Simultaneous Multiband Observations of the Inner Crab Nebula

Why is the Crab Nebula an important object?

– it is the bright ($L_X \sim L_{\text{opt}} \sim 10^{37} \text{ erg/s}$) and extended
  ($\sim 2' \times 2.5'$ in the X-rays, $\sim 4' \times 5'$ in the optical, $\sim 5' \times 7'$ in the radio)
  nebula powered by the Crab Pulsar ($L_{\text{spindown}} \sim 5 \times 10^{38} \text{ erg/s}$)

– it is the first object recognized as a remnant of a historical supernova
  (E. Hubble, 1928)

– it contains one of the first discovered pulsars
  (D. Staelin & E. Reifenstein, 1968)

– it is observable from radio- to the TeV gamma-ray band
  (e.g., Atoyan and Aharonian 1996, Hester 2008, Buehler and Blandford 2014)

– > 2500 publications are indexed by the ADS with «Crab» in their titles

– it serves as a standard candle
  for the hard X-ray and gamma-ray astrophysics

BUT: gamma-ray flares in the GeV range were discovered in 2009-2010, their origin is still unclear
The flares were also detected with AGILE (Tavani et al., Science, v. 331)

**Fig. 1.** Spectral energy distribution of the Crab Nebula. Black open circles indicate the average spectrum measured by the LAT in the first 25 months of observations. Red squares indicate the energy spectrum during the flare of February 2009 (MJD 54857.73 to 54873.73), and blue open squares indicate the spectrum in September 2010 (MJD 55457.73 to 55461.73). Gray squares indicate historical long-term average spectral data from the COMPTEL telescope, with 15% systematic errors (41). Arrows indicate 95% confidence flux limits.

Fermi/LAT spectra of gamma-ray flares from the Crab [Abdo et al., Science, v. 331 (2011)]
Since 2009 at least 6 GeV flares have been observed (about 1/year)

Figure 9. Spectral energy distribution at the maximum flux level for five of the six Crab nebula flares detected as of September 2013 (Abdo et al. 2011, Buehler et al. 2012, Striani et al. 2013, Mayer et al. 2013). No spectrum has been published for the low intensity flare of July 2012 (Ojha et al. 2012). The blue points show the average nebula flux values referenced in Fig. 2.
A model of gamma-ray flares in the Crab [Bykov, Pavlov, Artemiev, Uvarov, MNRAS, v. 421 (2012)]: the observed flaring sub-GeV emission comes from the wisp-bearing part of the PWN

\[ \Delta_0 = 2 \times 10^{16} \text{ cm for } E \sim 1 \text{ GeV}, \tau \sim 10^{5} \text{ s} \sim \text{days} \]

**Figure 2.** Normalized spectra of synchrotron radiation at two different time-moments, \( ct/\Delta_0 = 0.2 \) (solid line) and 0.6 (dashed line), which model the quiescent and flare spectra, respectively (see Fig. 1). The dotted curve shows the contribution of the variable magnetic field. The power emitted in the GeV flare is about \( 2 \times 10^{36} \text{ erg s}^{-1} \), for the Crab Nebula parameters.
Observations with Chandra ACIS
Observations with the Hubble Space Telescope (WFC3 and ACS)

- **near-IR**: HST WFC3/IR F160W
- **optical**: HST WFC3/UVIS F555W
- **far-UV**: HST ACS/SBC F140LP
Observations with the Jansky Very Large Array

JVLA S-band (3 GHz)
Red – X-rays (Chandra)
Blue – near-IR (HST)

Another «relic» jet in the near-IR?
yellow: ACIS 0.5 -- 8.0 keV
cyan: 3 GHz EVLA
magenta: HST F555W

Red = Opt + X
Blue = Opt + radio
Green = X + radio
Small-scale features chosen for detailed analysis

1, 2 – anvil, 3 – knot, 4 – knot1, 5 – knot2, 6 – wisp1, 7 – wisp2, 8 – wisp1s, 9 – wisp3
Wisp2 position in 3 bands

evolution of the stochastic magnetic field rather than particle distributions?

Modeling of magnetic field evolution in the PWN:
Korteweg — de Vries soliton-like solutions
Spectral indices

<table>
<thead>
<tr>
<th></th>
<th>$\Gamma_{\text{opt}}$ (dereddened)</th>
<th>$\Gamma_X$ (unpiled)</th>
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<tbody>
<tr>
<td>anvil</td>
<td>1.23 +/- 0.18</td>
<td>1.46$^{+0.22}_{-0.07}$</td>
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<tr>
<td>knot</td>
<td>1.18 +/- 0.29</td>
<td>1.61$^{+0.14}_{-0.20}$</td>
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<td>knot1</td>
<td>1.25 +/- 0.38</td>
<td>1.62$^{+0.13}_{-0.08}$</td>
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<td>knot2</td>
<td>1.26 +/- 0.50</td>
<td>1.68$^{+0.08}_{-0.26}$</td>
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<tr>
<td>wisp1</td>
<td>1.24 +/- 0.23</td>
<td>1.61$^{+0.17}_{-0.07}$</td>
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<td>wisp2</td>
<td>1.25 +/- 0.16</td>
<td>1.74$^{+0.14}_{-0.13}$</td>
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<tr>
<td>wisp3</td>
<td>1.25 +/- 0.17</td>
<td>1.56$^{+0.09}_{-0.05}$</td>
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<tr>
<td>wisp1s</td>
<td>1.33 +/- 0.31</td>
<td>1.70$^{+0.13}_{-0.05}$</td>
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$\Gamma_X \sim \Gamma_{\text{opt}} + (0.3-0.4)$

a spectral break?
Summary

* The small-scale features of the inner Crab Nebula are morphologically similar in the optical and X-ray bands, but in general the structure does not coincide.

* The NIR – FUV parts of individual features' spectra appear systematically harder than the X-ray ones.

* **No certain interpretation** of the observed spatial structure and spectral behavior is suggested, it might be due to:
  a) specific mechanisms of particle acceleration,
  b) energy-dependent diffusion in the nebula or
  c) nonlinear evolution of magnetic field perturbations.

* Additional simultaneous high-resolution multiband observations are required to study spectral shapes (and variability) of individual emitting regions in the Crab Nebula and to conclude on their nature.

* The existence of simultaneous multiband data implies that any model of the Crab PWN structure and emission has to reproduce and explain them.
Thank you for your attention!
Why do we need **simultaneous** observations of the Crab?

- the structure of the Crab Nebula has shown **variability on days to weeks scale**
- PWNe are dynamical structures by their nature

the Crab Nebula is ~ 2 kpc away (V. Trimble, 1968)

\[ 1'' \sim 3.3 \times 10^{16} \text{ cm} \]

may change on 0.1'' scales in \( \sim 10^5 \) s \( \sim 1 \) day

**Simultaneous observations in 2001 and in 2012**

A set of simultaneous observations (\( \Delta t \sim 1 \) day \( \Rightarrow \sim 2.5 \times 10^{15} \) cm scale) with Chandra, HST, and VLA was performed in 2001 (*J.J. Hester, M. Bietenholz* et al., published in 2002, 2004):

- only 1 HST band (F547M)
- 5 GHz VLA-B band – 1.4'' resolution
- only morphological studies, no spectra were produced
- conclusions:  a) some structures are matched, some are not
  b) the structures evolve on 1-2 weeks scale

We have performed a **new set of observations** (\( \Delta t < 13 \) hrs \( \Rightarrow \Delta x < 1.4 \times 10^{15} \) cm scale) with Chandra, HST, and JVLA on 2012 Nov 26:

- 3 HST bands (F140LP, F555W, F160W)
- 3 GHz EVLA-A band – 0.9'' resolution
- spectral studies of individual features
Data reduction and spectral analysis issues

- HST data reduction: AstroDrizzle 1.1.8
- Chandra data reduction: CIAO 4.5 + XSpec 12
- JVLA data reduction: NRAO CASA 4.2
- $N_H \approx 0.3 \times 10^{22} \text{ cm}^{-2} \pm 8\%$ across the PWN agrees with Mori et al. (2004)
- $A_V \approx 1.61$
  extinction curve measurements of Sollerman et al. (2000) agrees with the $N_H \rightarrow A_V$ relation (e.g., Tian et al. 2013)
- $A_V \rightarrow A_\lambda$ transformation according to Cardelli et al. (1989)
- Pileup effects in Chandra ACIS were accounted for with the model of Davis (2001)
<table>
<thead>
<tr>
<th>instrument</th>
<th>HST ACS F140LP</th>
<th>HST WFC3 F555W</th>
<th>HST WFC3 F160W</th>
<th>Chandra ACIS-S</th>
<th>JVLA-A band S</th>
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<tr>
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<td>140 – 170 nm</td>
<td>450 – 650 nm</td>
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<td>0.3 – 10 keV</td>
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