PROPERTIES OF FACULAE FROM OBSERVATIONS NEAR THE OPACITY MINIMUM

P. FOUKAL
CRI, Inc., 21 Erie Street, Cambridge, MA 02139, U.S.A.
and
T. MORAN
NASA/Goddard Space Flight Center, Greenbelt, MD 20771, U.S.A.

Abstract. Imaging of active regions in continuum around 1.6 μm shows that many facular regions are less bright than the photosphere when observed nearer to disk center than $\mu = \cos\theta \sim 0.75$. The contrast of these dark faculae increases with magnetic flux above a threshold of approximately 2×10^{18} Mx. This explains why not all faculae are dark at 1.6 μm, since the magnetic flux density in many regions of bright Ca K plage emission falls below this threshold. After correction for blurring, the typical contrast value is about 4-5%, so the brightness temperature deficit is about 130 K. Faculae are brighter than the photosphere at 1.63 μm nearer to the limb than $\mu \sim 0.5$. The negative contrast of dark faculae may arise from cooling of the surrounding photosphere, or from increased visibility of cool layers of the facular flux tube itself. Quantitative comparison of these IR data with MHD models awaits calculation of flux tube contrasts at realistic angular resolution.

Key words: infrared: stars – MHD – Sun: faculae, plages – Sun: photosphere

1. Introduction

Low photospheric continuum opacity near 1.6 μm enables observations of the deepest photospheric layers to be made in that wavelength region. Observations with comparable depth penetration may in principle be possible in the blue, due to higher temperature sensitivity of the Planck function at shorter wavelengths (Ayres, 1989), but the density of Fraunhofer lines in that spectral range makes it difficult to isolate the continuum, even with a spectrograph. The difference in geometrical depth between optical depth unity at 0.5 μm and 1.6 μm is only about 35 km (Vernazza, Avrett, and Loeser, 1976), but the energy balance of the sun changes rapidly between convective and radiative transport in this short interval, so the increased penetration is of great astrophysical interest.

Photometric measurements of facular contrast at this opacity minimum in the IR can yield important new information on the energy balance in these small-diameter magnetic flux tubes, and in their immediate surroundings. Semi-empirical models of faculae are largely based on the behavior of their photometric contrast at various positions in the profiles of lines such as Ca K (*e.g.*, Chapman, 1984; Walton, 1987). Wide-band photometry in the visible, especially near the limb, has been used in attempts to distinguish between different models of facular excess brightness away from disc center (Muller, 1975; Lawrence *et al.*, 1988; Wang and Zirin, 1987). Two-color photometry has been used to measure the temperature gradient in the facular atmosphere near $\tau_{0.5} = 1$ (Foukal and Duvall, 1985; Elste, 1985). Observations near 1.6 μm are of particular interest because the semi-empirical models are most weakly constrained at the deepest layers, where most of the facular radiation arises.

Early measurements of facular contrasts near the opacity minimum at 1.64 μm were made by Worden (1975) using a spectrometer and a single InSb detector in

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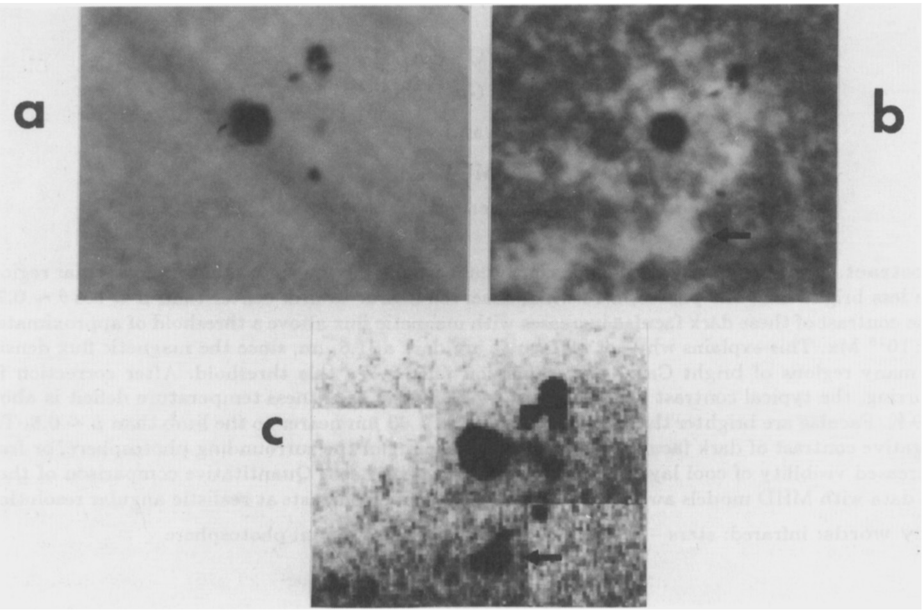

Fig. 1. Images of an active region in a) red continuum at 6558 Å; b) Ca K; and c) 1.63 μm. From Foukal *et al.* (1990).

a raster technique. His 2-D images of the quiet sun indicated a negative contrast of network faculae at 1.64 μm, while the same regions had positive contrast in a chromospheric line at 1.71 μm. This result was confirmed in the first images of active regions at 1.63 μm, made using a platinum silicide array and a narrow band filter (Foukal, Little, and Mooney, 1989). Better observations of facular contrast at 1.63 μm were obtained using the NOAO InSb infrared array (Foukal *et al.*, 1990). Examination of these images showed that while many faculae (indicated by Ca K plage emission) were dark at 1.63 μm, others showed little or no contrast. The most recent analysis, discussed below (Moran, Foukal, and Rabin, 1992), has since shown that the facular contrast at 1.63 μm is correlated with magnetic flux.

In this overview, the results of facular contrast measurements at 1.63 μm are summarized in Section 2. An analysis of the most recent observations is given in Section 3, and a discussion of the results and their relevance for flux tube models is reviewed in Section 4.

2. Results of Facular Photometry at 1.63 μm

Figure 1 shows a particularly clear example of dark facular structures. The arrows indicate a structure that is bright in Ca K, dark at 1.63 μm, but does not correspond to any spots that are visible in the red continuum. The contrast of such structures measured near disc center is tyically 1-2% (Foukal *et al.*, 1990). We stress that the invisibility of these structures in the red continuum is *not* simply a display artifact, since microdensitometry of such λ6558 spectroheliogram negatives has shown that such 1-2% intensity depressions over the spatial scale of the dark faculae seen in Figure 1 are easily detectable with a S/N ratio of better than 5:1 (Foukal, Little, and Mooney, 1989). After correction for seeing and scattering, the true contrast value is found to be at least 4-5% (Moran, Foukal, and Rabin, 1992).

Observations at various disc positions show that the 1.63 μm facular contrast passes through zero around $\mu = \cos\theta \sim 0.75$, and becomes positive again near the limb (Foukal *et al.*, 1990). Observations near 1.2 μm, close to disc center, indicate that the contrast of dark faculae is significantly reduced at that wavelength (Moran, Foukal, and Rabin, 1992).

3. Analysis

To investigate the finding that many, but not all, faculae observed near disc center were dark at 1.63 μm, facular images such as those in Figure 1 were coaligned with Kitt Peak magnetograms (Moran, Foukal, and Rabin, 1992). The structures were found to fall into three categories. The first consists of structures that are seen in the magnetograms, but have negligible contrast in the visible and at 1.63 μm. The second contains structures which have negligible contrast in the visible and negative contrast at 1.63 μm. These are the dark faculae. The third category contains structures which have negative contrast in the visible and at 1.63 μm (spots and pores). The structures of the first and second categories are bright in Ca K. The contrast and magnetic flux of each structure is plotted in Figure 2. We see that, at magnetic flux values corresponding to NSO magnetograph readings below about 375 gauss, the contrast is below 0.2%, the limit of detection. Points below this cut-off belong to category 1. They represent faculae that are bright in Ca K, but whose magnetic flux is below 2×10^{18} Mx. For magnetic fluxes above this cutoff, the contrast increases monotonically with the magnetic field. This holds for structures of categories 2 and 3.

4. Discussion

To summarize, faculae observed at 1.63 μm tend to appear dark near disc center, are not visible near $\mu \sim 0.75$, but become bright toward the limb. The corrected contrast values of 4-5% near disc center indicate a temperature deficit of about 130 K. Faculae at 1.2 μm have contrast below detection limits (0.2%) near disk center, consistent with measurements at similar opacity and spatial resolution in the visible region of the spectrum. Contrast of dark faculae at 1.63 μm is found to be correlated with magnetic flux; below a flux level of 2×10^{18} Mx contrast is below 0.2% and above this cutoff contrast increases nearly linearly with flux.

Measurements of the contrast of small (sub-arcsecond) network pores observed at high spatial resolution in the green show a similar cut-off and linear dependence on magnetic flux (Zirin and Wang, 1992). This suggests that these "invisible sunspot" structures might be similar to those which are seen as dark faculae at

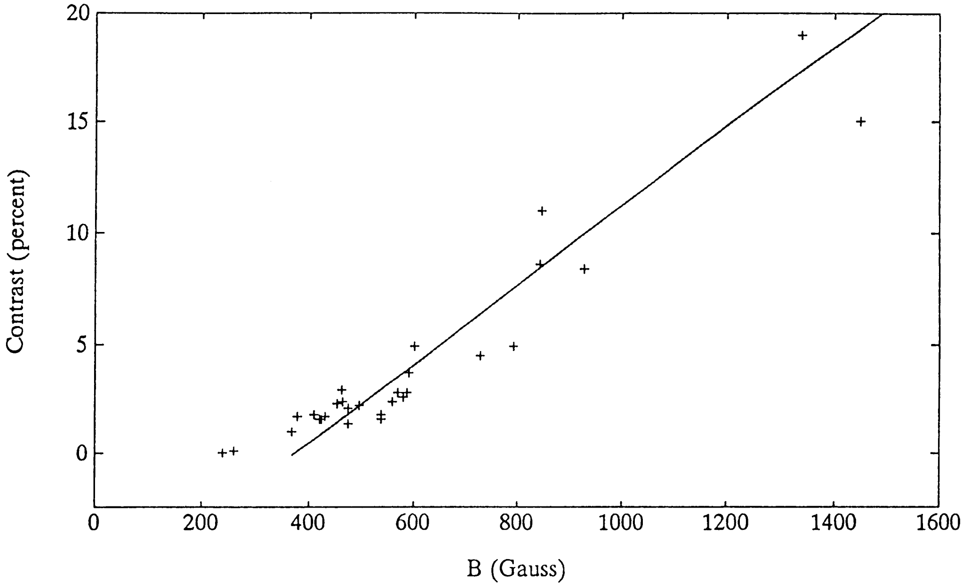

Fig. 2. A plot of 1.63 μm contrast versus NSO magnetic field strength for 29 selected structures (from Moran, Foukal, and Rabin, 1992).

1.63 μm. It appears that when the surrounding region is averaged into the measurement (*i.e.*, at lower spatial resolution), the contrast at 1.63 μm remains below unity while the visible contrast averages to zero.

MHD models have been constructed to explain facular contrast as a function of contributions from a hot, bright tube core, and from the relatively darker surrounding region. The surroundings are cooled below photospheric values by radiation into the (less opaque) flux tube (Deinzer *et al.*, 1984; Knölker and Schüssler, 1988; Spruit, 1976). Model parameters include a convective suppression factor, density reduction factor, field strength and tube diameter. For a particular choice of parameters, the model predicts facular contrast as a function of heliocentric angle and wavelength. The flux tube itself seems to be brighter than the photosphere in these models, even at 1.63 μm, so the observation of a dark facula may imply that the cooling of the flux tube surroundings becomes increasingly evident deeper in the photosphere (or the model may be in error).

Comparison between such models and observations of the kind described here could, in principle, provide important new insight into the temperature structure of plasma inside the flux tube and the region just outside it. But care must be exercised in such comparisons, since the calculations refer to flux tubes of diameter far below the angular resolution limit of the observations. Quantities that might be relatively insensitive to spatial resolution, like the ratio of contrasts at two wavelengths widely separated in H^- opacity, are more likely to prove useful than absolute contrasts at any one wavelength. To make progress, it will be important for modellers to generate observable quantities related to flux tubes *including* their surroundings, so that the new results of IR measurements with 2-3 arcsec resolution, such as those reported here, can be usefully interpreted.

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