

Molecular Bipolar Outflow in SN 1987A Supports the Jittering-Jets Explosion Mechanism

Noam Soker^{ID}

Department of Physics, Technion, Haifa, Israel

Email: soker@physics.technion.ac.il

How to cite this paper: Soker, N. (2026) Molecular Bipolar Outflow in SN 1987A Supports the Jittering-Jets Explosion Mechanism. *International Journal of Astronomy and Astrophysics*, 16, 309-324.
<https://doi.org/10.4236/ijaa.2026.164018>

Received: August 14, 2026

Accepted: October 11, 2026

Published: October 14, 2026

Copyright © 2026 by author(s) and Scientific Research Publishing Inc. This work is licensed under the Creative Commons Attribution International License (CC BY 4.0).
<http://creativecommons.org/licenses/by/4.0/>



Open Access

Abstract

I examine high-quality CO and SiO molecular maps of the core-collapse supernova (CCSN) remnant SN 1987A from the literature and find that the molecular gas exhibits a bipolar structure, correlated with the visible bipolar morphology (termed the keyhole) and the bipolar morphology of the iron emission map. I apply a method commonly used in the study of jet-shaped planetary nebulae. The keyhole has a morphology similar to that of many jet-shaped pairs of bubbles in cooling-flow clusters of galaxies and planetary nebulae. Therefore, the findings of this study, which make the bipolar structure of SN 1987A robust, strengthen the claim that a pair of energetic jets shaped the keyhole and its surroundings. According to the jittering-jets explosion mechanism (JJEM), this pair of jets was the most energetic of several pairs that exploded SN 1987A. This study adds to the accumulating evidence that the JJEM is the primary explosion mechanism for CCSNe, responsible for the majority, if not all, CCSNe.

Keywords

Stars: Massive, Supernovae: General, (Stars:) Supernovae: Individual (1987A), Stars: Jets ISM: Supernova Remnants, Planetary Nebulae

1. Introduction

The iconic core-collapse supernova (CCSN), now a CCSN remnant (CCSNR), SN 1987A, is one of the “battlegrounds” between the two competing theoretical explosion mechanisms that aim to explain CCSNe: the jittering-jet explosion mechanism (JJEM; [1] [2] for recent reviews and [3]-[8] for recent papers) and the neutrino-driven mechanism (the delayed neutrino mechanism; e.g., [9] [10] for re-

cent reviews and [11]-[16] for some recent papers). Observables during the explosion, such as neutrino emission and the explosion energy of SN 1987A, cannot distinguish between the two theoretical explosion mechanisms (e.g., [2]). Therefore, studies of the two explosion mechanisms compare the structure of SN 1987A ejecta with their predictions.

Some studies have argued that the neutrino-driven mechanism can explain the basic structural properties of SN 1987A (e.g., [17]-[20]). Some find that the neutrino-driven mechanism can explain some, but not all, properties of SN 1987A, e.g., [21], with references to [22] and [23]. In [24], I compared a three-dimensional (3D) iron structure of SN 1987A from [25] with 3D simulations of the neutrino-driven mechanism from [23], and found that they disagree; I argued for the JJEM. Later papers within the JJEM framework that studied SN 1987A found that the JJEM can explain its large-scale morphology [26]-[28]. Most recently, in [29], I referred to new observations of SN 1987A (e.g., [30] [31]) and strengthened the claim for a bipolar structure in relation to the dust distribution. Some more recent simulations also highlight the need for a bipolar explosion in SN 1987A (e.g., [32]-[34]).

In a recent study, [35] compared the 3D structure of SN 1987A with 3D simulations within the framework of the neutrino-driven mechanism and argued for some similarities, although their simulations could not account for all of SN 1987A's morphological properties. I find the agreement between the simulations and the 3D structure of SN 1987A poor. To compare the SiO and CO ALMA observations with the simulations, they generated intensity maps using a minimum intensity threshold set to twice the noise threshold. In Section 2, I use their new observational images of the outer regions, as well as earlier ones, to identify outflow components in SN 1987A. In Section 3, I show that these outflow components fit the bipolar structure of SN 1987A, the “keyhole”. In Section 4, I argue that this structure is compatible with the JJEM.

2. Outflow Components

In what follows, I apply a method commonly used in the study of planetary nebulae, and which brought a deep and thorough understanding of the shaping of planetary nebulae by jets (e.g., [36]-[59]). It begins with careful qualitative morphological identification and classification (e.g., [60]-[63]), which nonetheless establishes robust identification of jet-shaped structures (e.g., [41]). (For a recent quantitative analysis, see [64].) The qualitative and partially quantitative comparisons of simulations motivated by classification with observations (e.g., [51] [65] [66]) have established, over the years, that jets are a major factor in shaping and powering outflows in planetary nebulae. Outflows from massive stars, which can become very complicated processes (e.g., [67]-[74]), can also be shaped by jets (e.g., [75] [76]). The systematic comparison of 3D hydrodynamical simulations of CCSN jets in the framework of the JJEM is new (e.g., [77]-[81]). Therefore, any study, even if qualitative and short, that identifies jet-shaped structures in CCSNRs is of great value to the question of the explosion mechanism of CCSNe.

2.1. Iron Components

In this section, I identify outflow components that I relate to the bipolar structure of SN 1987A in Section 3. Towards that goal, I start with a set of Doppler maps from [82] that I present in **Figure 1**. I identify four bright, distinguishable outflow components and point to the tip of each. Two are bright regions, FeNB and FeS0, while two are much fainter, FeNR and FeSR; “Fe” indicates that the components are identified in the [Fe I] 1.443 μm line, “N” and “S” mark north and south, respectively, and the last letter indicates whether the component is blueshifted, redshifted, or has about zero Doppler shift.

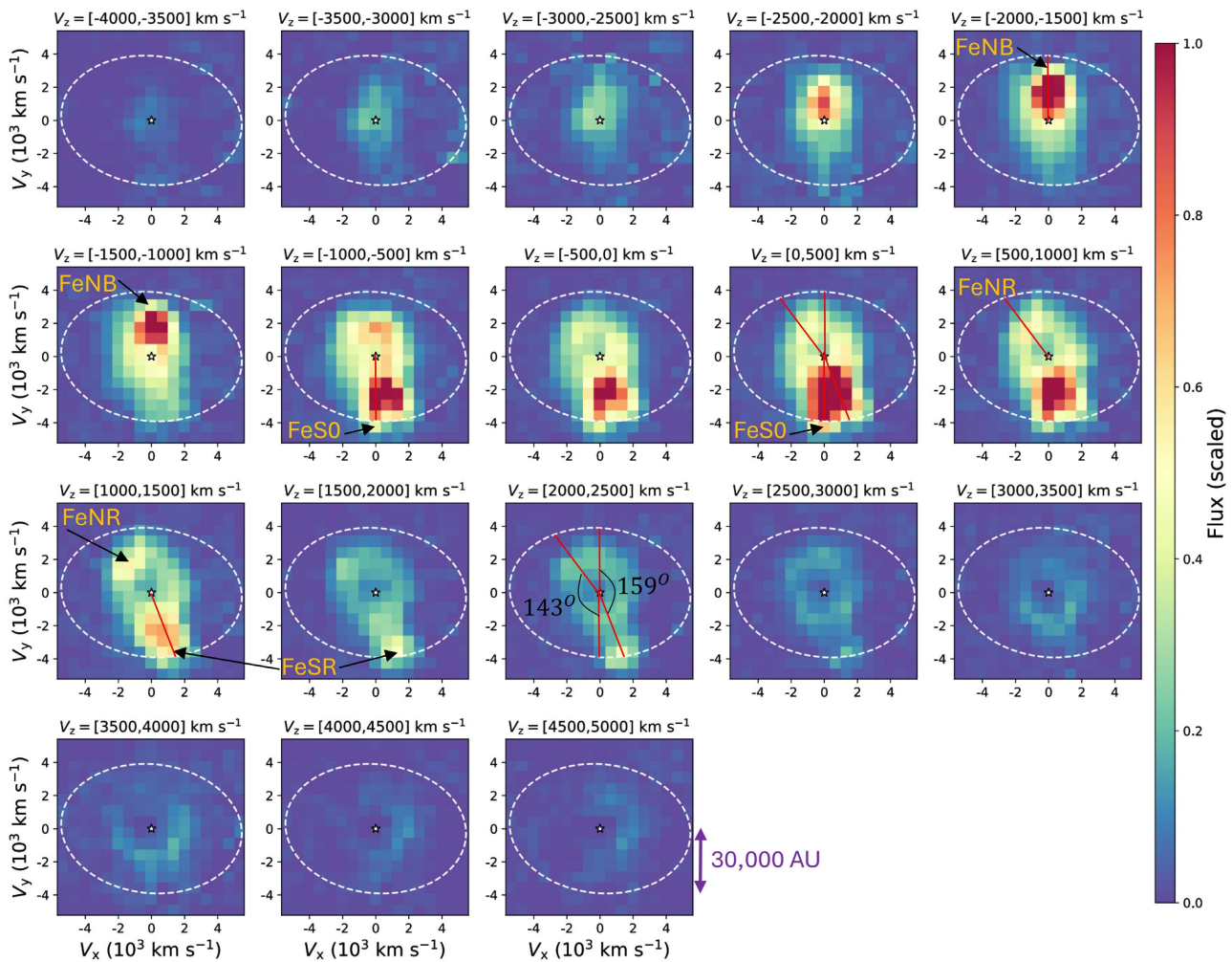


Figure 1. A figure adapted from [82], presenting images of the [Fe I] 1.443 μm emission line in Doppler velocity windows, as indicated. The dashed white line shows the position of the equatorial ring that the star lost $\approx 20,000$ yr before the explosion. I added the red lines and the names of the outflow components: “Fe” indicates that the components are identified in the [Fe I] 1.443 μm line, “N” and “S” mark north and south, respectively, and the last letter indicates whether the component is blueshifted, redshifted, or has about zero Doppler shift. The observation was at an age of 12,927 days after the explosion; one pixel in the image $0.1'' = 0.024$ pc, corresponds to 664 km s^{-1} in the freely expanding ejecta, for the distance to the LMC of 49.6 kpc that [82] assumed.

I identified the outflow components by visually inspecting the images. The center, common to all images, is from the original paper and is well defined. I then

identified each of the four components by these criteria: i) A pixel much brighter than its immediate surroundings (in half of the image) in at least one image. ii) It appears as a bright pixel (even if not the brightest) in at least two other images. iii) There are at least two other bright pixels adjacent to this pixel, in at least one image. These criteria robustly define the four components. The uncertainty in the direction is $\pm\Delta/2$, where Δ is the width of the pixel, at a distance of about 5Δ , implying an uncertainty of about $\pm 6^\circ$ on the plane of the sky.

Component FeNB is a highly blueshifted component prominent in the $[-2000, -1000]$ km·s⁻¹ range. The red line indicates that this component points north (up) in these images. Its Doppler counterpart, FeSR, is the redshifted component and is prominent in the Doppler range $[1000, 2000]$ km·s⁻¹. FeS0 is the second bright region in the Doppler images, and it is prominent in the range of $[-1000, 1000]$ km·s⁻¹. The line that indicates this component points straight south (down). The component FeNR is prominent in the Doppler shift range of $[500, 1500]$ km·s⁻¹. On one panel in **Figure 1**, I mark the angles between the lines.

2.2. Molecular Maps

[35] construct 3D distributions of CO ($J = 2 - 1$) and SiO ($J = 5 - 4$) molecules from ALMA observations of SN 1987A. In **Figure 2**, I present their CO (upper panels) and SiO (lower panels) intensity maps on the plane of the sky (left panels) and with respect to an observer on the right (right panels), *i.e.*, in a plane along the line of sight. On the left panels, I overlaid the four-line structure that I built in **Figure 1**, *i.e.*, the lines in the direction of the four outflow components that I identified from the [Fe I] 1.443 μm emission Doppler maps of [82]. The relative scale of the four lines is 0.67 times that in **Figure 1** so that they can fit into the images and serve for scaling. I added the orange arrow in the left panels, which bisects the angle between outflow components FeNR and FeNB.

Figure 2 clearly shows that the molecular gas distribution has a large-scale bipolar structure that is correlated with the Fe outflow components. The bisector between outflow components FeNR and FeNB is along an elongated structure in CO and SiO towards the north-north-east. On the plane of the sky, but not in a plane along the line of sight, it is almost opposite to the component FeSR direction, along which there are clumps of SiO; the angle between the two is 177° . In the SiO map along the line of sight (lower-right panel of **Figure 2**), the SiO southern clumps are projected on the FeS0 component. In Section 3, I suggest that the southern Fe outflow components and the far south molecular gas are concentrated around the nozzle, a faint radially extended zone in the keyhole (the optical bipolar bright structure) that I attributed to the action of one of the exploding jets [84]. The CO distribution correlated with the general direction of the FeS0 and FeSR components. The right panels of **Figure 2**, in the plane along the line of sight, also reveal the bipolar structure of the molecular gas. I drew two pink arrows in the SiO map to emphasize this bipolar structure; the CO map also shows it. The two pink lines are 170° apart.

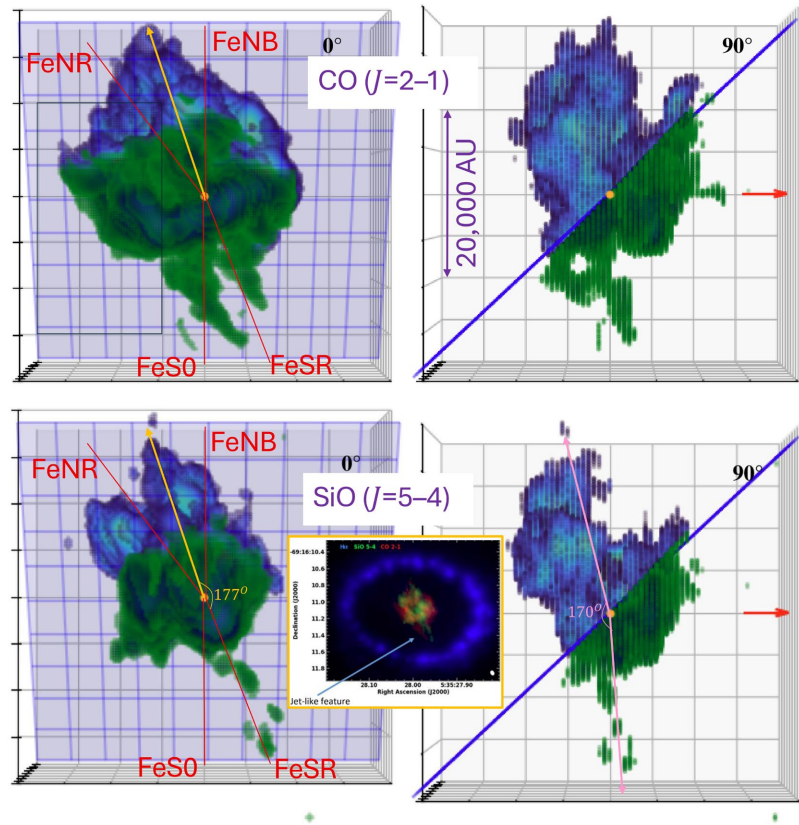


Figure 2. The four large panels are adapted from [35]. The two upper panels show 3D intensity maps of CO ($J = 2 - 1$) emission, and the two lower panels show 3D intensity maps of SiO ($J = 5 - 4$) emission. The left panel shows the plane of the sky; in the right panel, Earth is to the right (red arrows point toward Earth). The equatorial ring plane is indicated in blue. Blue regions are above the equatorial ring plane, and green material is below it. The orange point marks the explosion's position. Each side of a panel is 40,000 AU. I copied the four-line structures from Figure 1, but the lengths of the lines here are 0.67 times those in Figure 1 so they fit in the images. I also added the orange arrow in the left panels, which bisects the angle between outflow components FeNR and FeNB, and the two pink arrows in the lower-right panel to emphasize the bipolar structure of the molecular distribution. The inset between the two large lower panels is adapted from [26] and [83], showing CO ($J = 2 - 1$) in red, SiO ($J = 5 - 4$) in red, and H α in blue (*i.e.*, the equatorial ring); the jet-like feature is marked from [26], who already identified the molecular south outflow.

I drew the upper pink line from the center to the upper clump. The front of the blue region below the clump extends over 12° as viewed from the center, 6° to each side of the pink line. Therefore, I estimate the uncertainty in this direction to be about half this distance, or $\pm 3^\circ$. On the other side (lower region of the image), there are three clumps, so I drew the lower pink line through the central clump. The uncertainty in the direction is also $\pm 3^\circ$.

[26] already hinted at this bipolar structure when referring to the south protrusion in a molecular map from [83] as a jet-like feature. On the plane of the sky, it is in the direction of the component FeSR. I present their image between the two lower panels of Figure 2. [26] could not fully reveal the molecular gas bipolar

structure. The new high-quality images from [35] enable me to clearly identify the molecular bipolar structure. I will return to discuss this bipolar structure in Section 3.

[35] compare their observational findings with numerical simulations of explosions in the framework of the neutrino-driven mechanism. They argue that they can fit the observed CO morphology, but not the SiO velocity distribution and morphology. Specifically, their explosion simulations produce too little Si + O at high velocities, and overpredict the amount of low-velocity material. The JJEM can account for higher-velocity components with energetic jets (Section 4). The relevant point I make here is that to match the CO morphology, [35] examine only the brightest regions of the CO and SiO, *i.e.*, those brighter than twice the noise threshold. In panel (a) of **Figure 3**, I present the image they compare to one of their simulations. By also presenting the faint regions of the molecular gas, I find the bipolar structure, which I further discuss in Section 3.

To demonstrate the correlation between the molecular morphology and the Fe outflow components, I overlaid a partially transparent intensity map of CO (panel b) and SiO (panel c) from the right panels of **Figure 2** on panel (a) of **Figure 3**. These panels show that the CO and SiO morphologies are correlated, at least in a line-of-sight plane, with the outflow components FeNR, FeNB, and FeS0. The extension of the molecular gas towards FeSR, which is in any case a faint component in [Fe I] 1.443 μm emission, is marginal.

This section shows that the outflow components defined by the [Fe I] 1.443 μm emission and the molecular gas have a correlated bipolar outflow morphology. I turn to compare this with the visible band that exhibits the most prominent bipolar structure, the “keyhole”.

3. Relation to the Bipolar Structure of SN 1987A

HST and JWST observations reveal a bipolar structure of a northern low-intensity zone with a bright rim on its front and an elongated low-intensity nozzle in the south; this structure is termed “keyhole”¹. The morphological similarity of some CCSNRs, including SN 1987A, with the bipolar morphologies of pairs of bubbles in cooling flow clusters of galaxies (e.g., [85]) and planetary nebulae (e.g., [28]), brought me [85] to define the two bubbles and the rim-nozzle asymmetry in SN 1987A, as depicted in **Figure 4**, and to argue that jets shaped the bipolar structure of SN 1987A [84]. Specifically, that one pair of energetic jets was long-lived and shaped the keyhole (also [86]). Here, I examine the relationship between molecular gas, Fe outflow components, and the keyhole’s structure.

On the keyhole image in **Figure 4**, I overlaid the structure of four red lines and the orange arrow that I constructed in **Figure 1** and the left panels of **Figure 2**: The four red lines depict the Fe outflow components and the orange arrows the bisector of the two north components, which also coincide with the extended mo-

¹See press release by JWST:
<https://science.nasa.gov/missions/webb/webb-reveals-new-structures-within-iconic-supernova/>.

molecular gas structure to the north-north-east. In **Figure 3**, I showed that the molecular gas morphology coincides with three of the Fe outflow components. **Figure 4** shows that the bisector between the two northern outflow components is along the bubble and rim in the north, and the two southern outflow components are on the side of the nozzle in the south.

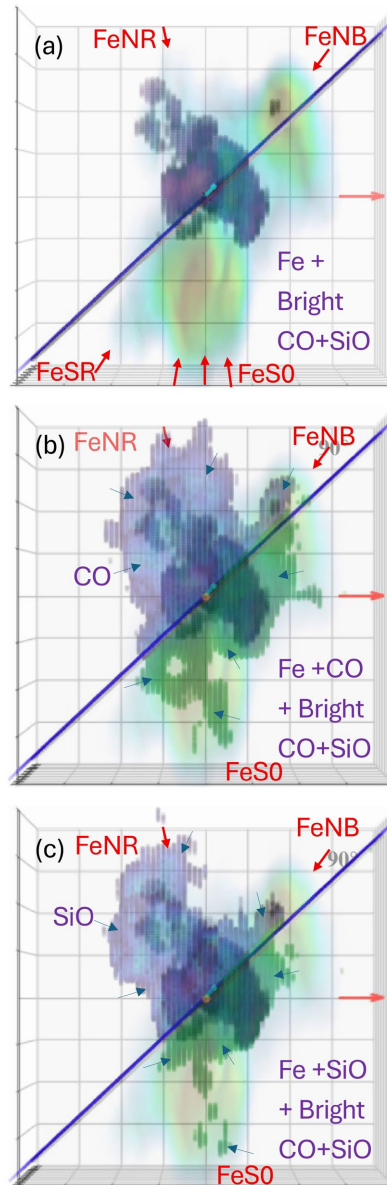


Figure 3. Images adapted from [35], with my identification of the four outflow components. (a) Bright CO (dark purple-orange) and SiO (dark purple-green) emission overlaid with the [Fe I] (faint blue to yellow-red) emission that [35] obtained from [82]. Only the regions with intensity above twice the noise threshold are shown by [35]. (b) A transparent full CO map from **Figure 2**, which I overlaid on the image from panel (a). The full CO map contains the bright CO parts from panel (a) and extended regions beyond that; I point to 8 arbitrary locations of this fainter CO region with narrow blue arrows. (c) A transparent full SiO map from **Figure 2**, which I overlaid on the image from panel (a). The 8 narrow blue arrows point on the fainter SiO region.

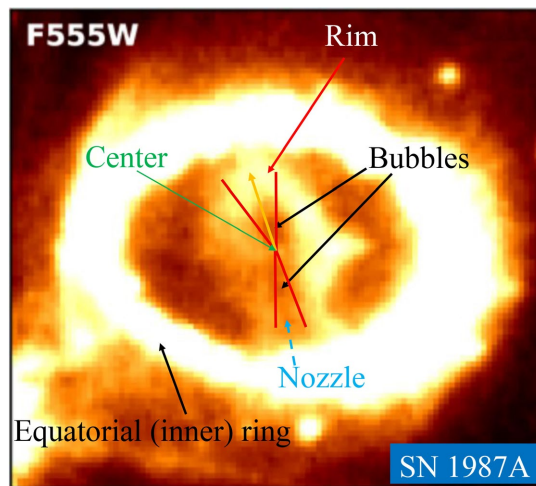


Figure 4. A figure adapted from [84] which includes an HST/WFC3 image of SN 1987A in one filter from [87]; north is up and east to the left. The field of view is $2.50'' \times 2.25''$. The “keyhole” is the north-south elongated bright structure within the equatorial ring. The identification of the rim, nozzle, and two bubbles is from [85] based on similarities to jet-inflated bubbles in cooling flow clusters of galaxies. Here, I added the structure of the four red lines and the orange arrow from Figure 2, at the same scale (0.67 times that of the four-line structure in Figure 1).

The conclusion of this section is that the Fe outflow components and the extended structure of the molecular gas, namely, the highest velocity components of the molecular gas, are part of the bipolar structure. The southern Fe outflow components are around the nozzle, and the northern ones are around the axis through the center of the northern bubble. The most elongated part of the molecular gas, which is along the orange arrow to the north-northeast (Figure 2), is extended through the bubble and to the front of the rim (the orange arrow in Figure 4). As the earlier papers cited above ([28] [85]) mentioned, the bipolar rim-nozzle asymmetry with two bubbles is a common structure in cooling flow clusters and planetary nebulae, where it is attributed to shaping by jets. Most likely, a pair of energetic jets shaped the bipolar outflow of SN 1987A [84].

4. Discussion and Summary

In this short study, I examined the high-quality new analysis of ALMA observations of CO and SiO by [35], which I present in Figure 2 and Figure 3. I find a correlation, although not perfect, between the molecular gas structure and the Fe outflow components that I identify in the Doppler maps by [82], which I present in Figure 1. Both the molecular gas structure and the Fe outflow components exhibit a general north-south bipolar structure. In Figure 4, I show that the bipolar structure of the [Fe I] $1.443 \mu\text{m}$ emission outflow components, the fast regions of the molecular gas, and the optical image of SN 1987A, *i.e.*, the keyhole, share the same general bipolar structure. The southern Fe outflow components and the molecular gas are concentrated around the nozzle. I estimated (Section 2) the uncertainties in the directions of the different lines I drew to be $\lesssim 6^\circ$ (projected on

the plane of the sky), implying that the bipolar morphology is robust.

This study concentrated on the large-scale bipolar morphology. I argued that the Fe (**Figure 1**), and the molecules CO and SiO (**Figure 2**) share the bipolar structure (**Figure 3**) of the keyhole (**Figure 4**). I also note, however, that their structures depend on differences in composition and excitation conditions. Reconstructing the ejecta three-dimensional structure also depends on assumptions such as homologous expansion, intensity threshold, and projection. Of these, the assumption of homologous expansion seems robust, as the keyhole did not yet interact with the inner ring of SN 1987A. For the above reasons, the apparent alignment does not automatically demonstrate that all three tracers belong to the same physical outflow. Nonetheless, the alignment I found in this study does suggest that these tracers share the bipolar structure.

As I discussed in earlier papers [84] [85], the keyhole has a morphology similar to that of many jet-shaped pairs of bubbles in cooling-flow clusters of galaxies and planetary nebulae. In [28], I argued that the two opposite arcs outside the keyhole appearing in a JWST image by [31], which share the same symmetrical axis as the keyhole, strengthen the claim for shaping by jets. Such arcs are common in jet-shaped bipolar planetary nebulae, and 3D numerical simulations of bipolar jets obtain them (e.g., [88]).

The JJEM simulations (e.g., [77] [78] [80] [81] [89]) are not yet at the stage to predict composition from nucleosynthesis or molecular structure in the ejecta, because these simulations at present follow only the first 10 - 20 seconds after the explosion. What these simulations do show is that along the jet direction (e.g., [77]) material can move somewhat faster than the ejecta average expansion velocity. The molecules and dust form in the ejecta long after the explosion, when the jets are long gone, hence long after the jets dissipated their energy into the core of the exploding star (which becomes part of the ejecta). Also, the jets contain too little mass to explain the molecules and dust; these are formed in the ejecta. The jets can compress the ejecta and, by that, promote dust formation [29] and molecules.

This study made the bipolar structure more robust, e.g., by emphasizing the nozzle, thereby strengthening the claim that an energetic pair of jets shaped the bipolar structure of SN 1987A. According to the JJEM, this pair was not the only one to participate in the explosion of SN 1987A (e.g., [86]), but was the most energetic. Other pairs could form more opposite structural features, as I tentatively identified in SN 1987A [27], *i.e.*, a point-symmetric morphology. Point-symmetric morphologies of about twenty CCSNRs are the most challenging observation for the neutrino-driven mechanism. However, there are others (see reviews cited in Section 1). The next most challenging observational property is the high explosion energies of some CCSNe that are way above the reach of the energies that simulations of the neutrino-driven mechanism can obtain, $E_{\text{exp}} \approx 2 \times 10^{51}$ erg. For example, three out of six CCSNe studied by [90] are beyond the reach of the neutrino-driven mechanism. Adding a powerful magnetar will not help much, as such magnetars require a jet-driven explosion (e.g., [91] [92]).

This study supports the claim that the JJEM is the primary explosion mechanism in CCSNe. Other energy sources can boost the jet-driven explosion (e.g., [93]), including neutrino heating [94], a magnetar (e.g., [91]), and, in rare cases, thermonuclear burning triggered by the collapse of a pre-collapse mixed layer of helium and oxygen ([95]; for the thermonuclear process itself see, e.g., [96] [97]).

Acknowledgements

I thank anonymous referees for helpful comments. A grant from the Pazy Foundation 2026 supported this research. I thank the Charles Wolfson Academic Chair at the Technion.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

References

- [1] Soker, N. (2024) The Two Alternative Explosion Mechanisms of Core-Collapse Supernovae: 2024 Status Report. *Universe*, **10**, Article No. 458. <https://doi.org/10.3390/universe10120458>
- [2] Soker, N. (2025) Learning from Core-Collapse Supernova Remnants on the Explosion Mechanism. *New Astronomy*, **121**, Article ID: 102453. <https://doi.org/10.1016/j.newast.2025.102453>
- [3] Soker, N. and Shiran, K. (2025) Multiple Shells in Supernova 2023ixf Support the Jittering Jets Explosion Mechanism. *The Astrophysical Journal Letters*, **995**, L3. <https://doi.org/10.3847/2041-8213/ae21da>
- [4] Shiran, K. and Soker, N. (2026) Double Shell Structure in Supernova 2024ggi. <https://arxiv.org/abs/2512.16554>
- [5] Klimov, A. and Soker, N. (2026) JWST Observations of a Planetary Nebula Support Jet-Driven Explosion of Core-Collapse Supernova Remnant RCW 103. <https://arxiv.org/abs/2605.22575>
- [6] Soker, N. (2026) The Supernova Remnant J0450.4-7050 Possesses a Jets-Shaped Point-Symmetric Morphology. <https://arxiv.org/abs/2602.09993>
- [7] Soker, N. (2026) The Failed Failed-Supernova Scenario of M31-2014-DS1. *The Open Journal of Astrophysics*, **9**, Article No. 65498. <https://doi.org/10.33232/001c.165498>
- [8] Wang, N.Y.N., Shishkin, D. and Soker, N. (2025) Jittering Jets in Stripped-Envelope Core-Collapse Supernovae. <https://arxiv.org/html/2510.02203v1>
- [9] Janka, H. (2025) Long-Term Multidimensional Models of Core-Collapse Supernovae: Progress and Challenges. *Annual Review of Nuclear and Particle Science*, **75**, 425-461. <https://doi.org/10.1146/annurev-nucl-121423-100945>
- [10] Janka, T. (2025) Core-Collapse Supernova Theory in 2025: Progress and Puzzles. *Video Memorie della Societa Astronomica Italiana*, **2**, 46.
- [11] Giudici, B., Gabler, M. and Janka, H.-T. (2025) Hydrodynamic Instabilities in Long-Term Three-Dimensional Simulations of Neutrino-Driven Supernovae of 13 Red Supergiant Progenitors. <https://arxiv.org/abs/2511.11796>
- [12] Luo, Y., Zha, S. and Kajino, T. (2026) Systematic Study of the Impact of Magnetic Fields on Neutrino Transport in Core-Collapse Supernovae. *Physical Review D*, **113**, Article ID: 023024. <https://doi.org/10.1103/PhysRevD.113.023024>

- [13] Murphy, R.D., Brinkman, E., Richardson, C.J., Semanak, E., Mezzacappa, A., Marro-netti, P., *et al.* (2026) Gravitational Waves as a Probe of Core Collapse Supernova Progenitor Structure. *Physical Review D*, **113**, Article ID: 084005. <https://doi.org/10.1103/2bdz-783t>
- [14] Orlando, S. (2026) Deciphering the Remnants of Core-Collapse Supernovae: Recon-structing Progenitor Star Properties and Explosion Mechanisms. *Proceedings of Mul-tifrequency Behaviour of High Energy Cosmic Sources—XV—PoS (MULTIF2025)*, Volume 506, 1-12. <https://doi.org/10.22323/1.506.0040>
- [15] Rusakov, A., Burrows, A., Wang, T. and Vartanyan, D. (2026) An Exploration of the Equation of State Dependence of Core-Collapse Supernova Explosion Outcomes and Signatures. *The Astrophysical Journal*, **1003**, Article No. 40. <https://doi.org/10.3847/1538-4357/ae61ac>
- [16] Varma, V. and Müller, B. (2026) Resolution Dependence in Magnetohydrodynamic Simulations of Neutrino-Driven Core-Collapse Supernovae. *Monthly Notices of the Royal Astronomical Society*, **548**, stag626. <https://doi.org/10.1093/mnras/stag626>
- [17] Janka, H., Gabler, M. and Wongwathanarat, A. (2017) Spatial Distribution of Radio-nuclides in 3D Models of SN 1987A and Cas A. *Proceedings of the International As-tronomical Union*, **12**, 148-156. <https://doi.org/10.1017/s1743921317004549>
- [18] Alp, D., Larsson, J., Maeda, K., Fransson, C., Wongwathanarat, A., Gabler, M., *et al.* (2019) X-Ray and Gamma-Ray Emission from Core-Collapse Supernovae: Compar-ison of Three-Dimensional Neutrino-Driven Explosions with SN 1987A. *The Astro-physical Journal*, **882**, Article No. 22. <https://doi.org/10.3847/1538-4357/ab3395>
- [19] Jerkstrand, A., Wongwathanarat, A., Janka, H., Gabler, M., Alp, D., Diehl, R., *et al.* (2020) Properties of Gamma-Ray Decay Lines in 3D Core-Collapse Supernova Mod-els, with Application to SN 1987A and Cas A. *Monthly Notices of the Royal Astro-nomical Society*, **494**, 2471-2497. <https://doi.org/10.1093/mnras/staa736>
- [20] Gabler, M., Wongwathanarat, A. and Janka, H. (2021) The Infancy of Core-Collapse Supernova Remnants. *Monthly Notices of the Royal Astronomical Society*, **502**, 3264-3293. <https://doi.org/10.1093/mnras/stab116>
- [21] McCray, R. and Fransson, C. (2016) The Remnant of Supernova 1987A. *Annual Re-view of Astronomy and Astrophysics*, **54**, 19-52. <https://doi.org/10.1146/annurev-astro-082615-105405>
- [22] Utrobin, V.P., Wongwathanarat, A., Janka, H.-Th. and Müller, E. (2015) Supernova 1987A: Neutrino-Driven Explosions in Three Dimensions and Light Curves. *Astron-omy & Astrophysics*, **581**, A40. <https://doi.org/10.1051/0004-6361/201425513>
- [23] Wongwathanarat, A., Müller, E. and Janka, H.-Th. (2015) Three-Dimensional Simu-lations of Core-Collapse Supernovae: From Shock Revival to Shock Breakout. *As-tronomy & Astrophysics*, **577**, A48. <https://doi.org/10.1051/0004-6361/201425025>
- [24] Soker, N. (2017) The Two Promising Scenarios to Explode Core Collapse Superno-vae. *Research in Astronomy and Astrophysics*, **17**, Article No. 113. <https://doi.org/10.1088/1674-4527/17/11/113>
- [25] Larsson, J., Fransson, C., Spyromilio, J., Leibundgut, B., Challis, P., Chevalier, R.A., *et al.* (2016) Three-Dimensional Distribution of Ejecta in Supernova 1987A at 10,000 Days. *The Astrophysical Journal*, **833**, Article No. 147. <https://doi.org/10.3847/1538-4357/833/2/147>
- [26] Bear, E. and Soker, N. (2018) Explaining the Morphology of Supernova Remnant (SNR) 1987A with the Jittering Jets Explosion Mechanism. *Monthly Notices of the Royal Astronomical Society*, **478**, 682-691. <https://doi.org/10.1093/mnras/sty1053>
- [27] Soker, N. (2024) Hints of Point-Symmetric Structures in SN 1987A: The Jittering Jets

- Explosion Mechanism. *New Astronomy*, **107**, Article ID: 102154. <https://doi.org/10.1016/j.newast.2023.102154>
- [28] Soker, N. (2024) Planetary Nebula Morphologies Indicate a Jet-Driven Explosion of SN 1987A and Other Core-Collapse Supernovae. *Galaxies*, **12**, Article No. 29. <https://doi.org/10.3390/galaxies12030029>
- [29] Soker, N. (2026) Jittering Jets Promote Dust Formation in Core-Collapse Supernovae. *International Journal of Astronomy and Astrophysics*, **16**, 112-125. <https://doi.org/10.4236/ijaa.2026.162008>
- [30] Bouchet, P., Gastaud, R., Coulais, A., Barlow, M.J., Fransson, C., Kavanagh, P.J., *et al.* (2024) JWST MIRI Imager Observations of Supernova SN 1987A. *The Astrophysical Journal*, **965**, Article No. 51. <https://doi.org/10.3847/1538-4357/ad2770>
- [31] Matsuura, M., Boyer, M., Arendt, R.G., Larsson, J., Fransson, C., Rest, A., *et al.* (2024) Deep JWST/NIRCam Imaging of Supernova 1987A. *Monthly Notices of the Royal Astronomical Society*, **532**, 3625-3642. <https://doi.org/10.1093/mnras/stae1032>
- [32] Ono, M., Nagataki, S., Ferrand, G., Takahashi, K., Umeda, H., Yoshida, T., *et al.* (2020) Matter Mixing in Aspherical Core-Collapse Supernovae: Three-Dimensional Simulations with Single-Star and Binary Merger Progenitor Models for SN 1987A. *The Astrophysical Journal*, **888**, Article No. 111. <https://doi.org/10.3847/1538-4357/ab5dba>
- [33] Orlando, S., Ono, M., Nagataki, S., Miceli, M., Umeda, H., Ferrand, G., *et al.* (2020) Hydrodynamic Simulations Unravel the Progenitor-Supernova-Remnant Connection in SN 1987A. *Astronomy & Astrophysics*, **636**, A22. <https://doi.org/10.1051/0004-6361/201936718>
- [34] Orlando, S., Miceli, M., Ono, M., Nagataki, S., Aloy, M., Bocchino, F., *et al.* (2025) Tracing the Ejecta Structure of Supernova 1987A: Insights and Diagnostics from 3D Magnetohydrodynamic Simulations. *Astronomy & Astrophysics*, **699**, A305. <https://doi.org/10.1051/0004-6361/202554862>
- [35] Wesson, R., Gabler, M., Lyons, M., Wildman, J., Matsuura, M., Janka, H.-T., *et al.* (2026) 3D Insights into SN 1987A: ALMA Observations Compared to Hydrodynamical Explosion Simulations. *Monthly Notices of the Royal Astronomical Society*, **548**, stag325. <https://doi.org/10.1093/mnras/stag325>
- [36] Morris, M. (1987) Mechanisms for Mass Loss from Cool Stars. *Publications of the Astronomical Society of the Pacific*, **99**, 1115-1122. <https://doi.org/10.1086/132089>
- [37] Soker, N. (1990) On the Formation of Ansaes in Planetary Nebulae. *The Astronomical Journal*, **99**, Article No. 1869. <https://doi.org/10.1086/115465>
- [38] Guerrero, M.A. and Manchado, A. (1998) A Precessing Collimated Outflow in the Quadrupolar Planetary Nebula NGC 6881. *The Astrophysical Journal*, **508**, 262-267. <https://doi.org/10.1086/306407>
- [39] Guerrero, M.A., Cazzoli, S., Rechy-García, J.S., Ramos-Larios, G., Montoro-Molina, B., Gómez-González, V.M.A., *et al.* (2021) Tomography of the Unique Ongoing Jet in the Planetary Nebula NGC 2392. *The Astrophysical Journal*, **909**, Article No. 44. <https://doi.org/10.3847/1538-4357/abe2aa>
- [40] Miranda, L.F., Torrelles, J.M., Guerrero, M.A., Aaquist, O.B. and Eiroa, C. (1998) The Nature and Structure of the Emission Line Nebula K 3-35: A Very Young Planetary Nebula with Precessing Bipolar Jet-Like Outflows? *Monthly Notices of the Royal Astronomical Society*, **298**, 243-250. <https://doi.org/10.1046/j.1365-8711.1998.01611.x>
- [41] Sahai, R. and Trauger, J.T. (1998) Multipolar Bubbles and Jets in Low-Excitation Planetary Nebulae: Toward a New Understanding of the Formation and Shaping of Planetary Nebulae. *The Astronomical Journal*, **116**, 1357-1366.

- <https://doi.org/10.1086/300504>
- [42] Sahai, R., Le Mignant, D., Sánchez Contreras, C., Campbell, R.D. and Chaffee, F.H. (2005) Sculpting a Pre-Planetary Nebula with a Precessing Jet: IRAS 16342-3814. *The Astrophysical Journal*, **622**, L53-L56. <https://doi.org/10.1086/429586>
 - [43] Boffin, H.M.J., Miszalski, B., Rauch, T., Jones, D., Corradi, R.L.M., Napiwotzki, R., *et al.* (2012) An Interacting Binary System Powers Precessing Outflows of an Evolved Star. *Science*, **338**, 773-775. <https://doi.org/10.1126/science.1225386>
 - [44] Akashi, M. and Soker, N. (2018) The Formation of “Columns Crowns” by Jets Interacting with a Circumstellar Dense Shell. *Monthly Notices of the Royal Astronomical Society*, **481**, 2754-2765. <https://doi.org/10.1093/mnras/sty2479>
 - [45] Sowicka, P., Jones, D., Corradi, R.L.M., Wesson, R., García-Rojas, J., Santander-García, M., *et al.* (2017) The Planetary Nebula IC 4776 and Its Post-Common-Envelope Binary Central Star. *Monthly Notices of the Royal Astronomical Society*, **471**, 3529-3546. <https://doi.org/10.1093/mnras/stx1697>
 - [46] Estrella-Trujillo, D., Hernández-Martínez, L., Velázquez, P.F., Esquivel, A. and Raga, A.C. (2019) Hydrodynamical Models of Protoplanetary Nebulae Including the Photoionization of the Central Star. *The Astrophysical Journal*, **876**, Article No. 29. <https://doi.org/10.3847/1538-4357/ab12e1>
 - [47] Rechy-García, J.S., Peña, M. and Velázquez, P.F. (2019) 3D Hydrodynamical Models of Point-Symmetric Planetary Nebulae: The Special Case of H 1-67. *Monthly Notices of the Royal Astronomical Society*, **482**, 1163-1175. <https://doi.org/10.1093/mnras/sty2758>
 - [48] Tafoya, D., Orosz, G., Vlemmings, W.H.T., Sahai, R. and Pérez-Sánchez, A.F. (2019) Spatio-Kinematical Model of the Collimated Molecular Outflow in the Water-Fountain Nebula IRAS 16342-3814. *Astronomy & Astrophysics*, **629**, A8. <https://doi.org/10.1051/0004-6361/201834632>
 - [49] Balick, B., Frank, A. and Liu, B. (2020) Models of the Mass-Ejection Histories of Pre-Planetary Nebulae. IV. Magnetized Winds and the Origins of Jets, Bullets, and FLIERs. *The Astrophysical Journal*, **889**, Article No. 13. <https://doi.org/10.3847/1538-4357/ab5651>
 - [50] García-Segura, G., Taam, R.E. and Ricker, P.M. (2020) Common Envelope Shaping of Planetary Nebulae. II. Magnetic Solutions and Self-Collimated Outflows. *The Astrophysical Journal*, **893**, Article No. 150. <https://doi.org/10.3847/1538-4357/ab8006>
 - [51] García-Segura, G., Taam, R.E. and Ricker, P.M. (2021) Common Envelope Shaping of Planetary Nebulae. III. the Launching of Jets in Proto-Planetary Nebulae. *The Astrophysical Journal*, **914**, Article No. 111. <https://doi.org/10.3847/1538-4357/abfc4e>
 - [52] Rechy-García, J.S., Guerrero, M.A., Duarte Puertas, S., Chu, Y., Toalá, J.A. and Miranda, L.F. (2020) Kinematical Investigation of Possible Fast Collimated Outflows in Twelve Planetary Nebulae. *Monthly Notices of the Royal Astronomical Society*, **492**, 1957-1969. <https://doi.org/10.1093/mnras/stz3326>
 - [53] Clairmont, R., Steffen, W. and Koning, N. (2022) Morphokinematic Modelling of the Point-Symmetric Cat’s Eye, NGC 6543: Ring-Like Remnants of a Precessing Jet. *Monthly Notices of the Royal Astronomical Society*, **516**, 2711-2717. <https://doi.org/10.1093/mnras/stac2375>
 - [54] Danehkar, A. (2022) Morpho-Kinematic Properties of Wolf-Rayet Planetary Nebulae. *The Astrophysical Journal Supplement Series*, **260**, Article No. 14. <https://doi.org/10.3847/1538-4365/ac5cca>
 - [55] Moraga Baez, P., Kastner, J.H., Balick, B., Montez, R. and Bublitz, J. (2023) Panchromatic HST/WFC3 Imaging Studies of Young, Rapidly Evolving Planetary Nebulae.

- II. NGC 7027. *The Astrophysical Journal*, **942**, Article No. 15.
<https://doi.org/10.3847/1538-4357/aca401>
- [56] Ablimit, I. (2024) Formation of Neutron Stars Inside Planetary Nebulae via Accretion-Induced Collapse and Core-Merger-Induced Collapse from White Dwarf Binaries. <https://arxiv.org/abs/2407.03985>
- [57] Derlopa, S., Akas, S., Amram, P., Boumis, P., Chiotellis, A. and de Oliveira, C.M. (2024) Planetary Nebula NGC 2818: Revealing Its Complex 3D Morphology. *Monthly Notices of the Royal Astronomical Society*, **530**, 3327-3341.
<https://doi.org/10.1093/mnras/stae1013>
- [58] Miranda, L.F., Vázquez, R., Olguín, L., Guillén, P.F. and Matías, J.M. (2024) Morphokinematical Study of the Planetary Nebula Me2-1: Unveiling Its Point-Symmetric and Unusual Physical Structure. *Astronomy & Astrophysics*, **687**, A123.
<https://doi.org/10.1051/0004-6361/202348173>
- [59] Sahai, R., Alcolea, J., Balick, B., Blackman, E.G., Bujarrabal, V., Castro-Carrizo, A., *et al.* (2024) High-Speed Outflows and Dusty Disks during the AGB to PN Transition: The PANORAMA Survey. *Proceedings of the International Astronomical Union*, **19**, 337-343. <https://doi.org/10.1017/s1743921324000498>
- [60] Balick, B. (1987) The Evolution of Planetary Nebulae. I—Structures, Ionizations, and Morphological Sequences. *The Astronomical Journal*, **94**, Article No. 671.
<https://doi.org/10.1086/114504>
- [61] Parker, Q.A., Acker, A., Frew, D.J., Hartley, M., Peyaud, A.E.J., Ochsenbein, F., *et al.* (2006) The Macquarie/AAO/Strasbourg H Planetary Nebula Catalogue: MASH. *Monthly Notices of the Royal Astronomical Society*, **373**, 79-94.
<https://doi.org/10.1111/j.1365-2966.2006.10950.x>
- [62] Sahai, R., Morris, M., Sánchez Contreras, C. and Claussen, M. (2007) Preplanetary Nebulae: A *Hubble Space Telescope* Imaging Survey and a New Morphological Classification System. *The Astronomical Journal*, **134**, 2200-2225.
<https://doi.org/10.1086/522944>
- [63] Kwok, S. (2024) Planetary Nebulae Research: Past, Present, and Future. *Galaxies*, **12**, Article No. 39. <https://doi.org/10.3390/galaxies12040039>
- [64] Shishkin, D. and Michaelis, A. (2026) Quantifying Symmetry: Transformation Information for Planetary Nebulae and Supernova Remnants. *Publications of the Astronomical Society of the Pacific*, **138**, Article ID: 064508.
<https://doi.org/10.1088/1538-3873/ae7692>
- [65] García-Segura, G., Taam, R.E. and Ricker, P.M. (2022) Common-Envelope Shaping of Planetary Nebulae—IV. From Protoplanetary to Planetary Nebula. *Monthly Notices of the Royal Astronomical Society*, **517**, 3822-3831.
<https://doi.org/10.1093/mnras/stac2824>
- [66] García-Segura, G., Manchado, A., Toalá, J.A., Guerrero, M.A. and Castro-Tirado, A.J. (2025) Planetary Nebula Evolution for Single Stellar Models. the Formation of Neutral Spikes. *Monthly Notices of the Royal Astronomical Society*, **543**, 3867-3884.
<https://doi.org/10.1093/mnras/staf1744>
- [67] Michaelis, A.M., Kashi, A. and Kochiashvili, N. (2018) Periodicity in the Light Curve of P Cygni-Indication for a Binary Companion? *New Astronomy*, **65**, 29-34.
<https://doi.org/10.1016/j.newast.2018.06.001>
- [68] Gilkis, A., Laplace, E., Arcavi, I., Shenar, T. and Schneider, F.R.N. (2025) The Landscape of Binary Core-Collapse Supernova Progenitors and the Late Emergence of Wolf-Rayet Winds. *Monthly Notices of the Royal Astronomical Society*, **540**, 3094-3120.
<https://doi.org/10.1093/mnras/staf884>

- [69] Grichener, A. (2025) Mergers of Compact Objects with Cores of Massive Stars: Evolutionary Pathways, R-Process Nucleosynthesis and Multi-Messenger Signatures. *Astrophysics and Space Science*, **370**, Article No. 11. <https://doi.org/10.1007/s10509-025-04402-1>
- [70] Mukhija, B. and Kashi, A. (2025) Accretion and Recovery in Giant Eruptions of Massive Stars. *The Astrophysical Journal*, **986**, Article No. 188. <https://doi.org/10.3847/1538-4357/add3f1>
- [71] Mukhija, B. and Kashi, A. (2026) Presupernova Multiple Giant Eruptions in Massive Stars. *The Astrophysical Journal*, **997**, Article No. 66. <https://doi.org/10.3847/1538-4357/ae2013>
- [72] Mukhija, B. and Kashi, A. (2026) Envelope Inflation and Outflow Driven by Energy Deposition in Massive Stars. *The Astrophysical Journal*, **999**, Article No. 123. <https://doi.org/10.3847/1538-4357/ae40c1>
- [73] Mukhija, B. and Kashi, A. (2026) High Power Accretion in Massive Binary Systems and the Impact of Metallicity. *New Astronomy*, **122**, Article ID: 102475. <https://doi.org/10.1016/j.newast.2025.102475>
- [74] Mukhija, B. and Kashi, A. (2026) Wind Accretion in Massive Binaries Experiencing High Mass Loss Rates. II. Eccentricity. *Publications of the Astronomical Society of the Pacific*, **138**, Article ID: 034207. <https://doi.org/10.1088/1538-3873/ae50bb>
- [75] Akashi, M. and Kashi, A. (2020) Fast Ejecta Resulted from Jet-wind Interaction in the Great Eruption of Eta Carinae. *Monthly Notices of the Royal Astronomical Society*, **494**, 3186-3199. <https://doi.org/10.1093/mnras/staa1014>
- [76] Kashi, A. (2023) Accretion in the Binary System GG Carinae and Implications for B[e] Supergiants. *Monthly Notices of the Royal Astronomical Society*, **523**, 5876-5886. <https://doi.org/10.1093/mnras/stad1758>
- [77] Braudo, J., Michaelis, A., Akashi, M. and Soker, N. (2025) Simulating the Shaping of Point-Symmetric Structures in the Jittering Jets Explosion Mechanism. *Publications of the Astronomical Society of the Pacific*, **137**, Article ID: 054201. <https://doi.org/10.1088/1538-3873/add08e>
- [78] Braudo, J., Michaelis, A., Akashi, M. and Soker, N. (2026) Simulating Observed Point-Symmetric Core-Collapse Supernova Morphologies with the Jittering Jets Explosion Mechanism. <https://arxiv.org/abs/2606.14364>
- [79] Soker, N. and Akashi, M. (2025) The Explosion Jets of the Core-Collapse Supernova Remnant Circinus X-1. *The Open Journal of Astrophysics*, **8**, Article No. 54770. <https://doi.org/10.33232/001c.154770>
- [80] Akashi, M. and Soker, N. (2026) Simulating the Jittering-Jets Explosion Mechanism: Circum-Jet Rings Account for Observed Core-Collapse Supernova Remnant Morphologies. *The Open Journal of Astrophysics*, **9**. <https://doi.org/10.33232/001c.172195>
- [81] Akashi, M. and Soker, N. (2026) Reproducing Morphological Features in the Supernova Remnant G11.2-0.3 by Simulating Jittering Jets. *Publications of the Astronomical Society of the Pacific*, **138**, Article ID: 064203. <https://doi.org/10.1088/1538-3873/ae7903>
- [82] Larsson, J., Fransson, C., Sargent, B., Jones, O.C., Barlow, M.J., Bouchet, P., *et al.* (2023) JWST NIRSpec Observations of Supernova 1987A—From the Inner Ejecta to the Reverse Shock. *The Astrophysical Journal Letters*, **949**, L27. <https://doi.org/10.3847/2041-8213/acd555>
- [83] Abellán, F.J., Indebetouw, R., Marcaide, J.M., Gabler, M., Fransson, C., Spyromilio, J., *et al.* (2017) Very Deep inside the SN 1987A Core Ejecta: Molecular Structures

- Seen in 3D. *The Astrophysical Journal Letters*, **842**, L24.
<https://doi.org/10.3847/2041-8213/aa784c>
- [84] Soker, N. (2024) Supernova 1987A's Keyhole: A Long-Lived Jet-Pair in the Final Explosion Phase of Core-Collapse Supernovae. *Research in Astronomy and Astrophysics*, **24**, Article ID: 075006. <https://doi.org/10.1088/1674-4527/ad4fc2>
 - [85] Soker, N. (2024) Comparing Jet-Shaped Point Symmetry in Cluster Cooling Flows and Supernovae. *The Open Journal of Astrophysics*, **7**, Article No. 49.
<https://doi.org/10.33232/001c.120279>
 - [86] Soker, N. (2026) Supernova 1987A Was a "Failed Supernova" Twenty Thousand Years before Its Jet-Driven Explosion. <https://arxiv.org/abs/2608.24801>
 - [87] Rosu, S., Larsson, J., Fransson, C., Challis, P., Kirshner, R.P., *et al.* (2024) Hubble Space Telescope Images of SN 1987A: Evolution of the Ejecta and the Equatorial Ring from 2009 to 2022. *The Astrophysical Journal*, **966**, Article No. 238.
<https://doi.org/10.3847/1538-4357/ad36cc>
 - [88] Akashi, M., Bear, E. and Soker, N. (2018) Forming H-Shaped and Barrel-Shaped Nebulae with Interacting Jets. *Monthly Notices of the Royal Astronomical Society*, **475**, 4794-4808. <https://doi.org/10.1093/mnras/sty029>
 - [89] Braudo, J. and Soker, N. (2026) The Jet-Shaped Pipe Morphology in Planetary Nebulae and Core-Collapse Supernova Remnants. *The Open Journal of Astrophysics*, **9**.
<https://doi.org/10.33232/001c.172148>
 - [90] Zhao, J., Jiang, J., Xu, Z., Zhang, Y., Fang, Q., Liu, L., *et al.* (2026) WFST Supernovae in the First Year. III. Systematical Study of the Photometric Behavior of Early-Phase Core-Collapse Supernovae. *The Astrophysical Journal*, **1004**, Article No. 137.
<https://doi.org/10.3847/1538-4357/ae657e>
 - [91] Soker, N. and Gilkis, A. (2017) Magnetar-Powered Superluminous Supernovae Must First Be Exploded by Jets. *The Astrophysical Journal*, **851**, Article No. 95.
<https://doi.org/10.3847/1538-4357/aa9c83>
 - [92] Kumar, A. (2025) Insights from Modelling Magnetar-Driven Light Curves of Stripped-Envelope Supernovae. *New Astronomy*, **116**, Article ID: 102346.
<https://doi.org/10.1016/j.newast.2024.102346>
 - [93] Soker, N. (2026) Point-Symmetric Morphology in Supernova Remnant G11.2-0.3: The Jittering Jets Explosion Mechanism. <https://arxiv.org/abs/2511.14578>
 - [94] Soker, N. (2022) Boosting Jittering Jets by Neutrino Heating in Core Collapse Supernovae. *Research in Astronomy and Astrophysics*, **22**, Article ID: 095007.
<https://doi.org/10.1088/1674-4527/ac7cbc>
 - [95] Klimov, A., Shishkin, D. and Soker, N. (2026) The Precessing Jet Axis of the Supernova Remnant 3C 397. <https://arxiv.org/abs/2603.21307>
 - [96] Kushnir, D. and Katz, B. (2015) Failure of a Neutrino-Driven Explosion after Core-Collapse May Lead to a Thermonuclear Supernova. *The Astrophysical Journal*, **811**, Article No. 97. <https://doi.org/10.1088/0004-637x/811/2/97>
 - [97] Blum, K. and Kushnir, D. (2016) Neutrino Signal of Collapse-Induced Thermonuclear Supernovae: The Case for Prompt Black Hole Formation in SN 1987A. *The Astrophysical Journal*, **828**, Article No. 31. <https://doi.org/10.3847/0004-637x/828/1/31>