

Spectral index map of the Crab Nebula in the optical range

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Abstract. Information about spatial distribution of the spectral index of the pulsar wind nebulae is important for understanding the structure of the nebulae and physical processes responsible for their formation. We present preliminary results on construction of a detailed index map of the Crab Nebula based on archival optical data obtained with the Hubble Space Telescope. Our map has much better spatial resolution than the previous one obtained by Veron-Cetty and Woltjer in 1993. It allows us to study in great details how the spectral slope of the synchrotron emission of the Crab varies along its torus and jet-like structures.

1. Introduction

Pulsar wind nebulae (PWNe) are the nebulae formed by the interaction between the interstellar medium and relativistic pulsar wind. The Crab nebula (NGC 1952, Taurus A) powered by the pulsar B0531+21 is a classical example of such nebulae. It lies at a distance about 2 kpc from the Earth and is well-observed from radio to gamma-rays. The optical radiation of the Crab is composed of a nonthermal continuum and emission lines from a net of thin filaments covering the nebula. In radio and X-gamma-rays only continuum emission is observed which is described by a power law spectrum with different spectral indices in various spectral domains. The nebula has a spectacular torus-like shape with jets along the symmetry axis of the torus. Information about spatial distribution of the spectral index of the continuum is important for understanding the PWNe structure and physical processes responsible for their formation by comparison of observations with theoretical models. While there are many observations of the Crab, only a few studies of the spectral index variation was performed. The X-ray index map with a $\sim 2.5''$ – $5''$ shows that the X-ray spectrum is hardest in the central area, close to the pulsar [3],[2]. The spectral index map in the radio with a resolution of $\sim 16''$ was presented by Bietenholz [4]. It shows a general steepening of the radio spectrum with the distance from the pulsar. In the mid-infrared the index map has a similar spatial resolution of $\sim 1''$ as in X-rays [5]. While in the optical the available map has significantly coarser spatial resolution of $\sim 10''$ [1], which does not allow to resolve properly the torus and jets. Here we present a preliminary results on the optical spectral index map constructed based on the archival Hubble Space Telescope (HST) data on Crab Nebula obtained with highest up to data subarcsecond spatial resolution.



2. Observations and data reduction

We used images of the Crab which were obtained with Wide Field and Planetary Camera 2 (WFPC2) on the HST. It images a 150" x 150" "L"-shaped region with a spatial sampling of 0.1" per pixel, and a smaller 34" x 34" square field with 0.046" per pixel¹. The data using the wide and medium band filters F300W, F547M, and F814W were obtained in 1995 August 14 (Program ID: 6129, PI Jeff Hester) with 3200s, 2000s, and 1400s total exposure times, respectively. These filters do not cover most bright emission lines from the Crab, hence, they are useful for continuum emission analysis. However, some emission lines can enter filter passbands. For construction spectral index map it is necessary to use a single set of observations because of high time variability of the Crab PWN features. Observations in 1995 are one of the first detailed broadband observations of the Crab with the HST. Besides that, we retrieved data for the narrow band filter F673N obtained on 1995 January 02 (Program ID: 5354, PI Kris Davidson) with 2300.0 exposure duration to determine Crab filaments emitting in S II line ($\lambda 6731$). Also we use Chandra ACIS-S data (Observation ID: 02001, PI Jeff Hester) obtained on 2001 January 30 to compare the optical data with the X-ray image.

Individual optical exposures obtained from the archive has been pipeline reduced, and we only combined them removing cosmic rays. After that we performed astrometric referencing of the resulting images. For data processing we used the IRAF, including STSDAS and DAOPHOT packages.

3. Construction of the spectral index map

To construct the index map we followed the same procedure as has been used by Temim et al. [5] for the mid-infrared. The continuum emission from the Crab Nebula can be described by a power law spectrum of the form $L_\nu \propto \nu^{-\alpha}$, where L_ν is the synchrotron specific luminosity and α is the spectral index. We compute index maps using the equation

$$\alpha = \frac{\ln(F_1/F_2)}{\ln(\lambda_1/\lambda_2)},$$

where F_1 and F_2 are the surface brightnesses in the images obtained in two different filters, and λ_1 , λ_2 are the pivot wavelengths of filters. All data were background subtracted, calibrated to the physical flux units, and derredded using $R=3.1$ and $A_V=1.61$ [8]. $A(\lambda)$ was obtained using analytic formula by J.A.Cardelli, G.C.Clayton, and J.S.Mathis [7]. The background was taken from the Crab Eastern Bay region. Arithmetical operations with the images following the above expression were performed using *imcalc* utility from the IRAF/STSDAS.

4. Results and discussion

In Fig. 1 we compare the soft X-ray and optical images of the Crab PWN obtained with Chandra ACIS and with the HST in F547M filter, respectively. As seen, the WFPC2 field of view (FOV) does not allow one to image the whole nebula. However, most important feature of the PWN, including the torus and southern jet structures, eastern bay, pulsar itself, anvil, moving wisps [6], are within the FOV. Some of them are marked in this figure.

At the left panel of Fig. 2 the same FOV is presented but in the F814W filter. The PWN morphology in this filter is identical to that in F547M. At the right panel of Fig. 2 we show the spectral index map created from these images. Bright features with a high α extended from east to west and from south to north at the south edge of the FOV are filaments where the emission in lines is dominated. They are not related to the continuum properties (see below). Excluding these features, generally the Crab spectrum in the PWN center, particularly, within the torus and jet regions, is harder and spectral index grows to the edge of the nebula. This is compatible

¹ http://documents.stsci.edu/hst/wfpc2/documents/handbooks/cycle17/wfpc2_cover.html

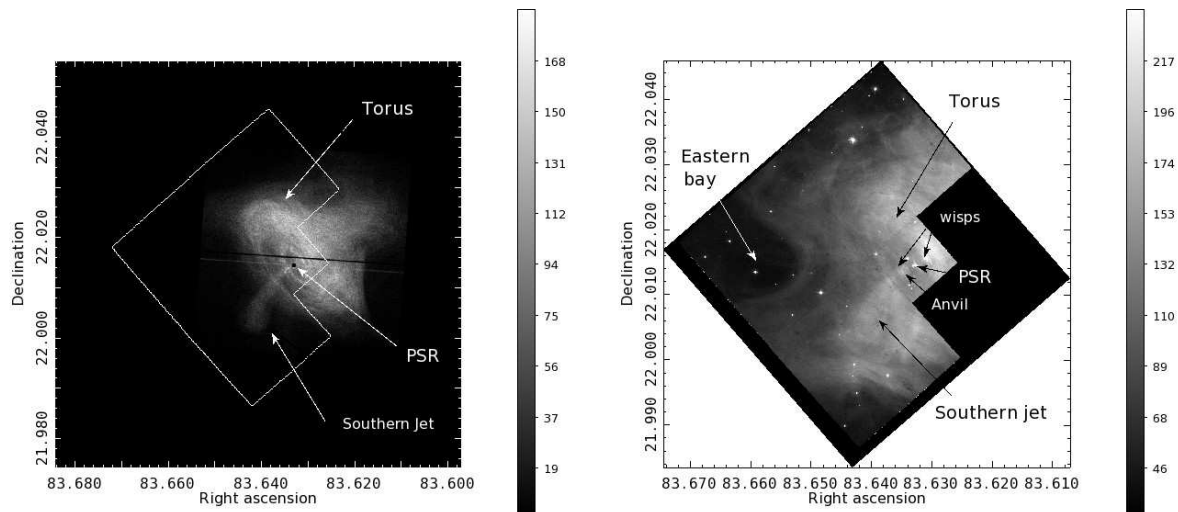


Figure 1. *Left:* The Chandra X-Ray image of the Crab PWN. North is up and east is left. The white region shows the FOV of HST/WFPC2. *Right:* The HST/WFPC2 image of the field in the F547M filter. Main features of the PWN are marked by arrows. Grey bars show the emission intensity scale in counts.

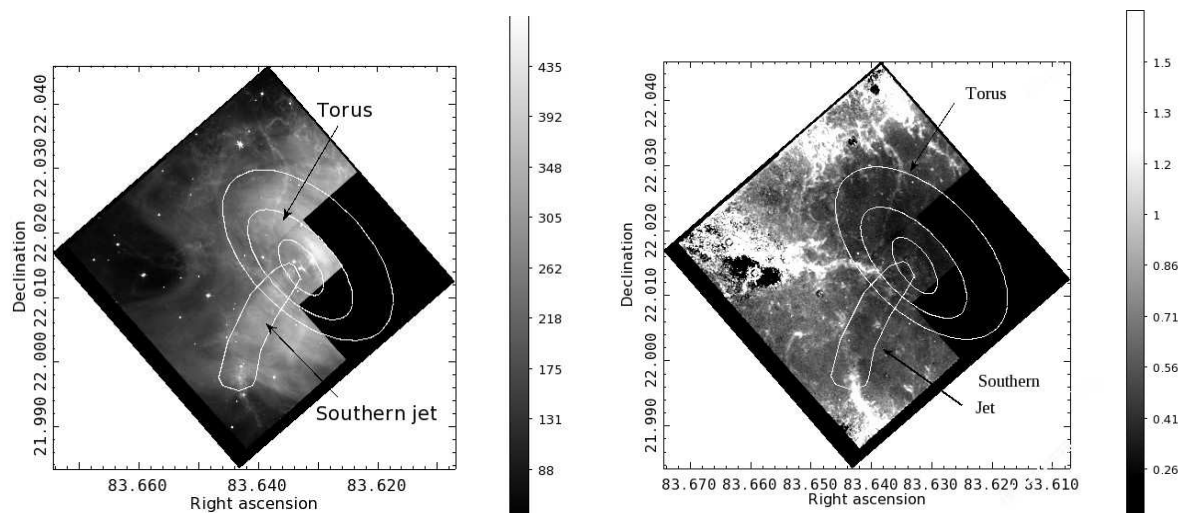


Figure 2. *Left:* The same as at the right part of Fig.1 but in F814W filter. *Right:* Spectral index map constructed using the data of the F547M and F814W filters. The torus, inner ring and jet are indicated for orientation. The grey bar in the *left* panel show the emission intensity scale in counts, while in the *right* panel it shows the scale of the spectral index α .

with the result of Veron-Cetty [1], but on their map the spectrum is systematically softer, i.e., α is in the range of about 0.57–1.0 vs our 0.3–1.0. A possible reason for this discrepancy is that they used a smaller interstellar extinction towards the Crab.

High spatial resolution of the HST allows us to resolve fine structures of the PWN in our index map. In Fig. 3 we show the immediate vicinity of the pulsar. As seen, the most bright extended features in the direct image, such as the anvil, wisp and the nearest part of the torus have much harder spectrum than their surroundings. The wisp and anvil are spatially associated with the internal X-ray PWN ring, which is interpreted as a termination shock of the pulsar wind.

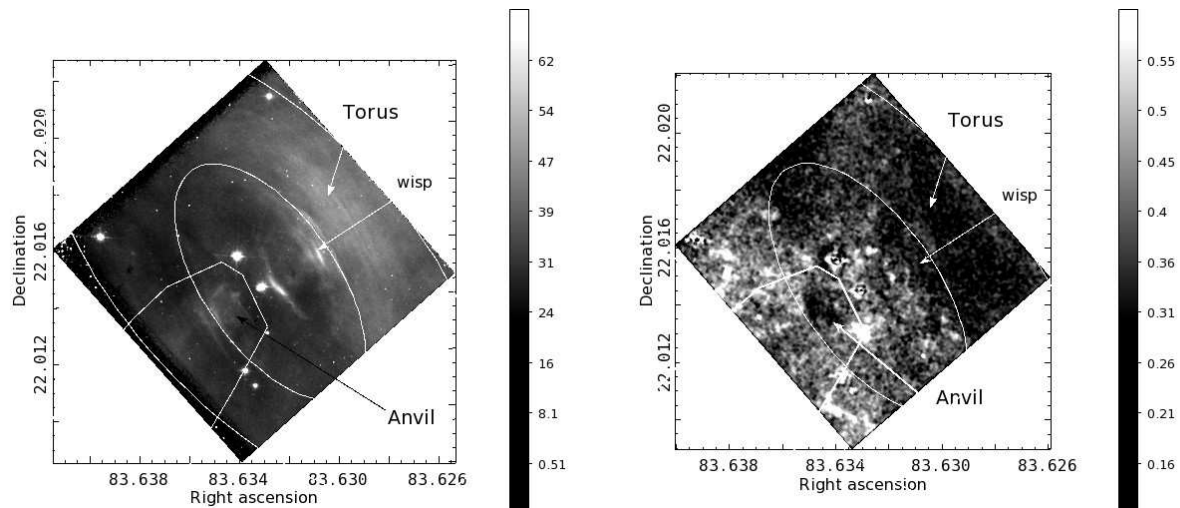


Figure 3. Enlarged image of the central part of the PWN shown in Fig.2. It contains the pulsar, beginning of the jet and the inner ring structures. *Left:* The direct image. *Right:* Spectral index map.

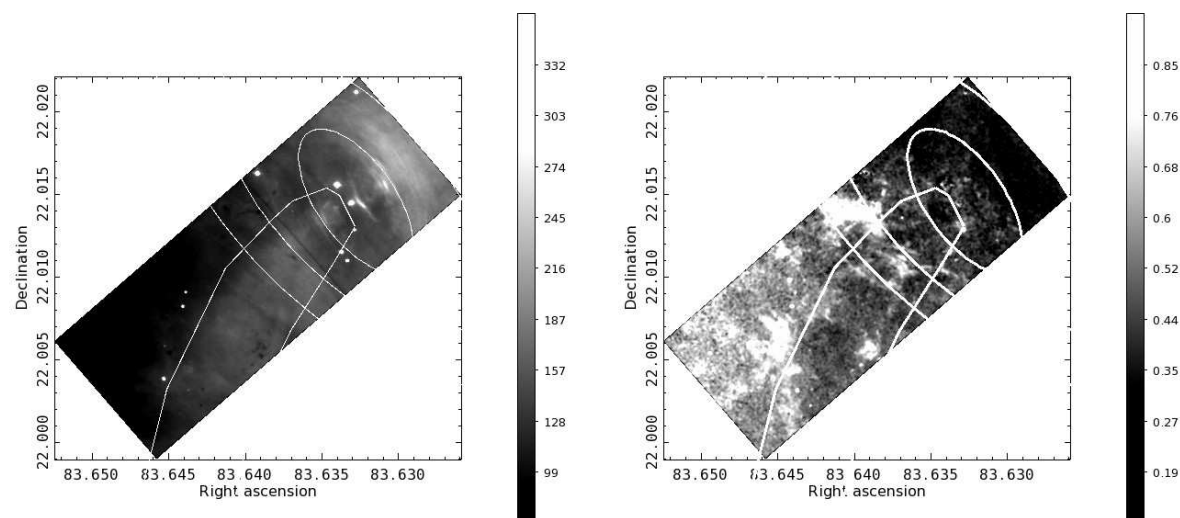


Figure 4. *Left:* HSR/WFPC2 central part of FOV in F547M filter focused on the jet. *Right:* Spectral index map of this part constructed using the data of F547M and F814W filters. Same features as at Fig.2 are marked.

The southern jet region is enlarged in Figs. 4-5. We can see that the spectral index is lower in the jet than in its nearest environments, but the emission of the jet is softer than emission from the torus. The jet itself is nonhomogenous both in the brightness and the index. It might have a spiral structure barely resolved in the X-ray and the direct optical continuum images. Brighter parts of the jet have apparently harder spectra. Comparing the index and F673N image we find that the jet is bounded by a filament which likely spirals with the jet.

We have obtained the index map images using F300W images as well. The structures in that map are almost the same as presented here.

To conclude, the described method of obtaining the optical spectral index maps from HST images appears to be quite productive and allows one to study structures of the Crab PWN in great details that has not been possible since the time of publishing of the first index map by

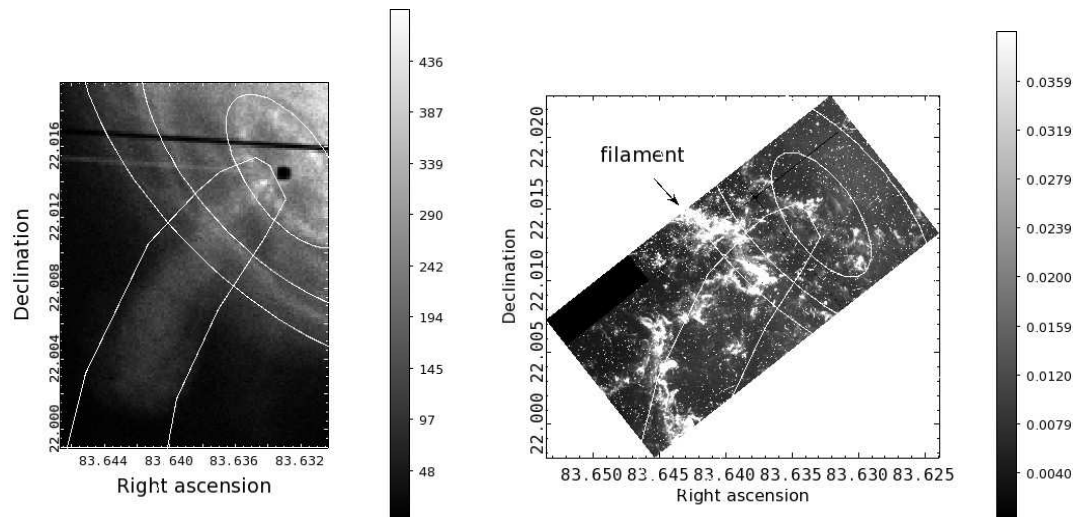


Figure 5. *Left:* Chandra image of the same region as at Fig.4 *Right:* Image in the filter F637N aimed to see Crab filaments emitting in S II line $\lambda 6731$

Veron-Cetty and Woltjer in early 90th. More detail description of our results will be published in a separate paper.

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