What are ‘Faculae’?

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**Abstract.** We present very high resolution filtergram and magnetogram observations of solar faculae taken at the Swedish 1-meter Solar Telescope (SST) on La Palma. Three datasets with average line-of-sight angles of 16, 34, and 53 degrees are analyzed. The average radial extent of faculae is at least 400 km. In addition we find that contrast versus magnetic flux density is nearly constant for faculae at a given disk position. These facts and the high resolution images and movies reveal that faculae are not the interiors of small flux tubes - they are granules seen through the transparency caused by groups of magnetic elements or micropores “in front of” the granules. Previous results which show a strong dependency of facular contrast on magnetic flux density were caused by bin-averaging of lower resolution data leading to a mixture of the signal from bright facular walls and the associated intergranular lanes and micropores. The findings are relevant to studies of total solar irradiance (TSI) that use facular contrast as a function of disk position and magnetic field in order to model the increase in TSI with increasing sunspot activity.

**1. Introduction**

Solar *Faculae* (Latin for “small torches”) are the bright extended structures seen in visible light near the limb of the sun around sunspot active regions. After sunspots they are the most obvious structures in the solar photosphere. They are of continued interest because of their contribution to the cyclic variation of total solar irradiance (TSI): TSI is approximately 0.1% greater during sunspot maximum compared to sunspot minimum primarily due to the cumulative facular brightening that exceeds sunspot dimming over time scales of months to years (deToma et al. 2004; Foukal and Lean 1988). Since it remains unclear whether TSI modulation is strictly a function of sunspot and facular irradiance or whether there exist other global-scale influences (e.g. luminosity variations), it is important to better understand the details of facular irradiance.

One of the primary inputs to irradiance models is the so-called center-to-limb variation (CLV) of facular contrast, i.e. the change in facular brightness,
relative to a reference, as a function of the location on the solar disk. Faculae in broadband images are seen to be brightest near the extreme limb where the line-of-sight angle to the surface normal, $\theta$, approaches 90 deg. Closer to disk center, faculae show much lower contrast relative to quiet Sun granulation. Defining $\mu = \cos \theta$, measurements of facular contrast as a function of $\mu$ show a monotonic increase from a minimum at $\mu = 1$ (disk center) to approximately $\mu = 0.2$ (near the limb). Atmospheric blurring and the extremely long integration path through the atmosphere combine to make ground-based measurement of facular contrasts at the extreme limb (below $\mu \sim 0.2$) difficult. Studies to date show ambiguous results with some claiming increasing facular contrast down to $\mu = 0$ (Chapman and Klabunde 1982) while others show a decline in contrast below $\mu = 0.2$ (Libbrecht and Kuhn 1984; Wang and Zirin 1987).

Why are faculae so bright at the limb and nearly invisible at disk center? It is well known that faculae are associated with small-scale (on the order of 100 km) magnetic flux elements around sunspots. Thus it is obvious that facular brightness is somehow caused by modified radiative transfer through the magnetic atmosphere. Spruit (1976) first constructed a model of magnetic facular irradiance based on an analogy with the Wilson depression in sunspots. Termed the “hot-wall” model, Spruit’s magnetostatic formulation posits that thin “flux tubes”, evacuated due to the magnetic pressure balance with the non-magnetic surroundings, appear as holes, or depressions, in the photosphere. When seen at the limb, oblique lines-of-sight traverse deeper into the flux tube atmosphere due to the density decrease and thus intersect the deeper, and hotter, walls of the tubes. The model predicts that facular brightness should decrease at the extreme limb when the line-of-sight is too oblique to intersect the limbward wall of the depression. The depth of the depression is calculated to be approximately 100 km for “facular points” that are 50–100 km in diameter. For pores with 1000 km diameters, the depression is calculated to be about 200 km.

The hot-wall model predicts that facular contrast should peak inside of the limb around $\mu = 0.2$ and this, as noted above, is confirmed in some observations. In addition, the model predicts that as the flux tubes increase in diameter, the brightness decreases at all disk positions as the relatively cool interior dominates over the hot wall signature. Topka et al. (1997) performed a thorough study of flux tube contrast as a function of magnetic flux density with 220-300 km spatial resolution. In agreement with the hot-wall model predictions, their data show that for a given magnetic flux density bin, continuum facular contrast increases from negative values near disk center (presumably caused by viewing the relatively cool, dark, floors of the flux tubes) to positive values approaching 15% for $\mu = 0.3$. At any given disk position, an increase in magnetic flux density results in a decrease in contrast, presumably because as the flux increases, the diameter of the tube increases thereby decreasing the proportion of hot-wall relative to cool-floor. Ortiz et al. (2002) use 2$''$ spatial resolution SOHO/MDI data to essentially confirm the facular contrast vs. magnetic flux density findings of Topka et al. (1997).

In 2002, new observations of faculae were obtained at the Swedish 1-meter Solar Telescope (SST) (SST, Scharmer et al. 2003) with twice the spatial resolution of the studies of Topka et al. (1997). These new data reveal a striking “three-dimensional” appearance to faculae not seen with in lower resolution observations (Lites et al. 2004). From 2003 to 2004 we collected further facular
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datasets, some including Stokes-V magnetograms taken with the Lockheed Martin SOUP tunable filter. Our measurements of facular contrast as a function of magnetic flux density differ significantly from those of Topka et al. (1997) and Ortiz et al. (2002), calling into question the validity of the simple hot-wall flux tube model for explaining facular irradiance.

2. Data

Table 1 lists the three datasets analyzed for this paper. All datasets included at least a G-band 430.5 nm filtergram and a nearly simultaneous SOUP Fe I 630.25 nm Stokes-V magnetogram. All images in the datasets are composites of at least three images taken in series and restored using the Multi-Frame Blind Deconvolution (MFBD) method (Löfdahl 2002).

<table>
<thead>
<tr>
<th>Date</th>
<th>AR</th>
<th>µ-range</th>
<th>µ</th>
<th>Wavelengths</th>
</tr>
</thead>
<tbody>
<tr>
<td>19-May-2003</td>
<td>10362</td>
<td>0.86–0.91</td>
<td>0.88</td>
<td>G-band, G-continuum, Ca II H-line, Fe I 630.25 nm magnetogram.</td>
</tr>
<tr>
<td>06-June-2003</td>
<td>10377</td>
<td>0.53–0.66</td>
<td>0.60</td>
<td>G-band, Fe I 630.25 nm magnetogram.</td>
</tr>
<tr>
<td>09-July-2004</td>
<td>10643</td>
<td>0.96–0.98</td>
<td>0.97</td>
<td>G-band, G-continuum, Fe I 630.25 nm magnetogram.</td>
</tr>
<tr>
<td>27-June-2005</td>
<td>10xxx</td>
<td></td>
<td></td>
<td>G-band, G-continuum, Fe I 630.25 nm magnetogram.</td>
</tr>
</tbody>
</table>

In each dataset, all restored images are scaled, aligned, and “destretched” to a common reference image (usually the G-band image) with a final precision of approximately 3 pixels (0′125 at the G-band plate scale). The magnetograms are calibrated using the method of Berger and Lites (2002) and the flux density values are corrected for line-of-sight angle (assuming vertical fields). Gaussian fits to the histograms of magnetic flux density indicate that the noise floor is approximately 150 to 300 gauss depending on the dataset. The maximum flux density measured in sunspot umbrae is approximately 2400 gauss; beyond this value the magnetogram algorithm used with the SOUP filter results in Zeeman saturation and the measured flux density values decrease. Figure 1 shows the G-band image and magnetogram from the 06-June-2003 dataset, 0.66 > µ > 0.53.

Using nearly cotemporal SOHO/MDI full-disk magnetograms, the precise location of the SST images on the solar disk is determined; every pixel in the SST images is assigned a disk position with an estimated precision of 0.02 in the final µ-value. Image segmentation techniques are then used to choose each bright faculae visible in the images for analysis. By segmenting the images in this way we separate the signal of bright faculae from the neighboring dark
Figure 1. AR 10377 imaged on 06-Jun-2003 at a \( \mu \)-value of 0.6. Left: G-band 430.5nm filtergram. Right: Fe I 630.25 nm Stokes-V magnetogram. Tickmarks are megameters. The spatial resolution in the G-band image is approximately 100 km; the magnetogram resolution is \( \sim 150 \) km.

intergranular lanes and micropores – something which has not been done in the previous studies cited in Sec. 1.

A shortcoming of the current dataset is that the range of \( \mu \)-values is limited to above about 0.53. An additional dataset including an active region imaged in 2005 at \( \mu \sim 0.2 \) is being reduced and will be included in a future paper on this subject.

3. Facular Profiles

Figure 2 shows radial cuts across several faculae and the neighboring intergranular lanes in the G-band image of Figure 1. The centerward side of the cuts is to the left; the limb is to the right in all profiles. We note that most, but not all, faculae show dark lanes in front of (i.e. centerward) of the peak brightness. This dark lane has been noted in previous high-resolution facular analyses (Hirzberger and Wiehr 2005) as well as 3D MHD models (Keller et al. 2004; Carlsson et al. 2004). Note that the magnetogram signal shows a very close correlation to the G-band signal both in peak location and general shape. In Cut 2, the dark lane is more pronounced in the magnetogram image than in the G-band.

Figure 3 shows the average radial cut produced by sampling 678 bright faculae from the G-band image of Figure 1. Note that the dark centerward lane is not present in the average cut in either the G-band or the magnetogram. This contrasts with results in Hirzberger and Wiehr (2005) in which the dark lane is clearly present in the average cut.

The average G-band profile is well fit by a gaussian function with a FWHM of 265 km. The average peak contrast is 41% and the average peak magnetic flux density is 1150 gauss. Defining the radial extent of facular brightening as the width of the average profile for which the brightness is at least 10% above the average floor (approx. 585 DN in Figure 3), we find a radial extent of approximately 400 km. This is the apparent “size” of the average facular brightening in the G-band image of Figure 1. It is interesting to note that the dark centerward lane is not a feature of the average facular profile. Apparently the dark lane is
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Figure 2. Cuts along a radial direction from Sun-center for several typical facular bright points in Figure 1. The left axis plots raw signal in the G-band filtergram. The right axis plots calibrated magnetogram signal in gauss.

Figure 3. Average radial cut through 678 sampled facular bright points in the G-band image of Figure 1. Note that the centerward dark lane is not present in the average profile. The average peak G-band contrast is 41%. The average peak magnetic flux density is 1150 gauss.
Figure 4. G-band contrast as a function of magnetogram signal for the three datasets listed in Table 1. For each dataset, the magnetogram pixels are grouped into 50-gauss bins and the corresponding pixels are measured for average contrast in the G-band image. Thin dotted lines span 1-σ standard deviation about the mean contrast.

neither a constant feature of all faculae nor is it of constant contrast when it does exist. Averaging over many faculae thus eliminates this feature, at least for this dataset.

4. Facular Contrast vs. Magnetic Flux Density

Figure 4 shows a facular contrast analysis using all three datasets listed in Table 1. The plot is made by segmenting the magnetogram in bins of 50 gauss. For each 50 gauss bin, all pixels in the bin are identified on all cotemporal images in the dataset. We include the sunspots in all datasets in this analysis. The contrasts of those pixels in the G-band image (relative to a quiet Sun area in the image) are then averaged to produce a “bin-averaged G-band contrast” as a function of magnetogram signal\(^1\). This is analogous to Figure 1 of Topka et al. (1997), although they plot pure continuum contrast at wavelengths near the Fe I 557.6 and 630.25 nm lines.

We find basically the same behavior as Topka et al. (1997, hereafter denoted T97): near disk center, the bin-averaged contrast is mostly negative and decreases with increasing magnetic flux density – a finding which led T97 to assert that faculae are dark at disk center in agreement with the hot-wall model. In T97, with increasing line-of-sight, the bin-averaged contrast increases for all mag-

\(^1\)We show G-band contrast because the 06-June-2003 dataset lacks a continuum image for comparison. The continuum plots for the other datasets are essentially identical to the G-band plots in functional form but at a lower contrast for all magnetogram signal levels.
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Figure 5. G-band (left) and 436.4 nm wideband continuum (right) contrast as a function of magnetogram signal for the datasets in Table 1. This plot is analogous to the one shown in Figure 4 although here we first segment the images to show only bright structures. The larger symbols indicate 50-gauss bin-averages.

netogram signals. For our dataset, the contrast in the $\theta = 26$ deg data decreases relative to the $\theta = 16$ deg dataset for magnetogram signals below 1700 gauss. However the curve for $\theta = 53$ deg in Figure 4 shows essentially the same behavior as their curve for $\theta = 52$ deg, namely a mostly positive, low, contrast for all but the highest magnetogram signals. We note that T97 also used the SOUP filter for magnetogram measurements. However they used a more ad hoc calibration procedure and were using the 50-cm SVST telescope with half the spatial resolution of the SST. Thus their magnetogram signals are substantially lower than ours.

Figure 5 shows a similar analysis of facular contrast vs. magnetogram signal and disk position, but with a key difference: here we analyze only the bright facular points segmented (by their brightness profiles) from each of the G-band (and continuum, when available) images. Instead of binning in magnetogram signal we average the contrast and magnetic flux density for every facular point segmented from the datasets. The left plot shows G-band contrast and the right plot shows continuum contrast. Both plots are strikingly different from the bin-averaged plots shown above. Although we still find increasing contrast as faculae are seen at more limbward positions, the facular contrast is essentially constant as a function of magnetogram signal at each disk position. The continuum does exhibit a slow decrease with flux density, but remains positive for all values. The differences seen in G-band and continuum contrast values for the same magnetogram signal are typical and are due to the higher temperature and density sensitivity of the CH molecules that dominate the G-band spectral region (Schüssler et al. 2003).

In addition the 50-gauss bin-averaged contrast values (indicated by the symbols) are much higher than the bin-averaged values in the plots above. The average G-band contrast and continuum contrast values for the datasets are shown in Table 2. For comparison, the typical continuum contrast values found in T97 for $\theta = 52$ deg is at most 2.5%. If we assume that facular contrast (corrected for limb darkening) remains constant for $\mu < 0.6$, then a least-squares quadratic fit to our G-band data is given by $C_g = 0.470 + 0.461\mu - 0.704\mu^2$. 
Table 2. Average facular contrasts for the three datasets of Table 1. Unlike
the G-band data, the G-continuum data are not well represented by a single
average because of the decrease of contrast with magnetogram signal seen in
Figure 5. We show the values here for rough comparison purposes only. “Mag.
Range” refers to the range of magnetogram signals associated with faculae
in the datasets. 125 gauss is the approximate noise floor of the SOUP Fe I
630.25 nm magnetograms.

<table>
<thead>
<tr>
<th>Date</th>
<th>$\bar{\mu}$</th>
<th>G-band [%]</th>
<th>G-cont [%]</th>
<th>Mag. Range [gauss]</th>
</tr>
</thead>
<tbody>
<tr>
<td>09-July-2004</td>
<td>0.96</td>
<td>20.9</td>
<td>9.5</td>
<td>125 – 2325</td>
</tr>
<tr>
<td>19-May-2003</td>
<td>0.88</td>
<td>39.5</td>
<td>39.3</td>
<td>125 – 1075</td>
</tr>
<tr>
<td>06-June-2003</td>
<td>0.60</td>
<td>46.6</td>
<td>NA</td>
<td>125 – 2425</td>
</tr>
</tbody>
</table>

5. Conclusions

The facular profile data shown in Sec. 3. are consistent with those shown in
Hirzberger and Wiehr (2005) although our average profile does not show the pro-
nounced centerward dark lane. This is possibly because the profiles of Hirzberger
and Wiehr (2005) are taken at $0.42 > \mu > 0.01$, significantly more limbward than
our most limbward dataset at $\bar{\mu} = 0.6$. The “size” of the facular brightening
is however comparable. Both studies find an average facular size, defined here as
the radial extent over which a facula is 10% brighter than the surrounding gran-
ulation, of approximately 400 km.

When facular contrast is measured by bin-averaging in magnetogram signal
we replicate the results of Topka et al. (1997) (Figure 4). However, with the
increased spatial resolution of the SST observations, we can isolate the bright
faculae from the darker structures and measure their contrast independently.
We thus find a significantly different facular contrast as a function of magnetic
flux density, with a nearly contrast constant across the entire range of measured
magnetic flux density (Figure 5).

Regarding contrast as a function of disk position, Hirzberger and Wiehr
(2005) find that contrast remains constant for disk positions from $\mu = 0.4$ out
to $\mu \sim 0.01$. They find an average G-band contrast of approximately 50% in
this range. Similarly we find an average G-band contrast of 46.6% in our $\mu =
0.6$ dataset. Combining the studies, average facular contrast apparently peaks
around $\mu = 0.5$, remaining relatively constant thereafter out to the limb.

These facular size and contrast measurements combine to argue for a rein-
terpretation of the mechanism of facular irradiance. The mean facular size of
400 km is a factor of two to four greater than the estimates of Wilson depres-
sions in small-scale magnetic flux tubes given by the hot-wall model. In addition,
the classic hot-wall model is incompatible with an approximately constant facu-
lar contrast for $\mu < 0.6$. These facts, combined with the high-resolution images
and movies of faculae taken at the SST, as well as from 3D MHD simluations
(Carlsson et al. 2004), make it clear that faculae are not depressions in the pho-
tosphere into which oblique lines-of-sight reveal deeper, hotter, layers in flux
tubes – they are granules whose centerward walls are made relatively bright by
the decrease in opacity caused by the magnetic fields directly “in front of” the
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granules. Thus it appears that the basic physics of the hot-wall model are correct in interpreting faculae as a relative opacity effect caused by the magnetic field. However the geometric interpretation of a Wilson depression into which oblique lines of sight penetrate into the flux tube appears outdated.

We can now see that the “hot wall” is not the interior of a flux tube depression but is instead the “granule wall” behind the flux element. Figure 4 of Keller et al. (2004) illustrates this (and the origin of the dark lane immediately centerward of many faculae) well. The large lateral extent, as well as the dynamic vertical striation, of faculae is explained by the fact that in plage regions, the intergranular lanes are typically filled with many small dynamic magnetic elements. Larger faculae are thus caused by looking through a group of several neighboring flux elements (sometimes coalesced into a small pore or micropore) at the granulation behind the group, as has recently been empirically modelled by Okunev and Kneer (2005). Thus viewing faculae is analogous to viewing a scene through a picket fence, with the magnetic field causing the gaps in the fence that allow us to see the scene behind the fence. A final aspect of facular formation is that the our observations seem to indicate that granulation is “bumpier” in plage regions (see also Lites et al. 2004). It appears that the granular walls behind the flux tube picket fences are higher than the walls in quiet Sun, thus further enhancing facular brightening. A possible explanation for this effect is an enhancement of f-mode amplitudes in magnetic regions leading to a more “corrugated” photosphere (Dziembowski and Goode 2005).

Our study and the one by Hirzberger and Wiehr (2005) are by far the highest resolution facular contrast studies to date. Our dataset complements that of Hirzberger and Wiehr (2005) in that we cover a more centerward range of $\mu$-values and include magnetogram data as well. Together these studies establish that facular contrast as a function of disk position is significantly different than any of the previous models used in irradiance modeling of the solar cycle. The studies also imply that the irradiance mechanism of faculae is distinct from that of the “internetwork” magnetic elements that have been hypothesized to play a role in solar irradiance modulation. It will be interesting to see how these new findings on facular contrast effect future solar irradiance modeling efforts.

As a final note, it is interesting to recall that R. Muller proposed the term “facular granules” in a study of Pic du Midi images from the 1970s (Muller 1977). Many of us believed that this was a misleading characterization—that faculae were not granules but were in fact magnetic flux tubes. It has been an educational experience to find that Muller’s characterization appears correct after all!

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References


