"Stray Light Analysis for the SOT (Hinode mission) high resolution imaging Observations and Applications"

by

Hadis Goodarzi[1,2], Serge Koutchmy[1] and Ali Ajabshirizadeh[2]

[1]- Institut d'Astrophysique de Paris, CNRS & UPMC 98 Bis Bd Arago F-75014 Paris France goodarzi@iap.fr koutchmy@iap.fr
[2]- Tabriz University, I.R. of Iran ali_ajabshir@yahoo.com a-adjab@tabrizu.ac.ir

Abstract: We discuss the determination of the Point Spread Function (PSF) defining the smearing of instrumental origin due to i) diffraction of the mirrors with a central obscuration system, ii) stray light and iii) optical very small aberrations, including the minute defocusing, for the excellent images obtained with the Solar Optical Telescope (SOT) of the Hinode mission. The stray light is evaluated from both the amount of light observed inside the 60 arcsec diameter disk of the silhouetted planet Venus in projection on the solar disk, at time of the 2012 transit, and from the amount of light registered outside the solar disk. The Point Spread Function (PSF) corresponding to the blue continuum Broadband Filter Imager (BFI) near 450 nm is deduced using a model of the limb of the Sun outside the inflection point and images of Venus taken during the transit of the planet Venus in 2010, during the egress. A combination of a Gaussian and a Lorentz functions is selected to construct a PSF in order to remove both the narrow angles smearing due to diffraction (core of the PSF) and the large angles stray light due to central obscuration and defects (wings of the PSF). Removing the stray light from the Venus image near the third contact (egress) by using a Max-likelihood deconvolution processing based on the adopted new PSF permits to better evaluate the Venus aureole effect related to the Venus atmosphere. The deconvolution procedure was mainly applied to the sunspot observed on March 2007 in order to illustrate how effective ly our restoration method works on umbral fine structures such as umbral dots and penumbral filaments. A movie was prepared from the images deduced after deconvolution, to illustrate the complexity of the dynamical behavior inside and around the sunspot for the deep layers seen in 450 nm. Finally a new feature appearing for the 1st time at the extreme- limb of the disk (the last 100 km is concerned) is deduced in the frame of the definition of the solar edge and of its diameter.

Key words: telescopic PSF; stray-light; Venus atmosphere; solar granulation; solar limb brightening; sunspot umbral dots; penumbral features; dynamical sunspot phenomena; local dynamo effects.

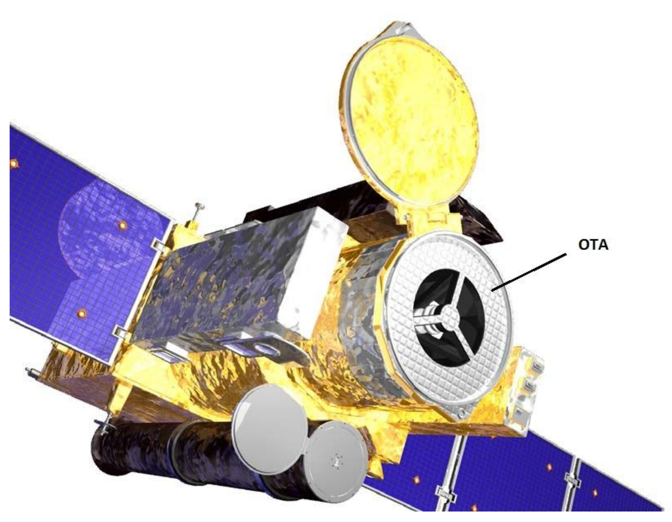

Figure 1. Solar-B (Hinode) looking at the Sun. Note the central obscuration. (Suematsu et al. 2008)

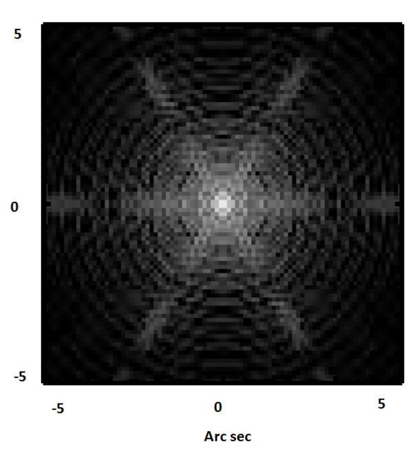

Figure 2. Theoretical diffraction-limited point spread functions for a wavelength of 555 nm on a logarithmic grey-scale (S. Wedemeyer-Böhm , 2008).

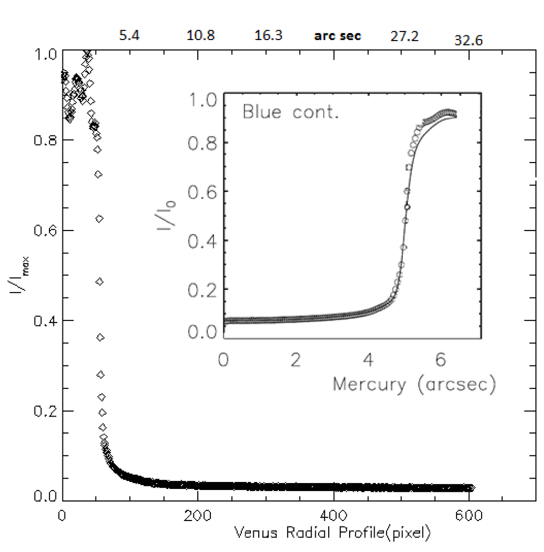

Figure 3- Average radial profile of Venus using a 30 rows average. Superposed is the cross section of Mercury from Mathew et al, 2009.

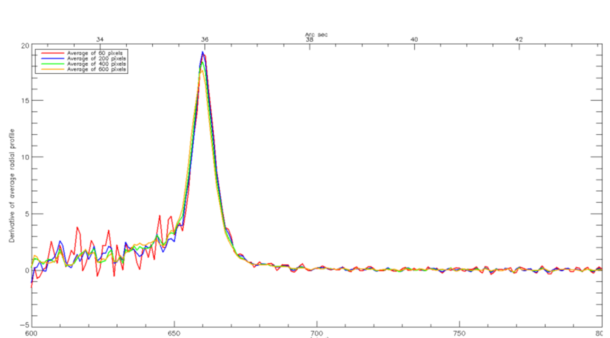

Figure 5. Derivative of the limb intensity variation of the solar disk and the aureole outside for different number of averaging

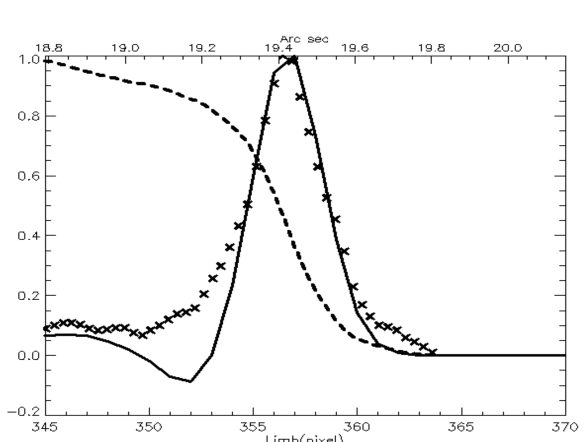

Figure 5bis. Theoretical extreme limb (dashed line) from Lites 1982 and its derivative (cross symbol). Solid line shows the derivative of the deconvolved limb using our PSF.

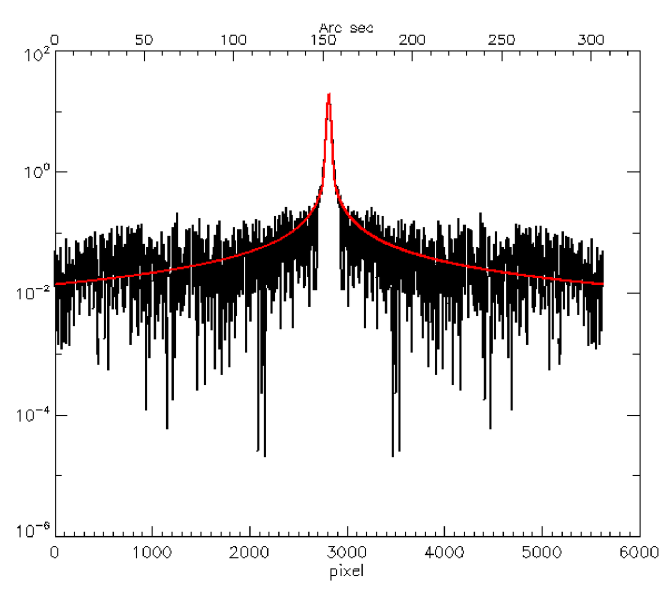

Figure 6- Full symmetrized derivative profile of the Solar limb from fig 5 after rebining by a factor 4 and going further out. Log scale. The fitting is used to deduce the 1st approximation PSF after computing a reverse of the Abel transform using the function:

$$PSF(x) = p_0 \frac{1}{{p_1}^2 + (x-p_2)^2} + p_3 e^{-(x-p_2)^2 / 2{p_4}^2}$$

Fig 5 shows the average derivative profile of the solar limb for 200 rows, see Fig. 4. The left part of Fig 5 is rough because of granules but the right side is smooth enough, so this curve should be cut at the centre of gravity to make it symmetrical. We can then fit the resulted curve with an appropriate function which is the Abel Transform (AT) of the PSF assuming the limb is sharp (as calculated using the VAL model) after the inflexion point. In other words, limb derivative is the projection of circularly symmetric point spread functions along a set of parallel lines and represents the Line spread function (LSF). The PSF could be deduced from LSF by inverse Abel transform. It gives the contribution of the core of the PSF.

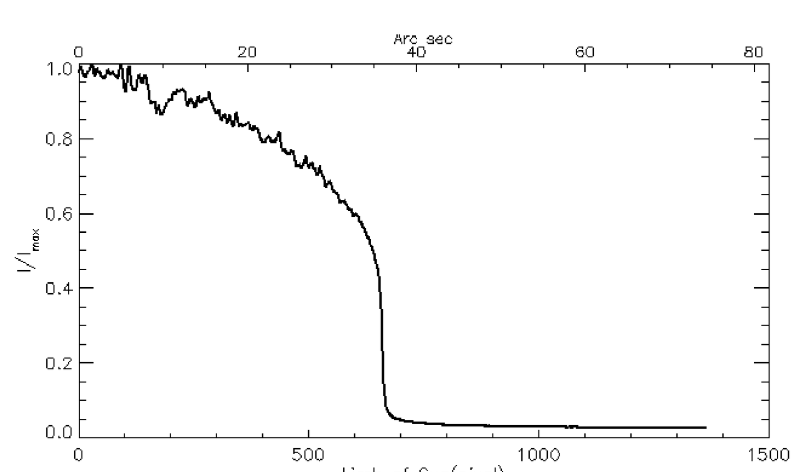

Figure 4. Radial profile of the limb of the sun using a 200 rows averaging. Note the aureole due to stray and scattered spurious light.

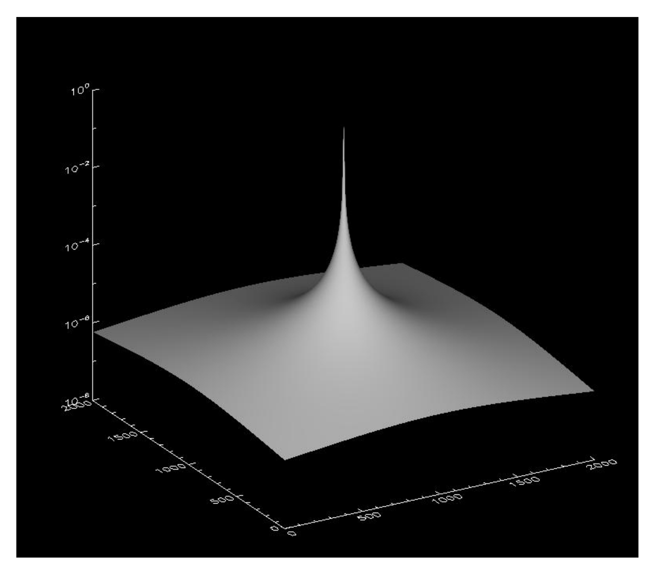

Figure 7- Three dimensional plot of the deduced PSF in logarithmic scale

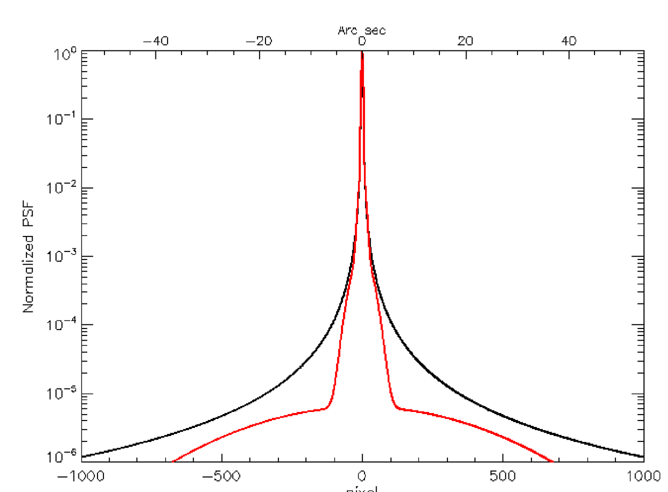

Figure 7bis- PSF deduced in this paper (black) and the one proposed in Mathew et al 2012(red).

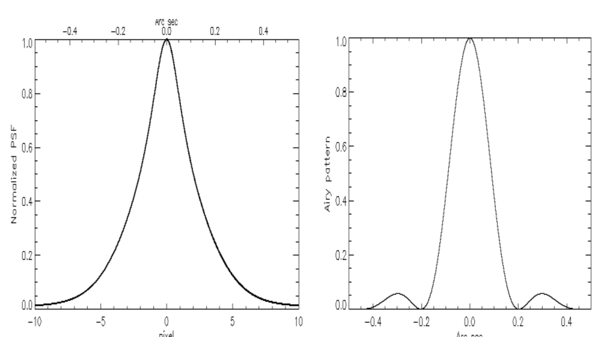

Figure 7tier- Airy pattern for a 50 cm aperture without central obscuration and illuminated by 450.4 nm light (right) and our deduced PSF (left).

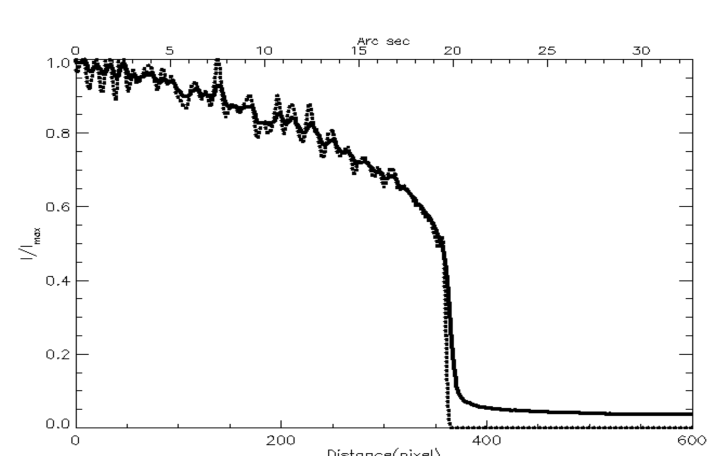

Figure 4bis. Observed (full line) and restored limb using our PSF Fig. 7(dotted line) of the Sun

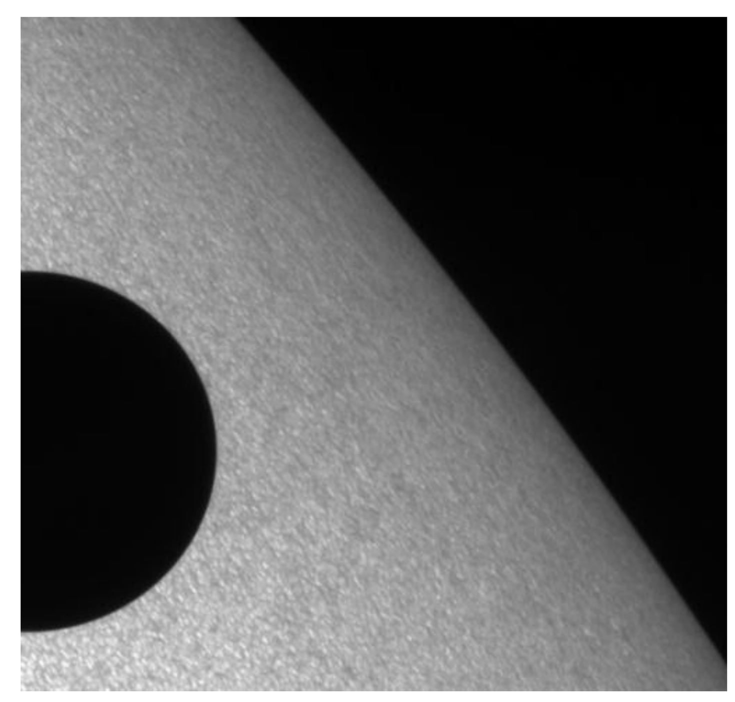

Figure 8- Observed image during the Venus transit. Note the limb darkening on the background image of the Sun.

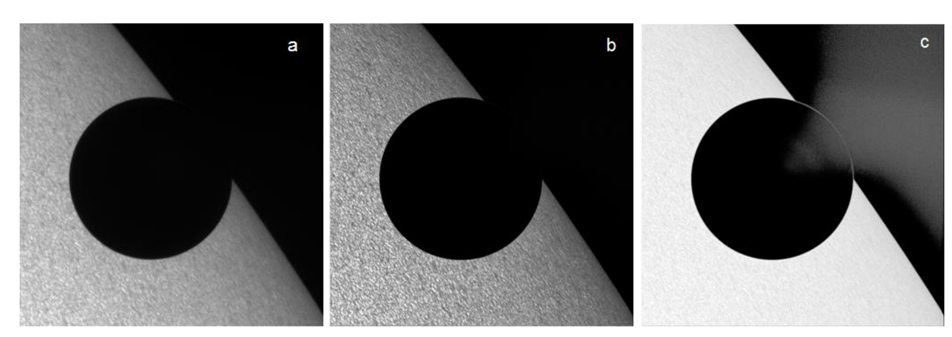

Figure 8 bis- Observed third contact (egress) after few minutes (a), deconvolved image (b), deconvolved image in logarithmic scale ©

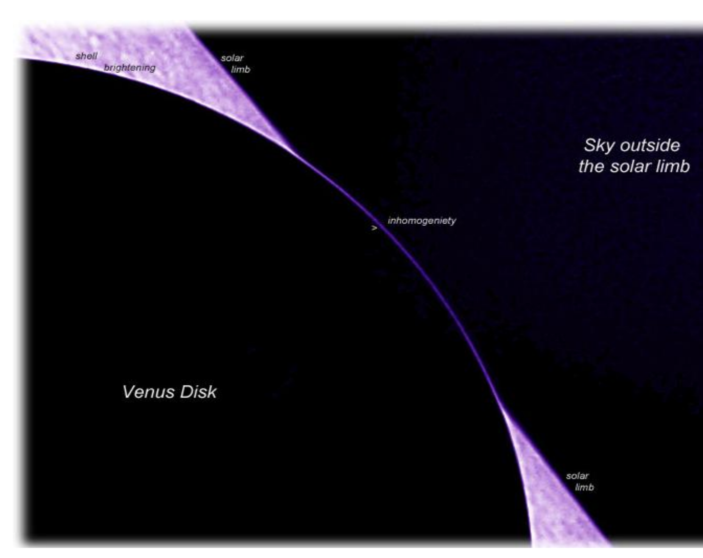

Figure 8 ter- Magnified deconvolved image showing new features, see the labels.

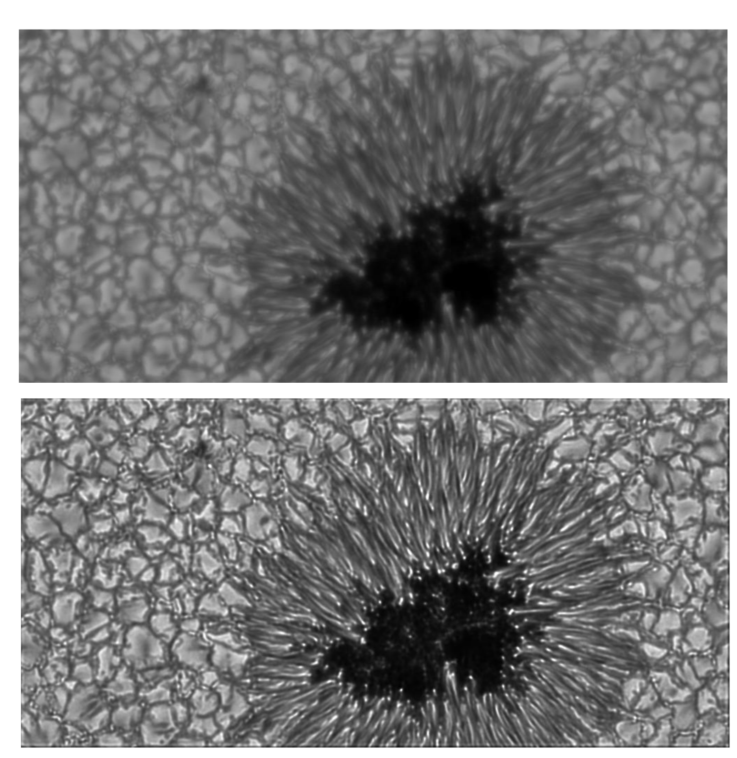

Figure 9- Observed SOT image of the sunspot on 2007 March 1, before and after deconvolution.

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