Deconvolution of Keck images of a Pillan eruption on Io UT 2007 August 14

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In this report we describe the reconstruction of the images of Pillan eruption observed with Keck II telescope on Mauna Kea, Hawaii, during UT 2007 August 14, in J, H, K, L and M band. For each band we have one image and three images of the star HD 161903 for PSF estimation.

The images of the first three bands do not have negative pixels; the L-band image has 477 negative values with a sum which is negligible with respect to the total flux while the M-band image has 9656 negative values with a sum of about -1×10^{-11} compared to a total flux of 8.11×10^{-10}. In all cases all the negative values are set to zero, without a significative change of the total flux, because the deconvolution algorithms require nonnegative images.

For each band the PSFs are obtained with the following procedure:

- normalization of the star images dividing by the peak value;
- sum of the three normalized images;
- suppression of "hot pixels" as follows:
  - for each pixel (i, j) we compute mean (m) and standard deviation (σ) of the 8 neighborhoods;
  - if the pixel value $psf(i, j) > m + 3\sigma$, then $psf(i, j) = m$;
- subtraction of a background value estimated with the (IDL) function `SKY` of `ASTROLIB`;
- zeroing of the negative values;
- application of a circular mask with radius 64 px (30 px in the case of L and M band);
- normalization of the result to unit sum.

The J, H and K band images with the corresponding PSFs are shown in Fig 1 while those in L and M band in Fig 2.

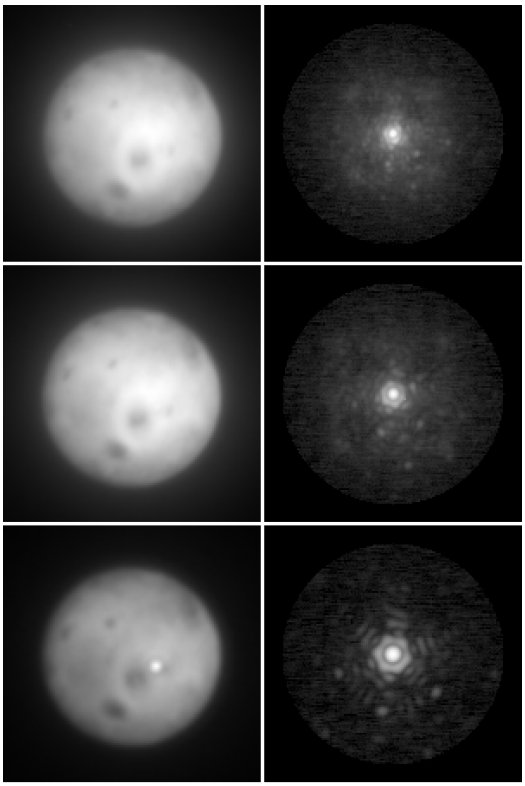

Figure 1: From top to down, J, H and K images of Pillan eruption (left panels; linear scale) and the corresponding PSFs (right panels; log scale).

It is evident that the L and M band PSFs are not satisfactory for attempting an image deconvolution. Therefore we decide to start from the K band PSF and to obtain the L and M band PSFs from that of K by means of the following approach:

- IDL's `CONGRID` by a factor $\lambda/2.27$ ($\lambda = 3.776\mu m$ for L band and $\lambda = 4.67\mu m$ for M band[1]);
- extraction of an array 256×256;

[1]More precisely, we used Jcont, Hcont, Kcont, Lp, and Ms bands. The definition of these bands is in the website:
`http://www2.keck.hawaii.edu/inst/nirc2/filters.html`

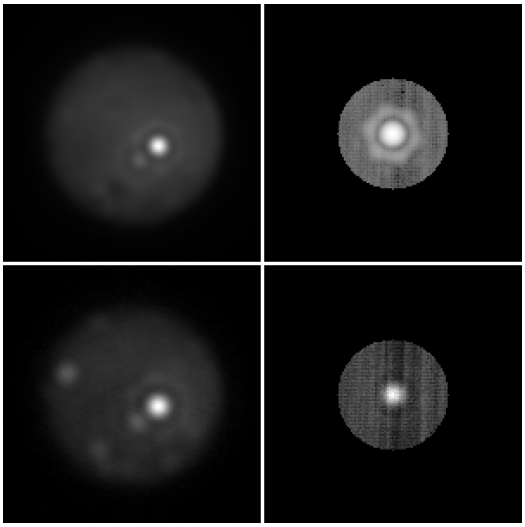

Figure 2: From top to down, L and M band images of Pillan eruption (left panels; linear scale) and the corresponding PSFs (right panels; log scale).

- application of a circular mask with radius 50 px;
- normalization of the result to unit sum.

The central parts of the two PSFs are displayed in Fig 3 together with the images of Pillan in the corresponding bands. By a comparison of these pictures we deduce that the computed PSFs are rotated with respect to Io images. Therefore, before deconvolution, we derotate the L band PSF by 137 degree and the M band one by 188 (clockwise direction). The final result is shown in Fig 4. It is not clear if the J, H, K band PSFs must also be derotated, because the side lobes are not visible on Io images.

For the deconvolutions of the five images in different bands we first apply SGP with MRF regularization (see the preprint: M. Prato et al., Efficient optimization methods for Richardson-Lucy regularization: algorithms, software and applications). As concerns the two parameters contained in this kind of regularization, for J and H band we choose $\delta = 10^{-12}$, $\beta = 5\ 10^{-4}$ and for K band $\delta = 10^{-13}$, $\beta = 10^{-3}$. The results are displayed in Fig. 5. These reconstructions look satisfactory.

We believe that Pillan eruption appears as a gray small spot in J band, close to the darker one in Pillan region, which becomes weakly bright in H band and finally very bright in K band.

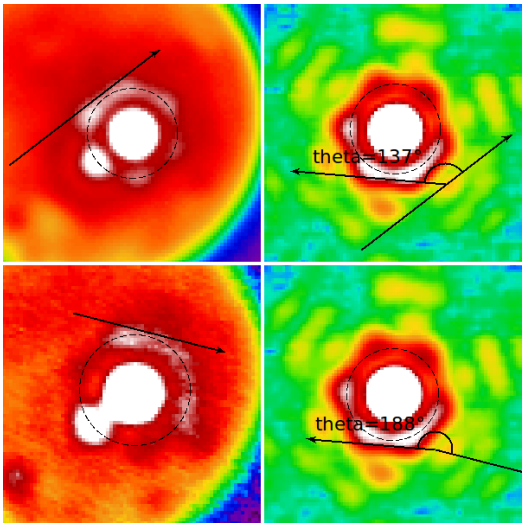

Figure 3: L and M band images of Pillan eruption (left panels) and the modeled PSFs (rigth panels) in false colors. We indicate corresponding side lobes and angles.

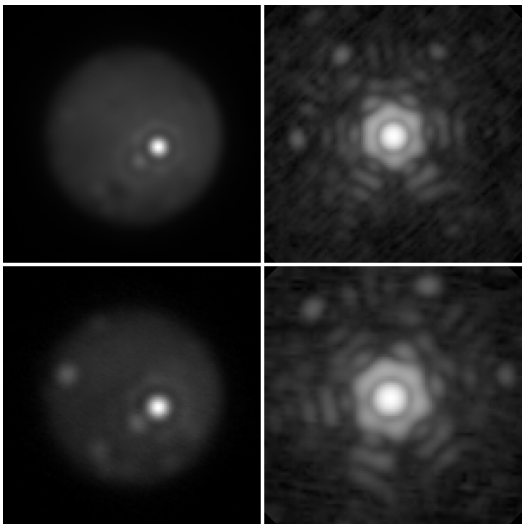

Figure 4: L and M band images of Pillan eruption (left panels, linear scale) and the modeled PSFs (right panels, log scale).

The L and M images are deconvolved with $\delta = 10^{-14}$ and $\delta = 10^{-15}$ respectively while $\beta = 10^{-3}$ in both cases. The results are displayed in

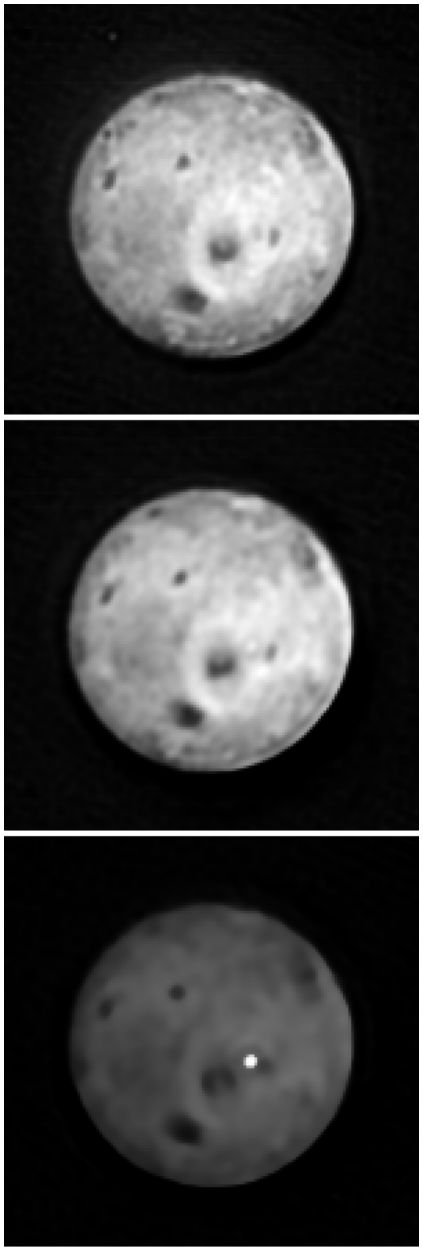

Figure 5: Reconstruction of Io images in J (up), H (middle) and K (down) band (linear scale).

Fig 6. It is obvious that these reconstructions are strongly affected by ringing artifacts and therefore we must use the multi-step approach proposed in the preprint.

The reconstructions of Fig 6 are the first step of the approach which is used for attempting an identification of the hot spots.

By comparing the images in the two bands we decide for 8 hot spots which are indicated in Fig 7, together with the corresponding masks. Remark that we attribute a single pixel to each hot spot, namely the closest one to its centroid.

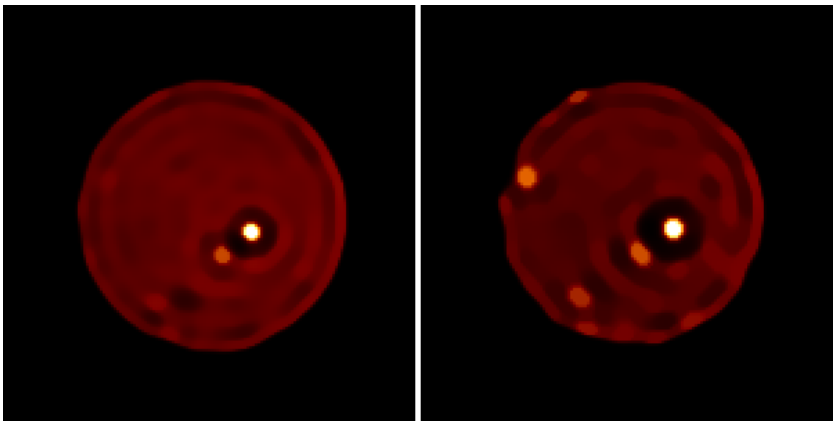

Figure 6: Reconstruction of Io images in L (left panel) and M (right panel) band (linear scale).

The next step is the application of the multi-component method, namely to consider Io image as the sum of a pointwise and a smooth component. No regularization is considered for the pointwise component while for the smooth one we use again MRF with the same values of δ used in step 1 and a larger value of β, namely $\beta = 5\ 10^{-3}$, for obtaining a larger smoothing effect. The result is shown in Fig 8.

The final step is a simple nonregularized SGP using the smooth component for background computation. The final reconstruction obtained by adding the SGP result to the smooth component is shown in Fig 9, while the result of SGP iterations is shown in Fig 10 (in reverse scale).

What is remarkable in the SGP reconstructions is that Pillan and Pele appear as isolated hot spots over a zero background. Therefore, by computing the sum of the pixel values for these two spots, we obtain a ratio between the

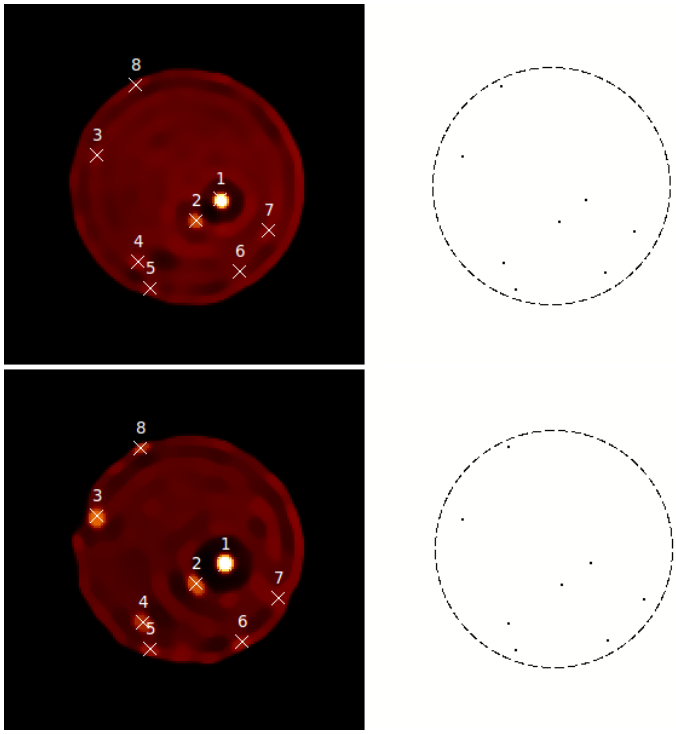

Figure 7: Identification of the hot spots (left panels) and the corresponding masks (right panels).

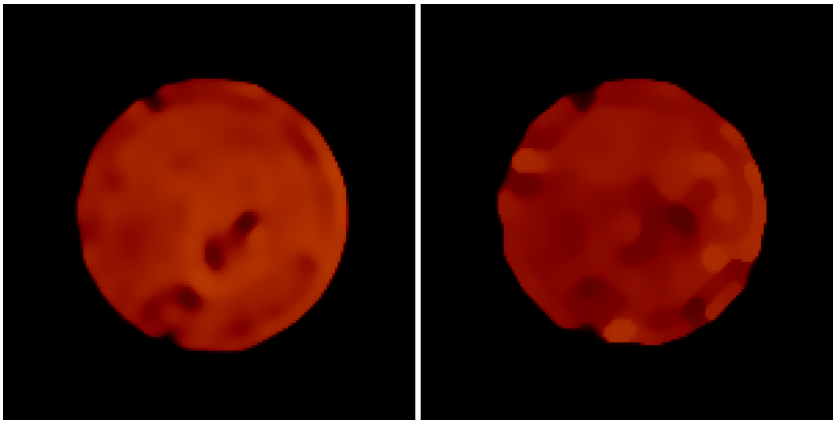

Figure 8: Reconstructed smooth component: L band (left panel) and M band (right panel).

flux of Pillan and that of Pele which is 5.3 in L band and 5.2 in M band; these values seem to be consistent with those derived from the paper of de Pater et al. (2015)[2], respectively 6.3 and 4.8, at least within the errors indicated in that paper.

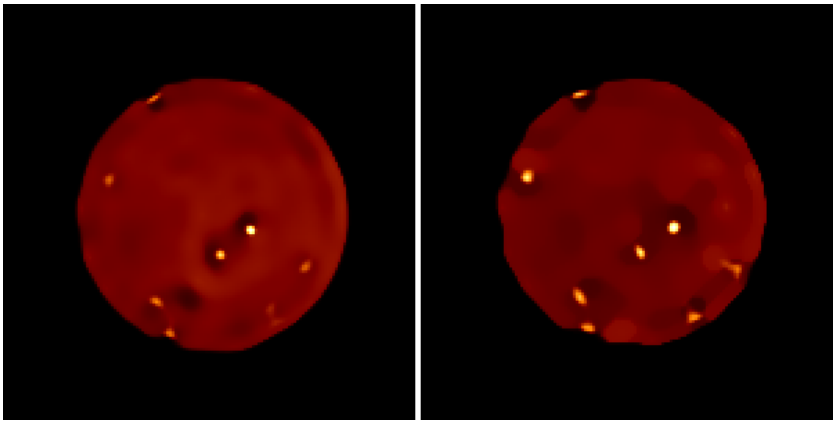

Figure 9: Final reconstructions: L band (left panel) and M band (right panel).

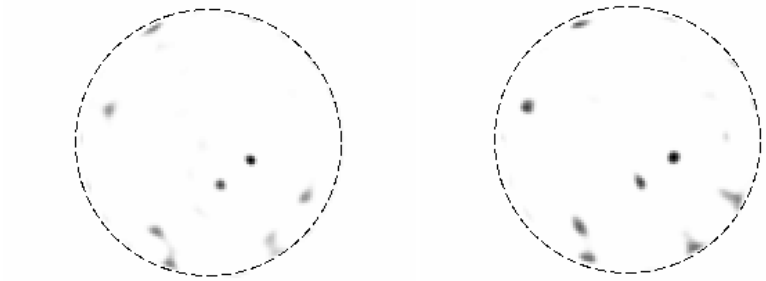

Figure 10: RL reconstructions of the hot spots: L band (left panel) and M band (right panel).

[2]de Pater, I., Laver, C., Davies, A.G., de Kleer, K., Williams, D.A., Howell, R.R., Rathbun, J.A., Spencer, J.R., 2015, *Io: Eruptions at Pillan, and the time evolution of Pele and Pillan from 1996 to 2015*, ICARUS 264, 198212. doi:10.1016/j.icarus.2015.09.006