to cross the penumbral boundary and move across the moat. We use polar time slice images to measure the radial velocities of both types of features.

Continuum Images of NOAO 10008

On 24 June 2002 the active region NOAO 10008 was located near the central meridian of the Sun just south of disk-center. The umbra of 10008 was not circular in shape, but contained a double structure. A rather uniform penumbra surrounded this umbra, and around the penumbra was a small moat, a relatively field-free region of quiet solar photosphere. A few smaller spots or pores of opposite polarity magnetic flux were found outside of this moat region.

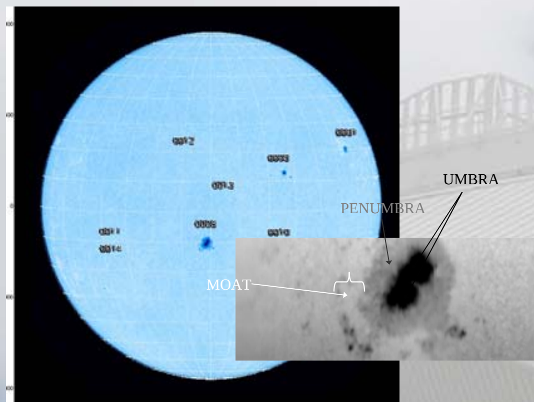

Figure 1. MDI continuum full disk image and continuum map at 1565nm of NOAO 10008.

Stokes V Magnetogram MMF observations

Movies were made of the active region line-of-sight magnetic field by summing the Stokes V blue wing and subtracting the sum of the Stokes V red wing of the Fe I 1564.8nm line. In the movie sequence, the sunspot is surrounded by small bi-polar magnetic features which move outward from the sunspot. The surprising thing is that of the 38 Stokes V features tracked during the 4 hour movie, nearly half originate inside the penumbra of the sunspot. The speeds of the magnetogram MMFs are about 0.4 km s^{-1}, similar to speeds from early studies such as Harvey and Harvey (1973).

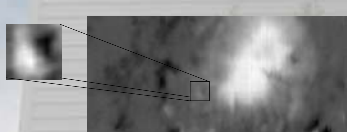

Figure 2. A magnetogram of NOAO 10008. Inset is a blow-up of a typical MMF bipole.

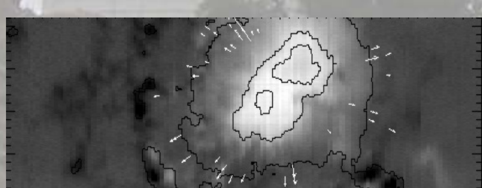

Figure 3. A magnetogram image with intensity contours, and arrows showing the direction and initial position of 38 MMF features. Inner most contour shows two dark centers in the umbra, middle contour shows the umbra, and the outer contour the penumbral boundary. Note that many of the MMFs start inside the penumbra. A typical speed is 0.4 km s^{-1}, but the observed range is from 0.2 to 2.5 km s^{-1}.

Milne-Eddington Line Inversion: penumbral MMFs

The full IQUV Stokes spectral profiles of the Fe I 1564.8nm line were calibrated to remove instrumental polarization (Kuhn et al. 1994). The resulting profiles were fit with a ME line code from HAO (Skumanich and Lites, 1987). Movies were made of the magnetic field strength and the magnetic field inclination relative to the line-of-sight. Features in both the magnetic field strength and magnetic field inclination are observed to move outward through the penumbra; in some cases features cross the penumbral boundary and become MMF features in the moat surrounding the sunspot. The moving features and the background penumbra are both fit well by the ME code. The speeds of 10 features tracked through the time sequence range from 0.2 to 1.8 km s^{-1}

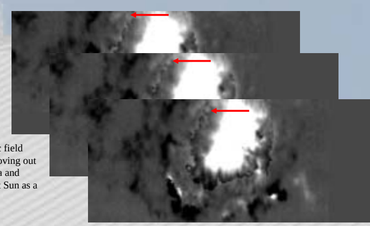

Figure 4. A magnetic field inclination feature moving out through the penumbra and appearing in the quiet Sun as a Stokes V MMF

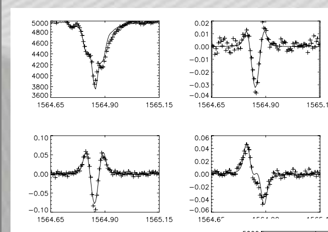

Figure 5a. Fits to the Stokes IQUV spectra at the pixel showing the more steeply inclined magnetic field in the penumbra. These spectra are from the 19:02 UT scan.

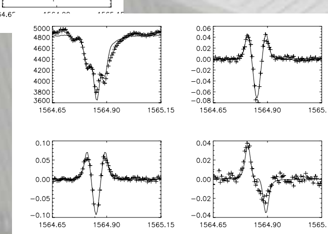

Figure 5b. Fits to the Stokes IQUV spectra at a pixel showing the typical penumbral magnetic field inclination, near the moving penumbral MMF. This is also from the 19:02 UT scan.

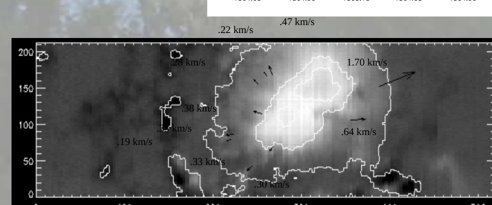

Figure 6. A magnetogram image with intensity contours, and arrows showing the direction and initial position of several penumbral MMFs. The velocities for some features are noted. In all cases the features were tracked in movies of the magnetic field inclination resulting from the Milne-Eddington spectral inversions.

Application to MMF models

These new observations of moving magnetic features inside sunspot penumbra are not directly considered in current models of MMFs. While it is possible that the physical processes discussed by all of these models could start inside the penumbra, none seem to address the idea that inclination features would move steadily from the penumbra out through the sunspot moat.

Figure 7a. Spruit et al (1987) present a MMF 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.

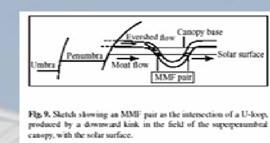

Figure 7b. Zhang and Solanki (2003) propose that MMFs are formed when the field lines in a small part of the magnetic canopy dip down to produce a 'falling' U-loop. They begin their scenario with a packet of dense, outward-flowing Evershed gas in the penumbra. The vertical field gradient of the penumbra 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. magnetic field in the penumbra.

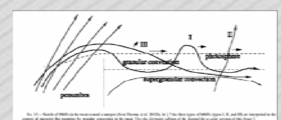

Figure 7c. Thomas and Weiss (2004) explain the production of MMFs through the interaction of the magnetic field with turbulent, compressible convection in the solar granules and supergranules. In their model, granules grab flux tubes, with their associated outflows of gas, from the sunspot penumbra and 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.

Conclusions

New observations of NOAO 10008 using the infrared g=3 Fe I 1564.8nm line reveal evolution of the penumbral magnetic field. Using a simple Milne-Eddington inversion, maps of the penumbral magnetic field strength and magnetic field inclination are produced. A four hour sequence of these maps shows features moving through the sunspot penumbra at speeds between 0.2 and 1.8 km s^{-1}. In some cases these features are directly seen to move across the penumbral boundary and become MMFs in magnetograms of the surrounding quiet Sun. Current models of MMFs create these features at the penumbral boundary, and must be revised to include moving features inside the penumbra.

This work is carried out through the National Solar ObservatoryResearch Experiences for Undergraduate (REU) site program, which is co-funded by the Department of Defense in partnership with the National Science Foundation REU Program.

References

Harvey, J., & Harvey, K.; 1973, Sol. Phys., 28, 61
Kuhn, J. et al.; 1994, Sol. Phys., 153, 143
Skumanich, A. & Lites, B.; 1987, ApJ 322, 473
Spruit, H.C., et al.; A&A 1987, Sol. Phys., 110, 115
Weiss et al.; 2004, ApJ 600, 1073
Zhang, J. et al.; 2003, A&A 399, 755