On neutron star/supernova remnant associations

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Abstract

It is pointed out that a cavity supernova (SN) explosion of a moving massive star could result in a significant offset of the neutron star (NS) birth-place from the geometrical centre of the supernova remnant (SNR). Therefore: a) the high implied transverse velocities of a number of NSs (e.g. PSR B1610-50, PSR B1757-24, SGR 0525-66) could be reduced; b) the proper motion vector of a NS should not necessarily point away from the geometrical centre of the associated SNR; c) the circle of possible NS/SNR associations could be enlarged. An observational test is discussed, which could allow to find the true birth-places of NSs associated with middle-aged SNRs, and thereby to get more reliable estimates of their transverse velocities.

Key words: stars: neutron – ISM: bubbles – supernova remnants

1 Introduction

Though the number of secure associations between NSs and SNRs continues to grow (Caraveo 1993, 1995; Allakhverdiyev et al. 1995, Kaspi 1996, 1998, 2000; Frail 1998; Helfand 1998, Mereghetti 1998, 1999; Marsden et al. 1999), it is considered that many of claimed associations are spurious and are merely the results of superposition (e.g. Gaensler & Johnston 1995a,b; cf. Lorimer, Lyne & Camilo 1998). It were proposed five criteria for the evaluation of possible NS/SNR associations which come to the following questions (Kaspi 1996):
- do independent distance estimates agree?
- do independent age estimates agree?
- is the implied transverse velocity reasonable?
- is there evidence for any interaction between the NS and SNR?
- does the proper motion vector of the NS point away from the SNR centre?

The last question is considered the most important one since ”a proper motion measurement has the potential to disprove an association regardless of the answers to the other questions” (Kaspi 1996).

In this Letter we point out that a cavity SN explosion of a moving massive star could result in a significant offset of the NS birth-place from the geometrical centre of the SNR (Sect. 2). Three important consequences can
be drawn from this: 1) the implied transverse velocity of the NS (i.e. the velocity derived from the displacement of the NS from the geometrical centre of the SNR) could be significantly overestimated; 2) the proper motion vector of the NS should not necessarily point away from the geometrical centre of the associated SNR (it even could be directed to the centre of the SNR!); 3) the circle of possible NS/SNR associations could be enlarged (Sect. 3). These facts are quite obvious, but have been largely overlooked in studies of NS/SNR associations. It is also suggested that the birth-place of a NS could be marked by a nebula of thermal X-ray emission (Sect. 3). The possible detection of such nebulae will allow to get more reliable estimates of transverse velocities of NSs associated with middle-aged SNRs.

2 Off-centred cavity SN explosion

Massive stars (the progenitors of most of SN stars; e.g. van den Berg & Tammann 1991; Tammann, Löffler & Schröder 1994) strongly modify, during their evolution from the main-sequence (MS) to the SN explosion, the ambient medium by ionizing emission and winds, that results in the origin of a system of cavities and shells (Avedisova 1972; Dyson & de Vries 1972; Dyson 1975; Castor, McCray & Weaver 1975; Steigmann, Strittmatter & Williams 1975; Weaver et al. 1977; McCray 1983; McKee, Van Buren & Lazzareff 1984; D’Ercole 1992). The subsequent interaction of the SN blast wave with the reprocessed circumstellar and interstellar medium results in the origin of a SNR (e.g. Fabian, Brinkmann & Stewart 1983; Shull et al. 1985; McKee 1988; Ciotti & D’Ercole 1989; Chevalier & Liang 1989; Chevalier & Emmerting 1989; Franco et al. 1991; McCray 1993; Brighenti & D’Ercole 1994). The structure of a young ($\leq 10^3$ years) SNR is mostly determined by the interaction of the SN blast wave with circumstellar structures created during the late evolutionary stages of the SN progenitor star (e.g. McCray 1993; Garsia-Segura, Langer & Mac Low 1996; Borkowski et al. 1996), while the appearance of a middle-aged SNR could be affected by the interaction of the SN blast wave with large-scale structures created in the interstellar medium by the stellar ionizing emission (the shell of neutral gas around a Strömgren sphere; e.g. Shull et al. 1985) and/or (fast) stellar wind (the density jump at the edge of a stalled wind-driven bubble or the dense large-scale shell swept-up from the interstellar medium by an expanding bubble; e.g. Ciotti
D’Ercole 1989; Franco et al. 1991; D’Ercole 1992; Gvaramadze 1999a,b).

It is clear that the SN explodes in the centre of the system of cavities and shells if the space velocity of the SN progenitor star is equal to zero. In this case the birth-place of the SN stellar remnant (e.g. a NS) coincides with the geometrical centre of the future SNR, and therefore the implied transverse velocity of the stellar remnant is equal to the true one.

But the SN explosion site could be significantly offset from the geometrical centre of large-scale structures created in the reprocessed ambient medium if the massive star moves relative to the interstellar medium (it is known that most of massive stars have a space velocity of a few km s$^{-1}$; e.g. Vanbeveren, De Loore & Van Rensbergen 1998). E.g. a 25 $M_\odot$ star moving with the velocity of 2 km s$^{-1}$ travels from the centre of the MS bubble for about 18 parsecs. The stellar motion does not affect the spherical shape of the bubble (here and below we assume that there is no large-scale density inhomogeneities in the ambient interstellar medium) since the sound speed in the hot interior of the bubble is about two orders of magnitude larger than the velocity of the star (e.g. Weaver et al. 1977). Correspondingly, the (middle-aged) SNR also acquires the spherical shape even if the SN exploded far from the centre of the wind-driven bubble (e.g. Różycka et al. 1993). The off-centred cavity SN explosion results, however, in the inhomogeneous distribution of the surface brightness over the SNR’s shell, that could explain the arc-like appearance of some of middle-aged SNRs (see Różycka et al. 1993, Brighenti & D’Ercole 1994). Note that the standard explanation of the origin of incomplete shells implies the interaction of the (Sedov-Taylor) blast wave with the inhomogeneous (e.g. cloudy) interstellar medium. Therefore, the non-detection of a dense large-scale cloud nearby to the arc-like SNR could serve as an indirect evidence that this SNR is generated by a moving massive star (cf. Brighenti & D’Ercole 1994). The anonymous referee mentioned that ”the direction of motion of the NS ought to depend on its location relative to the bright part of the shell”. This is correct, however, only in the absence of other factors affecting the brightness distribution over the SNR’s shell. The existence of large-scale density gradients in the interstellar medium and/or magnetized wind-driven shells leads to the more complex appearance of SNRs (see e.g. Gvaramadze 1999b), and therefore the enhanced brightness of a part of the shell not necessarily ought to be due to the proximity of the SN explosion site. The detailed study of this important issue is beyond the scope of this Letter and will be carried out elsewhere.
It should be mentioned that only a fraction of middle-aged and old SNRs is the result of cavity SN explosions. Indeed, one can show (e.g. Brighenti & D’Ercole 1994) that only slowly moving (1 − 2 km s\(^{-1}\)) and/or very massive stars explode inside the wind-driven bubbles created during the MS stage of their evolution. But even if a massive star is fast enough to cross the stalled MS bubble it could again find itself in the bubble interior if it ends its evolution as a red supergiant (RSG) star (i.e. if the zero age main sequence mass of the star is ≤ 15 − 20 \(M_\odot\); e.g. Vanbeveren et al. 1998). During the RSG stage the stalled bubble can re-expand (D’Ercole 1992) and catch up the moving star, provided that there are no external sources of ionizing emission. The high-velocity massive stars also could explode inside the large-scale bubbles, but this happens only for stars whose mass ≥ 15 − 20 \(M_\odot\). In this case, a massive star before it exploded as a SN becomes a Wolf-Rayet (WR) star (e.g. Vanbeveren et al. 1998), whose fast wind blows up a new large-scale bubble surrounded by a dense shell. And again, the proper motion of the WR star results in the significant offset of the SN explosion site from the centre of the wind-driven bubble. E.g. for the duration of the WR stage of ≃ 2 − 3 \times 10^5 \text{ yr} and the stellar velocity of 30 km s\(^{-1}\) the SN explosion site will be displaced from the centre of the bubble for about 6 − 9 pc (see Arnal 1992 for examples of non-central location of WR stars in bubbles created by their winds). On the other hand, most of massive stars are less massive than 15 \(M_\odot\), and therefore do not evolve through the WR stage before the SN explosion. Thus, if a massive star of mass < 15 \(M_\odot\) is fast enough to cross the MS bubble before it exploded as a SN, the SN blast wave mainly interacts with the unperturbed interstellar medium and the SN explosion site coincides with the geometrical centre of the resulting (middle-aged) SNR. In this case the shell of the SNR could appear as an incomplete circle, that is due to the presence of a low-density tunnel created by the stellar wind behind the moving star (see Brighenti & D’Ercole 1994).

It follows from the above discussion that though many of SNRs are produced by SN explosions outside of large-scale wind-driven bubbles (and therefore their structure could be described in the framework of the standard model based on the Sedov-Taylor solution), there are could exist SNRs whose origin is connected with off-centred cavity SN explosions\(^2\). Therefore the high

\(^2\)Though the knowledge of the fraction of these SNRs is very important for statistical studies of NS/SNR associations, we are now not in a position to quantify it. Two main
transverse velocities inferred for a number of NSs through their association with SNRs could be reduced (see next Sect.). The velocity reduction could be large enough for NSs associated with middle-aged and old SNRs, i.e. the SNRs whose origin could be connected with the interaction of SN blast waves with large-scale structures created by the fast stellar wind, and where the SN explosion sites could be significantly offset from the centres of the wind-driven bubbles. But the velocity reduction should be less considerable in the case of young (< \(10^3\) years) SNRs, whose appearance is mostly determined by the interaction of SN blast waves with circumstellar (i.e. small-scale) structures created during the late (RSG and WR) evolutionary stages of SN progenitor stars (see Sect. 3). These stages are significantly shorter than the MS stage and only sufficiently fast stars have time to became significantly displaced from the centres of associated circumstellar structures. Therefore, the geometrical centres of young SNRs better correspond to the SN explosion sites, that explains the quite symmetric appearance of these SNRs (a marked exception is the Kepler’s SNR, whose asymmetric shell is due to the very fast motion of the SN progenitor star (Bandiera 1987)). But even the slow motion of the SN progenitor star results in an appreciable asymmetry of circumstellar structures (e.g. the mass distribution over the nearly spherical circumstellar shell becomes inhomogeneous), that, for instance, results in the asymmetric expansion of young SNRs. A good example of such a young SNR is the Cas A. A compact X-ray source was recently discovered near the geometrical centre of this SNR (Tananbaum 1999). The implied transverse velocity of the compact source derived through the various determinations of the expansion centre of Cas A (e.g. van den Berg & Kamper 1983, Reed et al. 1995) ranges from 50 to 1000 km s\(^{-1}\) (Pavlov et al. 2000). We suggest that the separation of the SN explosion site (and the compact source) from the geometrical centre of Cas A could be caused to a large extent by the proper motion of the SN progenitor star. This motion (with the velocity less than the velocity of the RSG wind) will result in the deviation from spherical (or axialal) symmetry of the circumstellar matter, that in its turn could be responsible for the observed (see Vink et al. 1998, and references therein)
expansion asymmetry of Cas A.

3 Discussion

In Sect. 2 we showed that the large displacement of a NS from the geometrical centre of the associated SNR does not inevitably mean that this NS is moving with high transverse velocity. This could have an important impact on the understanding of the origin of the phenomenon of anomalous X-ray pulsars and soft gamma-ray repeaters (SGRs) since the high implied velocities of some of these objects were interpreted as a sign that they represent a high-velocity ($\sim 1000$ km s$^{-1}$) population of NSs (e.g. Thompson & Duncan 1995; Marsden et al. 1999). It seems that the recent association of two of known SGRs with clusters of massive stars (Fuchs et al. 1999, Vrba et al. 2000) should reduce the acuteness of the problem of high implied velocities of these objects, but the large angular offset of the SGR 0525-66 from the centre of the nearly spherical (in X-rays) SNR N 49 in LMC (e.g. Rothschild, Kulkarni & Lingenfelter 1994) still continues to raise doubts in the association of these two objects (e.g. Kaspi 2000, Kaplan et al. 2001). Note also that the high transverse velocities derived by Frail, Goss & Whiteoak (1994) for pulsars associated with SNRs were used to put forward a number of quite strong suggestions, e.g. that ”SNRs are produced preferentially by the (SN) explosions that yield fast kicks” (Cordes & Chernoff 1998).

The high implied transverse velocities of NSs are sometimes used to discard the possible NS/SNR associations. E.g. Stappers, Gaensler & Johnston (1999) suggested that the lack of a pulsar wind radio nebula around the PSR B 1610-50 means that the maximum space velocity $v_p$ of this pulsar is $450 (d/5$ kpc)$\text{km s}^{-1}$, where $d$ is the distance to the pulsar, and therefore it could not be associated with the nearby SNR Kes 32 since this association implies the transverse velocity of the pulsar of $\approx 2000$ km s$^{-1}$ (Caraveo 1993). The implied transverse velocity, however, could be reduced two times simply due to the possible off-centred SN explosion, and once again two or even more times if the braking index of the pulsar is similar respectively to that of the PSR B 0540-69 (Boyd et al. 1995) or the Vela pulsar (Lyne et al. 1996).

The association of PSR B 1610-50 with SNR Kes 32 was also recently questioned by Pivovaroff, Kaspi & Gotthelf (2000). They used the non-detection of an X-ray nebula around the PSR B 1610-50 to estimate $v_p$ to be
less than $170 \left(\frac{d}{7.3 \text{kpc}}\right)^2 \left(\frac{n}{1 \text{cm}^{-3}}\right)^{-1/2} \text{km s}^{-1}$. This estimate was derived under the assumption that the wind of the PSR B1610-50 has the same characteristics as that of the Crab pulsar, and for the number density of the ambient medium $n = 1 \text{cm}^{-3}$. One can, however, show that reasonable variations of the assumed parameters allow to increase the estimated velocity of the pulsar. E.g. for $n \leq 10^{-2} \text{cm}^{-3}$ and $d = 5 \text{kpc}$ (Stappers et al. 1999), one has $v_p \leq 780 \text{km s}^{-1}$.

The high transverse velocity was also inferred for the pulsar PSR B1757-24, which lies well outside the shell of the SNR G5.4-1.2 (e.g. Caswell et al. 1987). The physical association of these two objects was firmly established after the discovery (Frail & Kulkarni 1991; see also Manchester et al. 1991) of a tail of radio emission connecting the pulsar with the SNR. The pulsar PSR B1757-24 is, however, more interesting in that that its proper motion vector does not point away from the geometrical centre of the nearly circular shell of the remnant (the radius of which is about 16 arcmin), but misses it by nearly 5 arcmin (Frail, Kassim & Weiler 1994). To explain this inconsistency, Frail et al. (1994) suggested that the SN exploded in an exponentially stratified medium and used the Kompaneets (1960) solution to fit the shape of the remnant. This allowed them to put the possible SN explosion site closer to the present position of the pulsar, that reduces the implied velocity of the pulsar to the value between 1300 and 1700 km s$^{-1}$. We propose an alternative explanation and suggest that the SNR G5.4-1.2 is the result of the off-centred SN explosion in the pre-existing wind-driven bubble surrounded by a massive shell (Gvaramadze, in preparation). This suggestion allows to reduce considerably the transverse velocity of the pulsar and naturally explains why the tail behind the pulsar does not point back to the centre of the remnant. An indirect support of our suggestion comes from the recent observations of the radio nebula surrounding the pulsar (Gaensler & Frail 2000). These observations put an upper limit on the pulsar proper motion, which turns out to be much smaller than that expected if the pulsar velocity

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3The mass of the shell is a very important parameter since it determines the evolution of the SNR. If the mass of the shell is larger than about 50 times the mass of the SN ejecta (e.g. Franco et al. 1991), the SN blast wave merges with the shell and evolves into a momentum-conserving stage (i.e. it skips the Sedov-Taylor stage). In this case, even a young NS moving with a moderate velocity ($\geq 200 \text{km s}^{-1}$) is able to overrun the SNR’s shell (cf. Gaensler & Johnston 1995a), provided that it was born not far from the edge of the wind-driven bubble.
is indeed in the range derived by Frail et al. (1994). Assuming that the pulsar was born in the geometrical centre of the associated SNR, Gaensler & Frail (2000) argued that the true age of the pulsar should be more than 10 times larger than the characteristic age (cf. Istomin 1994). The off-centred cavity SN explosion provides another possible explanation for the low value of the pulsar proper motion.

Let us discuss the third criterion for the evaluation of NS/SNR associations suggested by Kaspi (1996). There are three factors which could affect the estimates of the characteristic age of a NS (e.g. Camilo 1996). First, the braking index could be different from that follows from the simplest spindown models (see e.g. Lyne et al. 1993, Kaspi et al. 1997, Marshall et al. 1998). Second, the NS could be born with the large initial spin period (e.g. Spruit & Phinney 1998), and therefore the true age could be much smaller than the characteristic one. Third, the spindown torque (as well as the braking index) could be a function of time. E.g. if the spindown of a NS is due to the magnetic dipole radiation, than the secular increase of the magnetic moment of the NS results in the increase of the braking torque (e.g. Blandford & Romani 1988). The spindown rate of a NS could be also enhanced due to the interaction of its magnetosphere with the dense ambient medium (Istomin 1994, Yusifov et al. 1995, Gvaramadze 1999c, 2001, Menou, Perna & Hernquist 2001). In both cases the true age of the NS could be much larger than the characteristic age derived from the present value of the spin period derivative. These arguments were used to reconcile the ages of the pulsar PSR B 1509-58 and the associated SNR MSH 15-52 (Blandford & Romani 1988, Gvaramadze 1999c, 2001), or to show that the implied transverse velocity of the pulsar PSR B 1757-24 could be reduced (Istomin 1994).

In Gvaramadze (1999c, 2001) we suggested that the high spin-down rate of the pulsar PSR B 1509-58 is inherent only for a relatively short period of its present spin history, and that the enhanced braking torque is caused by the interaction of the pulsar’s magnetosphere with the material of a dense circumstellar clump created during the late stages of evolution of the SN progenitor star. The origin of dense circumstellar clumps could be explained in the framework of the three-wind model (e.g. Garsia-Segura et al. 1996). The fast (WR) wind sweeps the slow (RSG) wind and creates a low-density cavity surrounded by a shell of swept-up circumstellar matter. This shell expands with the nearly constant velocity \( v_{\text{sh}} \approx (M_{\text{WR}}v_{\text{WR}}^2 \rho_{\text{RSG}}/3M_{\text{RSG}})^{1/3} \), where \( M_{\text{WR}}, M_{\text{RSG}} \) and \( v_{\text{WR}}, v_{\text{RSG}} \) are, correspondingly, the mass-loss rates
and wind velocities during the WR and RSG stages (e.g. Dyson 1981), until it catches up the shell separating the RSG wind from the MS bubble (the characteristic radius of this shell is a few pc; the high-pressure gas of the MS bubble interior hinders the free expansion of the RSG wind (e.g. Chevalier & Emmering 1989, D’Ercole 1992)). The interaction of two circumstellar shells results in the Rayleigh-Taylor and other dynamical instabilities, whose development is accompanied by the formation of dense clumps moving with radial velocities of $v_{cl} \simeq v_{sh}$ (Garsia-Segura et al. 1996). For parameters typical for RSG and WR winds, one has $v_{cl} \simeq 100 - 200 \text{ km s}^{-1}$. The radial velocity of quasi-stationary flocculy in Cas A (whose origin could be attributed to the processes discussed above; e.g. Garsia-Segura et al. 1996) ranges from $\simeq 80$ to $\simeq 400 \text{ km s}^{-1}$. The dense clumps could originate much closer to the SN progenitor star due to the stellar wind acceleration during the transition from the RSG to the WR stage (Brighenti & D’Ercole 1997). After the SN exploded, the SN blast wave propagates through the tenuous interclump medium, leaving behind the dense clumps embedded in the hot shocked interclump gas (the filling factor of the clumps is small (e.g. Gvaramadze 2001) and therefore they do not affect considerably the dynamics of the SN blast wave). The gradual evaporation of the dense material of radially moving clumps results in the origin of an expanding nebula of thermal X-ray emission, which marks the SN explosion site.

It is clear from the above discussion that the nebulae of thermal X-ray emission should exist only in those SNRs, whose origin is connected with explosions of massive stars with zero age main sequence mass $\geq 15 - 20 M_{\odot}$ (only in these cases one can expect that the (clumpy) circumstellar material will survive the passage of the SN blast wave). It is clear also that the motion of the SN progenitor star could result in a significant offset of the compact region of dense circumstellar matter from the centre of the MS bubble (the RSG and WR stages are about 10-20 times shorter than the MS stage), and correspondingly in the offset of the nebula of thermal X-ray emission from the geometrical centre of the associated middle-aged SNR. The possible detection of such nebulae will provide the direct observational test for our proposal, and could be used for the re-estimation of transverse velocities of the already known NSs, or for the search of new stellar remnants possibly associated with these SNRs.

To find a crude order of magnitude estimate of the luminosity of the nebula of thermal X-ray emission, we assume that all the X-ray emitting
interclump material (including the gas already evaporated from the clumps) is at the same temperature between $10^7$ and $10^8$ K, and that this material is uniformly dispersed over a sphere of radius $R = R_0 + v_{cl} t_{SNR}$, where $R_0 (\approx 1 - 2$ pc) is the radius of the region occupied by dense clumps at the moment of SN explosion, $t_{SNR}$ is the age of the SNR, then one has $L_x \approx 1.2 \times 10^{33} n^2 R_{pc}^3 \text{ergs s}^{-1}$, where $n$ is the number density of the emitting gas, $R_{pc} = R/1$ pc (Gorenstein & Tucker 1976). For $R_0 = 2$ pc, $v_{cl} = 100 \text{km s}^{-1}$ and $t_{SNR} = 10^4$ years, and assuming that the mass of the emitting gas is $\approx 5M_\odot$ (i.e. about a half of the mass lost by a $15M_\odot$ star during the RSG stage), one has $R \approx 3$ pc and $L_x \approx 4 \times 10^{34}$ ergs s$^{-1}$. The similar estimates were used by Gvaramadze (1999a) to show that the nebula of hard X-ray emission found by Willmore et al. (1992) around the Vela pulsar could be the dense material lost by the SN progenitor star in the form of the RSG wind and heated to the observed temperature after the SN exploded. The more detailed analysis of this problem constitutes a part of a project underway to study the origin of mixed-morphology SNRs (Rho & Petre 1998) and will be published elsewhere (for a different point of view see e.g. White & Long 1991 and Petruk 2000).

In conclusion we note that in Gvaramadze (1999c) we interpreted a bright X-ray spot (which nearly coincides with the error box for the SGR 0525-66; Rothschild et al. 1994) on the periphery of the SNR N 49 as an X-ray nebula marking the SN explosion site and suggested that the large implied transverse velocity of the NS associated with the SGR could be reduced about ten times. In our analysis we assumed that the spot is a thermal feature (cf. Dickel et al. 1995) and that the radius of the spot is about $5'' - 10''$ (i.e. $\approx 1 - 2$ pc; see Rothschild et al. 1994 and Dickel et al. 1995). We found that to explain the X-ray luminocity of the spot of $\approx 10^{36}$ ergs s$^{-1}$ (Rothschild et al. 1994), the mass of the X-ray emitting gas should be in a range $4 - 10 M_\odot$ (i.e. a reasonable value, provided that the zero age main sequence mass of the SN progenitor star was $\geq 15M_\odot$). However, recent high-resolution Chandra X-ray Observatory observations of the X-ray spot in N 49 (Kaplan et al. 2001 and references therein) showed that this source is pointlike and could be considered as the X-ray counterpart of SGR 0525-66. Though this result discards our interpretation of the spot as an X-ray nebula, we believe that the large angular displacement of SGR 0525-66 from the centre of N 49 is due to the effect discussed in this Letter.
4 Summary

A cavity SN explosion of a moving massive star could result in a significant offset of the NS birth-place from the centre of the nearly spherical middle-aged SNR. Therefore: a) the high transverse velocities inferred for a number of NSs (e.g. PSR B1610-50, PSR B1757-24, SGR 0525-66) through their association with SNRs could be reduced; b) the proper motion vector of the NS should not necessarily point away from the geometrical centre of the associated SNR. These two facts allow to enlarge the circle of possible NS/SNR associations and should be taken into account in evaluating of their reliability. The birth-place of the NS could be marked by a (compact) nebula of thermal X-ray emission. The discovery of such nebulae in middle-aged SNRs could be used for the re-estimation of transverse velocities of the already known NSs, or for the search of new stellar remnants possibly associated with these SNRs.

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