Constraining the Nature of Superluminous Supernovae and their Host Galaxies with ngVLA

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Abstract

Superluminous supernovae (SLSNe) are extremely luminous explosions, which are ∼10–100 times brighter than ordinary Type Ia and core-collapse SNe. The nature of SLSNe is still a matter of debate. Radio observations provide useful constraints on physical properties, environments, or models on progenitor/powering source of SLSNe. High-sensitivity, multi-frequency, long-term monitoring of light curves with ngVLA will open a new window for the understanding of such extreme transient events.

Key words: supernovae: general$_1$ — galaxies: star formation$_2$ — stars: magnetars$_3$ — radio continuum: ISM$_4$

1. Introduction

Superluminous supernovae (SLSNe) are extremely luminous explosions with absolute magnitudes of $\lesssim -21$ mag, which are ∼10–100 times brighter than typical Type Ia and core-collapse SNe (Gal-Yam 2012, for a review). SLSNe are a new class of SNe that were discovered by wide-field, untargeted, time-domain surveys (e.g., Quimby et al. 2007; Quimby et al. 2011). SLSNe are detected from local ($z = 0.03$) to high-redshift galaxies ($z \sim 4$; Cooke et al. 2012; Moriya et al. 2019), and therefore can be powerful indicators of environments in the distant universe. SLSNe are classified into two main subclasses depending on the presence of hydrogen signatures in the observed spectra: hydrogen-poor Type I (SLSNe-I) and hydrogen-rich Type II (SLSNe-II) (Gal-Yam 2012). Due to their huge luminosity and scarcity, the physical nature of SLSNe is still a matter of debate, and especially SLSNe-I are among the least understood SN populations. SLSNe-II are likely to be explained by a shock between the SN ejecta and surrounding dense hydrogen-rich circumstellar medium (e.g., Woosley et al. 2007; Moriya et al. 2013). On the other hand, several models have been proposed for SLSNe-I such as pair-instability SN (e.g., Woosley et al. 2007; Gal-Yam et al. 2009), spin-down of a newborn strongly magnetized neutron star (magnetar; e.g., Kasen & Bildsten 2010; Woosley 2010), fallback accretion onto a compact remnant (Dexter & Kasen 2013), and interaction with dense circumstellar medium (e.g., Chevalier & Irwin 2011).

Late-time radio observations are useful to constrain physical properties, environments, and models of progenitor or powering source of SLSNe. It is expected that radio emission arise from shock interaction between SN ejecta and circumstellar medium (CSM). Coppejans et al. (2018) compiled the radio observations of SLSNe-I and constrained energies and mass-loss rates or CSM densities for off-axis jets. Based on the the model of SN driven by a young pulsar or a magnetar (Murase et al. 2016), Omand et al. (2018) predicted quasi-state synchrotron radio emission peaking at $\gtrsim$10 years after the SN explosion the known bright SLSNe-I, which could dominate radio emission from their host galaxies. It is interesting that the magnetar engine model is also plausible for long-duration gamma-ray bursts (GRBs) and fast radio bursts (FRBs), mysterious radio transients with millisecond-scale bright flashes (Cordes & Chatterjee 2019, for a review). Magnetar models have been applied to the origin of FRB 121102 (e.g., Murase et al. 2016; Kashiyama & Murase 2017; Metzger et al. 2017; Margalit et al. 2018; Margalit & Metzger 2018), which is a repeating FRB at $z = 0.1927$ (Chatterjee et al. 2017; Tendulkar et al. 2017). Recently, FRB 200428 is identified as a Galactic magnetar, SGR $1935 + 2154$ (Andersen et al. 2020; Bochenek et al. 2020), showing a magnetar origin of at least one FRB. The applicability of the models to the central engine of SLSNe-I (Eftekhari et al. 2019; Law et al. 2019; Mondal et al. 2020; Hatsukade et al. 2021) may suggest the connection among different classes of transient events. So far, only a small fraction of SLSNe were followed-up with deep radio observations, where only upper limits were obtained in most cases (Figure 1).

In order to constrain the models, it is also important to understand the properties of their environments or host galaxies. Previous studies have shown that SLSN-I hosts are typically dwarf galaxies with low-luminosity, low stellar mass, low star-formation rate (SFR), and high specific SFR (sSFR) compared to local star-forming galaxies and the hosts of core-collapse SNe, while SLSN-II hosts show a wider range of those parameters than SLSN-I hosts (e.g., Lunnan et al. 2014; Leloudas et al. 2015; Angus et al. 2016; Perley et al. 2016; Chen et al. 2017; Schulze et al. 2018). The observations of SLSN hosts have been done mainly in the optical/near-infrared (NIR) wavelengths, which are subject to dust extinction in contrast to longer wavelengths, and it is possible that we are missing dust-obscured star formation in SLSN hosts. Radio observations provide an important probe of the star-forming activity in SLSN host galaxies without the effect of dust extinction (Schulze et al. 2018; Hatsukade et al. 2018; Hatsukade et al. 2020; Law et al. 2019; Eftekhari et al. 2020), however, the number of SLSN hosts with deep radio observations is still limited ($N \sim 20$).

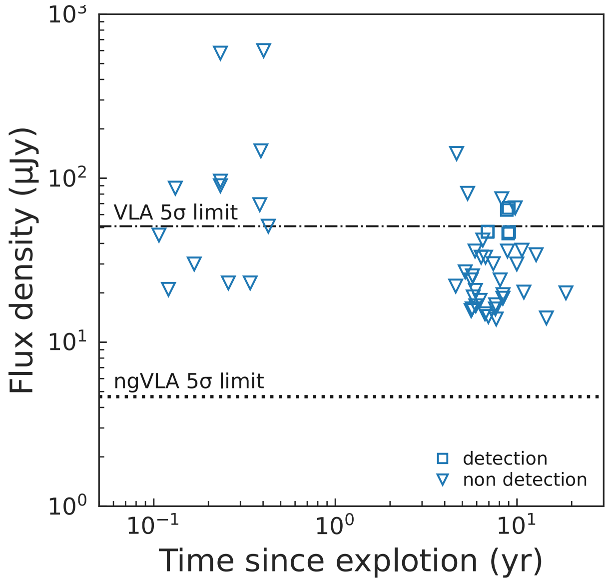

Fig. 1. Radio observations of SLSNe at 1–10 GHz compiled by Eftekhari et al. (2020). Triangles represent 3σ upper limits. 5σ detection limits at 3 GHz achieved with a 10-min on-source integration by using VLA and ngVLA are presented as dot-dashed and dotted line, respectively.

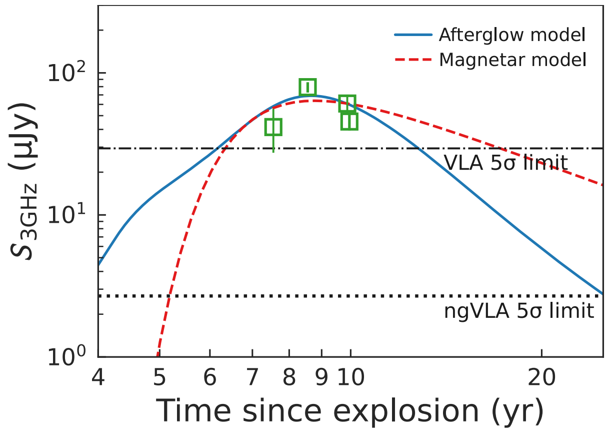

Fig. 2. Light curve of a SLSN at 3 GHz taken from Law et al. (2019), Mondal et al. (2020), and Hatsukade et al. (2021). An afterglow model generated using the `afterglowpy` code (Ryan et al. 2020) is shown as a solid line. We also plot the magnetar wind nebula model presented in Law et al. (2019) with 50% of the ejecta singly ionized as a dashed line, scaled by a factor of 1.6. 5σ detection limits achieved with a 30-min on-source integration by using VLA and ngVLA are presented as dot-dashed and dotted line, respectively.

2. Constraining Models of SLSNe from Late-time Radio Observations

Recently, Eftekhari et al. (2019) found an unresolved radio source coincident with the position of a SLSN-I based on radio observations conducted at about 7.5 years after the explosion. A time variability in the late-time radio light curve is also reported (Hatsukade et al. 2021). There are some possible scenarios for the origin of the radio emission, such as star formation activity, active galactic nucleus (AGN) in the host galaxy, interaction between the SN ejecta/jet and CSM, and pulsar wind nebulae powered by a magnetar (Eftekhari et al. 2019). Recent deep radio surveys have revealed extragalactic variable sources and AGN signatures in faint radio sources (e.g., Mooley et al. 2016; Radcliffe et al. 2019; Smolčić et al. 2017a; Algera et al. 2020; Reines et al. 2020). Sarbadhicary et al. (2020) conducted a deep blind survey of radio variable at 1-2 GHz probing down to faint sources ($<$100 μJy) and found variable sources whose host galaxies show AGN signatures. Deep radio continuum surveys found that faint sources with radio luminosities or stellar masses similar to those of typical SLSN host galaxies show AGN features based on various criteria (Smolčić et al. 2017a; Algera et al. 2020). A sensitive search for radio emission toward dwarf galaxies by Reines et al. (2020) found galaxies with compact radio sources that are almost certainly AGNs. Considering these studies, long-term monitoring observations are important to discriminate between AGNs and transient sources.

A radio afterglow is another scenario, where radio emission is arising from an initially off-axis jet that decelerates and spreads into the line of sight at late times. Eftekhari et al. (2019) generated afterglow models for a range of jet energies and CSM densities, and found that the observed flux density can be reproduced. The model light curve along with the radio data is shown in Figure 2. However, the spectral index predicted from afterglow models is inconsistent with the observed spectrum, showing the importance of multi-frequency observations in addition to long-term monitoring observations (Eftekhari et al. 2019; Mondal et al. 2020; Hatsukade et al. 2021).

Eftekhari et al. (2019) argued that the results of radio observations are also consistent with a magnetar wind nebula and can be reproduced by scaling the magnetar model for the persistent radio source associated with the repeating FRB 121102 (Metzger et al. 2017). Law et al. (2019) also found that the emission is consistent with the interpretation that it is powered by a magnetar with free-free absorption in partially ionized ejecta. They calculated the time evolution of radio emission from the pulsar wind nebulae (PWNe) based on the model of Murase et al. (2015) and Murase et al. (2016). Murase et al. (2016) show in their model that pulsar-driven SN remnants cause quasi-steady synchrotron radio emission associated with non-thermal electron-positron pairs in nascent PWNe on a timescale of decades. We plot the model light curve presented in Law et al. (2019) in Figure 2, showing that the data can be explained by the model.

In oder to constrain these possible scenarios, it is important to conduct long-term monitoring with high sensitivity. Figure 2 shows 5σ sensitivities with on-source integration time of 30 min by using VLA and ngVLA. While VLA achieves a 5σ detection only a bright phase of a light curve for bright sources, ngVLA will provide more significant constraints over longer periods. So far, only a few SLSNe have radio detections at late time. High sensitivity, long-term monitoring observations of a large sample of SLSNe will allow us to examine the physical nature of SLSNe.

3. Obscured Star Formation in Host Galaxies

Searches for radio emission toward host galaxies have been conducted to reveal the obscured star-formation. Schulze et al. (2018) searched radio emission for a sample of SLSN hosts from the survey data of Faint Images of the Radio Sky at Twenty-Centimeters (FIRST; Becker et al. 1995), the NRAO VLA Sky Survey (NVSS; Condon et al. 1998), and the Sydney University Molonglo Sky Survey (SUMSS; Bock et al. 1999), and found no radio detection. They also conducted deeper VLA observations of three hosts of SLSNe, and obtained upper limits. Hatsukade et al. (2018) performed a pilot study on radio properties of the host galaxies of 8 SLSNe at $0.1 < z < 0.3$ through VLA 3-GHz observations. They found the excess of SFRs derived from the radio emission compared to the extinction-corrected SFRs derived from optical studies (UV-based SFRs from SED fitting or Hα-based SFRs), suggesting the existence of dust-obscured star formation which cannot be traced by optical observations. This indicates the necessity of longer-wavelength observations for the understanding of true star-forming activity in SLSN hosts. They also found that three hosts, which were located within the range of the main sequence based on the previous optical observations, are actually above the main sequence in our radio observations, suggesting that they have a starburst nature. On the other hand, observations of 15 SLSNe-I at 6 GHz with VLA and 29 SLSNe-I at 100 GHz with ALMA by Eftekhari et al. (2020) do not find significant dust-obscured star formation in the host galaxies. Figure 3 compares SFRs derived from optical and radio observations including recent results. The current sensitivity of VLA is not enough to detect typical SLSN hosts even with stacking analysis. ngVLA allows us to examine the existence of obscured star formation for the majority of hosts, leading the understanding of true star-forming activity in SLSN hosts, as shown in Figure 3.

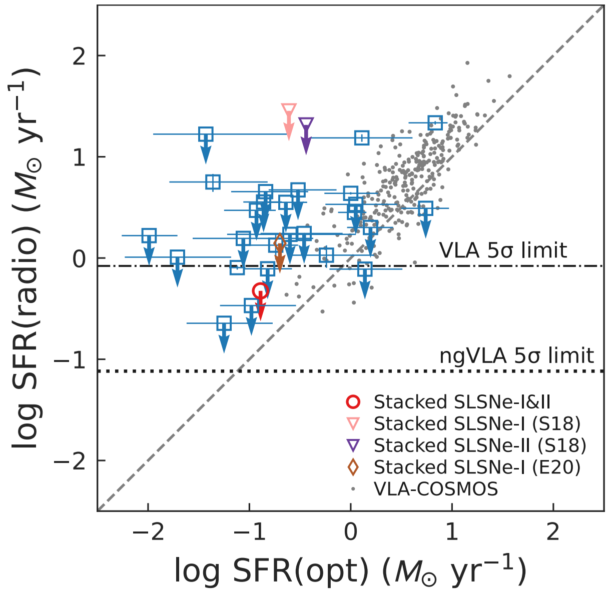

Fig. 3. Comparison of SFRs derived from optical and radio observations. The dashed line represents the one to one relation. Results on individual hosts and stacked are presented as squares and a circle, respectively (Hatsukade et al. 2018; Hatsukade in prep.). Arrows represent 3σ upper limits. Stacked results for 17 SLSNe-I and 13 SLSNe-II at $z < 0.5$ by Schulze et al. (2018) and for 13 SLSNe-I at $z < 0.4$ by Eftekhari et al. (2020) are also presented. We also plot star-forming galaxies without AGN feature from the VLA-COSMOS survey source catalog (Smolčić et al. 2017b; Smolčić et al. 2017a) at $z < 0.3$ (dots) as a control sample. 5σ detection limits achieved with a 30-min on-source integration by using VLA and ngVLA are presented as dot-dashed and dotted line, respectively.

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References

Algera, H. S. B., van der Vlugt, D., Hodge, J. A., et al. 2020, The Astrophysical Journal, 903, 139
Andersen, B. C., Bandura, K. M., Bhardwaj, M., et al. 2020, Nature, 587, 54
Angus, C. R., Levan, A. J., Perley, D. A., et al. 2016, Monthly Notices of the Royal Astronomical Society, 458, 84
Becker, R. H., White, R. L., & Helfand, D. J. 1995, The Astrophysical Journal, 450, 559
Bock, D. C.-J., Large, M. I., & Sadler, E. M. 1999, AJ, 117, 1578
Bochenek, C. D., Ravi, V., Belov, K. V., et al. 2020, Nature, 587, 59
Chatterjee, S., Law, C. J., Wharton, R. S., et al. 2017, Nature, 541, 58
Chen, T.-W., Nicholl, M., Smartt, S. J., et al. 2017, Astronomy & Astrophysics, 602, A9
Chevalier, R. A., & Irwin, C. M. 2011, The Astrophysical Journal, 729, L6
Condon, J. J., Cotton, W. D., Greisen, E. W., et al. 1998, The Astronomical Journal, 115, 1693
Cooke, J., Sullivan, M., Gal-Yam, A., et al. 2012, Nature, 491, 228
Coppejans, D. L., Margutti, R., Guidorzi, C., et al. 2018, The Astrophysical Journal, 856, 56
Cordes, J. M., & Chatterjee, S. 2019, Annual Review of Astronomy and Astrophysics, 57, 417
Dexter, J., & Kasen, D. 2013, The Astrophysical Journal, 772, 30
Eftekhari, T., Berger, E., Margalit, B., et al. 2019, The Astrophysical Journal, 876, L10
Eftekhari, T., Margalit, B., Omand, C. M. B., et al. 2020b, arXiv:2010.06612 [astro-ph].
Gal-Yam, A. 2012, Science, 337, 927
Gal-Yam, A., Mazzali, P., Ofek, E. O., et al. 2009, Nature, 462, 624
Hatsukade, B., Tominaga, N., Hayashi, M., et al. 2018, The Astrophysical Journal, 857, 72
Hatsukade, B., Morokuma-Matsui, K., Hayashi, M., et al. 2020, Publications of the Astronomical Society of Japan, 72, L6
Hatsukade, B., et al. 2021, submitted
Kasen, D., & Bildsten, L. 2010, The Astrophysical Journal, 717, 245
Kashiyama, K., & Murase, K. 2017, The Astrophysical Journal, 839, L3
Law, C. J., Omand, C. M. B., Kashiyama, K., et al. 2019, The Astrophysical Journal, 886, 24
Leloudas, G., Hsiao, E. Y., Johansson, J., et al. 2015, Astronomy & Astrophysics, 574, A61
Lunnan, R., Chornock, R., Berger, E., et al. 2014, The Astrophysical Journal, 787, 138
Margalit, B., & Metzger, B. D. 2018, The Astrophysical Journal Letters, 868, L4
Margalit, B., Metzger, B. D., Berger, E., et al. 2018, Monthly Notices of the Royal Astronomical Society, 481, 2407

Metzger, B. D., Berger, E., & Margalit, B. 2017, The Astrophysical Journal, 841, 14
Mondal, S., Bera, A., Chandra, P., & Das, B. 2020, Monthly Notices of the Royal Astronomical Society, 498, 3863
Mooley, K. P., Hallinan, G., Bourke, S., et al. 2016, The Astrophysical Journal, 818, 105
Moriya, T. J., Blinnikov, S. I., Tominaga, N., et al. 2013, Monthly Notices of the Royal Astronomical Society, 428, 1020
Moriya, T. J., Tanaka, M., Yasuda, N., et al. 2019, The Astrophysical Journal Supplement Series, 241, 16
Murase, K., Kashiyama, K., Kiuchi, K., & Bartos, I. 2015, The Astrophysical Journal, 805, 82
Murase, K., Kashiyama, K., & Mészáros, P. 2016, Monthly Notices of the Royal Astronomical Society, 461, 1498
Omand, C. M. B., Kashiyama, K., & Murase, K. 2018, Monthly Notices of the Royal Astronomical Society, 474, 573
Perley, D. A., Quimby, R. M., Yan, L., et al. 2016, The Astrophysical Journal, 830, 13
Quimby, R. M., Aldering, G., Wheeler, J. C., et al. 2007, The Astrophysical Journal, 668, L99
Quimby, R. M., Kulkarni, S. R., Kasliwal, M. M., et al. 2011, Nature, 474, 487
Radcliffe, J. F., Beswick, R. J., Thomson, A. P., et al. 2019, Monthly Notices of the Royal Astronomical Society, 490, 4024
Reines, A. E., Condon, J. J., Darling, J., & Greene, J. E. 2020, The Astrophysical Journal, 888, 36
Ryan, G., van Eerten, H., Piro, L., & Troja, E. 2020, The Astrophysical Journal, 896, 166
Sarbadhicary, S. K., Tremou, E., Stewart, A. J., et al. 2020, arXiv e-prints, 2009, arXiv:2009.05056
Schulze, S., Krühler, T., Leloudas, G., et al. 2018, Monthly Notices of the Royal Astronomical Society, 473, 1258
Smolčić, V., Delvecchio, I., Zamorani, G., et al. 2017a, Astronomy & Astrophysics, 602, A2
Smolčić, V., Miettinen, O., Tomičić, N., et al. 2017b, Astronomy and Astrophysics, 597, A4
Tendulkar, S. P., Bassa, C. G., Cordes, J. M., et al. 2017, The Astrophysical Journal, 834, L7
Woosley, S. E. 2010, The Astrophysical Journal, 719, L204
Woosley, S. E., Blinnikov, S., & Heger, A. 2007, Nature, 450, 390