Letter

Spatially Resolved Molecular Gas Properties of Host Galaxy of Type I Superluminous Supernova SN 2017egm

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Abstract

We present the results of CO(1–0) observations of the host galaxy of a Type I superluminous supernova (SLSN-I), SN 2017egm, one of the closest SLSNe-I at $z = 0.03063$, by using the Atacama Large Millimeter/submillimeter Array. The molecular gas mass of the host galaxy is $M_{\text{gas}} = (4.8 \pm 0.3) \times 10^9 \, M_\odot$, placing it on the sequence of normal star-forming galaxies in an $M_{\text{gas}}$–star-formation rate (SFR) plane. The molecular hydrogen column density at the location of SN 2017egm is higher than that of the Type II SN PTF10bgl, which is also located in the same host galaxy, and those of other Type II and Ia SNe located in different galaxies, suggesting that SLSNe-I have a preference for a dense molecular gas environment. On the other hand, the column density at the location of SN 2017egm is comparable to those of Type Ibc SNe. The surface densities of molecular gas and the SFR at the location of SN 2017egm are consistent with those of spatially resolved local star-forming galaxies and follow the Schmidt–Kennicutt relation. These facts suggest that SLSNe-I can occur in environments with the same star-formation mechanism as in normal star-forming galaxies.

Key words: supernovae: individual (Gaia17biu/SN 2017egm) — galaxies: ISM — galaxies: star forma-
1 Introduction

Superluminous supernovae (SLSNe) are extremely luminous explosions with absolute magnitudes of $\lesssim -21$ mag, which are $\sim 10$–100 times brighter than typical Type Ia and core-collapse SNe (Gal-Yam 2012). SLSNe are a new class of SNe that was discovered only recently by wide-field, untargeted, time-domain surveys (e.g., Quimby et al. 2007; Quimby et al. 2011). They are detected from local ($z = 0.03$) to high-redshift galaxies ($z \sim 4$; Cooke et al. 2012), 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 (SLSN-I) and hydrogen-rich Type II (SLSN-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.

Spatially resolving observations of molecular gas provide the physical properties of the interstellar medium (ISM) in the local environment of stellar explosions, such as molecular gas content, star-formation efficiency, and velocity field (e.g., Galbany et al. 2017; Arabsalami et al. 2019; Morokuma-Matsui et al. 2019). Arabsalami et al. (2019) conducted CO(1–0) observations of the host galaxy of a SLSN-II, PTF10tpz, at $z = 0.03994$ with the Atacama Large Millimeter/submillimeter Array (ALMA), and found that PTF10tpz is located close to the intersection of the gas lanes and the inner structure of the host galaxy. They suggested that in situ formation of massive stars due to the internal dynamics of the host galaxy and high densities are favorable conditions for the formation of SLSN progenitors.

SN 2017egm/Gaia17biu at $z = 0.03063$, one of the closest SLSNe-I, was discovered on May 23, 2017 (Dong et al. 2017; Albareti et al. 2017). The host galaxy, NGC 3191, is a massive spiral galaxy ($M_* = 5 \times 10^{10} M_\odot$) with active star formation (SFR $\sim 5$–15 $M_\odot$ yr$^{-1}$) (Stoll et al. 2013; Nicholl et al. 2017; Chen et al. 2017; Bose et al. 2018). The metallicity at the SN site shows a (super-)solar metallicity ($\sim 1.3$–2.6 $Z_\odot$; Nicholl et al. 2017; Chen et al. 2017; Bose et al. 2018), while there is a work showing a sub-solar metallicity (0.6 $Z_\odot$; Izzo et al. 2018). It is notable that NGC 3191 also hosted two other SNe: SN 1988B (Type Ia) and PTF10bgl (Type II). SN 1988B was reported to be located at 10$''$ north of the galaxy center (Schildknecht & Wild 1988; Filippenko et al. 1988), although the precise location was not provided. PTF10bgl was located $\sim$10$''$ north-west of the galaxy center (Arcavi et al. 2010). This enables us to compare the environments between a SLSN-I and a Type II SN located in the same galaxy.

In this Letter, we present the results of ALMA CO(1–0) observations of the host galaxy of SN 2017egm. This is the first study on molecular gas in a SLSN-I host galaxy. Throughout the paper, we adopt the cosmological parameters $H_0 = 67.8$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.308$, and $\Omega_{\Lambda} = 0.692$ (Planck Collaboration et al. 2016). The luminosity distance to the host galaxy is 138.7 Mpc, and 1$''$ corresponds to 0.65 kpc.

2 Observations and Results

ALMA CO(1–0) observations were conducted on Mar. 28 and 29, 2019, for a Cycle 6 program (Project code: 2018.1.00370.S). The redshifted CO(1–0) line was observed with Band 6. The correlator was used in the time-domain mode with a bandwidth of 1875 MHz (488.28 kHz × 3840 channels). Four basebands were used, providing a total bandwidth of 7.5 GHz. The array configuration was C43-2 with baseline lengths of 15.0–457.3 m. The number of available antenna was 46–48, and the on-source integration time was 79 min. Bandpass and flux calibrations were performed with J1058+0133 and phase calibrations with J0927+3902.

The data were reduced with Common Astronomy Software Applications (CASA; McMullin et al. 2007). Maps were processed with a tclean task with Briggs weighting and a robust parameter of 0.5. The synthesized beamsize is 3.9$''$ × 1.8$''$ (2.6 kpc × 1.2 kpc) with a position angle of $-3.7^\circ$. The rms noise level is 1.5 mJy beam$^{-1}$ for a spectrum with a velocity resolution of 5 km s$^{-1}$.

Figure 1 shows the obtained maps of CO(1–0) velocity-integrated intensity, intensity-weighted velocity field, and intensity-weighted velocity dispersion. The CO emission is clearly detected with a smooth rotation signature, which is consistent with the H$\alpha$ IFU observations (Chen et al. 2017). The bright CO peak $\sim$7$''$ west of the galaxy center coincident with an H$\alpha$ region (Chen et al. 2017; Izzo et al. 2018) and the brightest peak of a 10 GHz continuum map (Bose et al. 2018). SN 2017egm is located close to a bright CO blob east of the galaxy center. The CO emission is also detected at the location of PTF10bgl at the $\sim$2$\sigma$ level. Izzo et al. (2018) found a tangential or warp-like disturbance, based on a detailed kinematic analysis on the H$\alpha$ map,
and suggest that this could be a sign of interaction with its companion, MCG+08-19-017, at a projected distance of \( \sim 45 \) kpc and a radial velocity difference of \( \sim 200 \) km s\(^{-1}\). We do not find any atypical feature in the CO maps around the location of SN 2017egm or PTF10bgl.

3 Discussion

3.1 Host Galaxy

The CO luminosity of the host galaxy is calculated to be \( L'_{\text{CO}} = (1.1 \pm 0.1) \times 10^9 \, L_{\odot} \) following the equation of Solomon & Vanden Bout (2005). The molecular gas mass is \( M_{\text{gas}} = (4.8 \pm 0.3) \times 10^9 \, M_{\odot} \) derived from \( M_{\text{gas}} = \alpha_{\text{CO}} L'_{\text{CO}} \), where \( \alpha_{\text{CO}} \) is a CO-to-H\(_2\) conversion factor including the contribution of the helium mass. The conversion factor can vary with different environments (see, e.g., Bolatto et al. 2013 for a review). The conversion factor is thought to be dependent on gas-phase metallicity, increasing \( \alpha_{\text{CO}} \) with decreasing metallicity (e.g., Wilson 1995; Bolatto et al. 2013). Because the host galaxy has a metallicity close to the solar value, we adopt a Galactic conversion factor of \( \alpha_{\text{CO}} = 4.3 \, M_{\odot} \) (K km s\(^{-1}\) pc\(^2\))\(^{-1}\) (with 30% uncertainty; Bolatto et al. 2013). The derived physical quantities are presented in Table 1. Note that errors take into account only flux measurement uncertainties. The molecular gas mass fraction (\( \mu_{\text{gas}} = M_{\text{gas}}/M_* \)) is 0.095, which is comparable to those of local star-forming galaxies with a similar stellar mass (Saintonge et al. 2011; Saintonge et al. 2017; Bothwell et al. 2014). The molecular gas mass is compared with the SFR in Figure 2. Because the SFR of the host galaxy ranges from 5 to 15 \( M_{\odot} \) yr\(^{-1}\) in the literature (Stoll et al. 2013; Nicholl et al. 2017; Chen et al. 2017), we adopt the range as a vertical line in the plot. The host galaxy is located in a similar region for local galaxies and on the sequence of normal star-forming galaxies. The gas depletion timescale (\( \tau_{\text{gas}} = M_{\text{gas}}/\text{SFR} \)) is 0.32–0.95 Gyr, which is comparable to those of local star-forming galaxies with a similar stellar mass (Bothwell et al. 2014; Saintonge et al. 2017). The gas depletion timescale is also comparable to the host galaxies of PTF10tpz (SLSN-II; Arabsalmani et al. 2019) and SN 2009bb (broad-line Ic SN; Michalowski et al. 2018).

3.2 SLSN Site

The metallicity at the SN 2017egm site measured in previous studies is controversial. Nicholl et al. (2017) and
Table 1. Derived properties of the host galaxy and at the sites of SN 2017egm and PTF10bgl

| Host galaxy | \(L'_\text{CO} \) (K km s\(^{-1}\) pc\(^2\)) | (1.1 ± 0.1) \times 10^9 | \(M_{\text{gas}} \) (\(M_\odot\)) | (4.8 ± 0.3) \times 10^9 | \(\mu_{\text{gas}} \) \(^*\) | 0.095 | \(\tau_{\text{depl}} \) (Gyr) \(^\dagger\) | 0.32–0.95 | SFE \(^\dagger\) (Gyr\(^{-1}\)) | 1.0–3.1 |
|-------------|---------------------------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| SN 2017egm site | \(N(\text{H}_2)\) (cm\(^{-2}\)) | (1.6 ± 0.3) \times 10^{21} | \(\Sigma_{\text{gas}} \) (\(M_\odot\) pc\(^{-2}\)) | 35 ± 6 | \(\Sigma_{\text{gas}} \) (\(M_\odot\) pc\(^{-2}\)) | 12 ± 6 |
| PTF10bgl site | \(N(\text{H}_2)\) (cm\(^{-2}\)) | (5.6 ± 2.7) \times 10^{20} | \(\Sigma_{\text{gas}} \) (\(M_\odot\) pc\(^{-2}\)) | 12 ± 6 |

Errors take into account only flux measurement uncertainty (1\(\sigma\)). Galactic CO-to-\(\text{H}_2\) conversion factor of \(\alpha_{\text{CO}} = 4.3\) \(M_\odot\) (K km s\(^{-1}\) pc\(^2\))\(^{-1}\) is assumed.

\(^*\) Molecular gas fraction \((M_{\text{gas}}/M_\ast)\).

\(^\dagger\) Gas depletion timescale \((\mu_{\text{gas}} = M_{\text{gas}}/SFR)\) and star-formation efficiency \((\text{SFE} = \text{SFR}/M_{\text{gas}})\) assuming SFR = 5–15 \(M_\odot\) yr\(^{-1}\) based on the measurements in previous studies.

Chen et al. (2017) showed a (super-)solar metallicity of \(12 + \log (\text{O/\text{H}}) = 8.8\) and 9.11, respectively, using the \(R_{23}\) diagnostic with the Kobulnicky & Kewley (2004) calibration. Bose et al. (2018) also found a super-solar metallicity of \(12 + \log (\text{O/\text{H}}) = 9.0\) using [\text{NII}]/\text{H\alpha} diagnostic with the Nagao et al. (2006) calibration. On the other hand, Izzo et al. (2018) found a sub-solar metallicity of \(12 + \log (\text{O/\text{H}}) = 8.49\) and 8.45 using the N2 and O3N2 diagnostics, respectively, based on the calibrations of Marino et al. (2013). It is known that metallicity diagnostics are uncertain (e.g., Kewley, & Ellison 2008) and the differences in the previous studies can be due to different diagnostics (Chen et al. 2017; Izzo et al. 2018). In order to see the effect of metallicity on \(\alpha_{\text{CO}}\), we apply the relation between metallicity and \(\alpha_{\text{CO}}\) of Genzel et al. (2015), where they took the geometric mean of the empirical relations of Genzel et al. (2012) and Bolatto et al. (2013) and derived the relation for the local and high-redshift sample. To apply the relation, we convert the metallicity to the calibration of Pettini & Pagel (2004) by using the metallicity conversion of Kewley, & Ellison (2008). The derived metallicity-dependent \(\alpha_{\text{CO}}\) is 3.4–6.6 \(M_\odot\) (K km s\(^{-1}\) pc\(^2\))\(^{-1}\). In the following discussions, we assume a Galactic \(\alpha_{\text{CO}}\) of 4.3 \(M_\odot\) (K km s\(^{-1}\) pc\(^2\))\(^{-1}\) (corresponding \(X_{\text{CO}}\) is \(2 \times 10^{20}\) cm\(^{-2}\) (K km s\(^{-1}\))\(^{-1}\)), which is in the range of the metallicity-dependent conversion factor and is used in previous studies on the host galaxies of SNe (Galbany et al. 2017; Michałowski et al. 2018; Arabasalmi et al. 2019). The column densities of molecular gas at the positions of SN 2017egm and PTF10bgl are \(N(\text{H}_2) = (1.6 ± 0.3) \times 10^{21}\) cm\(^{-2}\) and \((5.6 ± 2.7) \times 10^{20}\) cm\(^{-2}\), respectively. Here we adopt the same \(\alpha_{\text{CO}}\) for both the SN sites, because Izzo et al. (2018) found that metallicities at the sites are similar. We note that even if we assume the higher \(\alpha_{\text{CO}}\), the following discussions and conclusions would not change. The column density at the SN 2017egm site is found to be higher than that of the PTF10bgl site by a factor of three. We compare the column densities with the results of spatially resolving CO(1–0) observations of host galaxies of Type Ia, Ibc/IIb, and II SNe in Galbany et al. (2017). Figure 3 shows the cumulative distributions of \(N(\text{H}_2)\) for the SNe. The vertical lines represent the values for SN 2017egm and PTF10bgl obtained in this study. We find that the column density at the SN 2017egm site is higher than those of SNe Ia and II, suggesting that SLSN-I progenitors have a preference for a higher-molecular-gas-density environment. The higher surface density of molecular gas is also reported for PTF10tpz, a SLSN-II, by Arabasalmi et al. (2019). This appears to suggest that a dense molecular gas environment...
is an important factor for producing SLSN progenitors.

On the other hand, the column density at the SN 2017egm site is comparable to the median value of Type Ib/c/IIb SNe ($N(H_2) = 1.5 \times 10^{21}$ cm$^{-2}$ for six CO-detected SN sites; Galbany et al. 2017). The molecular gas surface density is an order of magnitude lower than at the PTF10tpz site ($\Sigma_{\text{gas}} \sim 700 M_\odot$ pc$^{-2}$ over ~350 pc scale; Arabsalmani et al. 2019), where the SLSN occurred near the intersection region of gas lanes and the inner structure in the host galaxy. Note that although the gas surface density at the PTF10tpz site is corrected for the inclination of the host galaxy (Arabsalmani et al. 2019), its large inclination angle of 68$^\circ$ makes it difficult to estimate the actual column density. Figure 4 shows the map of the star-formation efficiency ($\text{SFE} = \text{SFR}/M_{\text{gas}}$) in the host galaxy. The map is created from the molecular gas surface density map based on our CO(1–0) observations and the SFR map based on the MaNGA H$\alpha$ observations by Chen et al. (2017). Both the maps are convolved with the beam of the other map to match the spatial resolution. The SFE at the location of SN 2017egm does not appear to be special within the host galaxy. This is illustrated in Figure 5, which compares the surface densities of the molecular gas and the SFR. The pixel-by-pixel variations within the host galaxy are plotted. We used the region where the CO(1–0) velocity-integrated intensity map is above 2$\sigma$. We also compare the results of spatially resolved (kpc-scale) observations of local star-forming galaxies. The location of SN 2017egm in Figure 5 is consistent with the kpc-scale properties of local spiral galaxies and with the Schmidt–Kennicutt relation. This suggests that SLSNe can occur in environments that follow the same star-formation law as normal star-forming galaxies.

It is not known whether the environment of SN 2017egm can be regarded as representative of SLSNe. The stellar mass is atypical among SLSN hosts, but is comparable to those of SNe Type Ib or Ic (that are not the broad-line type) (e.g., Kelly & Kirshner 2012). The similarity between the environments of Type Ib/c SNe and SN 2017egm is also presented in this study for the hydrogen column density. This could indicate that the progenitors of SLSNe-I are an extension of Type Ibc SNe. Because observations of molecular gas in the environments of SLSNe are very limited, it is important to increase the number of samples to achieve a better understanding of SLSNe.

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Fig. 5. Comparison of molecular gas mass surface density and SFR surface density. The data points for the SN 2017egm host galaxy are measured at pixels where the CO(1–0) velocity-integrated intensity map is above the 3σ. For comparison, we plot other type of galaxies in the literature, where size measurements are available: local spirals (Kennicutt 1998a; Bigiel et al. 2010), and local LIRGs (Kennicutt 1998a). The dashed line represents the relation of Kennicutt (1998b).

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