How Does the Stellar Wind Influence the Radio Morphology of a Supernova Remnant?

M. F. Zhang\textsuperscript{1,2}, W. W. Tian\textsuperscript{1,2}, and D. Wu\textsuperscript{1}

\textsuperscript{1} Key Laboratory of Optical Astronomy, National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, People’s Republic of China
zmf@bao.ac.cn

\textsuperscript{2} University of Chinese Academy of Sciences, 19A Yuquan Road, Shijingshan District, Beijing 100049, People’s Republic of China

Abstract

We simulate the evolution of the stellar wind and the supernova remnant (SNR) originating from a runaway massive star in a uniform Galactic environment based on three-dimensional magnetohydrodynamics models. Taking the stellar wind into consideration, we can explain the radio morphologies of many SNRs. The directions of the kinematic velocity of the progenitor, the magnetic field, and the line of sight are the most important factors influencing the morphologies. If the velocity is perpendicular to the magnetic field, the simulation will give us two different unilateral SNRs and a bilateral symmetric SNR. If the velocity is parallel to the magnetic field, we obtain a bilateral asymmetric SNR and a quasi-circular SNR. Our simulations show the stellar wind plays a key role in the radio evolution of an SNR, which implies that the Galactic global density and magnetic field distribution play a secondary role.

Key words: ISM: magnetic fields – ISM: supernova remnants – magnetohydrodynamics (MHD)

Supporting material: animation

1. Introduction

When a massive star dies, it then forms a supernova remnant (SNR). This process produces heavy elements, dust, and cosmic rays, which have an important impact on the Galactic interstellar medium (ISM). To understand this process, we need to study the evolution of SNRs. Truelove & McKee (1999) and Cioffi et al. (1988) performed many analytical and numerical calculations regarding SNR evolution. Comparing the results with observations, they developed a practical model. However, the diverse surrounding environment usually influences the evolution of SNRs. As a result, their radio morphologies are varied. The practical model can explain some regular morphologies, such as bilateral symmetric and circular SNRs, but is powerless to explain more complex morphologies. The latter can help us infer some important properties of SNRs, so it is important to study them in detail.

Numerical simulation is an effective method to describe the surrounding environment and obtain the evolution images of an SNR at different phases. With improvements in computation ability, two-dimensional (2D) hydrodynamics (HD) simulations are effective in studying the magnetic amplification, diffusive shock acceleration, and instability of SNRs (Jun & Norman 1996; Kang & Jones 2006; Fang & Zhang 2012). We can now perform three-dimensional (3D) simulations, and convert the results to radio, optical, or X-ray images to compare with observations (Orlando et al. 2007; Meyer et al. 2015; Zhang et al. 2017). Orlando et al. (2007) tried to explain the asymmetric morphologies of some bilateral SNRs by assuming an inhomogeneous density and magnetic field. They simulated some asymmetric structures in SNRs, but did not describe how the assumed surrounding environment is formed around them. West et al. (2016) suggested the surrounding environment is mainly influenced by the Galactic global ISM distribution and applied a magnetohydrodynamic (MHD) simulation to study the Galactic magnetic field model. They partly explained the surrounding environment assumed by Orlando et al. (2007), but could not accurately simulate many asymmetric structures.

Thus, there is probably another factor influencing the environment.

This factor is possibly the stellar wind of the progenitor. The progenitor runs in the ISM and blows a stellar wind bubble, which leads to an inhomogeneous density distribution and magnetic field structure. This certainly influences the subsequent remnant’s evolution and its radio morphology when a supernova explodes in such a bubble. This assumption is self-consistent and supported by theoretical calculations and observations (Chen et al. 1995; Zhang et al. 1996; Foster et al. 2004; Lee et al. 2010). Meyer et al. (2015) simulated the stellar wind, then took the result as the initial condition of the SNR simulation. They concluded that the stellar wind will strongly shape the density distribution of the SNR. They only performed 2D HD simulations and did not obtain radio images. The crucial parameters of the 3D MHD simulation include the density and magnetic field of the ISM, the spatial velocity and stellar wind of the progenitor, and the explosion energy and mass of the supernova. It is currently impossible to test all combinations of these. In particular, there are two vectorial parameters, the magnetic field of the ISM and the velocity of the progenitor. Each vector has three components, which largely complicates the conditions that one has to take into account for the 3D simulation.

We present a 3D MHD simulation where these parameters are fixed apart from the relative directions of the magnetic field and the velocity of the progenitor. We perform two simulations, one for the magnetic field perpendicular to the velocity, the other for the field parallel to the velocity. We refer to the former as perpendicular simulation and the latter as parallel simulation. Using canonical values of a massive star, we can obtain many radio morphologies of SNRs based on this simplification. We also take into account different types of SNRs, so that we can better understand our simulation results.

In Section 2, we describe the simulation model and list the parameters we use. In Section 3, we present and discuss the results. Section 4 contains a summary.
2. Simulation Model

The simulation model is based on a 3D MHD frame with a grid of $128 \times 128 \times 128$. The spatial scale is set to $60 \, \text{pc} \times 60 \, \text{pc} \times 60 \, \text{pc}$, i.e., its resolution is $0.47 \, \text{pc} \, \text{pixel}^{-1}$. Viscosity and gravitation have little influence on the simulation, so we ignore them. The cooling and heating effect mainly influences the luminosity of optical and X-ray radiation, and we mainly focus radio radiation, so these are not included in the simulation. In a stellar wind simulation, thermal conduction is an important process (Meyer et al. 2014b) which can govern the shape, size, and structure of the stellar wind. However, it is not the dominant factor in the SNR simulation, so we only discuss its influence in the perpendicular scenario. The simulation is based on the ideal conservation equation set:

\[
\begin{align*}
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) &= 0, \\
\frac{\partial \rho \mathbf{v}}{\partial t} + \nabla \cdot (\rho \mathbf{v} \mathbf{v} - \mathbf{B} \mathbf{B}) + \nabla P^* &= 0, \\
\frac{\partial E}{\partial t} + \nabla \cdot [(E + P^*) \mathbf{v} - \mathbf{B} (\mathbf{v} \cdot \mathbf{B})] &= 0, \\
\frac{\partial \mathbf{B}}{\partial t} + \nabla \times (\mathbf{v} \times \mathbf{B}) &= 0,
\end{align*}
\]

in which $\rho$ is mass density, $\mathbf{v}$ is velocity, $\mathbf{B}$ is magnetic field intensity, $P^*$ is total pressure, and $E$ is total energy density.

The simulation contains two models, the stellar wind model and the SNR model. First we simulate the evolution of the stellar wind, and the results are taken as the initial conditions in the SNR simulation. Then we perform the SNR simulation and convert the results to relative radio density images. Finally, we compare the simulation radio images with the observed radio images.

We perform the simulations using the code PLUTO\(^3\) (Mignone et al. 2007, 2012), and summarize the parameters in Table 1. Those without references are our estimated canonical values.

| Parameters                        | Value       | References                  |
|-----------------------------------|-------------|-----------------------------|
| Progenitor velocity               | 40 km s\(^{-1}\) | 1                           |
| Mass-loss rate                    | $3 \times 10^{-6} \, M_\odot \, \text{yr}^{-1}$ | 2                           |
| Stellar wind velocity             | 800 km s\(^{-1}\) | 2                           |
| Stellar wind Density              | 0.05 cm\(^{-3}\) | 2                           |
| Inner radius                      | 0.5 pc      | ...                         |
| Evolution time                    | 10\(^6\) yr | 1                           |
| Ejecta mass                       | 15.3 $M_\odot$ | 3                           |
| Initial explosion energy          | $1.3 \times 10^{51}$ erg | 4, 5                      |
| Initial radius                    | 4 pc        | ...                         |
| Initial time                      | 650 yr      | 6                           |

Other Parameters

| Parameters                        | Value       | References                  |
|-----------------------------------|-------------|-----------------------------|
| Mean density                      | 0.5 cm\(^{-3}\) | 7, 8                      |
| Magnetic field intensity          | $9 \, \mu \text{G}$ | 9                           |
| Mean atomic weight                | 1.3         | ...                         |
| Adiabatic coefficient             | 1.7         | ...                         |
| Synchrotron index ($\beta$)       | 0.5         | ...                         |

References. (1) Meyer et al. (2014b); (2) Meyer et al. (2015); (3) Sukhbold et al. (2016); (4) Poznanski (2013); (5) Müller et al. (2016); (6) Leahy & Williams (2017); (7) Nakanishi & Sofue (2006); (8) Nakanishi & Sofue (2016); (9) Haverkorn (2015).

2.1. The Stellar Wind Model

How the stellar winds of runaway massive stars evolve is still an unsolved problem, so we only use a reasonable simplified model. If the stellar winds clearly influence the SNRs, their spatial scales should be similar. The typical diameters of SNRs are usually several parsecs (pc). Meyer et al. (2014b) showed that the mass of a star should be at least $40 \, M_\odot$ to reach this scale, if its speed is $40 \, \text{km} \, \text{s}^{-1}$. Lower mass means lower speed (Mackey et al. 2015), but lower speed means lower asymmetry, which is inconsistent with the aim of this paper. We therefore choose $40 \, M_\odot$ and $40 \, \text{km} \, \text{s}^{-1}$ as the initial parameters in our simulation. It is known that the star’s lifetime is composed of the main sequence and the red supergiant phase. However, our tests show the stellar wind in the main sequence phase has little impact on the evolution of an SNR, so we only simulate it for the last $10^6\, \text{yr}$.

The mass loss of a $40 \, M_\odot$ star usually varies from $1 \times 10^{-6}$ to $1 \times 10^{-5} \, M_\odot \, \text{yr}^{-1}$ during the last $10^6\, \text{yr}$ of the star’s life (van Marle et al. 2012, 2015; Meyer et al. 2014b), so we use a mass-loss rate of $3 \times 10^{-6} \, M_\odot \, \text{yr}^{-1}$ for simplicity. Here we caution readers that it is not realistic to accurately estimate the mass-loss rate of a massive star to this extent (Gvaramadze et al. 2014; Meyer et al. 2014a). Also, we set the inner radius as $0.5\, \text{pc}$, i.e., the stellar wind is generated from this small region in the simulation. This radius is large enough to guarantee the wind blows spherically in the square grid of the numerical simulation and small enough to be consistent with the simplified stellar wind model. The mass-loss rate $M$, inner radius $r$, velocity $v$, and mass density $\rho$ of the stellar wind are linked by

\[
M = 4 \pi r^2 \rho v. \tag{2}
\]

The initial velocity of the stellar wind originating from the progenitor will not change over $0.5\, \text{pc}$ if we assume it propagates freely in such a short radius. Then the velocity should be about $800 \, \text{km} \, \text{s}^{-1}$ and the density about $0.05 \, \text{cm}^{-3}$ (Meyer et al. 2014b).

We set the initial surrounding environment before the stellar wind evolution. We assume the ISM is an ideal gas, where the mean atomic weight is 1.3 and the adiabatic coefficient is 1.7. We set a uniform magnetic field of $9 \, \mu \text{G}$ (Haverkorn 2015) and a uniform ISM number density of $0.5 \, \text{cm}^{-3}$ (Nakanishi & Sofue 2006, 2016), the typical values of the Galactic ISM. The environment is usually inhomogeneous, which will result in a more complex radio morphology in the simulation. However, we only want to test how the SNRs are influenced by the stellar winds, so we use a homogeneous ISM in this work.

2.2. The SNR Model

The evolution of an SNR is divided into three phases, the ejecta-dominated (ED) phase, the Sedov–Taylor (ST) phase, and the pressure-driven snowplow (PDS) phase (Truelove & McKee 1999). The first two phases are classified as “nonradiative,” but radiative loss becomes important in the

3 http://plutocode.ph.unibo.it/
PDS phase. Our simulations only cover the first two phases, so we do not need to estimate radiative loss. For a 40 $M_e$ star, the ejecta mass is about 15.3 $M_\odot$ (Suhrboid et al. 2016) and the explosion energy is about $3.6 \times 10^{51}$ erg according to the function (Poznanski 2013; Müller et al. 2016),

$$\log(E/10^{50} \text{ erg}) = 2.09 \log(M_\odot/M_e) - 1.78. \quad (3)$$

To simulate a spherically symmetric explosion, we set an initial radius of 4 pc. The shock wave of the supernova explosion will take 650 yr to reach 4 pc. Because the ST phase starts from 1365 yr for such a star (Leahy & Williams 2017), it is still in the ED phase. Therefore, we can obtain the 650 yr evolution directly from existing theory (Truelove & McKee 1999), which gives the density, pressure, and velocity profiles. The magnetic field is not important at this time, so we ignore it. In short, the initial conditions are the evolution results after 650 yr.

Next we start to simulate the evolution of an SNR in the surrounding environment blown by the stellar wind. Our simulation shows the density, magnetic field, velocity, and pressure in the whole simulation space. We convert these results into radio images to compare with real observations.

Assuming the radio emission is totally from the synchrotron mechanism, we obtain the radio flux volume density by employing $i(\nu) = C \rho B_\perp^{\alpha+1}$ (Orlando et al. 2007), in which $\nu$ is the radiation frequency, $C$ a constant, $\rho$ the density, $B_\perp$ the magnetic field perpendicular to the line of sight (LoS), and $\alpha$ the synchrotron spectral index. The absolute radio flux density is dependent on the constant $C$, but $C$ contains the electron acceleration efficiency, which is difficult to obtain. Moreover, $\nu^{\alpha-\beta}$ is also excluded from the equation since it is meaningless if we do not want to calculate the absolute radio flux density. As a result, the final equation used in this work is $i(\nu) = \rho B_\perp^{\alpha+1}$. Then we integrate $i(\nu)$ along the LoS to obtain relative radio flux density. The resolution of the simulation is usually higher than that of the observation, so we smooth the simulation radio images using a 2D Gaussian function with $\sigma = 1$.

3. Results and Discussion

We give the results and compare them with the observations in this section.

Based on West et al.’s (2016) collection of all radio SNR images, we classify the SNRs into seven types: unilateral small-radian, unilateral large-radian, bilateral symmetric, bilateral asymmetric, multi-layer, circular, and irregular. A multi-layer SNR means there are two or more layers on one or two sides. Typical multi-layer, circular, and irregular SNRs are shown in Figure 1. The statistics of the seven types are listed in Table 2. We only select 288 SNRs in these statistics, because the other images are obscure. However, we list all samples except for the irregular type for convenience.

3.1. Perpendicular Simulation

The perpendicular simulation is shown in Figure 2. The top panels show the initial conditions in three directions. The simulation is composed of two parts: the surrounding environment and the inner supernova explosion region. The surrounding environment results from the stellar wind evolution and the inner region’s physics status is calculated based on the work of Leahy & Williams (2017). The initial magnetic field and the progenitor velocity are set to follow the $y$-axis and $z$-axis respectively. This leads to an obvious bow structure in the $y-z$ plane and the very chaotic magnetic field in the $x-z$ plane. To clarify the patterns, the white arrows and colors are set with different scales in different images. The values labeled on the color bar are absolute, so they can be used to compare the densities in different images.

The second row of Figure 2 shows the SNR simulation results after 1200 yr. If we add the initial 650 yr, then the age of this artificial SNR is 1850 yr. The radio morphologies, shown in the third row, are a little surprising, especially in the $x-z$ plane. Our simulations simultaneously result in bilateral symmetric, unilateral large-radian, and small-radian SNRs. As a comparison, three real SNRs (West et al. 2016) are shown in the bottom panels of Figure 2. This proves that three kinds of SNRs may originate from the same progenitor, and their morphologies depend on the view angle at which we see them. Bilateral symmetric SNRs have been well studied by simulations and observations (Gaensler et al. 1999; Petruk et al. 2009), but there are still many ambiguities for unilateral SNRs. Here we show the images toward three directions, but in fact the SNR morphology varies following different view angles.

We take SNR G116.9+0.2 as an example. If we rotate 45° along the $z$-axis, we get a unilateral larger-radian morphology SNR in the $z-xy$ plane (see Figure 3), which is similar to that of G116.9+0.2. Moreover, the magnetic field of G116.9+0.2 is parallel to the shell (Sun et al. 2011) in the polarization observation, which is totally different from the result in the $x-z$ plane. However, if we rotate 45° along the $z$-axis, the magnetic field becomes similar to the observation (see Figure 4). The X-ray emission region of G116.9+0.2 is extended away from

![Figure 1](image-url)
the radio shell (Pannuti et al. 2010), which is also revealed by our simulation (see Figure 5). In the left panel of Figure 5, the bottom high-temperature region is low density comparing with the middle panel of the second row of Figure 2, which hints it is a high-temperature, low-density region full of ionized gas. This is an appropriate environment to generate X-ray emission by bremsstrahlung. Therefore it is possible that the high speed of the progenitor leads to extensive X-ray emission. Craig et al. (2015) obtained similar radio morphologies based on inhomogeneous field evolution around the SNR. The radio morphology should not be used to infer the motion of the progenitor into consideration and successfully explained the morphology of the Kepler SNR by including the magnetic field evolution in the equation of motion. Craig et al. (2015) also revealed that the bow shell has two layers and the magnetic field evolution around the SNR. The fact that the number of the observed SNRs is much less than the simulation results is partly explained by the simulation results. Therefore there should exist more undiscovered unilateral large-radian SNRs in our Galaxy. The third row of Figure 2 shows that the top flux density of the \( y \)-plane is about 20 times larger than that in the \( x \)-plane, so it is possible to detect more unilateral large-radian SNRs once we have 20 times better sensitivity. The fact that the number of the observed SNRs (about 300; see Green 2014) is much less than the current theory prediction of about 1000 (Frail et al. 1994; Tammann et al. 1994) can be partly explained by the simulation results.

We also check the influence of thermal conduction in the simulation, because this plays an important role in the evolution of stellar wind (Meyer et al. 2014b). We apply an explicit scheme and standard thermal conduction coefficients in the code PLUTO. Figure 6 shows our simulation results. They reveal that the bow shell has two layers and the magnetic field is also different from that without thermal conduction (see Figure 2). Meyer et al. (2015) showed the effects of the mixing of material, which is not obvious in our work because we use different parameters. The simulation including thermal conduction does not show an obvious change in the density and magnetic field evolution around the SNR. The radio morphologies are similar to those in Figure 2, so we do not show them.
Figure 2. Simulation images assuming the velocity is perpendicular to the magnetic field. The top three images show the stellar wind simulation results at different views. The second row shows the SNR simulation results which use the top three images as the initial conditions. The third row shows the relative radio flux density converted from the second row. The last row shows the real observed radio images of the SNRs G332.0+0.2, G116.9+0.2, and G12.2+0.3 (West et al. 2016). The three SNRs are bilateral symmetric, unilateral large-radian, and unilateral small-radian, respectively. In the top two rows, the colored patterns indicate the density distribution with a unit of log(cm$^{-3}$). The length and direction of the white arrows respectively indicate the intensity and direction of the magnetic field.
In conclusion, thermal conduction plays a small role in the radio evolution of an SNR.

### 3.2. Parallel Simulation

The parallel simulation is shown in Figure 7. All initial parameters are same as the perpendicular simulation and the age is also 1850 yr. We caution that the stellar wind region shows obvious radio emission, which is wrong, because there are no relativistic electrons in this region and the synchrotron mechanism is not important. However, it is impossible for us to exclude it from the radio images, because we do not know the boundary of the relativistic electron region. This flaw also influences other simulation radio images. We only show the y–z plane in Figure 7, because the x–z plane is same. Moreover, we should see a circular SNR in the x–y plane, but in fact we see a square SNR in our simulation, because the resolution is not high and every pixel is square. The stellar wind simulation is time-consuming, so we selectively set a reasonable resolution.

Figure 7 shows that the radio morphology is a bilateral asymmetric SNR. van Marle et al. (2014a) showed that the magnetic field would shape the stellar wind nebulae of asymptotic giant (AGB) stars as bilateral symmetric morphologies. Including the motion of AGB stars, van Marle et al. (2014b) studied the instabilities in such a system. Meyer et al. (2017) also simulated the bow shock nebulae of hot massive stars in a magnetized medium, which shows similar results to our parallel stellar wind simulation. However, they did not add the supernova explosion and convert the results to radio images. Taking the circular SNR into account, we are able to simulate five types of SNR in our classification. Only the multi-layer and irregular SNRs are difficult to simulate. Their formations are likely influenced by the inhomogeneous initial surrounding environment or the unusual progenitor (Orlando et al. 2007, 2017).

The upper images of Figure 8 show the simulation morphologies at 1450, 1850, and 3050 yr respectively. As a comparison, three real SNRs, G53.6–2.2, G29.7–0.3, G28.6–0.1, are shown in the lower panels of Figure 8. Because of the similar morphologies between the simulation and observation images, the three SNRs are likely all a few thousand years old. In fact, G29.7–0.3 is about 1000 yr old (Leahy & Tian 2008) and G28.6–0.1 (Bamba et al. 2001) is no more than 2700 yr old. G53.6–2.2 seems older (about 15,000 yr; see Long et al. 1991), which is worth further checking. In addition, the X-ray emissions of the three SNRs are all more or less separated from the radio shell (Bamba et al. 2001; Su et al. 2009; Broersen & Vink 2015), similar to SNR G116.9+0.2. The simulation results also coincide with these observations, just like the perpendicular simulation for G116.9+0.2, so we do not show them here.

Since the parameters are same in the two simulations, we are able to compare the relative flux density in the parallel with that in the perpendicular simulation at the same age. Figure 7 shows the relative flux density in the y–z plane for the parallel simulation is much lower than that for the perpendicular simulation.
simulation. In other words, bilateral asymmetric SNRs should be fewer than unilateral small-radian SNRs. This is supported by the statistics in Table 2. Unilateral large-radian SNRs should be fewer than bilateral asymmetric SNRs, if we take only the $x$–$z$ plane into consideration in the simulation results. However, the direction of the LoS might influence this estimation. For example, Figure 3 shows a unilateral large-radian SNR is brighter than a bilateral asymmetric SNR. In fact, Table 2 implies that unilateral large-radian SNRs are more numerous than bilateral asymmetric SNRs.

4. Summary

Taking the evolution results of the stellar wind as the initial conditions, we simulate the SNR evolution of a runaway 40 $M_\odot$ progenitor star. The stellar wind simulations include two
models: perpendicular and parallel simulation. Based on real radio morphologies, we classify the SNRs into seven types. Our conclusions are summarized as follows.

1. The stellar wind of the massive progenitor plays a key role in shaping the radio morphologies of SNRs, and is possibly more important than the initial surrounding environment.

2. Considering the stellar wind, we can explain many radio morphologies of SNRs, except for multi-layer and irregular SNRs.

3. We do not suggest that we can infer the large-scale magnetic field or density distribution in Milky Way based on the radio morphologies of SNRs.

4. Thermal conduction might slightly influence the SNR radio morphologies, but is not very important.

5. The separation between X-ray and radio emission of some SNRs is possibly related to the motion of the progenitor.

We note that there are many simplifications in our work. It will be interesting to study the formation of multi-layer and irregular SNRs using more detailed simulations in the near future, e.g., by including an inhomogeneous initial surrounding environment or a special progenitor, etc.

We thank Dr. Meyer for explaining the thermal conduction of the stellar wind. We acknowledge support from the NSFC (11473038, 11163039). This work is partially supported by

Figure 7. Simulation images assuming the velocity is parallel to the magnetic field. The left panel shows the stellar wind simulation result in the y–z plane. The middle panel shows the SNR simulation result in the y–z plane. The right panel shows the relative radio flux density converted from the middle panel.

Figure 8. Upper images: simulation relative radio flux density at different ages. Lower images: observed radio images of SNRs G53.6–2.2, G29.7–0.3, and G28.6–0.1 (West et al. 2016), all of which are bilateral asymmetric.
National Key R&D Program of China (2018YFA0404203, 2018YFA0404202).

Software: PLUTO (Mignone et al. 2007, 2012).

ORCID iDs
M. F. Zhang @ https://orcid.org/0000-0001-8261-3254
W. W. Tian @ https://orcid.org/0000-0003-3775-3770

References

Bamba, A., Ueno, M., Koyama, K., & Yamauchi, S. 2001, PASJ, 53, L21
Broersen, S., & Vink, J. 2015, MNRAS, 446, 3885
Chen, Y., Liu, N., & Wang, Z.-R. 1995, ApJ, 446, 755
Cioffi, D. F., McKee, C. F., & Bertschinger, E. 1988, ApJ, 334, 252
Craig, W. W., Hailey, C. J., & Pisarski, R. L. 1997, ApJ, 488, 307
Fang, J., & Zhang, L. 2012, MNRAS, 424, 2811
Foster, T., Routledge, D., & Kothes, R. 2004, A&A, 417, 79
Fraile, D. A., Goss, W. M., & Whiteoak, J. B. Z. 1994, ApJ, 437, 781
Gaensler, B. M., Brazier, K. T. S., Manchester, R. N., Johnston, S., & Green, A. J. 1999, MNRAS, 305, 724
Green, D. A. 2014, BASI, 42, 47
Gvaramadze, V. V., Menten, K. M., Kniazev, A. Y., et al. 2014, MNRAS, 437, 843
Haverkorn, M. 2015, in Magnetic Fields in Diffuse Media, Vol. 407, ed. A. Lazarian, E. M. de Gouveia Dal Pino, & C. Melioli (Berlin: Springer), 483
Jun, B.-I., & Norman, M. L. 1996, ApJ, 465, 800
Kang, H., & Jones, T. W. 2006, ApPh, 25, 246
Leahy, D. A., & Tian, W. W. 2008, A&A, 480, L25
Leahy, D. A., & Williams, J. E. 2017, AJ, 153, 239
Lee, J.-J., Park, S., Hughes, J. P., et al. 2010, ApJ, 711, 861
Long, K. S., Blair, W. P., Matsui, Y., & White, R. L. 1991, ApJ, 373, 567
Mackey, J., Gvaramadze, V. V., Mohamed, S., & Langer, N. 2015, A&A, 573, A10
Meyer, D. M.-A., Gvaramadze, V. V., Langer, N., et al. 2014a, MNRAS, 439, L41
Meyer, D. M.-A., Langer, N., Mackey, J., Velázquez, P. F., & Gusdorf, A. 2015, MNRAS, 450, 3080
Meyer, D. M.-A., Mackey, J., Langer, N., et al. 2014b, MNRAS, 444, 2754
Meyer, D. M.-A., Mignone, A., Kuiper, R., Raga, A. C., & Kley, W. 2017, MNRAS, 464, 3229
Mignone, A., Bodo, G., Massaglia, S., et al. 2007, AIPS, 170, 228
Mignone, A., Zanni, C., Tzeferacos, P., et al. 2012, AIPS, 198, 7
Müller, B., Heger, A., Liptai, D., & Cameron, J. B. 2016, MNRAS, 460, 742
Nakanishi, H., & Sofue, Y. 2006, PASJ, 58, 847
Nakanishi, H., & Sofue, Y. 2016, PASJ, 68, 5
Orlando, S., Bocchino, F., Reale, F., Peres, G., & Petruk, O. 2007, A&A, 470, 927
Orlando, S., Drake, J. J., & Miceli, M. 2017, MNRAS, 464, 5003
Panntui, T. G., Rho, J., Borkowski, K. J., & Cameron, P. B. 2010, AJ, 140, 1787
Petruk, O., Beshley, V., Bocchino, F., & Orlando, S. 2009, MNRAS, 395, 1467
Poznanski, D. 2013, MNRAS, 436, 3224
Schneider, E. M., de La Fuente, E., & Velázquez, P. F. 2006, MNRAS, 371, 369
Su, Y., Chen, Y., Yang, J., et al. 2009, ApJ, 694, 376
Sukhbold, T., Ertl, T., Woosley, S. E., Brown, J. M., & Janka, H.-T. 2016, ApJ, 821, 38
Sun, X. H., Reich, P., Reich, W., et al. 2011, A&A, 536, A83
Tammann, G. A., Lodders, W., & Schroeder, A. 1994, ApJS, 92, 487
Tian, W.-W., & Leahy, D. 2006, ChJAA, 6, 543
Toledo-Roy, J. C., Esquivel, A., Velázquez, P. F., & Reynoso, E. M. 2014a, MNRAS, 442, 229
Toledo-Roy, J. C., Velázquez, P. F., Esquivel, A., & Giacani, E. 2014b, MNRAS, 437, 899
Truelove, J. K., & McKee, C. F. 1999, ApJS, 120, 299
van Marle, A. J., Cox, N. L. J., & Decin, L. 2014a, A&A, 570, A131
van Marle, A. J., Decin, L., & Meliani, Z. 2014b, A&A, 561, A152
van Marle, A. J., Meliani, Z., & Markowith, A. 2012, A&A, 541, L8
van Marle, A. J., Meliani, Z., & Markowith, A. 2015, A&A, 584, A49
van Marle, A. J., Smith, N., Owoki, S. P., & van Veelen, B. 2010, MNRAS, 407, 2305
Vigh, C. D., Velázquez, P. F., Gómez, D. O., et al. 2011, ApJ, 727, 32
West, J. L., Sañ-Harb, S., Jaffe, T., et al. 2016, A&A, 587, A148
Yar-Uyaniker, A., Uyaniker, B., & Kothes, R. 2004, ApJ, 616, 247
Zhang, M. F., Tian, W. W., Leahy, D. A., et al. 2017, ApJ, 849, 147
Zhang, Q.-C., Wang, Z., & Chen, Y. 1996, ApJ, 466, 808