Neutron Star Natal Kick and Jets in Core Collapse Supernovae

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Abstract

We measure the angle between the neutron star (NS) natal kick direction and the inferred direction of jets according to the morphology of 12 core collapse supernova remnants (SNR), and find that the distribution is almost random, but missing small angles. The 12 SNRs are those for which we could both identify morphological features that we can attribute to jets and for which the direction of the NS natal kick is given in the literature. Unlike some claims for spin-kick alignment, here we rule out jet-kick alignment. We discuss the cumulative distribution function of the jet-kick angles under the assumption that dense clumps that are ejected by the explosion accelerate the NS by the gravitational attraction, and suggest that the jet feedback explosion mechanism might in principle account for the distribution of jet-kick angles.

Key words: ISM: supernova remnants – stars: jets – supernovae: general

1. Introduction

Many core collapse supernovae (CCSNe) leave behind a neutron star (NS) remnant that is born with a significant nonzero velocity, called natal kick velocity, with typical values of 200–500 km s$^{-1}$ and up to about 1000 km s$^{-1}$ (e.g., Cordes et al. 1993; Lyne & Lorimer 1994; Chatterjee et al. 2005). These values are larger than what can be accounted for by the disruption mechanism the jets of the NS is the two asymmetrical opposite jets, according to this work. Asymmetric neutrino emission by itself cannot account for the connection of NS natal kick to asymmetrical explosion. Elements between silicon and calcium are generally ejected in the direction opposite that of NS motion. This, they argue, supports the observed kick velocities. The jets we discuss here might be weaker and the high natal kick velocities because they require massive jets, and hence, as argued by, e.g., Nordhaus et al. (2012), they require rapid pre-collapse core rotation, and therefore, this scenario might be, at best, viable for a small portion of natal kick cases. Possible combinations of these scenarios have also been raised, for example, the combination of magnetic fields and rapid rotation, which can cause jets that might induce a kick (e.g., see the discussion by Wang et al. 2006). As the source of the momentum of the NS is the two asymmetrical opposite jets, according to this mechanism the jets’ axis (defined as the line along the directions of the two opposite jets) and kick direction tend to be aligned. This is in contradiction with the results we present in the current study. In what follows, we will not consider these and other mechanisms (e.g., Charbonneau & Zhimitsky 2010), and we will refer only to asymmetrical explosion mechanisms that impart momentum to the newly born NS.

Many observational and theoretical papers study and discuss the relation between the spin and kick directions (e.g., Spruit & Phinney 1998; Fryer & Kasenko 2006; Ng & Romani 2007; Wang et al. 2007; Kuranov et al. 2009). In the Crab Nebula (Kaplan et al. 2008) and the Vela nebula (Lai et al. 2001), observations imply that the NS kick direction and the spin direction are almost aligned. While some papers find a strong correlation between the kick and the spin directions (e.g., Dodson et al. 2003; Johnston et al. 2005, 2006), other papers, such as Bray & Eldridge (2016), find no statistical preference for the kick orientation. Ng & Romani (2006) find that the spin-kick angle in the pulsar of the Crab Nebula is 26° rather than the previously determined angle of 8° (also Wang et al. 2007).

In a recent study, Holland-Ashford et al. (2017) compare both the directions and magnitudes of the NS kick velocities with the asymmetrical geometry of SNRs. They look at the dipole, quadrupole, and octupole power ratios of the SNR morphologies, and find no correlation of SNR asymmetry with the magnitude of the kick velocity. They do find that the NS kick directions are preferentially opposite to the bulk of the X-ray emission.

In the present study, we compare kick directions with another geometrical property of the SNRs. We examine the relation between the kick direction and the line connecting the two opposite ears of SNRs, or other morphological features that hint at jets. We follow Grichener & Soker (2017) and generally define ears as two opposite protrusions from the main SNR shell. We further take the view that the ears were shaped by jets launched from the newly born NS during the explosion of the SN (Bear et al. 2017; Grichener & Soker 2017). The ears’ axis is defined as the line connecting the tips of the two ears. Hence, from here on, we will refer to ears’ axis and jets’ axis as meaning the same, but keep in mind that what we observe in the SNRs are the ears.

It is not clear if the jets we study here can leave a mark during the SN phase itself. Piran et al. (2018) attribute the excess of high velocity material in hydrogen-stripped CCSNe to relativistic choked jets that accelerated material to high velocities. The jets we discuss here might be weaker and the SN main shell more massive. From the typical ears we observe during the SNR phase, we can estimate that the velocity of the ears is only $\approx 10\%$–$20\%$ higher than the main shell. We also do not expect the ears to change the luminosity as they cover a small area and the emissivity of the ears will not differ much.
from that of the main shell. However, a more detailed study should be conducted to answer this question.

The motivation to our study that focuses on the relation between the direction of ears’ (or jets’) axis and the direction of the natal kick is our view that in all cases with ears the explosion was driven by jets. The ears are shaped by the last jet-launching episode because these jets are launched just after the previous jets have expelled the inner core. Therefore, the last jets might flow freely to the edge of the expanding envelope, and gently breakout, leaving the imprint of two opposite ears (similar to the modeling of Cassiopeia A by Orlando et al. 2016). The energy of the jets that inflated the ears is only a fraction of the explosion energy because the explosion was driven by several earlier jet-launching episodes (Bear et al. 2017).

There is no need for the pre-collapse core of the exploding star to have fast rotation, or even a mild rotation as in the model of Wheeler et al. (2002) for jets, as convective regions in the pre-collapse core (Gilkis & Soker 2014, 2016) and/or instabilities in the shocked zones around the newly born NS (Papish et al. 2015) can supply stochastic angular momentum to the gas that is accreted onto the NS. Most pronounced of these instabilities that might supply stochastic angular momentum are the spiral modes of the standing accretion-shock instability (SASI; on the spiral SASI modes see, e.g., Blondin & Mezzacappa 2007; Rantsiou et al. 2011; Fernández 2015; Kazeroni et al. 2017). If the accreted gas launches jets, then because of its stochastic angular momentum the jets’ axis will change its direction over time. This is termed the jittering-jets explosion mechanism (Papish & Soker 2011, 2014). If the pre-collapse core is rapidly rotating, then the jets will maintain a more or less constant axis. In both cases, the jets operate in a negative feedback mechanism (see the review by Soker 2016b). We adopt here the view that the jet feedback explosion mechanism can account for all CCSNe, from typical energies of about $10^{51}$ erg (Papish & Soker 2011) and up to super-energetic (or superluminous) CCSNe, even when a magnetar is formed (e.g., Soker 2016a; Chen et al. 2017; Soker & Gilkis 2017).

We construct our paper as follows. In Section 2, we discuss each of the 12 SNRs for which we could both identify ears (or another morphological feature that hints at jets) in available images and find the kick direction in the literature. The important new result in that section is the collection of the 12 projected angles between the kick direction and the direction of the ears’ (jets’) axis in the 12 SNRs. These angles are summarized in Section 2.1. We discuss each SNR in more detail in Section 2.2. Readers who are interested only in the results and their analysis can skip Section 2.2. In Section 3, we analyze the distribution of these angles and compare it with two distributions, a random distribution, and a distribution that assumes the kick and jets’ axis are perpendicular to each other. We discuss the results in the frame of the jets’ feedback explosion mechanism. We present a short summary in Section 4.

2. The Angles between the Kick Direction and Jets’ Axis

2.1. Sample and Measured Angles

In this section, we review 12 SNRs for which we found in the literature both morphological features that we can identify with jets and the direction of the motion of their central NS. We list the SNRs and the name of their NSs in the first and second columns of Table 1, respectively. We measured the angle $\alpha$ between the direction of the NS natal kick and the line along the directions of the two opposite jets, which we term the jets’ axis. We list the values of $\alpha$ in the third column, and the source for the assumed jets’ axis in the fourth column of Table 1. Because, in some cases, the two ears are not exactly on opposite sides of the center and/or in some cases one or two of the ears do not possess exact symmetry around an axis, we cannot always determine an accurate axis direction for the jets. We estimate that these departures from pure axisymmetry lead to general uncertainties in the values of $\alpha$ for the different SNRs that are about several degrees, e.g., about $\pm 5^\circ$. When available, we also list the angle $\phi$ between the NS spin and the kick direction (fifth column), and the references for that value (sixth column).

Morphological features that we identify with jets are mainly two opposite ears (defined in Section 1) and two opposite bright arcs. The identification of jets with ears follows our earlier papers, and it is based on the morphologies of planetary nebulae with ears and similar structures that are attributed to jets (Bear & Soker 2017; Bear et al. 2017; Grichener & Soker 2017). Furthermore, Tsebrenko & Soker (2013) demonstrated that jets can form ears in SNRs of Type Ia SNe. The flow that leads to ears in remnants of CCSNe is somewhat different than that in Type Ia SNe. The last jets to be launched by the exploding massive star carry a small, but non-negligible energy of the main supernova shell. Each jet pushes its way from inside and leaves a mark on the outskirts of the SNR (Tsebrenko & Soker 2013). If the jets are stronger, they can penetrate throughout the shell and form a morphology like in RCW 103 (Bear et al. 2017). The jets’ axis is taken to be along the line connecting the two opposite ears or along the arcs. For nine SNRs, we take the direction of the jets from previous papers, as listed in the fourth column of Table 1. For three other SNRs, we assume here the axis of the two opposite jets.

In the present study, we are concerned only with the morphologies of the ears and other features that indicate jets. The relative brightness of the ears and the main SNR shell

| SNR     | PSR    | $\alpha$ | Jets | $\phi$ | Spin |
|---------|--------|----------|------|--------|------|
| Cassiopeia A | ... | 88 | G | ... | ... |
| Puppis A | PSR J0821+4300 | 40 | G | ... | ... |
| RCW 103 | 1E 1613+5055 | 80 | B | ... | ... |
| PKS 1209-51 | 1E 1207.4-5209 | 54 | Here | ... | ... |
| CTB 109 | 1E 2259+586 | 42 | Here | ... | ... |
| S147 | PSR J0538+2817 | 40 | G | 12 | NR |
| G292.0+1.8 | PSR J11245916 | 70 | B | 22, 70 | W, P |
| Vela | B0833+45 | 30 | G | 10 | NR |
| G327.1-1.1 | ... | 45 | Here | ... | ... |
| 3C58 | PSR J0205+6449 | 60 | G | 21 | NR |
| Crab | PSR B0531+21 | 18 | G | 26 | NR |
| W44 | PSR B1853+01 | 15 | G | ... | ... |

Note. The first and second columns list the name of the SNR and the NS, respectively. The angle $\alpha$ (in degrees) is our measured angle between what we take as the jets’ axis and the NS kick direction. The fourth column lists the source for the jets’ axis—G: Grichener & Soker (2017), B: Bear et al. (2017), Here: this study. The angle $\phi$ (in degrees) is the angle between the NS kick direction and the SNR spin for which the references are given in the last column—NR: Ng & Romani (2007), W: Wang et al. (2006), P: Park et al. (2007).
might depend on local conditions that include the intensity and morphology of the magnetic field lines, the population of high energy electrons, and clumps that result from the CSM or ISM. The magnetic fields and high energy electrons determine the X-ray and radio synchrotron emission. Thermal X-ray emission and the population of high energy electrons depend on shocks, that in turn also depend on dense clumps. But neither of these factors that determine the emission will change the morphology of the ears in any significant manner. Only a massive CSM or ISM medium can do that.

In Section 2.2, we describe each SNR in more detail. Readers who are interested only in the results and their analysis can skip Section 2.2 and go directly to the analysis in Section 3.

### 2.2. Detailed Description of SNRs

In the figures that follow, we draw both the jets’ axis and the NS natal kick direction in the upper panel for each of the 12 SNRs. From there, we calculated the angle between the kick direction and jets’ axis, as listed in the third column of Table 1. Other panels in the figures are intended to show the NS natal kick direction and the jets’ direction as taken from the literature. We turn to describe in short each SNR and its basic properties that might be relevant to the analysis.

**Cassiopeia A (Cas A, 3C 461, G111.7−2.1).** Cas A is at a distance of 3.4 kpc (e.g., Reed et al. 1995). The mass of the progenitor prior to the explosion could have reached at 20$M_\odot$ (e.g., Willingale et al. 2003), and its age is assumed to be 330 years (e.g., Yakovlev et al. 2011). It resulted from an asymmetric type IIb explosion (e.g., Krause et al. 2008). Jets have previously been modeled for Cas A (e.g., Schure et al. 2008). One of the outcomes from their model is that jets can accompany the explosion even if the SNR appears spherically symmetric. DeLaney & Satterfield (2013) estimate the proper motion of the NS star as $V_{\text{NS}} = 390 \pm 400$ km s$^{-1}$. The upper panel in Figure 1 is an X-ray image from Hwang et al. (2004), where the white arrow points in the direction of NS motion taken from Holland-Ashford et al. (2017) as presented in the middle panel. The red double-headed arrow in the upper panel is along the direction of the two opposite jets taken from Grichener & Soker (2017) as presented in the lower panel.

**Puppis A (G260.4−03.4).** Its age is estimated as ranging from 3700–4450 years (e.g., Becker et al. 2012). Jets have already been proposed to be the shaping mechanism of this SNR (e.g., Castelletti et al. 2006). Furthermore, Reynoso et al. (2003) claim that the morphological features of this SNR (e.g., the alignment between optical expansion center and the lobes) are caused by jets. The NS (called RX J08224300) transverse motion is measured at $1570 \pm 240$ km s$^{-1}$ toward the west–southwest, assuming a distance of 2 kpc (Winkler & Petre 2007). We draw the jets’ axis and the kick direction in the upper panel of Figure 2. The NS motion is taken from Holland-Ashford et al. (2017) as shown in the middle panel, and the jets’ axis is taken from Grichener & Soker (2017) as shown in the lower panel.

**RCW 103 (G332.4−00.4).** In the upper panel of Figure 3 (taken from Bear et al. 2017 and based on Rea et al. 2016), we mark the proposed jets’ axis with yellow arrows. The NS motion is marked by a white arrow taken from Holland-Ashford et al. (2017) as noted in the lower panel. Although there are no ears in this SNR, in a previous paper (Bear et al. 2017; see Figure 3 there), we have compared the morphology of this SNR to several planetary nebulae and from that deduced the direction of the jets that have shaped this SNR. RCW 103’s estimated age is $\approx 2000$ years (e.g., Carter et al. 1997) and its estimated distance is $\approx 3.3$ kpc (e.g., Reynoso et al. 2004; Xing et al. 2014 and references therein). The kick velocity of the NS (1E 16134825055) is estimated to be $\approx 810–1300$ km s$^{-1}$ (for more details, see Torii et al. 1998).

**PKS 1209−5152 (G296.5−10.0).** This SNR is at a distance of $\approx 2.1$ kpc (e.g., Giacani et al. 2000) and its age is estimated to be $\approx 7000$ years (e.g., Pavlov et al. 2002). We take the NS kick direction from Holland-Ashford et al. (2017) and mark it with a white arrow in Figure 4. Similar to RCW 103, this SNR has no
clear ears, and we propose that the jets that shaped this SNR were launched in a direction between the two bright arcs, which we mark with yellow arrows connected by a cyan-dotted line in Figure 4.

**CTB 109 (G109.1–01.0).** CTB 109 is a radio and X-ray bright shell-type SNR at a distance of ≈3.2 kpc (e.g., Kothes & Foster 2012; Sánchez-Cruces et al. 2018). We take its image together with a white arrow that marks the direction of motion of the NS from (Holland-Ashford et al. 2017) and present it as the upper panel of Figure 5. The morphology of these ears is not exactly as observed in some other SNRs. They are very bright in the radio, as presented in the lower panel of Figure 5. We take the line connecting the two bright ears to be the jets’ axis, and mark our proposed jet direction with a dotted cyan double-headed arrow in the two panels of Figure 5.

**S 147 (G180.0-1.7).** Its distance is estimated as 1.47 kpc, its age is taken to be 20–100 kyr, and the spin-kick angle is 12° (e.g., Romani 2005; Ng et al. 2007). The kick velocity of the NS (PSR J0538+2817) of S147 is estimated to be ≈800 km s⁻¹ (e.g., Romani & Ng 2003). The upper panel of

![Image of SNR PKS 1209-51 with the NS direction of motion marked by a white arrow](image1)

**Figure 3. Upper panel is an X-ray image of RCW 103 in three energy bands (low = red, medium = green, highest = blue) combined with an optical image from the Digitized Sky Survey.** The original image is from the Chandra website and it is based on Rea et al. (2016), while the yellow arrows that depict the direction of the jets were added by Bear et al. (2017). A white arrow is the NS kick direction, copied from the lower panel that is taken from Holland-Ashford et al. (2017). Arrows in the lower panel are the same as in Figure 1.

![Image of SNR PKS 1209-51 with the NS direction of motion marked by a white arrow](image2)

**Figure 4. Image of SNR PKS 1209-51 with the NS direction of motion marked by a white arrow (taken from Holland-Ashford et al. 2017).** Green arrow is the same as in Figure 1. The yellow arrows present our proposed direction of the two jets that shaped this SNR during the explosion.

Figure 6 is taken from Gvaramadze (2006) based on Drew et al. (2005). We added the white arrow to mark the NS motion as reported by Gvaramadze (2006). It is consistent with the direction from the geometric center of S 147 to the present position of the pulsar as marked by a white plus sign. We mark
the jets’ direction according to the lower panel taken from Grichener & Soker (2017). G292.0+1.8. G292.0+1.8 is a Galactic oxygen-rich CCSNR (e.g., Bhalerao et al. 2015). Its pulsar J11245916 is apparently off the geometric center of the SNR and with an estimated velocity of 770 km s\(^{-1}\), a distance of 4.8 kpc, and an age of 1660 years (e.g., Hughes et al. 2001 and references therein). Park et al. (2007) suggest that the angle between the spin and the kick direction can be 70° or less. Others also point to a misalignment but derive much smaller angles, e.g., 22° (Wang et al. 2006). In the upper panel of Figure 7, we mark the NS motion (white arrow) copied from the middle panel taken from Holland-Ashford et al. (2017), and the jets’ axis (double-headed red arrow) based on the lower panel taken from Grichener & Soker (2017).

Vela (G263.9–03.0). Vela is at a distance of ≈350–500 pc (e.g., Aschenbach et al. 1995; Miceli et al. 2008 respectively) and at an age of ≈10^4 years (e.g., Miceli et al. 2008). The progenitor mass is estimated to be ≈15M\(_\odot\) (e.g., Chen & Gehrels 1999). The angle between the NS spin and kick direction is considered to be aligned at 10° (e.g., Pavlov et al. 2001; Ng & Romani 2007). García et al. (2017) analyze two opposite Si-rich knots in Vela, and argue that they were ejected by jets. The direction of the axis of their suggested two opposite jets is almost perpendicular to the NS kick velocity, and is different than what we take here to be the jets’ axis. Such a case might be the outcome of the jittering-jets’ explosion mechanism (see Section 1). The two double jets were launched at two different times out of several jet-launching episodes (Papish & Soker 2011). The two upper panels in Figure 8 focus on the NS (pulsar B083345) and its direction of motion. The two lower panels indicate possible jet directions, taken from Grichener & Soker (2017) and García et al. (2017), respectively. We assume that the jets’ axis is the same as in the third panel (Grichener & Soker 2017). Taken the jets’ axis from the fourth panel as suggested by García et al. (2017) would give a larger value of \(\alpha\).

G327.1–1.1. Its estimated age is \(\approx11000–29000\) years depending on the model that is used (e.g., Temim et al. 2009 and references therein). The NS direction of motion is marked (in the original figure) in the upper panel of Figure 9 by a yellow arrow (taken from the Chandra Gallery, based on Temim et al. 2009). We identify no ears in this SNR. However, Temim et al. (2015) identify a torus that is seen in the small lower-right panel of Figure 9. Based on its similarity to bright tori in other pulsar wind nebulae (e.g., Kargaltsev & Pavlov 2008), we draw, with a double-headed yellow arrow, the plane of the torus on that image. We take the jets’ axis to be perpendicular to the torus, as drawn in the upper panel of Figure 9 with a cyan dashed double-headed arrow.

3C58 (G130.7+03.1). It is at a distance of \(\approx2\) kpc with an estimated age of \(\approx830\) years (e.g., Kothes 2013). Slane et al. (2004) discuss the jet morphology of this SNR, but they focus on the curved features of the jet. Ng & Romani (2007)
measured the angle between the spin and the kick direction of the NS (PSR J0205+6449) to be 21°. The NS motion as we marked it in the upper panel of Figure 10 is according to Bietenholz et al. (2013). The lower panel shows the jets’ axis as was marked by Grichener & Soker (2017).

Figure 7. Upper panel is a composite image of G292.0+1.8 taken from the Chandra gallery and based on Park et al. (2007). Red, orange, green, and blue colors represent different X-ray lines, while white represents the optical band. The middle panel is taken from Holland-Ashford et al. (2017). We copied the white arrow that represents the NS motion to the upper panel. Green arrow is the same as in Figure 1. The lower panel is taken from Bear et al. (2017) to indicate the jets’ axis between the protrusions. We copied the jets’ axis to the upper panel (red double-headed arrow).

Figure 8. Upper panel is a 2.4 GHz radio image of the Vela SNR taken from Gaensler & Slane (2006) and based on Duncan et al. (1996). The cross indicates the location of the associated pulsar B083345, while the white arrow indicates its direction of motion. The second panel is taken from the Max Planck Institute for Radio astronomy newsletter (Pavlov et al. 2008; Noutsos et al. 2012). The third panel is the Vela SNR taken from Grichener & Soker (2017), where the proposed jets’ axis is marked as a line connecting the ears. It is a ROSAT all-sky survey image (0.1–2.4 keV) taken from Aschenbach et al. (1995). We mark the jet direction on the upper panel according to the third panel (Grichener & Soker 2017), so the angle between the jets’ axis and the NS motion will be clearer. The fourth panel is a recent observation of Vela, which suggests a different jets’ axis (García et al. 2017).
The Crab (G184.6−05.8). It was formed by either a Type II or a Type Ib SN (e.g., Polcaro & Martocchia 2006) that exploded in 1054. The upper panel of Figure 11 is taken from Caraveo & Mignani (1999), where they marked the direction of the NS (PSR B0531+21) with a black arrow. The lower panel shows the jets’ axis as was marked by Grichener & Soker (2017), that we copied as a red double-headed arrow to the upper panel. As discussed by Wang et al. (2007), the spin-kick angle of the crab pulsar B0531+21 has previously been considered to be aligned (8°) but now the angle is estimated to be 26° (e.g., Ng & Romani 2006).

W44 (G034.6−00.5). The age and distance of W44 are estimated to be 80,000 years and 3.1 kpc, respectively (e.g., Cardillo et al. 2014 and references therein). The direction of the NS motion is estimated according to the inset in the upper panel of Figure 12 (taken from Gaensler & Slane 2006). As noted by Frail et al. (1996), the synchrotron trail points in a northwest direction, which is opposite to the direction of the NS, and this supports their contention that the pulsar originated close to the geometric center of W44. We mark the general direction of the NS motion with a white dotted arrow in the upper panel. Grichener & Soker (2017) marked the two jets to be in opposite directions but not along the same line, as we show in the lower panel of Figure 12. We take the jets’ axis to be the line connecting the two ears, which we mark with a cyan double-dotted arrow in the upper panel.

3. Analysis

In Figure 13, we present the cumulative distribution function of the projected angle $\alpha$ between the NS kick direction and the jets’ axis. We recall that we assume that the ears are formed by jets and take the direction of each ear as the direction of a jet that inflated the ear (see Section 1). In some SNRs that have no ears, we take the jets’ axis to be along the two opposite bright arcs. The straight orange line in Figure 13 depicts the expected distribution for a random angle (no correlation) between the SN kick and jets’ directions, while the convex blue line represents the expected distribution when, for all objects, the NS kick is perpendicular to the jets’ symmetry axis.

The equation for the convex blue line is derived by projecting the two perpendicular lines (those of the jets’
direction and of the kick direction) onto the plain of the sky, giving each possible orientation in space the appropriate weight. Let \( 0 \leq \theta \leq \pi \) be the angle between the kick direction and the line of sight. The direction of the jets’ axis is in the plane perpendicular to the kick direction. Let \( 0 \leq \phi < \pi \) be the angle of the jets’ axis in that plane, where \( \beta = 0 \) corresponds to the case when the jets’ direction is just behind the kick direction. The relative weight of this position is \( 2 \sin \theta \, d\theta \, d\phi \). The projected angle on the sky between the kick and jets’ axis is given by \( \tan \alpha = \tan \phi / \cos \theta \). Numerically integrating over all possible values of \( \theta \) and \( \phi \) with the appropriate weight, gives the distribution for the perpendicular case.

We performed a Kolmogorov–Smirnov test for the compatibility of the sample of 12 objects with the two distributions. We find the maximum distance on the graph between the observed and expected random distributions to be \( D = 0.2 \). From this, we calculate \( P_r = 0.67 \), namely, there is a chance of 67% that the 12 objects are compatible with the random distribution (straight line). If we remove any of the three objects with the smallest angles \( \alpha \), we find a much lower probability of \( P_r = 0.34 \), while if we remove any of the nine objects with the largest angles we find a higher probability of the random distribution of \( P_r = 0.88 \).

We further did four tests where we remove two systems, leaving 10 systems in the sample. Removing the two systems with angles of \( \alpha = 18^\circ \) and \( \alpha = 80^\circ \) we find the probability for a random distribution to be \( P_r(-18^\circ, -80^\circ) = 0.50 \), and for the other three cases we test with 10 objects we find \( P_r(-18^\circ, -45^\circ) = 0.50 \), \( P_r(-42^\circ, -45^\circ) = 0.91 \), and \( P_r(-42^\circ, -80^\circ) = 0.910 \).

For the compatibility with the perpendicular distribution (lower blue line), we find \( D = 0.33 \) from which we calculate \( P_r = 0.12 \). Namely, we can reject the perpendicular distribution with 88% confidence. If we remove any of the eight objects with the smallest angles, we find a higher probability for the perpendicular distribution of \( P_r = 0.20 \), while if we remove any of the four objects with the largest angles we find \( P_r = 0.04 \). For the four tests where we remove two systems, we find the probability for the perpendicular distribution to be \( P_r(-18^\circ, -80^\circ) = 0.08 \), \( P_r(-18^\circ, -45^\circ) = 0.35 \), \( P_r(-42^\circ, -45^\circ) = 0.35 \), and \( P_r(-42^\circ, -80^\circ) = 0.08 \).

In addition to these two theoretical distributions, we raise a third possibility below. Before we raise this third possibility,
we must emphasize in the strongest possible way that we obtain this distribution from only 12 objects. Therefore, there are very large uncertainties in how the real distribution should look. With many more objects, it might turn out to be a random distribution, or else it might turn out to be more like the perpendicular distribution, which is less likely. Below, we simply assume, with all the caution we can apply, that the cumulative distribution function we find here is close to the real one. Nonetheless, our test of removing one object from the 12, shows that even for any group of 11 objects we do get the same basic distribution. This holds as well, although to a lesser degree, when we leave any 10 objects in the sample. The basic feature in the cumulative distribution function is that, relative to a random distribution, systems are missing for angles of $\alpha \lesssim 15^\circ$.

This is the place to reemphasize that while most previous studies of the kick direction in CCSNe have assumed that the explosion is driven by neutrinos, basically the delayed neutrino mechanism (e.g., Muller (2016), for a recent review), we adopt the jet feedback explosion mechanism (for a review, see Soker (2016b)).

The cumulative distribution function of the angle $\alpha$ has a very interesting pattern. Below about $40^\circ$, it follows a perpendicular distribution. This is mainly because objects with $\alpha \lesssim 15^\circ$ are missing. From about $40^\circ$ to $90^\circ$, it follows the random distribution. In any case, the possibility that the NS kick velocity is parallel to the axis of the jet direction is ruled out.

We can think of two basic types of relations between the kick and the jet directions that can explain the missing objects with low values of $\alpha \lesssim 15^\circ$. In the first possibility, the jets determine the allowed kick direction, while in the second possibility the mechanism that leads to an NS natal kick forces jets in a specific direction.

To demonstrate these, we assume that the kick is formed by dense clumps that are formed by instabilities in the ejecta near the NS (e.g., Scheck et al. 2006; Wongwathanarat et al. 2010). We note that four of the SNRs in our sample (Cassiopeia A, Puppis A, RCW 103, G292.0+1.8) were studied by Katsuda et al. (2018) who find that the kick is due to asymmetrical explosion. The instabilities are likely to result from the standing accretion-shock instability (SASI; see, e.g., Abdkamalov et al. 2015; Fernández 2015; Moreno Méndez and Cantillero 2016; Blondin et al. 2017; Kazeroni et al. 2017), or convective overturn that is formed by neutrino heating (Wongwathanarat et al. 2013). One or more dense clumps that are expelled by the explosion, gravitationally attract the NS and accelerate it, in what is termed the gravitational tug-boat mechanism (Nordhaus et al. 2010; Janka 2017). The gravitational tug-boat mechanism is a relatively long-duration process that lasts several seconds after accretion has ended, and when the dense regions are accelerated from about 100 km to several thousands of kilometers from the origin (Nordhaus et al. 2010; Wongwathanarat et al. 2013; Janka 2017).

Wongwathanarat et al. (2010) find (their Figure 2) for their four models that the angles between the NS spin and the NS kick are in the range of $\approx 50^\circ$–$150^\circ$. Namely, they are more likely to be perpendicular than aligned. Wongwathanarat et al. (2013) find in their simulations that according to the gravitational tug-boat mechanism in the frame of the delayed neutrino explosion mechanism, there is no correlation between the spin and kick directions. Müller et al. (2017) obtain similar results. In their simulation, the NS spin and NS kick start out as almost perpendicular. After further mass accretion onto the newly born NS, the angular momentum axis changes, and the relative angle decreases to $42^\circ$. What they find as the spin of the NS is analog to the general direction of the jets’ axis in the jet feedback explosion mechanism. It is not necessarily the exact jets’ axis because the jets might jitter (see Section 1).

Wongwathanarat et al. (2010, 2013) also find that in the gravitational tug-boat mechanism in the frame of the delayed neutrino mechanism the NS final velocity is opposite to the direction of the maximum explosion strength. Janka (2017) discusses how the ejection of mass along the polar directions (spin-axis) is delayed, and more mass resides there. As a consequence the kick direction tends to align with the angular momentum axis, but only when a strong spiral SASI mode is present. In the jet feedback explosion mechanism, more mass is concentrated at late times in the equatorial regions, and there is no spin-kick alignment.

Let us then return to the two possibilities within the frame of the jet feedback explosion mechanism, where the angular momentum axis of the accreted gas tends to avoid small angles with respect to the direction of concentration of mass in the instabilities. In the first possibility, the pre-collapse core has a non-negligible angular momentum. When it collapses, not much material is accreted onto the neutron star from the polar directions (Papish et al. 2015). Jets are launched in the general direction of the angular momentum axis. Instabilities can lead to a stochastic component of the accreted angular momentum, and the jets might jitter in the vicinity of the angular momentum direction. In any case, the jets further prevent accretion in the vicinity of the polar directions. Dense clumps will not form close to the polar directions, but rather will tend to form closer to the equatorial plane. Hence, the NS kick will not occur close to the polar directions. The direction of the jets and the direction of the NS natal kick will avoid each other.

In the second possibility, the initial angular momentum does not play a significant role. We start with dense clumps and follow the numerical results of Papish & Soker (2014). When dense clumps are accreted to form an accretion disk, the jets tend to be perpendicular to the accretion direction of dense
clumps, and the jets in turn further force accretion perpendicular to their direction of propagation. This behavior leads to a planar jittering-jets pattern (Papish & Soker 2014), where the jets’ symmetry axes of different jet-launching episodes tend to share the same plane. Dense clumps tend to form along directions perpendicular to this plane. If the natal kick is caused by dense clumps, this again causes the NS natal kick direction and the direction of the jets’ axis to avoid each other.

The real situation might be even more complicated. The “jump” from the perpendicular distribution to the random one comes with concentration of objects, basically two extra objects, around $\alpha = 45^\circ$. Due to the small number statistics, we cannot tell whether this effect is real. It might be, however, a real effect if the missing objects at low values of $\alpha$ are not distributed equally at higher values of $\alpha$, but rather are concentrated on the boundary between the “forbidden” and “allowed” regions of $\alpha$.

Overall, the jet feedback explosion mechanism might account for the tentative cumulative distribution function for the angle $\alpha$ that we find in the present study.

4. Summary

We searched the literature for SNRs of CCSNe, where we could both identify morphological features, such as ears, that we can attribute to jets and for which the direction of the NS natal kick was determined. We found 12 such SNRs, which we present in Figures 1–12, and measured the projected (on the plane of the sky) angle between the line connecting the two assumed opposite jets, i.e., the jets’ axis, and the NS kick. We summarized the results in Table 1 and plotted the cumulative distribution function (black line) of the angles in Figure 13. We also plotted there the cumulative distribution functions that are expected from a random distribution (straight orange line) and the distribution expected for a case where the NS kick is always perpendicular to the jets’ axis (convex blue line).

In Section 3, we compared the cumulative distribution function to the distribution expected from a random distribution and to the distribution expected for a case where the NS kick is always perpendicular to the jets’ axis. The cumulative distribution function we find for the 12 SNRs has a 67% chance of being compatible with the random distribution (straight orange line on Figure 13), and 12% of being compatible with the perpendicular distribution (lower convex blue line). The basic feature of the cumulative distribution function is that it fits the random distribution at large angles but is missing systems with small angles relative to the random distribution.

We discussed two possibilities to explain this property, if it is real. Both possibilities assume that dense clumps that are ejected by the explosion accelerate the NS by the gravitational tug-boat mechanism (Wongwathanarat et al. 2013; Janka 2017), and that jets explode the CCSNe (Papish & Soker 2011; Soker 2016b). Basically, the jets prevent the formation of dense clumps along their propagation direction, or the dense zones supply most of the gas to the accretion disk that launches jets more or less perpendicular to the directions of the dense zones.

The motivation behind this study is the jet feedback explosion mechanism of massive stars. According to the jet feedback explosion mechanism, jets that are launched by the newly born NS or black hole drive the explosion of CCSNe. The negative feedback mechanism implies that as long as the jets did not explode the entire core the NS (or black hole if formed) continues to accrete mass from the core. The jets shut themselves off only when they remove the entire core. The last episodes of mass accretion occur while jets have already expelled the core. Therefore, the last jets that the NS (or black hole) launches expand more freely and can leave an imprint on the ejecta. One of the imprints might be two opposite ears in the SNR (Bear et al. 2017; Grichener & Soker 2017).

The main finding of our study is that the jet feedback explosion mechanism, which we consider to be the most promising mechanism to explode all CCSNe, can in principle account for the distribution of angles between the jets’ axis and the NS kick velocity.

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