ON SUNSPOT AND FACULAR CONTRAST VARIATIONS NEAR 2 μm AND 4 μm

V. A. KOTOV

CSSA, Stanford University, Stanford, CA 94305, U.S.A.

and

Crimean Astrophysical Observatory, Nauchny, Crimea 334413, USSR

and

S. KOUTCHMY

Institut d'Astrophysique, CNRS, 98 bis, Boulevard Arago, F-75014 Paris, France

Abstract. Observations of the Sun at 2.2 and 3.75 μm have been made at the Pic-du-Midi and Crimean observatories. High resolution ($\sim 1''$) records of the sunspot and facular contrasts at various heliocentric distances as well as those at the extreme solar limb are presented. We find substantial variations in the sunspot-core relative intensity caused by magnetic activity of the spot. The extreme-limb contrasts of faculae at 3.75 μm are strong thus support flux-tube models which result in an enhancement of the extreme-limb facular brightness.

Key words: flux tubes – infrared: stars – Sun: faculae, plages – sunspots

1. Introduction

Observations of the Sun at 2.2 and 3.75 μm were made in 1974 at the Pic-du-Midi and Crimean observatories but were never reported. Because of possible contamination by absorption lines within the filter passband the 2.2 μm records were not suitable for accurate determination of spot contrasts. The basic observations were carried out at the CrAO Solar Tower (with the 90-cm main mirror) using the liquid-nitrogen cooled PbS cell combined with a Ge-filter and a 0.34-μm interference filter centered at 3.75 μm (Koutchmy *et al.*, 1977). We used the main optical system of the Tower producing a 50-cm image of the Sun with resolution $\sim 1''$ at 3.75 μm. The detector had a circular entrance aperture, chosen to sample at the $\sim 1''$ diffraction limit of the telescope; the sampling frequency was 400 Hz.

2. Extreme Limb Profile

Observations of the extreme limb made at 2.2 and 3.75 μm showed that, in the first approximation, the blurring function may be represented by $S(r) = (\pi b^2)^{-1} e^{-(r/b)^2}$ with $b \approx 1.4''$. Since the aureole at $r \approx 7''$ outside the limb did not exceed 0.5%, the influence of blurring on the contrast measurements (for umbral diameters $\geq 15''$) is of small significance. The total contribution of stray light was estimated to be $\leq 1\%$.

The 3.75 μm records of the extreme limb differ appreciably from those obtained at 2.2 μm: the former reveal the existence of intensity enhancement $\approx 1.4\%$ at $r \approx 13''$. This enhancement should be probably attributed to an excess due to faint "invisible" IR faculae located near the limb. The intensities near the limb, corrected for seeing, together with the Allen's (1976) values, are given in Table 1. Our data significantly improve the limb profile for $r < 10''$, due to the higher spatial resolution of the present observations.

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TABLE I
The extreme limb intensities at 3.75 μm (outside faculae).

r ($''$)	44	19	5	4	3	2.0	1.3
Observed	-	0.858	0.800	0.790	0.768	0.735	0.690
Corrected	-	0.860	0.819	0.814	0.800	0.790	0.780
Allen (1976)	0.889	0.856	0.803	-	-	-	0.704

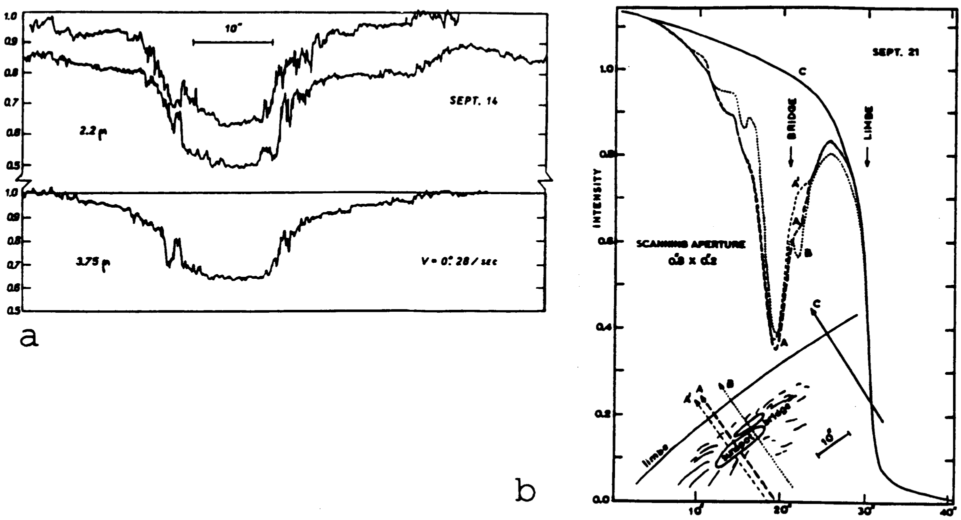

Fig. 1. (a) Typical IR photometric scans across the same location of a sunspot at 2.2 μm (top) and 3.75 μm (bottom); and (b) the continuum intensity near the Hα line of the spot shown in Figure 2 (21 September; 3.75 μm).

3. Sunspot Contrasts

Figure 1*a* presents records across a large sunspot (the spot group N 225, *Solar Geophysical Data*) on 14 September 1974 where the bright bridges are clearly seen at both wavelengths. The 3.75 μm records across the same spot made on 19-21 September are shown in Figure 2. One can readily see a *prominent facular area*, accociated with the "Secci" ring, with contrasts up to $\approx$ 4% and $\approx 1''$ fine structure. The maximum contrast substantially *increased*, from 2-3 to 3-4%, as the area approached the limb.

On 21 September the spot was photographed almost simultaneously in the continuum near $H\alpha$ with a 2 Å passband interference filter (Fig. 1*b*). A bright bridge $\approx 1.2''$ in width was clearly seen in both passbands, near Hα and at 3.75 μm. The bridge (and faculae) had larger contrasts in the IR than near Hα (bridge contrasts $\approx$ 8.2 and 4.4% respectively). The Hα faculae clearly seen in the penumbra were

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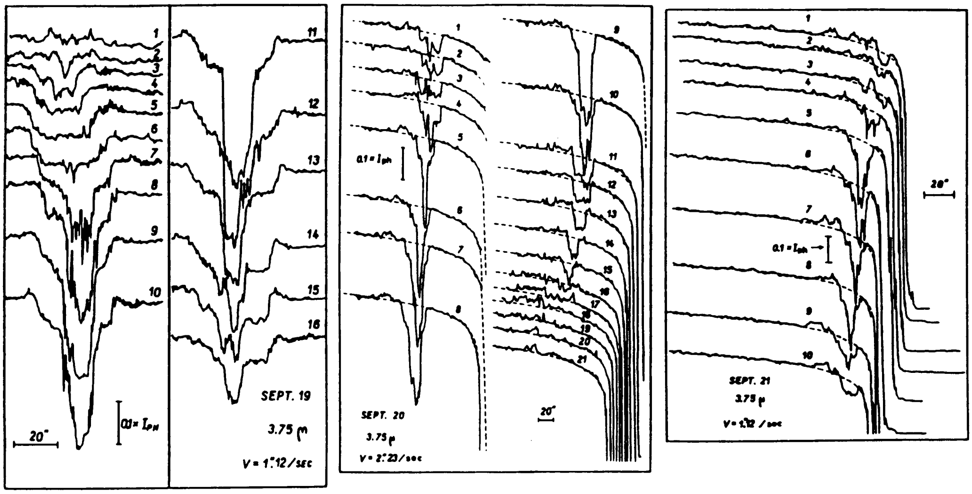

Fig. 2. The 3.75 μm photometric scans across a single spot obtained on 19 (left), 20 (middle) and 21 (right) September; the spacings between subsequent scans is 2.6″.

practically invisible outside the spot. Near Hα, we also did not observe any significant facular enhancements for $r > 22''$, contrary to the IR data, which explicitly showed facular regions with contrasts up to $\approx 4\%$.

The average contrasts for the umbra I_u and penumbra I_p at various heliocentric distances R are listed in Table 2. (The August observations of the same spot were performed by Koutchmy at Pic-du-Midi.) We see significant changes of I_u, presumably caused by the spot evolution and/or variation in the spot magnetic field (Fig. 3). The mean values $I_u = 0.65$ and $I_p = 0.94$ fairly agree with Allen's (1976) data for 3.75 μm. Our September average contrast I_p coincides also with the Maltby's (1972) result 0.936 ± 0.008 for 3.8 μm. The noticable tendency of I_u to increase slightly toward the limb is compatible with Wittmann and Schroter's (1969) conclusion based on observations at 0.468 and 0.790 μm. (However it contradicts the results of Makita and Morimoto (1960) obtained at similar wavelengths by averaging contrasts of various spots. Mattig (1969) argued that these latter measurements actually showed an increase of I_u toward the limb if one considers individual spots separately.) We mighty therefore conclude that the temperature gradient in the spot was a bit smaller than in the photosphere; however another interpretation can also be valid: a time evolution of the spot itself.

Ekmann and Maltby (1974) stressed the necessity of IR observations of spots. They propose that the scatter in IR intensities for different spots be considered as real. This could easily explain the variation in spot contrasts obtained by different observers. We note that the contribution of umbral dots in sunspot core measurements is often ignored; it is therefore difficult to discuss further the discrepancies in results reported by different authors.

The intensity gradient across the penumbra at the W-side of the spot (Fig. 2) appears to be larger than that at the E-side. This supports a similar observation

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TABLE II
Sunspot contrast variations at 3.75 μm (uncorrected for a stray light).

Date (1974)	$R = \sin\theta$	Umbra	Penumbra
8 August	0.527	0.553	-
9 - " -	0.415	0.527	-
10 - " -	0.341	0.770	-
11 - " -	0.368	0.680	-
12 - " -	0.475	0.675	-
14 - " -	0.807	0.692	-
15 - " -	0.944	0.695	-
14 September	0.201	0.622	0.930
19 - " -	0.810	0.652	0.933
20 - " -	0.922	0.658	0.938
21 - " -	0.986	0.653	0.958

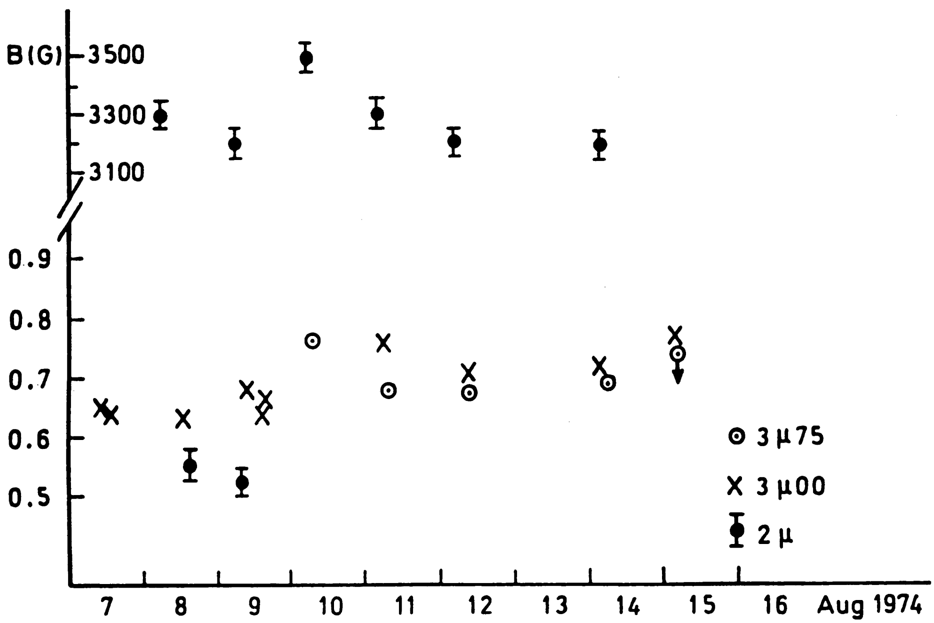

Fig. 3. Time variation of the magnetic field B (as measured by N.N.Stepanyan and colleagues at CrAO) and of the umbral core intensity I_u recorded in August 1974. If one ignores a plausible center-limb effect, a striking correlation emerges between B(top) and I_u (bottom).

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TABLE III
Mean facular contrasts at 2.2 and 3.75 μm.

$R = \sin\theta$	0.402	0.200	0.810	0.922	0.986
Contrast, 2.2 μm	< 0.01	-	0.020	0.014	-
Contrast, 3.75 μm	-	< 0.01	≈ 0.012	0.027	0.042

by Maltby (1972) (though he suggested that the difference might be caused by an observational selection). We suppose that the asymmetry is real and indicates more regular structure of the leading side of the penumbra. In general, our data do not show a substantial decrease of I_u or I_p toward the limb found earlier by Albregtsen *et al.* (1984) for the 0.387–2.35 μm range. This may be due to several circumstances: (a) the difference in wavelength; (b) that we studied only a single spot at various radial distances instead of averaging contrasts of different spots; (c) temporal variations in the spot, see Figure 3.

4. Facular Contrast

The deduction of true facular contrasts near the limb is of a paramount importance for the modelling of filigree (magnetic flux tubes), especially in view of the controversy between different authors: models with a Wilson depression with "hot walls", as opposed to "hot hill" or "cloud" models. We believe that both models coexist, and predominance of one or other depends on the magnetic field configuration (Koutchmy and Stellmacher, 1978).

The most recent summary of monochromatic measurements of facular contrasts for the range 0.33 to 1.00 μm at various $\cos\theta$ values has been compiled by Foukal *et al.*, (1991). Our near-IR contrasts (Table 3) agree well with their values (Figure 4) and may presumably represent true IR contrasts due to high ($\approx 1''$) spatial resolution of the observation. We note also that our contrasts appear to be significantly different from those obtained by Lindsey and Heasley (1981) for 10-25 μm. This discrepancy might be attributed to the differencies in wavelengths and especially in spatial resolutions. It confirms our poor understanding of the geometry and temperature distribution of real solar faculae as corrections for the filling factor cannot, at this stage, be properly introduced.

5. Conclusion

High resolution photometry of sunspots and faculae in the 2 to 4 μm region shows important properties needed for modelling these magnetic structures and their dynamics. More detailed measurements are now possible due to the availability of new IR imaging technology (see these proceedings). This makes precise identification of the origin of these variations a possibility. It is important that telescopes now be adapted for such observations.

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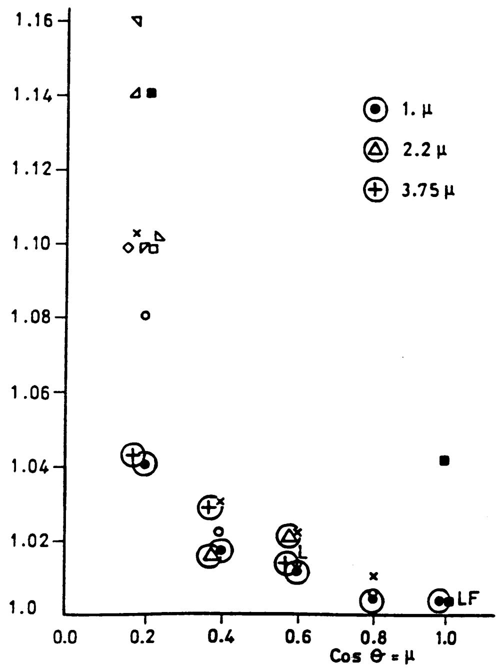

Fig. 4. Observed facular contrast vs $\mu = \cos\theta$ as adopted from Foukal *et al.* (1991) but plotted with our values for 2.2 μm (triangles) and 3.75 μm (crosses). Contrasts at 1.00 μm, taken from Foukal *et al.*, 1991, are represented by filled dots. All IR contrasts are shown inside circles; other symbols correspond to the 0.33-0.87 μm range.

References

Albregtsen, F., Joras, P.B., and Maltby, P.: 1984, *Solar Phys.* **90**, 17.
Allen, C.W.: 1976, *Astrophysical Quantities*, Athlone Press, London.
Ekmann, G., and Maltby, P.: 1974, *Solar Phys.* **35**, 317.
Foukal, P., Harvey, K., and Hill, F.: 1991, *Astrophys. J.* **383**, L89.
Koutchmy, S., Koutchmy, O., and Kotov, V.: 1977, *Astron. Astrophys.* **59**, 189.
Koutchmy, S., and Stellmacher, G.: 1978, *Astron. Astrophys.* **67**, 93.
Lindsey, C., and Heasley, J.N.: 1981, *Astrophys. J.* **247**, 348.
Makita, M., and Morimoto, M.: 1960, *Pub. Astron. Soc. Japan* **12**, 63.
Maltby, P.: 1972, *Solar Phys.* **26**, 76.
Mattig, W.: 1969, *Solar Phys.* **6**, 413.
Wittmann, A., and Schröter, E.H.: 1969, *Solar Phys.* **10**, 357.

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