A Study Based on Na D_2 Profiles in Sunspots*

Hong Sik Yun

Bartol Research Foundation of The Franklin Institute
Swarthmore, Pennsylvania 19081
U. S. A.

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ABSTRACT

The earlier findings on the radiative heating through the umbral walls in large sunspots are further investigated. No significant evidence for the umbral heating has been found in small-sized sunspot umbrae.

1. Introduction

In the last few years much interest has been aroused by new evidence that the umbra-to-the adjacent photospheric intensity ratio $\phi_\lambda(u)=I_\lambda^*(u)/I_\lambda^0(u)$ (where $u=\cos\theta$ and θ is the heliocentric angle) for large sunspots increases as they move towards the solar limb. This was first considered to be real by Rödberg(1966), but it has remained as a disputed point of interest to many workers until Wittmann and Schröter(1969) reported circumstantial evidence on Rödberg's observations(see figs. 1 and 2). What is most intriguing in the new observations is that, contrary to earlier belief, the atmospheres of these large umbrae are not in radiative equilibrium. According to radiative equilibrium atmosphere of an effective temperature $T_{eff}^*=4000°$K(see fig. 2), the intensity ratio, $\phi_\lambda(u)$ decreases towards the limb in contradiction to the new observations.

As is known, the Na D lines are eminently useful for studying the temperature structure in the visible umbral atmospheres since the shapes of their

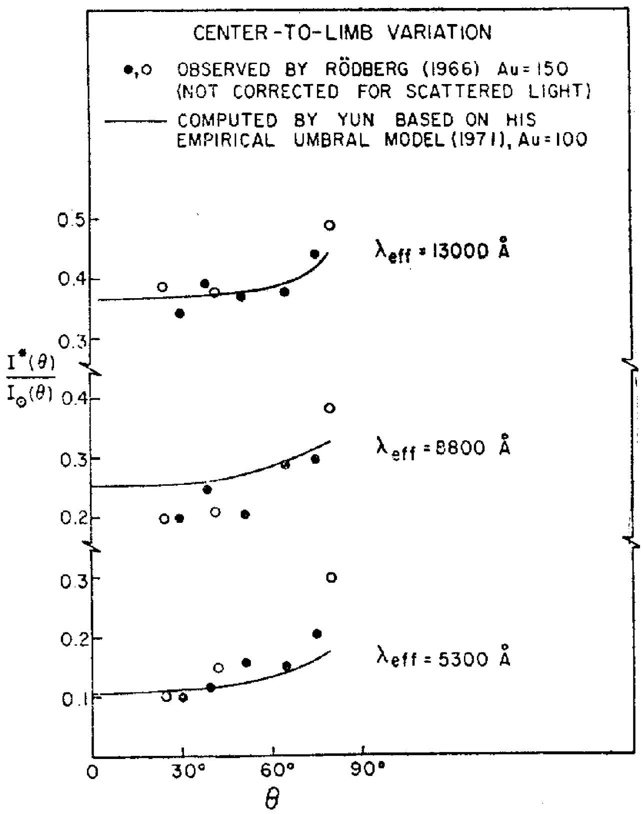

Fig. 1

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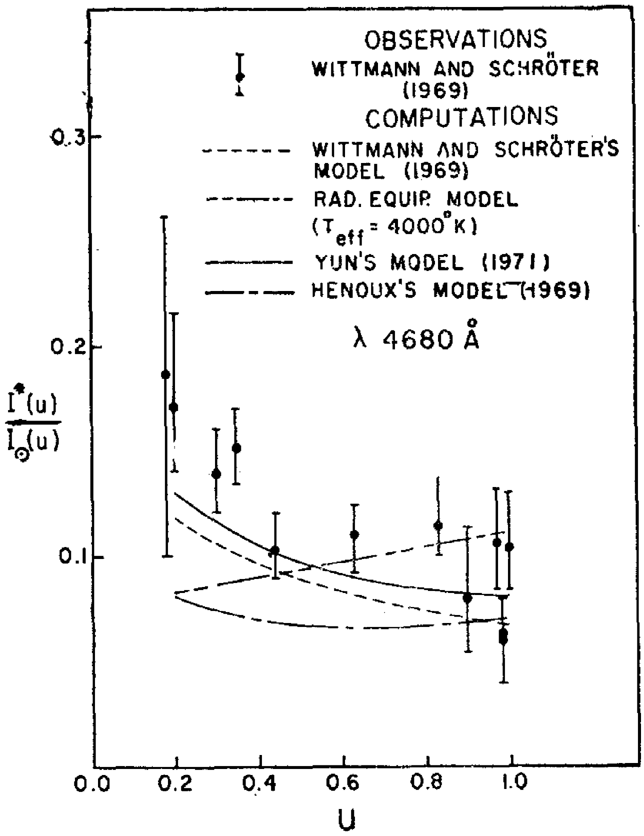

Fig. 2

wing profiles are quite sensitive to the temperature distribution in the umbral atmospheres. Accordingly, the "limb brightening" effect demonstrated by the new observations has been investigated by Yun(1971), looking into the Na D line profiles based on the temperature distribution computed from Wittman and Schröter's infrared observations. From this study it has been found that at least for the *large*-sized spots significant heating from the penumbra is indeed present in the upper layers of the atmospheres, thus affecting their physical conditions in the region with consequent departure from radiative equilibrium.

According to an earlier study on internal models of sunspots by Yun(1970a), the umbrae are depressed geometrically by 350km to 850km below the visible normal photosphere, (i.e., "Wilson's depression") depending on their effective temperature. As a result, a major part of the sunspot atmospheres is located below the photospheric base and is exposed to considerable heating from the penumbra and the adjacent normal photosphere.

In view of a possible dependence of the umbral heating on the depression of individual spots, we have taken *small*-sized spots as worthy of further investigations.

2. Observations

Many of the sunspot observations are often severely hampered by the annoying problem of eliminating the scattered photospheric light caused by the inadequate guiding of the telescope and atmospheric seeing fluctuations. In the past years, many ingenious reduction techniques have evolved to solve this problem, but none of the presently applicable techniques are known to be truly satisfactory as noted by Zwaan(1965) recently. Thus, it appears quite desirable to introduce a new technique of intensity recordings capable of selecting some clean samplings out of observations of good seeing, keeping the level of the scattered light intensity as low as possible.

In the last two years a new technique has been successfully developed by Wyller and Fay at Bartol Research Foundation, capitalizing on the favorable combination of instrumnetal and operational techniques. Because of the use of pinholes instead of slits in their spectrometer, the level of the scattered light is reduced considerably as compared to that often experienced in other observational techniques. In addition, the dual channel pulse counting techniques make it possible to record the uncontaminated umbral light by integrating the pulse counts both from the continuum channel and the line channel synchronously for a fairly short time interval (e.g., 0.8 seconds of time) so as to minimize the image excursion due to the atmospheric inhomogeneities and then by selecting the time channel with lowest umbral continuum counts relative to the photospheric disk. The selected raw umbral intensity countings both for the line and continuum are then corrected for the photospheric scattered light, following the procedure by Zwaan(1965) based on the theoretical study of David and Elste(1962). More detailed discussions on the reduction techniques and the observational procedures are found in Fay, Wyller and Yun(1971).

Three small sized spots have been observed during the months of January and February in 1969. The resulting scan of the Na D_2 line profile observed from a typical small-sized umbra is presented in fig. 3(a).

3. Results and Discussions

For the computations of the Na D_2 line profiles four different umbral atmospheres have been considered, varying their effective temperature from 4000°K to 5000°K. In order to construct umbral atmospheres close to radiative equilibrium, the scaled empirical solar T-τ_0 relation of Krishna Swamy(1967) has been employed in the present investigation. The detailed physical structures of these models are described in Table 1, where the gas pressure P_g has been computed from the equation of hydrostatic equilibrium, considering that on the umbral axis of symmetry, the magnetic field does not affect the vertical structure.

With the aid of these models the line profiles of Na D_2 have been calculated, assuming that the line is formed by pure

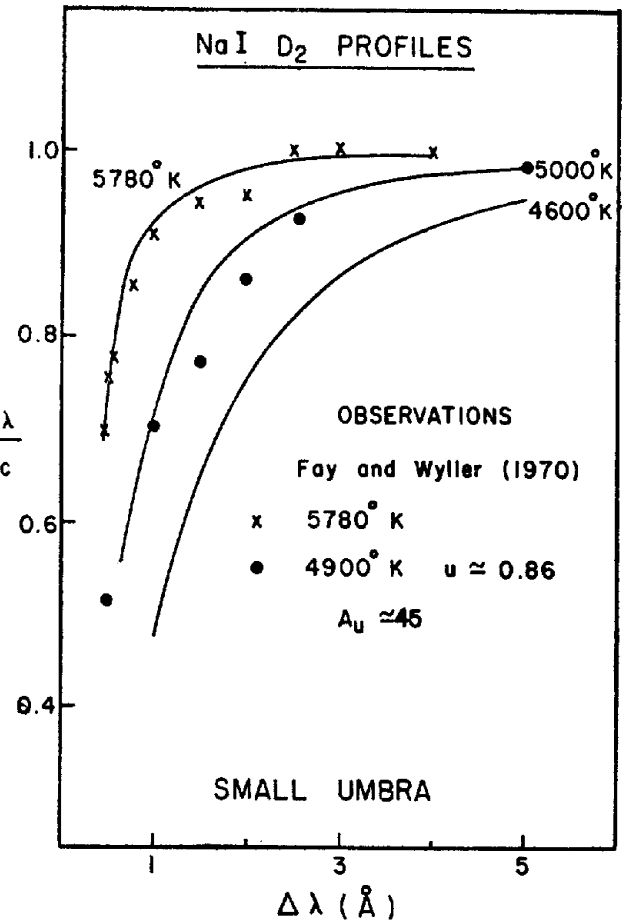

Fig. 3-(a)

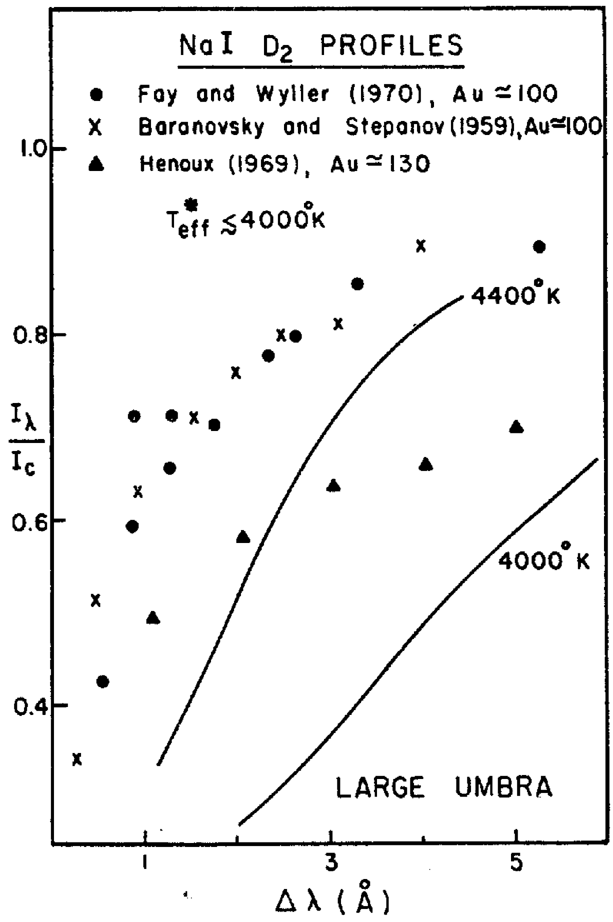

Fig. 3-(b)

absorption except for the immediate neighborhood of the line center. The computed profiles are presented in fig. 3, where the values of the effective temperature are indicated beside each corresponding profile.

In order to compare the computed profiles with the observations, the temperature of each observed umbra has been determined by comparing the observed intensity ratio $I_\lambda^*(u)/I_\lambda^0(1)$ with the computations as illustrated in fig. 4, where the triangle and the circle refer to the averaged upper and lower counts of the

Table 1. Umbral Atmospheres

	(a) T^*_{eff}=4000°K					(b) T^*_{eff}=4400°K				
$\log \tau_0$	$\log P_g$	$\log p$	$\log k_0$	$\log P_e$	$\log T$	$\log P_g$	$\log p$	$\log k_0$	$\log P_e$	$\log T$
−3.0	3.850	−7.437	−2.153	−1.492	3.505	3.818	−7.509	−2.102	−1.230	3.547
−2.6	4.071	−7.216	−1.978	−1.309	3.507	4.036	−7.293	−1.944	−1.065	3.548
−2.2	4.294	−6.997	−1.802	−1.115	3.510	4.261	−7.072	−1.774	−0.877	3.552
−1.8	4.517	−6.782	−1.625	−0.896	3.518	4.485	−6.855	−1.593	−0.657	3.560
−1.4	4.739	−6.576	−1.443	−0.635	3.534	4.704	−6.652	−1.395	−0.383	3.575
−1.0	4.958	−6.382	−1.250	−0.321	3.558	4.911	−6.469	−1.174	−0.047	3.600
−0.8	5.064	−6.290	−1.146	−0.149	3.573	5.010	−6.385	−1.059	0.135	3.614
−0.6	5.167	−6.202	−1.034	0.039	3.588	5.106	−6.304	−0.944	0.320	3.630
−0.4	5.266	−6.120	−0.915	0.240	3.606	5.200	−6.228	−0.831	0.511	3.647
−0.2	5.363	−6.036	−0.809	0.404	3.618	5.293	−6.150	−0.727	0.684	3.663
0.0	5.457	−5.901	−0.683	0.616	3.637	5.387	−6.079	−0.619	0.887	3.685
0.2	5.548	−5.894	−0.554	0.849	3.661	5.481	−6.008	−0.515	1.087	3.708
0.4	5.634	−5.839	−0.426	1.111	3.692	5.574	−5.944	−0.392	1.331	3.737
0.6	5.718	−5.795	−0.296	1.408	3.733	5.657	−5.898	−0.183	1.685	3.774
0.8	5.793	−5.766	−0.069	1.815	3.778	5.717	−5.878	0.145	2.165	3.814
1.0	5.850	−5.741	0.183	2.186	3.890	5.756	−5.878	0.488	2.644	3.853
	(c) T^*_{eff}=4600					(d) T^*_{eff}=5000°K				
−3.0	3.788	−7.559	−2.054	−1.088	3.566	3.690	−7.693	−2.015	−0.877	3.602
−2.6	4.001	−7.347	−1.904	−0.931	3.568	3.921	−7.463	−1.844	−0.699	3.604
−2.2	4.225	−7.127	−1.739	−0.748	3.571	4.151	−7.237	−1.671	−0.509	3.607
−1.8	4.450	−6.910	−1.558	−0.529	3.579	4.378	−7.018	−1.489	−0.291	3.615
−1.4	4.668	−6.707	−1.356	−0.253	3.595	4.598	−6.813	−1.294	−0.024	3.631
−1.0	4.874	−6.526	−1.135	0.082	3.619	4.811	−6.625	−1.091	0.288	3.655
−0.8	4.973	−6.442	−1.024	0.257	3.633	4.915	−6.536	−0.991	0.449	3.670
−0.6	5.070	−6.360	−0.917	0.434	3.649	5.018	−6.448	−0.893	0.614	3.685
−0.4	5.166	−6.281	−0.812	0.615	3.666	5.121	−6.363	−0.794	0.788	3.703
−0.2	5.264	−6.197	−0.718	0.766	3.680	5.223	−6.280	−0.687	0.976	3.722
0.0	5.362	−6.118	−0.616	0.950	3.699	5.324	−6.197	−0.574	1.153	3.738
0.2	5.460	−6.047	−0.502	1.176	3.726	5.416	−6.127	−0.412	1.407	3.761
0.4	5.550	−5.991	−0.330	1.483	3.760	5.490	−6.087	−0.134	1.814	3.795
0.6	5.623	−5.953	−0.063	1.884	3.795	5.539	−6.078	0.227	2.321	3.835
0.8	5.671	−5.944	0.284	2.374	3.834	5.566	−6.106	0.098	2.963	3.890
1.0	5.704	−5.944	0.572	2.772	3.866	5.578	−6.153	1.198	3.623	3.947

observations. In the figure, the solid lines represent the computed intensity ratios at different values of *u* on the solar disk. From this analysis the effective temperature of the observed umbrae has been determined as listed in fig. 3, which is shown in good agreement with the estimates from the area-effective temperature relation of Elste(1967).

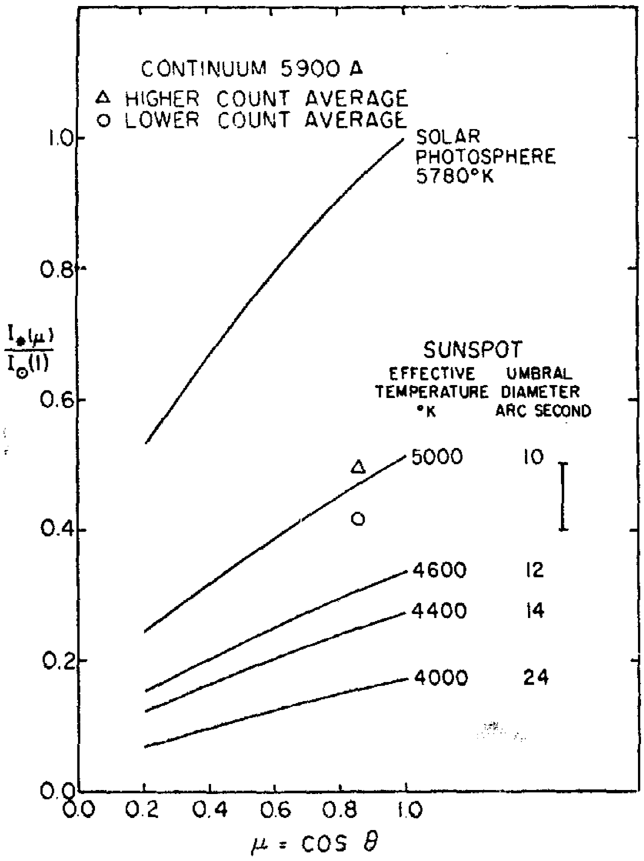

Fig. 4

As can be seen from fig. 3(a), the observed Na D_2 profile of our small-sized umbra is explained remarkably well by radiative equilibrium models, while for the large-sized umbra, a considerable disagreement exists between the observed and computed profiles based on these models(see fig. 3(b)). This discrepancy has been successfully accounted for by a new empirical model by Yun(1971), taking into account moderate heating by 300 to 400 degrees in the upper umbral atmospheres. It is quite evident from fig. 3 (a) that no significant heating effect is present in the small-sized umbrae. A similar study based on H_α and CaI 4227 also yields the identical conclusion(Yun 1970b). Thus, it appears that the umbral heating becomes significant, only when the umbra evolved fairly large in size.

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REFERENCES

Baranovsky, E. A. and Stepanov, V. E.; 1959, *Izv. Crim. Astrophys. Obs.* 21, 180.

David, K. H. and Elste, G.; 1962, *Z. Astrophys.* **54**, 12.

Elste, G.; 1967, in private communication.

Fay, T.D., Wyller, A. A. and Yun, H. S.; 1971, *Solar Phys.*(submitted).

Henoux, J. C.; 1969, *Astron. Astrophys.* **2**, 288.

Krishna Swamy, K. S.; 1967, *Astrophys. J.* **150**, 1161.

Rödberg, H.; 1966, *Nature* **221**, 394.

Wittmann, A. and Schröter, E. H.; 1969, *Solar Phys.* **10**, 357.

Yun, H. S.; 1970(a), *Astrophys. J.* **162**, 975.

Yun, H. S.; 1970(b), Annual Report to National Aeronautic and Space Administration by Bartol Research Foundation.

Yun, H. S.; 1971, *Solar Phys.* **16**, 379.

Zwaan, C.; 1965, *Rech. Inst. Astron. Utrecht* **17**, 4.