A 3D Kinematic Reconstruction of the Crab Nebula That Includes the Northern Chimney

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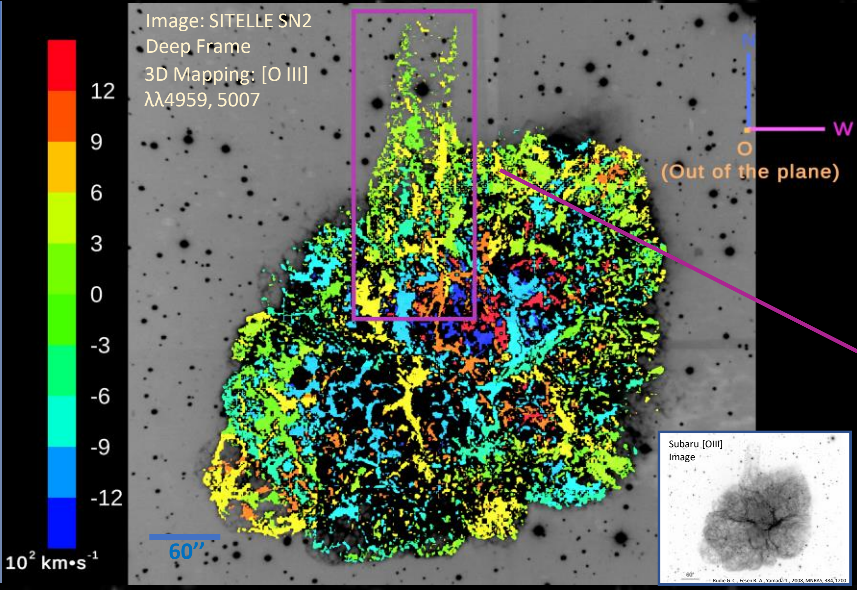
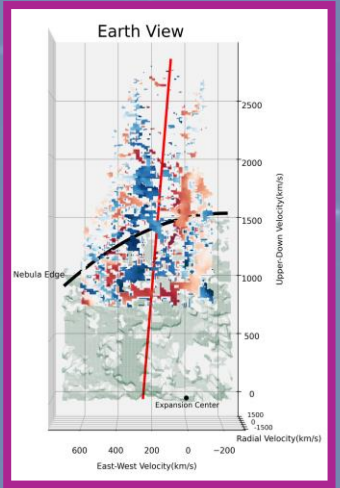
Introduction

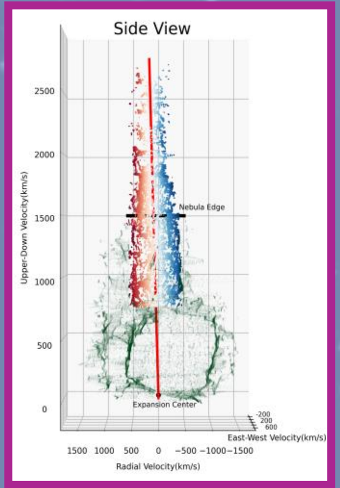
We present a new, high-resolution three-dimensional (3D) kinematic reconstruction of the entire Crab Nebula in optical [O III] 4959, 5007 line emission. Data were obtained with the imaging Fourier transform spectrometer SITELLE on the Canada–France–Hawaii telescope in SN2 (R= 1000), SN3 (R=10000), and C2 (R=1500) filters sensitive to many emission lines including Hβ, [O III] 4959, 5007, He I 5876, and Hα. The morphology of the ejecta revealed by our reconstruction shows numerous differences when compared to a previous 3D reconstruction published by Martin et al. (2021) [1] using the SN3 filter (sensitive to emission lines [N II] 6548, 6583, H α, [S II] 6717, 6731), including multiple locations where [O III]-emitting material extends conspicuously beyond the bulk of the ejecta. Most prominent of these extensions is the well-known northern "chimney" or "jet," which is a 45 arcsec wide funnel-like structure that stretches 100 arcsec off the nebula's northern limb [2]. We discuss how these [O III]-emitting features often correlate with the synchrotron nebula powered by the pulsar, and test various possible formation mechanisms. Our kinematic reconstruction connects the shell of ejecta filaments with the northern jet in 3D for the first time, and provides new opportunities to finally resolve its long-debated origin.



Northern Chimney

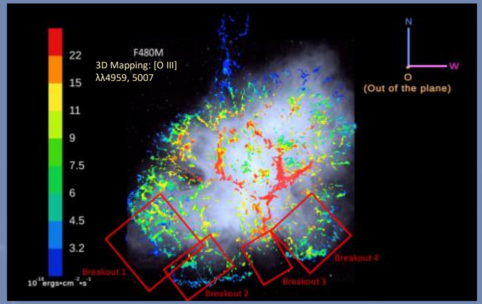
Our new 3D reconstruction shows that the funnel-like structure of the chimney extends inward beyond the nebula's outer edge, continuing into its interior. The alignment of the chimney traces back to the expansion center, slightly offset to the east.

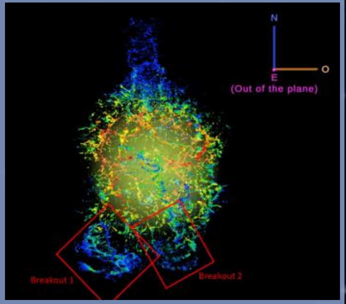




Breakout Regions

In addition to the already well-studied northern chimney, we identify four regions that extend beyond the bulk of the nebula body. We conclude that the "breakout" regions have a different origin than that of the northern chimney. Comparison with JWST observations [3] leads us to conclude the breakout regions are where ejecta have been pushed outward by the strong pulsar wind.

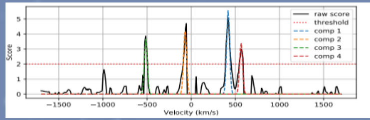




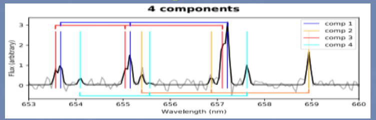
Data Reduction

For each pixel along the line of sight, we extract the spectra and obtain the velocity information of the ejecta following these steps:

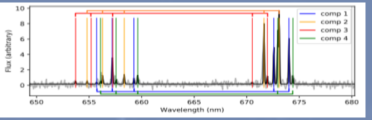
1. Evaluation of the probability of having one component at a given velocity.



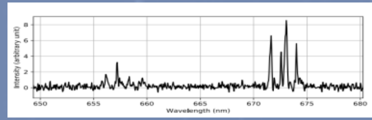
2. Enumeration of all the individual velocity components.



3. Fit spectrum with a model combining all the velocity components.



4. Compare with the original spectrum and confirm.



A total of 1,742,738 data points have been extracted from the spectra to make our 3D reconstruction map across all emission lines..

Testing the Origin

Theory	Presence of the Hole	Lack of Southern Counter-Jet	Different from Other Breakouts	Early Formation Time	Cylindrical Shape
(1) Mass-loss Trail	✓	✓	✓	✓	✓
(2) Filaments in Expanding Magnetic Field	✗	✓	✗	✓	✓
(3) PWN Instability Breakout	✗	✓	✗	✗	✗
(4) Expansion into a Low Density ISM Region	✗	✓	✓	✗	✗
(5) Highest-Velocity Ejecta of N-S Bipolar Expansion	✗	✗	✓	✓	✗
(6) Interaction with a Local Interstellar Cloud	✗	✓	✓	✗	✓
(7) A Relativistic Pulsar Beam	✓	✗	✗	✗	✓

Table 3: Summary for checking all the possible theories for the origin of the jet. Reference: (1) Blandford et al. (1983); Cox et al. (1991), (2) Bychkov (1975); Marcelin et al. (1990), (3) Chevalier & Gull (1975); Sankrit & Hester (1997); Smith (2013), (4) Kundt (1983); Veron-Cetty et al. (1985), (5) Fesen & Staker (1993); Fesen et al. (1997); Rudie et al. (2008); Black & Fesen (2015), (6) Morrison & Roberts (1985), (7) Shull et al. (1984); Benford (1984); Michel (1985); Bietenholz & Kronberg (1990).

Our results provide new ways to test previous interpretations of the northern chimney. We find the most likely scenario to be one where the supernova explosion expanded into an under-density of surrounding material. This cavity of density may have been sculpted by a mass loss trail left behind by the progenitor star's movement through the ISM.

Reference: [1] Martin, T., Milisavljevic, D., and Drissen, L. "3D Mapping of the Crab Nebula with SITELLE. I. Deconvolution and Kinematic Reconstruction." Monthly Notices of the Royal Astronomical Society, vol. 000, 2019, pp. 1–15. Preprint, 11 Jan. 2021. [2] Black, C., and Fesen, R. "A 3D Kinematic Study of the Northern Ejecta 'Jet' of the Crab Nebula." Monthly Notices of the Royal Astronomical Society, vol. 447, no. 3, 2015, pp. 2540–2550. [3] Temim, T., et al. "Dissecting the Crab Nebula with JWST: Pulsar Wind, Dusty Filaments, and Ni/Fe Abundance Constraints on the Explosion Mechanism." The Astrophysical Journal Letters, vol. 968, 20 June 2024, p. L18.

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