The Vela Supernova Remnant: The Unique Morphological Features of Jittering Jets Postprint

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Abstract

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Full Text

Preamble

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Abstract

We identify an S-shaped main-jet axis in the Vela core-collapse supernova remnant (CCSNR) that we attribute to a pair of precessing jets—one of the tens of pairs of jets that exploded the progenitor of Vela according to the jittering jets explosion mechanism (JJEM). A main-jet axis is defined as a symmetry axis that extends across the CCSNR and through its center. We identify this S-shaped main-jet axis by the high abundance of ejecta elements: oxygen, neon, and magnesium.

We increase the tally of identified pairs of clumps and ears in Vela to seven, with two pairs shaped by the precessing jets that formed the main-jet axis. These pairs and the main-jet axis together constitute the point-symmetric wind-rose structure of Vela. The other five pairs of clumps/ears show signatures only on two opposite sides of the CCSNR, not near the center. We discuss various possible jet-less shaping mechanisms for creating such point-symmetric morphology and dismiss them because they cannot simultaneously explain Vela's point-symmetric morphology, the S-shaped high ejecta abundance pattern, and the enormous energy required to shape the S-shaped structure. Our findings strongly support the JJEM and pose a severe challenge to the neutrino-driven explosion mechanism.

Key words: stars: massive -stars: neutron -(stars:) supernovae: general -stars: jets -ISM: supernova remnants -(stars:) supernovae: individual (Vela)

1. Introduction

Recent studies discuss two alternative theoretical explosion mechanisms for core-collapse supernovae (CCSNe): the delayed neutrino-driven mechanism and the jittering jets explosion mechanism (JJEM; for a recent review, see Soker 2024a). Current research on the neutrino-driven mechanism focuses on three-dimensional simulations beginning with the pre-collapse stellar core and extending to seconds after the revival of the stalled shock at ~100 km from the newly born neutron star (NS; e.g., Burrows et al. 2024; Janka & Kresse 2024; Müller 2024; Müller et al. 2024; van Baal et al. 2024; Wang & Burrows 2024; Nakamura et al. 2025). Some studies also consider hadron-quark phase transition within the neutrino-driven explosion framework (e.g., Huang et al. 2025). The magnetorotational explosion—which occurs when the progenitor core rotates rapidly and possesses strong magnetic fields (e.g., Shibagaki et al. 2024; Zha et al. 2024) —is included as neutrino-driven because it still attributes most CCSNe to the neutrino-driven mechanism, reserving jet-driven explosions only for rare cases with a fixed axis.

In contrast, recent JJEM studies focus on finding signatures of jittering jets in core-collapse supernova remnants (CCSNRs; e.g., Shishkin et al. 2024; Soker 2024b, 2024c, 2024d, 2024e, 2024f; Bear & Soker 2025; Bear et al. 2025; Shishkin & Soker 2025). Last year' s discoveries of such signatures in several CCSNRs, along with other expected JJEM signatures, represent a major advance in establishing the JJEM as the main—or even sole—explosion mechanism for CCSNe (reviews by Soker 2024a, 2024g). Neutrino heating plays a role in the JJEM, but not the primary one. Specifically, neutrino heating can assist in launching jets from intermittent accretion disks (or belts) around the newly born NS (though magnetic fields are also needed) and can boost jet energy after launch (Soker 2022a).

In the JJEM, the newly born NS (or black hole in some cases) launches pairs of jets with varying directions that explode the star (e.g., Soker 2010; Papish & Soker 2011, 2014; Gilkis & Soker 2014, 2016; Soker 2020, 2022b). The source of the stochastic angular momentum in the accreted gas is pre-collapse convective angular momentum fluctuations in the core (e.g., Shishkin & Soker 2021, 2023) that instabilities above the newly born NS amplify, primarily through spiral standing accretion shock instability (SASI) modes (e.g., Andresen et al. 2019; Walk et al. 2020; Nagakura et al. 2021; Shibagaki et al. 2021). Envelope convection can seed angular momentum fluctuations in electron-capture supernovae (Wang et al. 2024). If core material accretion fails to trigger explosion and a black hole forms, envelope convection can also seed the angular momentum fluctuations (Quataert et al. 2019; Antoni & Quataert 2022, 2023).

According to the JJEM, a black hole forms when a rapidly rotating pre-collapse core causes the central newly born NS (before collapsing to a black hole) to launch exploding jets along a fixed axis, implying an inefficient jet feedback mechanism (e.g., Soker 2023a). Large amounts of accreted mass can result in a super-energetic CCSN (e.g., Gilkis et al. 2016). There is only small jittering around this fixed axis.

The JJEM involves several to a few tens of jet-launching episodes (e.g., Soker 2024h). Most of these jets are choked by stellar core material that did not collapse to the newly born NS, which acquires their energy and leads to core explosion. From that point, the explosion resembles the neutrino-driven mechanism in many aspects—e.g., numerous instabilities develop and the NS receives a kick—though not in all respects. Later jets expand more freely and can leave imprints on the ejecta; these remain part of the exploding jets, not post-explosion jets. Each late jet pair can create two opposite morphological features (relative to the explosion center).

When two or more jet pairs align along different axes, the outcome is point-symmetric morphology, which the Vela CCSNR exhibits (e.g., Soker 2023b, 2024d). In many cases, the two opposite jets in a pair are unequal in power or opening angle due to the short-lived launching accretion disk (Soker 2024e), potentially imparting a kick to the NS (Bear et al. 2025). Unequal opposite jets also appear in young stellar objects (e.g., Murphy et al. 2024).

The JJEM allows the last pair or two of jets to be long-lived, producing substantial morphological impact by forming features that extend from one side through the center to the other side of the CCSNR (Soker 2024b). Examples include the main jet-axis of SN 1987A (the keyhole structure), the main jet-axis of SNR 0540-69.3 (Soker 2022c), and the S-shaped hose that is the main jet-axis of the Cygnus Loop (Shishkin et al. 2024). In this study, we reveal the main-jet axis of the Vela Supernova Remnant (Section 2) and argue that only jets can shape it. The point-symmetric morphology of the Vela CCSNR leaves only the JJEM as a viable explanation for its explosion and shaping. We add this finding to earlier discoveries in other CCSNRs and compare the JJEM with alternative explanations for these morphological features, concluding that only the JJEM can account for all observed properties (Section 3). We summarize our results in Section 4.

2.1. The Point-symmetric Wind-rose of Vela

Earlier Vela studies identified several clumps, labeled A-L in Figure 1 [Figure 1: see original paper]. Aschenbach et al. (1995) marked clumps A-F, García et al. (2017) added clump G and drew line AG, Sapienza et al. (2021) added more clump labels, and Mayer et al. (2023) identified possible clump L. Sapienza et al. (2021) argued that clumps K and G, counter to clump A, form a jet-like structure from the explosion process. Soker (2024d) identified clump H2 from X-ray images by Mayer et al. (2023) and extended Vela’ s point-symmetric wind-rose from Soker (2023b) to include symmetry lines (axes) AG, DE, FJ, and HH2.

The high Si abundance in clumps A (Katsuda & Tsunemi 2006), G, and K (García et al. 2017) implies they originate deep inside Vela’ s progenitor core. Katsuda & Tsunemi (2005) found clump D has ONeMg overabundance, indicating its origin near the remnant’ s center, as Sankrit et al. (2003) previously suggested. Grichener & Soker (2017) took ears D and E to compose Vela’ s main jet-axis and, based on the ears’ relative volume, estimated the total energy of the two jets that inflated these ears to be 1% of the Vela explosion energy—very low energy.

We identify a new main-jet axis (Section 2.2) that, together with other jet pairs, has a total volume 20 times larger than ears D and E. The identified pairs can therefore bring the total energy of the shaping jets to 20% of the explosion energy. According to the JJEM, the remaining explosion energy comes from earlier jets that did not imprint on the point-symmetric morphology because they exploded the stellar progenitor’ s core.

Although clumps B2 and C2 (defined in Figure 1) are small, they are (i) prominent in their surroundings and (ii) not smaller than clumps A and L and not much smaller than clump G, which past studies identified as significant. Clump L2, which we also identify in Figure 1, shares this property. When we connect B2 to B, C2 to C, and L2 to L (three dashed lines in Figure 1), the three lines cross the center defined by the other five symmetry lines (within the uncertainty of the clump centers at the line ends). In Section 2.2, we argue that pairs LL2 and HH2 belong to one pair of precessing jets.

Three crucial comments regarding the seven clump pairs composing Vela’ s point-symmetric wind-rose are appropriate here. (1) In the JJEM, the two jets in each pair are expected to be unequal in opening angle and power because the intermittent accretion disk that launches them has no time to fully relax (Soker 2024e). Therefore, the symmetry line centers (marked by blue dots) might not intersect the lines' cross-point, and not all lines will cross at precisely the same point. (2) Not every clump pair necessarily represents the heads of two opposite jets. Dense clumps can form in compressed zones between jet-inflated bubbles, as observed in galaxy cluster hot gas (e.g., A2597; Tremblay et al. 2018) and found in JJEM hydrodynamical simulations (Papish & Soker 2014). (3) The distance of the average line centers (blue asterisk) from the NS location (red asterisk) and the distances of symmetry axis cross-points from the NS location are similar to the distance the NS has moved from the explosion site to its present location.

Considering the unequal jets in a pair (point 1), the center of the seven symmetry axes is sufficiently close to both the present NS location and the NS location at explosion to be associated with the explosion. In other words, pairs of jets exploded Vela' s progenitor.

We now turn to identifying Vela' s main-jet axis.

2.2. The Main-jet Axis of Vela

We use new results from the eROSITA X-ray telescope to identify Vela' s main-jet axis. A main-jet axis extends across the SNR diameter, with structure inside the main SNR shell in addition to outer zones. For example, in the most prominent ear pair, ears (clumps) D and E have prominent structures in the SNR' s outer zones, but near the center, no signatures appear along the symmetry axis connecting ears D and E.

Mayer et al. (2023) performed an extensive X-ray study of the Vela SNR using eROSITA Data Release 1 (DR1) data, including abundance distributions derived from spectral models fitted to the X-ray data. They identified enhanced abundances (relative to solar ratios) of oxygen, neon, and magnesium along a north-south zone extending through the remnant' s center. In Figure 2 [Figure 2: see original paper], we present the neon and oxygen abundance distributions. The region of enhanced neon and oxygen abundance through the center shows an S-shaped morphology (magnesium maps from Mayer et al. 2023 show a similar feature). We identify this S-shaped structure as the main-jet axis and draw it as a dotted line in Figure 2. Its northern end includes clumps H and L2, while its southern end includes clumps H2 with L further out. We attribute the HH2 and LL2 pairs to the same precessing jet pair.

Immediately south of our marked center (blue asterisk in Figure 2) is an enhanced abundance feature that slightly deviates from our identified S-shape. This feature coincides with a "cocoon" region south of the pulsar wind nebula (PWN), which Slane et al. (2018) attribute to reverse shock interaction with the PWN. Therefore, we do not expect it to be consistent with other explosion-associated features. Indeed, as we emphasize in this study, the PWN and other processes smear the point-symmetrical morphology.

In Figure 3 [Figure 3: see original paper], we present Vela SNR X-ray images separated by energy ranges: soft (0.2–0.7 keV, upper panel), combined (including the higher range where the SNR remains visible, 1.1–2.3 keV, middle panel), and 0.7–1.1 keV (lower panel). In the upper and lower panels, we draw two symmetric sides of an S-shaped axis (dashed lines) different from the one in Figure 2. These two sides are less secure than those in Figure 2. The southern line follows a thin X-ray filament that might not be a jet-axis, while the northern one is parallel and close to the northwest side of the dashed-white line we draw in the middle panel. This more bent S-shaped structure (compared to Figure 2) might not signify the tracks of the two jets. Nonetheless, the difference between the two S-shaped axes conveys the uncertainty in the exact center of the north-south S-shaped structure.

We identify another structure attributable to the precessing jet pairs that formed the main-jet axis. Figure 3 reveals a sharp boundary between an inner elongated bright S-shaped structure and a fainter outer structure. We mark this boundary in the middle panel of Figure 3. While the brightness jump is clear in some boundary segments, it is less distinct in others. This boundary encloses the S-shaped main-jet axis, and we suggest the enclosed material was shaped by the main-jet axis’ s energetic jets.

In Figure 4 [Figure 4: see original paper], we overlay the point-symmetric wind-rose from Figure 1, the dotted S-shaped line from Figure 2, and the dashed-blue S-shaped line and dashed-white boundary from Figure 3 onto the same Vela X-ray image. The point-symmetric structure appears here in its full glory. We emphasize that the two S-shaped lines (dotted and dashed) represent not two jet pairs but one precessing pair with uncertain location—this is Vela’ s main-jet axis. The HH2 and LL2 axes do not represent separate jet pairs but rather clumps belonging to the same precessing jet pair.

Near the center, the direction of the S-shaped structure we draw with the dashed blue line in Figures 3 and 4 is parallel to the jet direction of Vela’ s pulsar, PSR B0833-45 (e.g., Helfand et al. 2001; Fateeva et al 2023). To within the accuracy of determining the S-shaped line (e.g., comparing the dashed and dotted S-shaped lines in Figure 4), the S-shaped segment near the center is more or less parallel to the pulsar’ s spin. However, the HH2 and LL2 symmetry axes are almost perpendicular to the spin direction. We also note that the PWN covers only a small sky region, ~8 across (e.g., Helfand et al. 2001; Fateeva et al. 2023). Therefore, the PWN cannot be responsible for shaping the S-shaped structure.

3. Observational Evidence for Point-symmetric Exploding Jets

According to the JJEM, energetic jets expected to explode the star can account for the properties of point-symmetric structures in CCSNRs, including pairs of opposite clumps, filaments, ears, lobes, and nozzles. Other processes may contribute to CCSNR shaping but cannot explain the majority of observed point-symmetric morphologies. Table 1 lists four shaping processes and their ability to account for specific morphologies in some CCSNRs.

Although the interstellar medium (ISM) also influences CCSNR morphology (e.g., Sofue 2024 for a recent study), it cannot explain the basic morphological features we study here, particularly point symmetry. The ISM performs even poorer than circumstellar material (CSM) in accounting for the CCSNR properties we examine. Only the JJEM can explain all the morphological structures in the table.

We did not include shaping by a possible PWN because most CCSNRs we study show no PWN indication (e.g., SN 1987A). Generally, PWN power is insufficient to explain the shaping of large structures along polar directions. Instead, the PWN' s shocked material fills the CCSNR volume.

According to the neutrino-driven explosion mechanism, post-explosion jets might shape CCSNRs like Cassiopeia A (e.g., Orlando et al. 2021). Table 1 shows that post-explosion jet shaping can occur only in some cases—specifically, when jet-launching episode axes change and the jets are energetic. This raises the question of why earlier jets could not be launched to explode the star. In some cases, post-explosion jets cannot account for observed properties. Only exploding jets with varying directions can explain all observed morphologies. Janka et al. (2022) discuss ear pair formation by fallback material (see also Müller 2023) but note that this outflow should not be energetic. Akashi & Soker (2022) simulated post-explosion jets that can only shape the very inner ejecta zones; this also applies to jets launched by an NS companion (e.g., Akashi & Soker 2020). Akashi & Soker (2021) show that very late jets, launched weeks after explosion, can power a light curve peak, but these cannot form large-scale point-symmetric morphologies. The famous case of SNR W50, shaped by precessing jets from the central binary system SS 433, belongs to a different category not considered here because it involves a post-explosion active binary system.

We emphasize that all listed processes can occur. In particular, we expect the ISM (e.g., Wu & Zhang 2019; Yan et al. 2020; Lu et al. 2021; Meyer et al. 2024a), CSM (e.g., Chiotellis et al. 2021, 2024; Meyer et al. 2022, 2024b; Velázquez et al. 2023), and instabilities (e.g., Wongwathanarat et al. 2015) to play roles in shaping most CCSNe (CSM may influence only older CCSNRs, as SN 1987A' s CSM has not yet affected the inner massive ejecta). Additionally, an NS natal kick may be similar to that in the neutrino-driven explosion mechanism (e.g., Wongwathanarat et al. 2013) and/or may result from the kick by early asymmetrical pair jet (kick-BEAP) mechanism (Bear et al. 2025); the kick direction avoids small angles relative to the main-jet axis (e.g., Bear & Soker 2023). However, instabilities and ejecta-CSM interaction smear and dilute point-symmetric morphology rather than produce it. Moreover, hot ejecta themselves expand and smear point-symmetrical features; hot ejecta result from the explosion itself, nickel decay (nickel bubbles; e.g., Milisavljevic & Fesen 2013), and the reverse shock (e.g., Hwang & Laming 2012). These smearing processes make it difficult to identify point-symmetric morphological components in many cases. The NS kick, accompanied by asymmetrical mass ejection, further smears point symmetry. Instability and ejecta-CSM interaction properties in the JJEM are similar to those in the neutrino-driven explosion mechanism. The JJEM features jets that carry more energy than instabilities, enabling them to form point-symmetric morphological structures, though instabilities still somewhat smear the point symmetry.

Other features further support the JJEM. **Jittering in a plane:** Cassiopeia A' s ejecta concentrate around one plane (Milisavljevic & Fesen 2013). Papish & Soker (2014) speculated that Cassiopeia A' s torus morphology—a tilted thick disk with multiple jets as observations find (e.g., Willingale et al. 2003; DeLaney et al. 2010; Milisavljevic & Fesen 2013)—results from the JJEM' s tendency for jittering jets to share a plane, up to fluctuations that change jet axes and can even avoid planar jittering. Bear & Soker (2025) confirmed this speculation by identifying Cassiopeia A' s point symmetry; because dense clumps concentrated in this plane are much brighter than their surroundings, emission from this plane may be biased (e.g., Hwang & Laming 2012), implying possible massive ejecta perpendicular to this plane. Planar jittering may have also shaped SNR 0540-69.3, though this requires further study.

Main-jet axis: Examples include SN 1987A' s "keyhole" structure, SNR 0540-69.3' s jet axis, and the S-shaped hose that is the Cygnus Loop' s main jet-axis (Shishkin et al. 2024). The JJEM explanation (Soker 2024b) is that at the end of accretion onto the newly born NS, decreasing mass accretion increases the angular momentum timescale, allowing long-lived jet-launching episodes, particularly the last one. This final jet pair might form the main-jet axis. Note that this axis need not align with the pre-collapse core rotation axis if pre-collapse rotation is slow. CSM interaction shapes SNR outskirts but cannot form a main jet-axis with central imprints, as seen in Vela (Section 2.2). Based on this, we dismiss Gvaramadze' s (2000) suggestion that CSM shaped the Vela SNR.

4. Summary

This study' s main result is identifying a main-jet axis in the Vela CCSNR—the S-shaped structure drawn in Figures 2–4. We base this identification on the high abundance of ejecta material (O, Ne, and Mg) revealed by Mayer et al.' s (2023) X-ray analysis of Vela (Figure 2) and on the boundary of the X-ray bright inner zone drawn in Figures 3 and 4.

Earlier studies (Soker 2023b, 2024d) discussed Vela CCSNR' s point-symmetric morphology and its JJEM formation based only on outer ears and clumps. Identifying the S-shaped ejecta-rich main-jet axis has two critical implications: (1) The high O, Ne, and Mg abundance implies the S-shaped material was ejected during explosion, as these metals originate from the deep core. (2) The large volume enclosed by the boundary drawn in Figures 3 and 4, which we attribute to the precessing jets that formed the S-shaped main-jet axis, implies these jets were very energetic.

Grichener & Soker (2017), considering only pair DE, found the energy in jets that inflated these two ears to be only 1% of Vela' s explosion energy. Now, including the other pairs and the two precessing jets that shaped the main-jet axis, the energy increases to a much more significant fraction– 20% of the explosion energy. This is compatible with the JJEM, as early jets in the explosion process that supplied the remaining energy left no morphological imprint.

As discussed in Section 3, other shaping processes cannot explain the main-jet axis' s extension through the center, the ejecta abundance pattern, the large volume, and the point-symmetric wind-rose morphology (see Table 1). We consider CCSNR point-symmetric morphologies to pose the most severe challenge to the neutrino-driven explosion mechanism, as Table 1 demonstrates. These point-symmetric CCSNRs may even rule out the neutrino-driven explosion mechanism entirely. We emphasize that neutrino heating does occur, but its role is to boost jittering jet energy at launch and during inner core interaction, rather than being the primary explosion process (Soker 2022a).

Studies have identified point-symmetric morphology in about twelve CCSNRs, some with clear point-symmetric wind-roses and others with more subtle point-symmetric features; we expect this number to increase in 2025.

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