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Multiband observations of the Crab Nebula

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Abstract. Results of simultaneous imaging of the Crab Nebula in the radio (JVLA), optical (*HST*), and X-ray (*Chandra*) bands are presented. The images show a variety of small-scale structures, including wisps mainly located to the north-west of the pulsar and knots forming a ring-like structure associated with the termination shock of the pulsar wind. The locations of the structures in different bands do not coincide with each other.

1. Introduction

Produced by the wind of the young and powerful Crab pulsar, the Crab Nebula is one of the best studied sky objects. Several thousand scholarly publications have been devoted to it by now, but still a vast number of phenomena observed in the nebula are not understood well enough (see recent reviews [1, 2]).

One of such phenomena is the recently discovered flaring activity in the 0.1 − 1 GeV band [3–5], which is not accompanied by substantial flux variations in any other observable energy range (e.g., [6]). A number of models have been proposed to explain such flaring activity (e.g., [7–9]), but none of them is widely accepted as complete and fully convincing. According to the model by Bykov et al. [10], the gamma-ray flares are due to synchrotron emission of the electrons accelerated at the pulsar wind termination shock in the intermittent and stochastically enhanced magnetic field of the nebula. To assess the predictions of this model and evaluate its parameters, it is important to study the small-scale structure of the Crab Nebula in the vicinity of the termination shock.

As both the optical and X-ray emissions of the Crab Nebula are highly variable [1], simultaneous multiband observations are required to understand the nature of its bright small-scale features and physical processes that govern their emission. A multiband campaign was carried out in 2001 [11, 12], but the intervals between observations were quite long (upto 4 days), only one *HST* band (F547M) was empolyed making it impossible to measure the spectral slope in the optical, and the VLA-B configuration was used at about twice lower angular resolution than that of the JVLA-A configuration employed in the present work. Thus, only some general conclusions on the spatial structures in the three bands were drawn, but no spectra of individual varying features of the nebula were analysed.

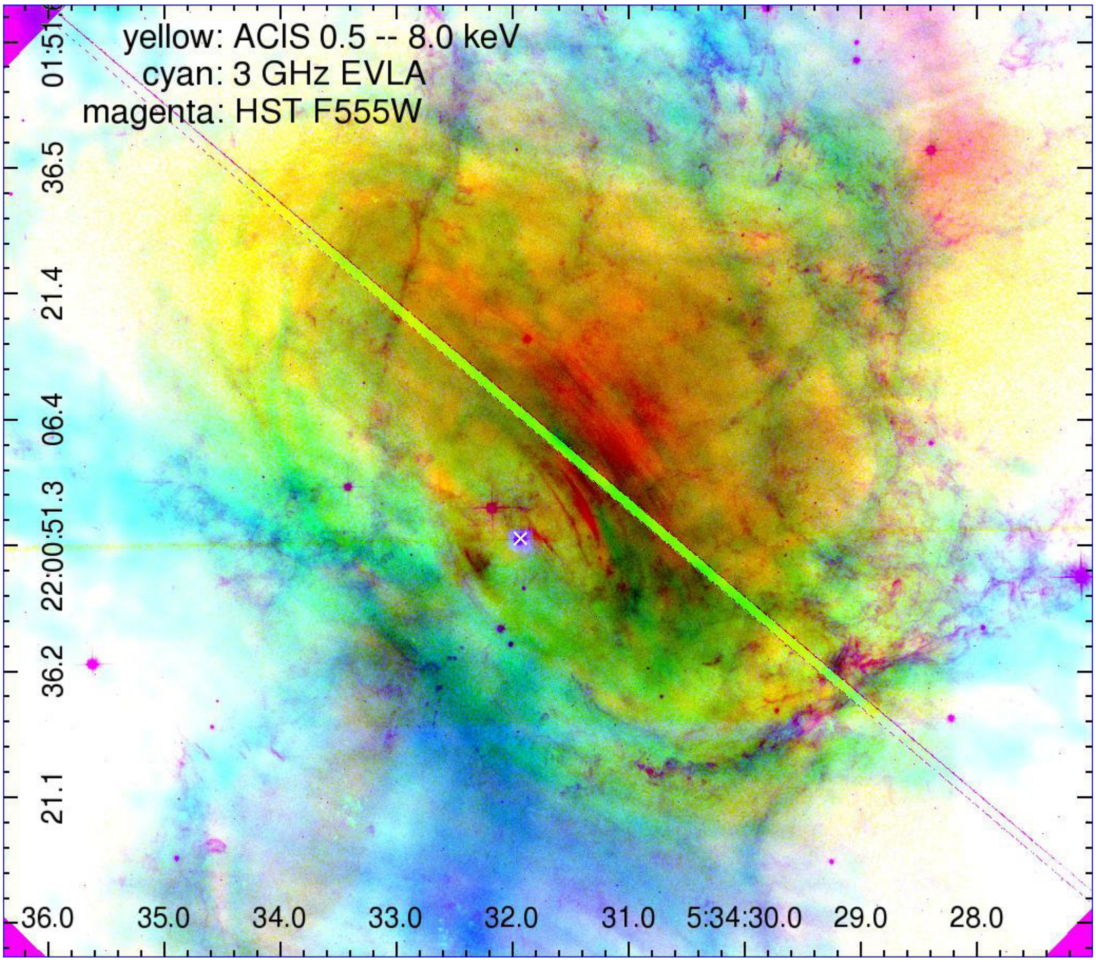

Figure 1. Three-color CMY image of the inner part of the Crab Nebula. The Crab pulsar is marked with the white cross. In the chosen color model red color indicates the presence of both optical and X-ray emission, blue color indicates the presence of both optical and radio emission, and green color indicates the presence of both radio and X-ray emission.

In order to provide a deeper study of such features, a new set of simultaneous multiband observations of the inner Crab Nebula was performed by the authors in November 2012. The first results of these observations are briefly reported below.

2. Observations and data reduction

On Nov 27, 2012 the inner $\sim 2.5' \times 2.5'$ field of the Crab Nebula was simultaneously observed with JVLA-A, *HST* (ACS and WFC3 cameras), and *Chandra* ACIS-S (see Table 1 for main parameters of the observation setup). At the 2 kpc distance to the object [13] the maximal temporal intervals between the observations correspond to spatial scales below 10^{15} cm ($\sim 0.03''$), since the speed of any motions cannot exceed the speed of light.

The *HST* data were processed via the standard pipeline of AstroDrizzle v. 1.1.8 [14] to arrive at combined images in each of the three bands. Using the pulsar and 4 other prominent point-like objects in the field as reference points, we aligned the resulting mosaics to the F555W band image to better than $0''.1$. The ACIS data reduction was made with the CIAO 4.5 software [15], using appropriate detector calibration data (CALDB 4.5.5.1). An additional $0''.3$ shift, based

Table 1. Main parameters of the observational setup.

Instrument	*HST* ACS F140LP	*HST* WFC3 F555W	*HST* WFC3 F160W
Band	140 – 170 nm	450 – 650 nm	1.4 – 1.7 μm
Program id	13043	13043	13043
Start time, MJD	56257.673416	56257.738460	56257.751070
End time, MJD	56257.706155	56257.748980	56257.771880
Exposure, s	2592	774	1612
PSF FWHM, arcsec	0.06	0.07	0.15

instrument	*Chandra* ACIS-S	JVLA-A band S
band	0.3 – 10 keV	2.5 – 3.5 GHz
program id	14458	12B-380
start time, MJD	56257.873616	56257.132951
end time, MJD	56258.018533	56257.296331
exposure, s	10000	11967
PSF FWHM, arcsec	0.49	0.9

on the pulsar position, was applied to align the X-ray image to the *HST* F555W image at the $0\overset{''}{.}1$–$0\overset{''}{.}2$ level. Reduction of the JVLA data was performed with the NRAO CASA package [16]. The alignment of the subsampled JVLA image with the *HST* F555W image is better than $0\overset{''}{.}2$.

A 3-color multiband image of the inner part of the Crab Nebula is shown in figure 1. The reddish color of the region to the north-west of the pulsar, where wisps are evolving, shows that it is bright both in the optical and X-ray bands, while the periphery of the nebula is dominated by radio emission and patchy structures emitting in the optical.

A closer look into the central part of the nebula reveals the presence of small-scale emitting features (figure 2). Some of them (often dubbed "knots") form a $\sim 10''$ diameter ring around the pulsar, which is usually associated with the termination shock of the pulsar wind. Wisp-shaped structures are mainly located to the north-west of the pulsar. The density of the wisps seems to increase with the distance from the pulsar, which may indicate that they are moving outward with a certain deceleration (cf. [17]).

It should be noted that only about half of the structures seen in the optical and near-infrared bands have clear counterparts in the X-ray image. In most cases we do not see prominent structures in the radio images at (or near) the knots and wisps seen in the optical and/or X-rays. This might be partly due to the fact that the radio emitting volume of the nebula is much larger that the optical and X-ray emitting volumes. As a result, the radio intensity, proportional to the integral of emissivity along the line of sight, could be dominated by outer layers of the nebula instead of the relatively small structures responsible for the optical and X-ray emission, so that a narrow synchrotron feature in the radio band would have much less contrast than in the optical and X-rays. Thus, the radio fluxes measured at the positions of optical knots and wisps can be treated as conservative upper limits.

3. Conclusions

Based on the obtained simultaneous multiband images of the Crab Nebula we arrived at the following conclusions.

- The small-scale features of the inner Crab Nebula are morphologically similar in the optical and X-ray bands, but their locations do not coincide with each other. We do not see radio counterparts of these features.

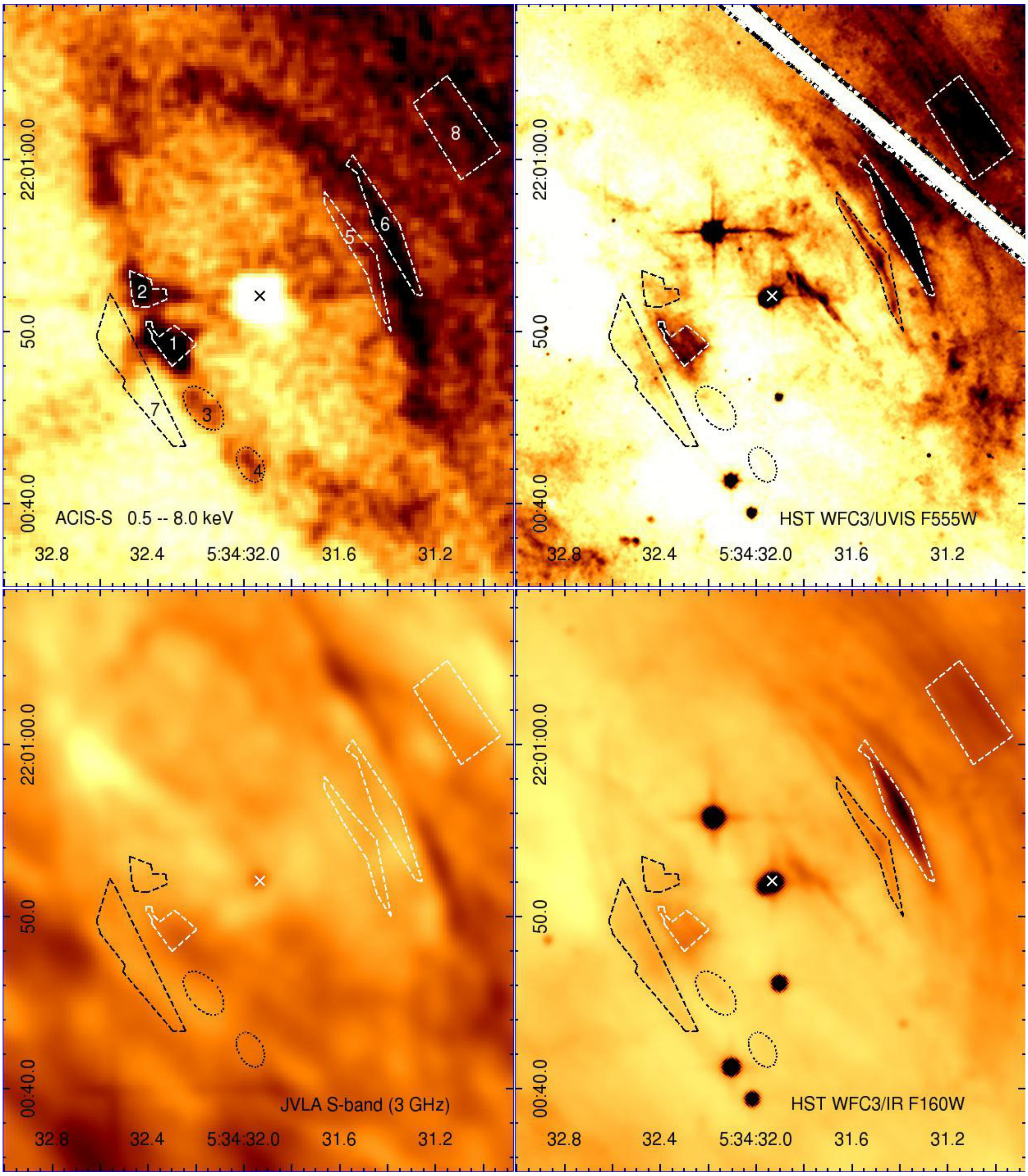

Figure 2. *Chandra* ACIS, *HST* F555W, *HST* F160W, and JVLA-A images of the inner part of the nebula showing prominent emission structures, chosen for further morphological and spectral studies.

- The observed multiwavelength spatial structure can be understood in the framework of the models of nonlinear evolution of magnetic field perturbations in the shocked relativistic wind (e.g., [18]) which predict the presence of localized enhancements of magnetic field with a rich fine structure.
- To assess the variability of the multiwavelength structure and understand the nature of the detected features, additional deep simultaneous high-resolution multiband observations are required.
- Detailed models of the shocked pulsar wind and Crab Nebula structure are required to reproduce and explain the observed multiwavelength data.

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