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Abstract. The Cycle 23–Cycle 24 minimum was deep and prolonged, similar to minima of the late 19th and early 20th centuries but quite different from those between the overlapping cycles of the early space age. This provides a unique opportunity to study the Sun at very low levels of magnetic activity. Here we examine the quiet Sun, defining it to be those portions of the Sun for which continuum intensity variations are dominated by thermal perturbations as opposed to opacity fluctuations due to the presence of magnetic fields. We briefly present evidence that: (1) The expected thermal signature of the solar supergranulation can not be separated from magnetic contributions without masking the contribution of at least 95% of the pixels. By this measure, at most 5% of the Sun is truly quiet. (2) There was a rapid decay of active network magnetic fields entering this solar minimum, a consequent increase in the internetwork area, but a nearly constant fractional area covered by network fields. This suggests the continuous fragmentation and decay of active region fields into weaker field components, but also, possibly, an underlying continuous flux concentration mechanism maintaining the network field. (3) One of the first flux emergence episodes of Cycle 24 did not occur as a coherent active region, but instead in the form of disorganized spatially-dispersed small-scale magnetic elements. Under the paradigm of a deep-rooted dynamo, this suggests an episode of incoherent field loss from the generation region or a failed/shredded omega loop rise through the convection zone.

1 Introduction

The term quiet Sun is used with quite varied meanings in the solar physics community: the non-active or solar-minimum Sun, the non-active-region portion of the Sun, the non-coronal-hole portion of the Sun in chromospheric, transition region, or coronal emission, the non-magnetized portion of the Sun, the internetwork, and others. This paper aims to address the question posed by its title quite narrowly, and thus defines quiet Sun as those portions of the Sun for which photospheric continuum intensity variations are dominated by thermal perturbations, as opposed to opacity fluctuations due to the presence of magnetic fields. Of course the magnetic and thermal contributions are intertwined, as the photosphere of the Sun is a radiating magnetized plasma, but we are interested in the dominant contribution. Moreover, the definition is scale-dependent because thermal fluctuations peak at subgranular scales. We are not interested here in separating magnetized and nonmagnetized plasma contributions to intensity fluctuations at granular scales, and so consider only scales larger than granulation, typically those accessible via full-disk observations. Throughout, we rely on continuum and Ca II K image data taken with the Precision Solar Photometric Telescope (PSPT) at Mauna Loa Solar Observatory (MLSO). These data are described in detail by Rast et al. (2008).

2 Implications of the Supergranular Contrast Profile

The solar supergranulation is thought to be a convective phenomenon associated with rising horizontally diverging fluid flows near the network cell centers, the horizontal advection of magnetic field elements to the boundaries, their accumulation to form network there, and finally, the descent of cooler fluid. The ultimate cause of the supergranular scale of motion on the Sun remains unclear, with suggestions ranging from the depth of He II ionization (Leighton et al. 1962) to self-organization of the granular flows (e.g., Rieutord et al. 2000; Rast 2003a, and references therein) possibly including an active radiative role for the network field elements (Goldbaum et al. 2009). Independent of scale selection, the observed supergranular flow implies, by mass conservation, rising warmer fluid near cell centers and cooler descending material near the cell boundaries. Measurements of the radial (cell center to network boundary) profile of the supergranular intensity, however, show increased brightness at the cell boundaries at most continuum wavelengths (Beckers 1968; Foukal & Fowler 1984; Lin & Kuhn 1992). These measurements are dominated by opacity changes due to the presence of magnetic flux elements (e.g., Spruit 1976; Pizzo et al. 1993; Steiner 2005; Criscuoli & Rast 2009) which obscure any thermal signature of temperature fluctuations in the plasma. By masking out the network element contribution, the thermal signature can be recovered (Rast 2003b; Meunier et al. 2007, 2008; Goldbaum et al. 2009), with supergranules showing on average a $\sim 0.1\%$ decrease in continuum brightness from the center outward. This corresponds to a ~ 1.0 K decrease in brightness temperature.

What is critical to the theme of this paper is the degree of masking required for the thermal signature to emerge. As discussed in detail by Goldbaum et al. (2009), and as illustrated here by Figure 1, 95% of the pixels in solar continuum images must be masked out based on their corresponding Ca II K emission, a proxy for magnetic flux density (Skumanich et al. 1975; Schrijver et al. 1989; Harvey & White 1999; Rast 2003b; Ortiz & Rast 2005), before the thermal contrast of the supergranulation is revealed. This corresponds to eliminating all pixels with magnetic flux densities greater than ~ 0.7 Gauss. By this measure, only those locations with even weaker fields, only about 5% of the Sun, is on average quiet. Specifically what this implies is that, on scales larger than granulation, or when averaging over many granule lifetimes, continuum intensity fluctuations are dominated by opacity variations due to the presence or absence of even very weak magnetic fields, not by thermal perturbations. Any underlying thermal contribution to the continuum intensity variations sits on top of the magnetically corrugated optical depth surface.

3 Magnetic Structure Coverage through the Minimum

The deep minimum between Cycle 23 and Cycle 24 provided an opportunity to investigate the extended decay of active region magnetic fields. Figure 2 shows

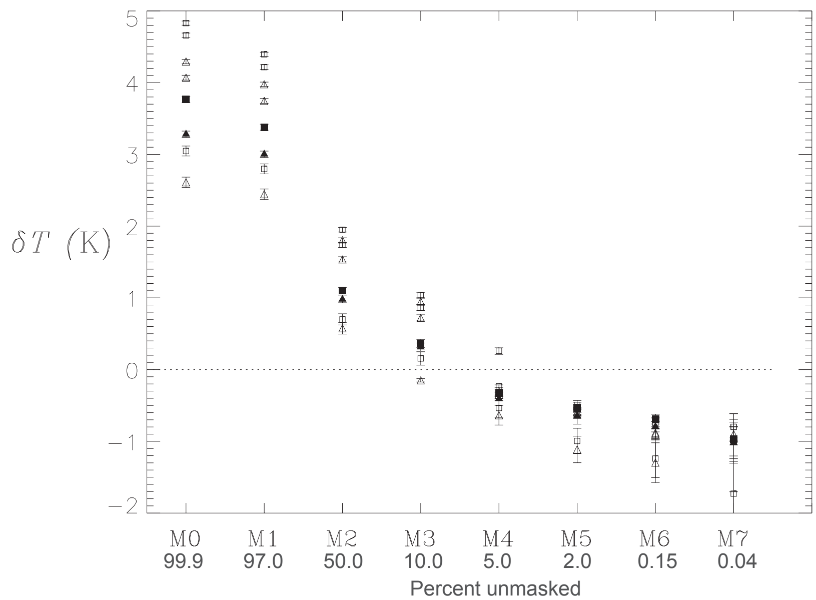

Figure 1. Red continuum (triangles) and blue continuum (squares) brightness temperature difference across supergranular cells as derived from the maxima and minima of radial (cell center to network boundary) intensity profiles. Elimination of 95% of the pixels is required before the brightness temperature difference (edge minus center) reflects the thermal contribution due to convection.

the fractional disk area covered by magnetic structures as a function of time. The structures were identified by their simple center-to-limb dependent contrast (Fontenla et al. 2006).[1]

There was a rapid decay of facular, plage, and active network magnetic fields entering this solar minimum, a corresponding increase in the internetwork area, but a nearly constant fractional area covered by network fields, even during the deepest part of the minimum. This suggests that network field coverage is less sensitive to the emergence of active regions and their decay, and thus may reflect the more local supergranular process of field concentration. Alternatively, the rate of decay of active network fields to network flux densities could be exactly balanced, in areal coverage, by the decay of network field to even weaker field concentrations with contrast values below the resolution of the structure identification scheme.

4 Possible Failed Active Region Emergence Early in Cycle 24

Close examination of Figure 2 shows a period in early 2009 during which the facular, plage, and active network areas increased without the emergence of a sunspot. Images from this time period (corresponding to observations made at

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[1] Exact values used in the structure definitions can be found in the mask image headers available at `lasp.colorado.edu/pspt_access/`.

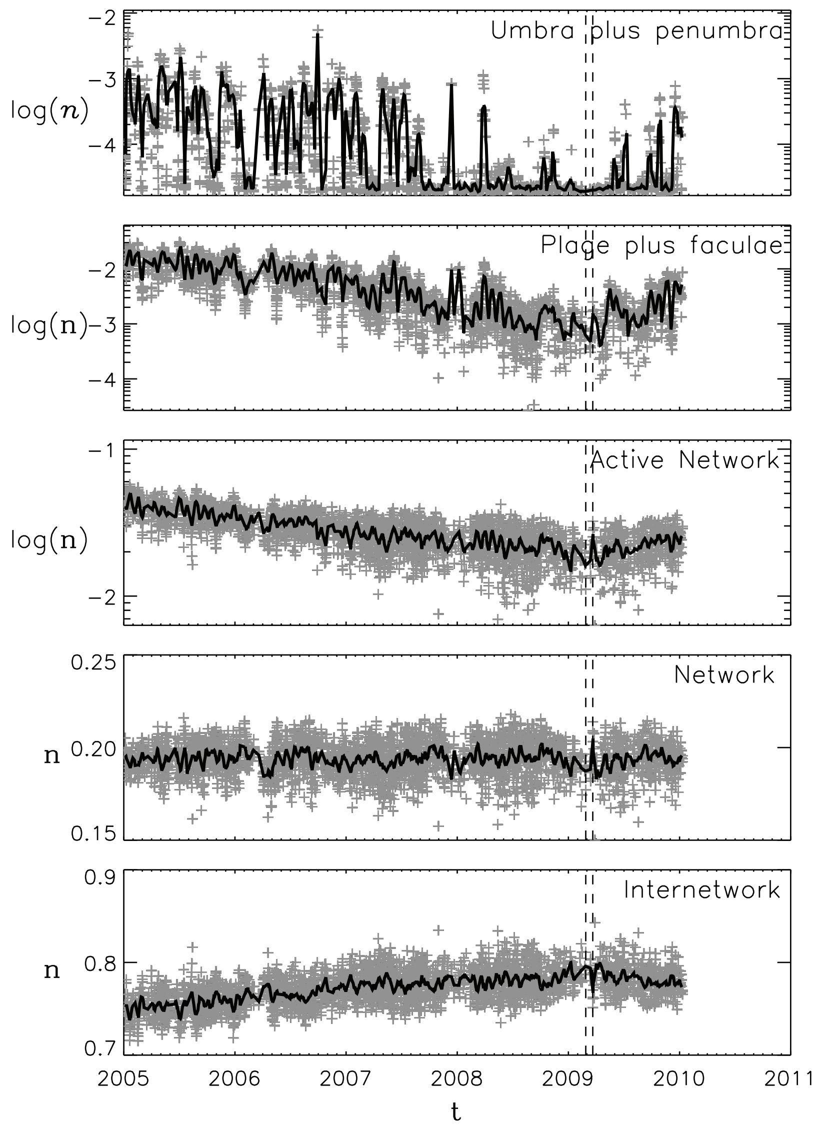

Figure 2. Fractional solar disk area n covered by magnetic structures. Bold lines indicate average values over running 13.5 day periods. A clear minimum in magnetic activity occurs in early 2009, with a corresponding maximum in internetwork area. Network area appears roughly constant over the entire period. Vertical dashed lines mark times of observations before and after the disorganized flux emergence event discussed in § 4 and imaged in Figure 3.

the times indicated by vertical dashed fiducial lines in Figure 2) show a change in the field distribution, from the more typical solar disk near its minimum (Figure 3a; 26 February 2009, 1750 UT) to the rather remarkable appearance on 21 March 2009, 1740 UT (Figure 3b). The field distribution changed from very weak network with a single plage region to rather remarkable small-scale clumped but widely spatially-distributed magnetic flux elements. This may be

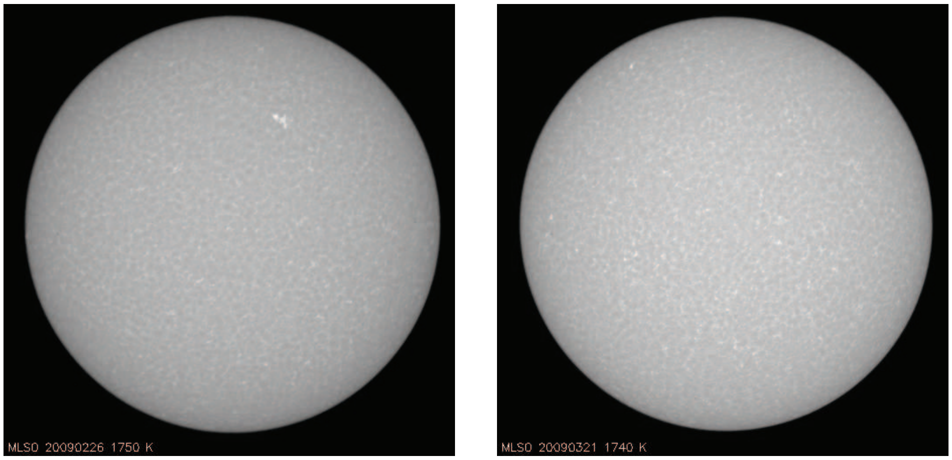

Figure 3. Two images of very similar seeing quality, one showing the very inactive Sun of 26 February 2009 (left) and the other after the apparent emergence of small-scale spatially distributed flux elements on 21 March 2009 (right). Higher resolution images and image data are available at `http://lasp.colorado.edu/pspt_access/`.

evidence of a failed active-region emergence episode. Such episodes would be difficult to find during recent previous minima because of cycle overlap, but be apparent here because of the sustained non-active period during which it occurred.

It is worth noting that the seeing conditions are nearly identical for these two images as is the image grey scale, so the change in appearance is not due to these factors. Moreover, the later image (on the right, after the flux emergence episode) has more total facular, plage, and active network area than does the earlier image (on the left, during the deep solar minimum) even though it is distributed quite differently. Although the interpretation is not unambiguous because of our inability to detect flux emergence on these scales on the far side of the Sun, the later distribution suggests that the magnetic field emerged as small elements over a broad region of the solar surface rather than as a more coherent small active region or plage.

5 Conclusion

Truly quiet Sun may be a very rare phenomenon, with continuum intensity on scales larger than granulation being dominated by magnetic rather than thermal contributions. The convective signature of the solar supergranulation is apparent only after masking out 95% of the pixels (down to magnetic flux densities of ~ 0.7 G). Since the photosphere is almost everywhere magnetized to that degree, its radiative properties at large scales are likely to be dominated by opacity variations induced by the presence of the field. Irradiance changes attributed to changes in the quiet Sun likely reflect underlying changes in the filling factor of very weak field, not directly changes in stellar structure, although interpretation is difficult and requires detailed modeling. New photospheric magnetic flux may emerge as small-scale spatially-distributed elements as well as coherent active regions, either because of incoherent field loss from the dynamo source region or because of the disintegration of a more coherent flux structure during its interaction with convection below the surface. These distributed emergence events may be more common during the onset of a new cycle, or they may just be more difficult to identify during periods of significant solar activity.

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