ALMA Observations of Molecular Gas in the Host Galaxy of AT2018cow

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Abstract

We investigate the molecular gas in and star formation properties of the host galaxy (CGCG 137–068) of a mysterious transient, AT2018cow, at kpc and larger scales, using archival band-3 data from the Atacama Large Millimeter/submillimeter Array (ALMA). AT2018cow is the nearest fast-evolving luminous transient (FELT); this is the first study unveiling molecular-gas properties of FELT hosts. The achieved rms and beam size are 0.21 mJy beam−1 at a velocity resolution of 40 km s−1 and 3′′66 × 2′′71 (1.1 kpc × 0.8 kpc), respectively. CO(J = 1–0) emission is successfully detected. The total molecular gas mass inferred from the CO data is (1.85 ± 0.04) × 109 M⊙ with the Milky Way CO-to-H2 conversion factor. The H2 column density at the AT2018cow site is estimated to be 8.6 × 1020 cm−2. The ALMA data reveal that (1) CGCG 137–068 is a normal star-forming (SF) dwarf galaxy in terms of its molecular gas and star formation properties, and (2) that AT2018cow is located between a CO peak and a blue star cluster. These properties suggest ongoing star formation and favor the explosion of a massive star as the progenitor of AT2018cow. We also find that CGCG 137–068 has a solar or super-solar metallicity. If the metallicity of the other FELT hosts is not higher than average, then some properties of SF dwarf galaxies other than metallicity may be related to FELTs.

Key words: galaxies: dwarf – ISM: molecules – supernovae: general

1. Introduction

Recent high-cadence and wide-field surveys have discovered a new class of objects: fast-evolving luminous transients (FELTs; e.g., Drout et al. 2014; Arcavi et al. 2016; Tanaka et al. 2016; Rest et al. 2018), providing various observed properties such as light curves, spectral energy distributions, and environments. The properties of FELTs that distinguish them from other classes of transients are their featureless spectra and quickly declining light curves (t1/2 ~ several days). AT2018cow is one of the FELTs, but its close proximity (60 Mpc) provides us a unique opportunity to study in detail the physical properties of a FELT for the first time. It was discovered by the ATLAS survey on 2018 June 16, in the disk of dwarf star-forming (SF) galaxy CGCG 137–068 (Prentice et al. 2018), and since that time it has been monitored at various wavelengths from radio to γ-ray (e.g., Ho et al. 2019; Margutti et al. 2019; Perley et al. 2019). It is characterized by a rapid rise in brightness (a few days), a blue spectrum (~30,000 K), high optical luminosity (4 × 1044 erg s−1), initial featureless optical spectra, no γ-ray flash, high radio luminosity, and long-lived mm-wavelength emission (Prentice et al. 2018; Ho et al. 2019; Kuin et al. 2019; Margutti et al. 2019; Perley et al. 2019). With these observational constraints, various scenarios for the event have been proposed, and are roughly classified into two groups: massive star explosions (Margutti et al. 2019; Perley et al. 2019), and tidal disruption events (TDEs) in which a white dwarf is torn apart by an intermediate-mass black hole (Kuin et al. 2019; Perley et al. 2019).

Insight into the nature of transients is provided not only by observing the objects themselves but also their host galaxies, especially in order to distinguish whether or not events are related to the deaths of massive stars (i.e., ongoing star formation). Roychowdhury et al. (2019) found that AT2018cow resides in a ring-like H I structure seen in ~6′ resolution data taken with the Giant Metrewave Radio Telescope (GMRT). They concluded that the H I data indicates a massive-star scenario for AT2018cow, as such a ring is an ideal site for active star formation. In contrast, Michalowski et al. (2019) reported an absence of atomic gas at the AT2018cow site with a ~14′′ beam, and claimed that a TDE is a more plausible scenario for the progenitor of AT2018cow based on their GMRT observations. The cold gas properties of the AT2018cow site are still controversial, and it is important to investigate it using molecular gas, the raw material of star formation.

In this Letter, we study the molecular-gas and star formation properties of CGCG 137–068 and local AT2018cow site using CO(J = 1–0) data taken with the Atacama Large Millimeter/submillimeter Array (ALMA). We adopt a distance to CGCG 137–068 of 60 Mpc (1″ ~ 291 pc) and cosmology parameters of (h, ΩM, ΩΛ) = (0.7, 0.3, 0.7) throughout the Letter.

2. Data and Analysis

ALMA band-3 Time-Division-Modes (TDM) data were obtained on 2018 June 30 and July 16, with an antenna configuration of C43-1 in a target-of-opportunity observation (project code of 2017.A.00045.T, PI: S. Schulze). Antenna...
baselines range from 15 to 161 m, and a maximum recoverable scale is 29″ or 8.4 kpc. Because the original purpose of this observation is to measure the continuum flux of AT2018cow at band 3 (100.00–115.99 GHz), the data are taken in TDM mode, i.e., a frequency resolution of 15.625 MHz, corresponding to a velocity resolution of 40.64 km s$^{-1}$ at the observing frequency. The on-source integration time of each execution was 19.7 min. The CO($J = 1$–0) emission line (rest frequency $v_{\text{rest}}$ of 115.271202 GHz) was covered in one of the upper-sideband spectral windows (a CO spectrum is shown in Figure 1).

Data calibration and imaging were conducted with the standard ALMA data analysis package, the Common Astronomy Software Applications (CASA; McMullin et al. 2007; Petry & CASA Development Team 2012). The absolute flux and gain fluctuations of the 12 m data were calibrated with the ALMA Science Pipeline (version of r40896 of Pipeline-CASA51-P2-B) in the CASA 5.1.1 package. The flux accuracy of the ALMA 12 m band-3 data is reported to be better than 5% (ALMA proposer’s guide). Continuum emission is subtracted using the UVCONTSUB task and a $^{12}$CO($J = 1$–0) mosaic data cube is generated with the TCLEAN task in CASA version 5.4 with options of Briggs weighting with a robust parameter of 0.5, auto-multithresh mask with standard values for 12 m array data provided in the CASA Guides for auto-masking9 (sidelobethreshold of 2.0, noisethreshold of 4.25, minbeamfrac of 0.3, lownoisethreshold of 1.5, and negativethreshold of 15.0), and niter of 10,000. The achieved synthesized beam is $3″66 × 2″71$ (1.1 kpc × 0.8 kpc at the distance of CGCG 137–068) with a P.A. of $–27°8$. The achieved rms noise ($\sigma_{\text{rms}}$) is 0.21 mJy beam$^{-1}$ after primary beam correction at the velocity resolution of 40.64 km s$^{-1}$ in the box area centered on the galaxy center with a width and height of 25″ in the emission-free channels (Figure 1(b)).

3. Properties of an CGCG 137–068

In this section, we present local-site (Section 3.1) and host-galaxy properties of AT2018cow derived with the ALMA data (Section 3.2).

3.1. 1 kpc Scale Properties

Figure 1 shows ALMA CO($J = 1$–0) moment maps and optical images obtained in the Sloan Digital Sky Survey (SDSS) of CGCG 137–068. The basic and derived parameters of AT2018cow site are summarized in Table 1. The ALMA data reveal that AT2018cow is located at the edge of one of the CO peaks to the west of the galaxy center. The H$_2$ column density, $N$(H$_2$), at the AT2018cow site is estimated to be $8.6 × 10^{20}$ cm$^{-2}$, using the standard CO-to-H$_2$ conversion factor from the Milky Way of $X_{\text{CO}} = 2.0 × 10^{20}$ cm$^{-2}$ (K km s$^{-1}$)$^{-1}$ (Bolatto et al. 2013) as CGCG 137–068 has a solar or super-solar metallicity (see below). This corresponds to a molecular gas mass surface density, $\Sigma_{\text{mol}}$, of 14 M$_{\odot}$ pc$^{-2}$ (Figure 1). The CO velocity field is qualitatively consistent with a position angle of 66°.

9 https://casaguides.nrao.edu/index.php/Automasking_Guide

10 The conversion from Jy beam$^{-1}$ to Kelvin is done based on the Rayleigh–Jeans approximation with an equation of $T = 1.222 × 10^6 \frac{\nu_{\text{rest}}}{\theta_{\text{maj}} \theta_{\text{min}}}$, where $T$ is the brightness temperature in Kelvin, $\nu$ is the observing frequency in GHz, $\theta_{\text{maj}}$ and $\theta_{\text{min}}$ are half-power beam widths along the major and minor axes in arcsec, respectively, and $I$ is the brightness in Jy beam$^{-1}$.
with the H I velocity field, showing a monotonic velocity increase from south to north. No disturbed velocity field is observed at the AT2018cow site with a velocity resolution of \(\sim 40 \text{ km s}^{-1}\).

### 3.2. Galactic-scale Properties

The properties related to molecular gas are presented in Table 1, together with other basic properties. The total molecular gas mass is estimated to be \((1.85 \pm 0.04) \times 10^{8} M_{\odot}\). Both the stellar mass \((M_{\text{star}})\) and star formation rate (SFR) values are taken from Perley et al. (2019), the gas-phase metallicity is measured from the SDSS spectrum, and the atomic gas mass \((M_{\text{atom}})\) is from Roychowdhury et al. (2019).

| Parameter | Value | References |
|-----------|-------|------------|
| Local Site (AT2018cow) | | |
| R.A. | 16\(^{h}\)16\(^{m}\)00\(^{s}\)+2\(^{d}\)22\(^{h}\)42 | SDSS |
| Decl. | +2\(^{d}\)16\(^{m}\)04\(^{s}\)890 | SDSS |
| \(R_m\) | 6\(^{d}\)0 (1.75 kpc) | This study |
| \(\Sigma_{\text{mol}}(M_{\odot} \text{pc}^{-2})\) | 14 | This study |
| \(N(H_{2})(\text{cm}^{-2})\) | \(8.6 \times 10^{20}\) | This study |

| Host Galaxy (CGCG 137–068) | | |
| R.A. | 16\(^{h}\)16\(^{m}\)00\(^{s}\)+57 | SDSS |
| Decl. | +2\(^{d}\)16\(^{m}\)08\(^{s}\)24 | SDSS |
| Redshift | 0.014 | SDSS |
| Distance (Mpc) | 60 | 2 |
| \(M_{\text{gas}}(M_{\odot})\) | 10\(^{8}\)15 | 2 |
| SFR \((M_{\odot} \text{yr}^{-1})\) | 0.22 | 2 |
| \(SFE\) \((\text{yr}^{-1})\) | 1.56 \(\times 10^{-10}\) | 2 |
| \(12+\text{log}(O/H)_{\text{HI-MPa-HDU}}\) | 8.96 | SDSS |
| \(M_{\text{atom}}(M_{\odot})\) | \((6.6 \pm 0.9) \times 10^{8}\) | 3 |
| \(I_{\text{CO}}(\text{K km s}^{-1})\) | 0.575 \(\pm 0.020\) | This study |
| \(L_{\text{CO}}(\text{K km s}^{-1} \text{pc}^{2})\) | \((4.34 \pm 0.15) \times 10^{7}\) | This study |
| \(\text{FWHM}_{\text{CO}}(\text{K km s}^{-1})\) | 85.5 | This study |
| \(M_{\text{mol}}(M_{\odot})\) | \((1.85 \pm 0.04) \times 10^{8}\) | This study |
| SFE(mol) \((\text{yr}^{-1})\) | 1.2 \(\times 10^{-9}\) | This study |
| \(\text{SFE(gas)}(\text{yr}^{-1})\) | 2.6 \(\times 10^{-10}\) | This study |
| \(M_{\text{atom}}/M_{\text{star}}\) | 0.47 | 3 |
| \(M_{\text{mol}}/M_{\text{star}}\) | 0.13 | This study |
| \(M_{\text{mol}}/M_{\text{atom}}\) | 0.29 | This study |

Notes.
- \(^a\) Galactocentric distance.
- \(^b\) From Gaussian fitted curve.

References. (1) Bietenholz et al. (2018), (2) Perley et al. (2019), (3) Roychowdhury et al. (2019).

In Figure 2, we compare the integrated galactic properties (SFR, metallicity, \(M_{\text{atom}}/M_{\text{star}}\), \(M_{\text{mol}}/M_{\text{star}}\), star formation efficiency (SFE) of molecular gas \((\text{SFE(mol)})\), and \(M_{\text{mol}}/M_{\text{atom}}\) as a function of \(M_{\text{star}}\) of CGCG 137–068 with those of xGASS (Catinella et al. 2018) and xCOLD GASS galaxies (Saintonge et al. 2017) at similar redshifts. Note that SFE(mol) of CGCG 137–068 is comparable to that of host galaxies of long-duration gamma-ray bursts (GRBs; e.g., Hatsukade et al. 2019), which are thought to be associated with the explosion of massive stars. Overall, CGCG 137–068 is a normal low-mass SF galaxy in terms of molecular-gas and star formation properties, but has a relatively high metallicity considering its low stellar mass.

### 4. Implications for the AT2018cow Progenitor

The ALMA data revealed that AT2018cow is located at the edge of one of the CO peaks to the west side of the galaxy center, and its host is a normal low-mass SF galaxy in terms of star formation and cold-gas properties, except for its high metallicity. These properties of the AT2018cow site and CGCG 137–068, i.e., abundant material for future star formation and proximity to a young star cluster, are suggestive of the progenitor scenarios featuring the explosion of a massive star. In this section, we first compare local-site and host-galaxy properties of AT2018cow with those of core-collapse SNe (CCSNe) and TDEs, then further compare with subclasses of CCSNe. The comparison is summarized in Table 2. In addition, we also mention other FELTs, comparing the properties of their host galaxies to the properties of CGCG 137–068.

First, in terms of location within a host galaxy, CCSNe tend to reside in the outskirts of galaxies (Galbany et al. 2017), whereas TDEs are found generally at galactic centers (Komossa & Bade 1999; Gezari et al. 2012; Miller et al. 2015). AT2018cow is located at \(\sim 6^\circ\) (1.75 kpc) from the galaxy center, which favors the CCSNe scenario. However, it should be noted that an off-center TDE event (12.5 kpc from center) was recently detected in X-rays in a large lenticular galaxy (Lin et al. 2018). This event is considered to be a TDE by a few \(10^\circ\) \(M_{\odot}\) black hole.

Second, it is claimed that transients of different types may arise preferentially in certain types of galaxies. TDEs are claimed to reside primarily in quiescent Balmer-strong galaxies (i.e., post-starburst galaxies) unlike CGCG 137–068 (e.g., Arcavi et al. 2014; French et al. 2016). In addition, TDE hosts tend to have a low-ionization nuclear emission-line region/ Seyfert nucleus based on BPT diagnostics, similar to those in other quiescent Balmer-strong galaxies (French et al. 2017). Statistical studies of CCSNe host galaxies, on the other hand, show that the number ratio of Type-I (H-poor, Ib and Ic) to Type-II (H-rich) CCSNe is not a strong function of the Hubble type (Hakobyan et al. 2014), that the Type-I-to-Type-II CCSNe number ratio tends to be high for SF galaxies based on BPT diagnostics (Hakobyan et al. 2014), and that Type-I CCSNe found in dwarf galaxies are either SNe Ib or broad-line SNe Ic (SNe Ic-BL), whereas normal SNe Ic dominate in giant galaxies (Arcavi et al. 2010). Thus, the galaxy type of CGCG 137–068 also suggests a CCSN scenario, especially SNe Ib or SNe Ic-BL.

Third, it is claimed that the kpc-scale \(N(H_{2})\) tends to be higher at Type-I CCSNe sites than Type-II CCSNe sites in nearby galaxies (Galbany et al. 2017). Compared to these SNe, \(N(H_{2})\) at the AT2018cow site is slightly higher than the
Type-II CCSNe (mostly upper limits in the previous study), but comparable to Type-I CCSNe, which have a median of $N(H_2) \sim 9.4 \times 10^{20} \text{ cm}^{-2}$ (Figure 3).

Fourth, the association between CCSNe and H II regions is claimed to be different according to types of SNe: a higher association is found for Type-I CCSNe than Type-II CCSNe, suggesting that the progenitors of Type-I CCSNe are more massive than Type-II CCSNe (Anderson & James 2008; Crowther 2013). In the bottom of Figure 1, AT2018cow seems to be located between a $u$-band bright cluster and the molecular gas peak. The cluster tends to be brighter at shorter wavelengths, suggesting that it is young. The distance between the AT2018cow site and the cluster is 640 pc, which is much larger than the typical H II region but comparable to supergiant H II regions such as NGC 5461 of M101 (a radius of ~500 pc, Crowther 2013). Although we do not have H$_2$ data, the proximity between the AT2018cow and the nearby young stellar cluster may suggest that the AT2018cow site resembles local environments of Type-I CCSNe.

Finally, the high metallicity of CGCG 137–068 is one of its more noteworthy properties. Generally, it is reported that the metallicity at explosion sites is not a strong function of CCSNe types (Kuncarayakti et al. 2018), though the sites of SNe I may have a slightly higher metallicity than those of SNe II (Anderson et al. 2010). Some observations suggest that metallicity at the site of SNe Ic-BL without a long GRB tends to be higher than that of SNe Ic-BL with a long GRB (e.g., Modjaz et al. 2008; Japelj et al. 2018), although the sample size is small and the statistical significance is low (see also Modjaz et al. 2019). If the difference is real, these two populations are likely to be intrinsically different, possibly in terms of success or failure of break-out of a jet (Lazzati et al. 2012; Japelj et al. 2018). Considering that CGCG 137–068 was not accompanied by a GRB, the observed properties of CGCG 137–068 resemble those of SNe Ic-BL without a GRB.

In Figure 2(a), we plot other FELTs listed as the “Gold sample,” i.e., most secure sample, with stellar mass and SFR estimations in Pursiainen et al. (2018). We can see that these host galaxies are also SF galaxies at their redshifts ($0.12 < z < 1.56$, a median redshift of 0.485) and tend to...

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$12$ The “SF main sequence” evolves with time (Speagle et al. 2014).
Table 2

| Scenario          | AT2018cow Site | CGCG 137–068 |
|-------------------|----------------|---------------|
|                   | \(R_{\text{AT2018cow}}\) | \(N(\text{H}_2)\) | H II | BPT | SF Activity | Morphology | Metallicity |
| TDEs              | ×              | ×              | ×    | ×   | ×           | ×           | ×           |
| CCSNe SNe II      | ✓              | ✓              | ✓    | ×   | ×           | ×           | ×           |
| SNe Ic            | ✓              | ✓              | ✓    | ×   | ×           | ×           | ×           |
| SNe Ic-BL w/ GRB  | ✓              | ✓              | ✓    | ×   | ×           | ×           | ×           |
| SNe Ic-BL w/o GRB | ✓              | ✓              | ✓    | ×   | ×           | ×           | ×           |

1. AT2018cow is located between one of the CO peaks and a blue stellar cluster, both of which are indicators of ongoing star formation.
2. The \(\text{H}_2\) column density of the AT2018cow site is \(8.6 \times 10^{20} \text{ cm}^{-2}\), which is slightly higher than that of Type-II CCSNe sites and comparable to that of Type-I CCSNe sites.
3. The total molecular gas mass is \((1.85 \pm 0.04) \times 10^9 \text{ M}_\odot\), using a Milky Way CO-to-\(\text{H}_2\) conversion factor. With the literature data, \(M_{\text{mol}}/M_{\text{star}}\), SFE(mol), and \(M_{\text{mol}}/M_{\text{atom}}\) of CGCG 137–068 are 0.13, \(1.2 \times 10^{-3} \text{ yr}^{-1}\), and 0.29, respectively.
4. Compared to reference galaxies at similar redshift (xGASS and xCOLD GASS galaxies), CGCG 137–068 is a normal SF dwarf galaxy in terms of SFR, \(M_{\text{mol}}/M_{\text{star}}\), \(M_{\text{mol}}/M_{\text{star}}\), SFE(mol), and \(M_{\text{mol}}/M_{\text{atom}}\). The gas-phase metallicity of CGCG 137–068 is relatively high (solar or super-solar) for the stellar mass of CGCG 137–068.
5. Compared to the previous studies on known transients, both the host-galaxy and local-site properties of the AT2018cow are indicative of massive-star explosions, especially SNe Ic-BL without GRB, although the observed properties of AT2018cow itself cannot be fully explained by SNe Ic-BL models.

For a more detailed understanding of AT2018cow, deep integral-field-spectroscopy observations of CGCG 137–068 are necessary to investigate the \(\text{H}\alpha\) distribution and metallicity around the AT2018cow site, and to determine the age of the nearby young cluster. In addition, follow-up observations of the other FELT hosts, such as metallicity measurements, are required to place AT2018cow among the general population of FELT hosts. If the metallicity of the other FELT hosts is not higher than average, then some property of dwarf SF galaxies other than metallicity may be related to FELTs.

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Figure 3. Comparison between \(\text{H}_2\) column density at the AT2018cow site and that of other SNe sites from Galbany et al. (2017). Note that most of the SNe Ia and II data are upper limits.

We investigate the molecular-gas and star formation properties of the host galaxy (CGCG 137–068) and local site of AT2018cow using archival ALMA CO(\(J = 1 \rightarrow 0\)) data. We found the following.

\(^{13}\) 8.60 (Tremonti et al. 2004) with “MPA-JHU” calibration; 8.82 (McGaugh 1991), 8.93 (Zaritsky et al. 1994), and 8.45 (Pilyugin & Tuan 2005) with “R21”; 8.51 (Denicoló et al. 2002) and 8.36 (Pettini & Pagel 2004) with “N2”; 8.38 with “O3N2” (Pettini & Pagel 2004).

5. Summary

We have low stellar mass \((8.26 < \log(M_{\text{star}}/M_\odot) < 11.15\), a median of 9.33), as CGCG 137–068. One of the FELT hosts in Pursiainen et al. (2018) without SFR estimation has SDSS spectroscopic data. In Figures 2(a) and (b), we plotted this host using SDSS data, showing that it is a low-mass SF galaxy with a relatively low metallicity. Meanwhile, some metallicity calibrations suggest that it has a super-solar metallicity.\(^{13}\) This suggests that some properties of dwarf SF galaxies other than metallicity may be related to FELTs. However, the sample size \((N = 2)\) is too small to conclude this, and metallicity measurements of other FELT hosts are required.
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