Observational Signatures of Cloud–Cloud Collision in the Extended Star-forming Region S235

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Abstract

We present a multi-wavelength data analysis of the extended star-forming region S235 (hereafter E-S235), where two molecular clouds are present. In E-S235, using the 12CO (1–0) and 13CO (1–0) line data, a molecular cloud linked with the site “S235main” is traced in a velocity range [−24, −18] km s⁻¹, while the other one containing the sites S235A, S235B, and S235C (hereafter “S235ABC”) is depicted in a velocity range [−18, −13] km s⁻¹. In the velocity space, these two clouds are separated by ~4 km s⁻¹, and are interconnected by a lower-intensity intermediate velocity emission, tracing a broad bridge feature. In the velocity channel maps, a possible complementary molecular pair at [−21, −20] km s⁻¹ and [−16, −15] km s⁻¹ is also evident. The sites, “S235ABC,” east 1, and south–west, are spatially seen in the interface of two clouds. Together, these observed features are consistent with the predictions of numerical models of the cloud–cloud collision (CCC) process, favoring the onset of the CCC in E-S235 about 0.5 Myr ago. Deep UKIDSS near-infrared photometric analysis of point-like sources reveals significant clustering of young stellar populations toward the sites located at the junction, and the “S235main.” The sites “S235ABC” harbor young compact H II regions with dynamical ages of ~0.06–0.22 Myr, and these sites (including south–west and east 1) also contain dust clumps (having Mclump ~ 40 to 635 M☉). Our observational findings suggest that the star formation activities (including massive stars) appear to be influenced by the CCC mechanism at the junction.

Key words: dust, extinction – H II regions – ISM: clouds – ISM: individual objects (S235) – stars: formation – stars: pre-main sequence

1. Introduction

Young stellar populations can be formed spontaneously throughout a given molecular cloud (e.g., Preibisch & Zinnecker 2007). On the other hand, the collapse and star formation can be influenced by some external agents such as the expansion of H II regions (e.g., Elmegreen & Lada 1977; Elmegreen 1998) and cloud–cloud collision (CCC) process (e.g., Habe & Ohta 1992; Anathpindika 2010; Inoue & Fukui 2013; Takahira et al. 2014). In recent years, the study of star formation triggered through the CCC process has been an interesting and important issue instar formation research (e.g., Torii et al. 2017a, and references therein). It has also been suggested that the CCC process can form massive OB stars and young stellar clusters at the junctions of molecular clouds (e.g., Habe & Ohta 1992; Furukawa et al. 2009; Ohama et al. 2010; Inoue & Fukui 2013; Fukui et al. 2014, 2016; Takahira et al. 2014; Haworth et al. 2015a, 2015b; Torii et al. 2015, 2017a; Dewangan 2017). In hydrodynamical numerical simulations, it has been shown that the CCC triggers the birth of dense clumps/cores in the shock-compressed interface, and these dense clumps/cores can further lead to the formation of a new generation of stars (Habe & Ohta 1992; Anathpindika 2010, and also see Figure 1 in Torii et al. 2017a). Furthermore, Takahira et al. (2014) studied the formation and evolution of pre-stellar gas cores in the collision of non-identical clouds with Bonner–Ebert profiles using hydrodynamical simulations. Recent magnetohydrodynamical numerical simulations have demonstrated that the CCC process can enable the formation of the massive clumps in the collisional-compressed layer (Inoue & Fukui 2013). More recently, based on comparisons between observations and existing models, Torii et al. (2017a) reported the characteristic features of the CCC, such as the complementary distribution of the two colliding clouds, the bridge feature at the intermediate velocity range, and its flattened CO spectrum. These features are promising for obtaining convincing evidence to support the idea that two molecular components are interacting with each other in a given star-forming complex. Torii et al. (2017a) also provided a table of promising star-forming sites where the star formation process could be explained by the CCC process. However, the investigation of observational signatures of star formation (including massive stars) via the CCC mechanism is still rare and very challenging.

The extended star-forming region S235 (hereafter E-S235) is part of the giant molecular cloud G174+2.5 in the Perseus Spiral Arm (e.g., Heyer et al. 1996) and is a very well studied site using the multi-wavelength data covering from optical, near-infrared (NIR) to radio wavelengths (e.g., Georgelin et al. 1973; Israel & Felli 1978; Evans & Blair 1981; Evans et al. 1981; Nordh et al. 1984; Brand & Blitz 1993; Felli et al. 1997, 2004, 2006; Allen et al. 2005; Kirsanova et al. 2008, 2014; Boley et al. 2009; Camargo et al. 2011; Dewangan & Anandarao 2011; Wang et al. 2012; Chavarría et al. 2014; Burns et al. 2015, 2016; Foster & Brunt 2015; Navarete et al. 2015; Bieging et al. 2016; Dewangan et al. 2016; Ladeyschikov et al. 2016, etc.). Located at a distance of 1.8 kpc (Evans & Blair 1981), E-S235 is a nearby star-forming region that consists of previously known star-forming sites, the “S235 complex (or S235main),” S235A, S235B, and S235C (or “S235ABC”) (see Figure 1 in Dewangan & Anandarao 2011 (hereafter Paper I) and also in Kirsanova et al. (2014)). In E-S235, Evans & Blair 1981 found two velocity components at −20 km s⁻¹ (linked with “S235main”) and −17 km s⁻¹ (containing the sites “S235ABC”). This implies that the molecular gas linked with the sites...
“S235ABC” is redshifted with respect to the S235main molecular cloud. Furthermore, using $^{13}$CO (1−0) line data, Kirsanova et al. (2008) traced three molecular gas components (i.e., $-18 \text{ km s}^{-1} < V_{lsr} < -15 \text{ km s}^{-1}$ (red), $-21 \text{ km s}^{-1} < V_{lsr} < -18 \text{ km s}^{-1}$ (central), and $-25 \text{ km s}^{-1} < V_{lsr} < -21 \text{ km s}^{-1}$ (blue)) in the direction of E-S235. An extended H\ II region linked with the “S235main” is ionized by a single massive star BD+35°1201 of 09.5V type (Georgelin et al. 1973), while the sites, S235A, S235B, and S235C are associated with compact H\ II regions, which are mainly excited by B1V–B0.5V stars (see Table 1 in Bieging et al. 2016, and references therein). The existing observations and interpretations of E-S235 suggest that the H\ II regions associated with “S235main” and “S235ABC” are interacting with their surrounding molecular clouds. Photometric analysis of point-like sources indicated the intense star formation activities in these molecular clouds (Kirsanova et al. 2008; Dewangan & Anandarao 2011; Chavarra et al. 2014; Bieging et al. 2016; Dewangan et al. 2016). Furthermore, these sites have been cited as promising regions of triggered star formation by the expanding H\ II regions (Kirsanova et al. 2008, 2014; Camargo et al. 2011; Bieging et al. 2016). Dewangan et al. (2016, hereafter Paper II) performed a multi-wavelength study of star formation activity in “S235main” and found that at least five subregions (i.e., Central E, east 2, north, north–west, and Central W, having $A_V > 8$ mag) appear to be nearly regularly spaced along the sphere-like shell surrounding the ionized emission. These results have also been seen in the molecular and dust continuum maps. They concluded that “S235main” can be considered as a promising nearby site of triggered star formation. Furthermore, in E-S235 they also found an almost broad bridge feature in the velocity space and suggested the possibility of the applicability of the CCC process. They suggested that the CCC process might have influenced the star formation activity at the interface between the S235main molecular cloud and the “S235ABC” molecular cloud (i.e., south–west subregion). In Paper II, the analysis was focused mainly on the “S235main” site. Hence, a detailed study of the CCC process concerning the formation of young stellar clusters and massive stars in E-S235 is yet to be carried out.

To explore the CCC process in E-S235, we have used the narrowband H\alpha image from the Isaacs Newton Telescope Photometric H\alpha Survey of the northern Galactic Plane (IPHAS; Drew et al. 2005), NIR data from the UKIDSS Galactic Plane Survey (GPS; Lawrence et al. 2007), radio continuum data at 610 MHz from the Giant Meter-wave Radio Telescope (GMRT) database, and dust continuum 1.1 mm data (Aguirre et al. 2011; Ginsburg et al. 2013) from the Bolocam Galactic Plane Survey (BGPS). Additionally, several published data (i.e., Spitzer NIR and mid-infrared (MIR) data (from Dewangan & Anandarao 2011), and the Five College Radio Astronomy Observatory (FCRAO) $^{12}$CO (1−0) and $^{13}$CO (1−0) line data (Heyer et al. 1998; Brunt 2004)) were also utilized.

This paper is structured as follows. In Section 2, we discuss the data selection. The results of our extensive multi-wavelength data analysis are presented in Section 3. The implications of our findings concerning the star formation are discussed in Section 4. Finally, the results are summarized and concluded in Section 5.

2. Data and Analysis

In this work, we have selected a region of $\sim 24'' \times 24''$ (or $\sim 12.5$ pc $\times 12.5$ pc at a distance of 1.8 kpc) (central coordinates: $\alpha_{2000} = 05^h 41^m 02^s$, $\delta_{2000} = +35^\circ 47' 25''$) containing E-S235. In the following, we provide a brief description of the adopted multi-frequency data-sets.

2.1. Narrowband H\alpha Image

The narrowband H\alpha image at 0.6563 $\mu$m was retrieved from the IPHAS database. The survey was carried out using the Wide-Field Camera (WFC) at the 2.5 m Isaac Newton Telescope, located at La Palma. The WFC contains four $4k \times 2k$ CCDs, in an L-shape configuration. The pixel scale is $0.23''$ and the instantaneous field of view is about 0.3 square degrees. More details about the IPHAS can be found in Drew et al. (2005).

2.2. Near-infrared Data

We analyzed the deep NIR photometric HK magnitudes of point sources extracted from the UKIDSS-GPS sixth archival data release (UKIDSSDR6plus) and Two Micron All Sky Survey (2MASS; Skrutskie et al. 2006). The UKIDSS observations (resolution $\sim 0.8''$) were performed with the WFCAM mounted on the United Kingdom Infra-Red Telescope. 2MASS photometric data were utilized to calibrate the final fluxes. In this work, we extracted only a reliable NIR photometric catalog. More information about the selection procedures of the GPS photometry can be found in Dewangan et al. (2015). Our resultant GPS catalog consists of point sources fainter than $H = 12.3$ and $K = 11.4$ mag to avoid saturation. In our final catalog, the magnitudes of the saturated bright sources were obtained from the 2MASS catalog.

Additionally, we also obtained a Spitzer 3.6 $\mu$m image from Paper I.

2.3. Dust Continuum 1.1 mm Data

The Bolocam 1.1 mm image and Bolocam source catalog (v2.1) at 1.1 mm were extracted from the BGPS. The effective full width at half maximum (FWHM) of the 1.1 mm map is $\sim 33''$.

2.4. Radio Continuum Data

The 610 MHz continuum data were obtained from the GMRT archive and were observed on 2005 June 18–19 (Project Code: 08SKG01). The data reduction was performed using AIPS software, in a manner similar to that highlighted in Mallick et al. (2013). Since the S235 complex was distant from the center of the observed field, the primary beam correction for 610 MHz was also done, using the AIPS PBCOR task and parameters from the GMRT manual. The synthesized beam size of the final 610 MHz map is $\sim 48'' \times 44''$.2 (also see Paper II).

2.5. Molecular CO Line Data

In E-S235, we probed the molecular gas content using the FCRAO $^{12}$CO ($J = 1−0$) and $^{13}$CO ($J = 1−0$) line data. The FCRAO beam sizes are $45''$ and $46''$ for $^{12}$CO and $^{13}$CO, respectively. The observations of E-S235 were made as part of the Extended Outer Galaxy Survey (E-OGS, Brunt 2004), which extends the coverage of the FCRAO Outer Galaxy Survey

http://gmrt.ncra.tifr.res.in/gmrt_hpage/Users/doc/obs_manual.pdf
Figure 1. The $^{12}$CO($J = 1-0$) velocity channel contour maps. The molecular emission is integrated over a velocity interval, which is given in each panel (in km s$^{-1}$). The contour levels are 10%, 20%, 25%, 30%, 35%, 40%, 50%, 60%, 70%, 80%, 90%, and 98% of the peak value (in K km s$^{-1}$), and are also provided in each panel. The positions of ionizing stars of S235A, S235B, and S235C are marked by open stars. In the “S235main,” the location of an O9.5V star (BD+35°1201) is highlighted by a filled red star. The solid box shows the area investigated in Paper II, which is related to the site “S235main.”
Figure 2. The $^{13}$CO($J = 1-0$) velocity channel contour maps. The molecular emission is integrated over a velocity interval, which is given in each panel (in km s$^{-1}$). The contour levels are 10%, 20%, 25%, 30%, 35%, 40%, 50%, 60%, 70%, 80%, 90%, and 98% of the peak value (in K km s$^{-1}$), and are also provided in each panel. In each panel, the other marked symbols and labels are similar to those shown in Figure 1.
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Figure 3. The distribution of molecular gas toward E-S235 (including “S235main” and “S235ABC”). (a) Integrated intensity map of $^{12}$CO ($J = 1–0$) from $−24$ to $−13$ km s$^{-1}$. The contour levels are 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, and 98% of the peak value (i.e., 130.929 K km s$^{-1}$). (b) Declination–velocity map of $^{12}$CO. The $^{12}$CO emission is integrated over the right ascension range from 05°42′02″ to 05°40′00″. (c) Two molecular components (a redshifted and a blueshifted) in the direction of E-S235. The $^{12}$CO emission contours from $−24$ to $−18$ km s$^{-1}$ are overplotted on the $^{12}$CO emission map. The background $^{12}$CO emission map (from $−18$ to $−13.5$ km s$^{-1}$) is shown with levels of 79.628 K km s$^{-1}$ × (0.1, 0.15, 0.25, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, and 0.98). The $^{12}$CO contours (in blue) are shown with levels of 121.6 K km s$^{-1}$ × (0.1, 0.15, 0.2, 0.3, 0.45, 0.5, 0.6, 0.7, 0.8, 0.9, and 0.98). (d) Right ascension-velocity map of $^{13}$CO. The $^{13}$CO emission is integrated over the declination range from $+35°35′9″$ to $+36°0′0″$. In both of the left panels (i.e., Figures 3(a) and (c)), the marked symbols are similar to those shown in Figure 1. There are two velocity peaks (a blueshifted one at $−20.5$ km s$^{-1}$ and a redshifted one at $−16.5$ km s$^{-1}$) seen in the position–velocity maps (i.e., Figures 3(b) and (d)), which are highlighted by dashed magenta lines. These peaks are separated by a lower-intensity intermediate velocity emission (i.e., a broad bridge feature; also see the text).

(OGS, Heyer et al. 1998) to Galactic longitude $l = 193^°$, over a latitude range of $−3.5 \leq b \leq +5.5$. However, the data cubes of E-S235 were further reprocessed and a document describing the re-processing data methods is given in Brunt (2004; C. M. Brunt et al. 2017, in preparation). These $^{13}$CO data cubes were collected from M. Heyer and C. Brunt (through private communication). The FCRAO $^{13}$CO ($J = 1–0$) line data were also used in Paper II.

3. Results

In this section, we present a multi-wavelength analysis of E-S235 to understand the ongoing physical processes operating in this target region.

3.1. Kinematics of Molecular Gas in E-S235

The study of molecular gas in a given star-forming complex can help to trace the physical associations of different subregions. As mentioned earlier, two velocity components (at $−20$ and $−17$ km s$^{-1}$) are seen in the direction of E-S235 (Evans & Blair 1981). To explore the spatial distribution of molecular gas in E-S235, we present $^{13}$CO ($J = 1–0$) and $^{12}$CO ($J = 1–0$) velocity channel maps at different velocities covering a range from $−24$ to $−12$ km s$^{-1}$ in steps of 1 km s$^{-1}$ in Figures 1 and 2, respectively. The analysis of channel maps of both $^{13}$CO and $^{12}$CO emission reveals that the molecular cloud associated with the site “S235main” is traced in a velocity range of $−23$ to $−18$ km s$^{-1}$, while the molecular cloud linked with the sites “S235ABC” is depicted in a velocity range of $−18$ to $−13$ km s$^{-1}$. Together, our analyses are in agreement with the previously reported fact that the S235main molecular cloud is blueshifted with respect to the molecular cloud harboring the sites “S235ABC.” To further examine the velocity field and kinematical structure of the molecular gas in E-S235, using the $^{12}$CO line data, we present the integrated intensity map and the position–velocity maps in Figure 3. In
The 13CO emission is integrated over the right ascension range from 05h42m02s to 05h40m00s. The 13CO emission is integrated over the right ascension range from 05h42m02s to 05h40m00s. (b) Declination–velocity map of 13CO. The 13CO emission is integrated over the right ascension range from 05h42m02s to 05h40m00s. (c) Two molecular components (a redshifted and a blueshifted one in the direction of E-S235. The 13CO emission contours from −24 to −18 km s$^{-1}$ are overplotted on the 12CO emission map. The background 13CO emission map (from −18 to −13.3 km s$^{-1}$) shows levels of 3.587 K km s$^{-1}$ at (0.09, 0.15, 0.25, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, and 0.98). The 13CO contours are shown with levels of 32.252 K km s$^{-1}$ at (0.08, 0.1, 0.15, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, and 0.98). (d) Right ascension–velocity map of 13CO. The 13CO emission is integrated over the declination range from +35°35′59″ to +36°00′00″. In both of the left panels (i.e., Figures 4(a) and (c)), the marked symbols are similar to those shown in Figure 1. There are two velocity peaks (a blueshifted one at $\sim$−20.5 km s$^{-1}$ and a redshifted one at $\sim$−16.5 km s$^{-1}$) seen in the position–velocity maps (i.e., Figures 4(b) and (d)) that are highlighted by dashed magenta lines. These peaks are separated by a lower-intensity intermediate velocity emission (i.e., a broad bridge feature; also see the text).

Figure 4. The distribution of molecular gas toward E-S235 (including “S235main” and “S235ABC”). (a) Integrated intensity map of 13CO ($J = 1-0$) from −24 to −13 km s$^{-1}$. The contour levels are 10%, 20%, 30%, 35%, 40%, 50%, 60%, 70%, 80%, 90%, and 98% of the peak value (i.e., 36.046 K km s$^{-1}$). (b) Declination–velocity map of 13CO. The 13CO emission is integrated over the right ascension range from 05h42m02s to 05h40m00s. (c) Two molecular components (a redshifted and a blueshifted one) in the direction of E-S235. The 13CO emission contours from −24 to −18 km s$^{-1}$ are overplotted on the 13CO emission map. The background 13CO emission map (from −18 to −13.3 km s$^{-1}$) shows levels of 31.587 K km s$^{-1}$ at (0.09, 0.15, 0.25, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, and 0.98). The 13CO contours are shown with levels of 32.252 K km s$^{-1}$ at (0.08, 0.1, 0.15, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, and 0.98). (d) Right ascension–velocity map of 13CO. The 13CO emission is integrated over the declination range from +35°35′59″ to +36°00′00″. In both of the left panels (i.e., Figures 4(a) and (c)), the marked symbols are similar to those shown in Figure 1. There are two velocity peaks (a blueshifted one at $\sim$−20.5 km s$^{-1}$ and a redshifted one at $\sim$−16.5 km s$^{-1}$) seen in the position–velocity maps (i.e., Figures 4(b) and (d)) that are highlighted by dashed magenta lines. These peaks are separated by a lower-intensity intermediate velocity emission (i.e., a broad bridge feature; also see the text).

Figure 3(a), the 12CO emission is integrated over −24 to −13 km s$^{-1}$, tracing the gas distribution toward the sites “S235main” and “S235ABC.” In Figures 3(b) and (d), we present the position–velocity diagrams of 12CO emission, tracing two molecular components as well as noticeable velocity gradients. In both of the position–velocity maps, a redshifted molecular component (velocity peak at $\sim$−16.5 km s$^{-1}$) and a blueshifted component (velocity peak at $\sim$−20.5 km s$^{-1}$) are evident that are consistent with those observed in the channel maps of 12CO emission. This implies that these peaks are separated by $\sim$4 km s$^{-1}$. Furthermore, in Figure 3(b), we find that these two velocity peaks are interconnected by a lower-intensity intermediate velocity emission, suggesting the presence of a broad bridge feature. In Figure 3(c), we present the spatial distribution of 12CO gas associated with the redshifted and blueshifted molecular components within E-S235.

Using the 13CO line data, we also show the integrated intensity map and the position–velocity maps in Figure 4. Figure 4(a) shows the 13CO intensity map integrated over −24 to −13 km s$^{-1}$. Figures 4(b) and (d) present the position–velocity diagrams of 13CO emission, also depicting two molecular components as well as the broad bridge feature. We have found that the bridge feature is more noticeable in the velocity space of 12CO compared to 13CO data. Note that in Paper II, only the declination–velocity map of 13CO related to E-S235 was discussed. In Paper II, the presence of an expanding H II region was reported in “S235main,” on the basis of the detection of arc-like or ring-like features in the velocity space. Hence, in this work, we do not focus on the features seen in the velocity space. Figure 4(c) presents the spatial distribution of 13CO gas linked with the blueshifted and the redshifted molecular components within E-S235. The distribution of 12CO and 13CO gas associated with both the clouds is spatially seen toward the sites “S235ABC” and a few subregions located in the east and south–west with respect to the location of the O9.5V star (BD+35°1201) (see Figures 3(c) and 4(c)). This implies the presence of junction/intersection...
zones in both the space and velocity between two molecular clouds. To further explore the boundaries of these two clouds, we present $^{12}$CO and $^{13}$CO first moment maps in Figures 5(a) and (b), respectively. These maps allow us to reveal the $V_{lsr}$ of the peak emission at each grid point and are measures of the intensity-weighted mean velocity of the emitting gas. These maps clearly trace two distinct molecular clouds and also depict their boundaries in E-S235. Figures 5(c) and (d) show maps of $^{12}$CO and $^{13}$CO velocity dispersions ($\delta V$) (i.e., the second-order moment), enabling us to infer the line width at each pixel. A large dispersion may be explained by a broad single velocity component and/or may indicate the presence of two or more narrow components with different velocities along one line of sight. In Figures 5(c) and (d), the distribution of velocity dispersion has also enabled us to trace the boundaries of the molecular clouds or the colliding interface (where $\delta V > 2 \text{ km s}^{-1}$; see a white contour in Figure 5(c)).

We have further examined the broad bridge feature in E-S235 that contains H II regions. There are many physical processes (such as radiative/mechanical feedback from massive stars) that might act to remove the broad bridge feature in the vicinity of the H II regions. Hence, it seems reasonable to look for the broad bridge features away from the H II regions. Figures 6(a)–(c) show the observed $^{12}$CO ($J = 1-0$) profiles toward three small areas, reg 1, reg 2, and reg 3, respectively (see boxes in Figure 5(a)). Note that the area reg 1 is chosen near the boundary of two molecular clouds, while areas reg 2 and reg 3 are selected near the sites “S235AB” and “S235main,” respectively. Each spectrum is obtained by averaging the area highlighted by the respective box in Figure 5. Each spectrum shows the previously known two molecular clouds and also reveals a bridge feature seen at the intermediate velocity range that has an almost flattened profile.

In the star-forming region M20, Torii et al. (2017a) also
observed a similar feature in the $^{12}$CO spectra (see their Figure 14). In the velocity space, the existence of a broad bridge feature indicates an observational signature of collisions between molecular clouds (i.e., the CCC process; Haworth et al. 2015a, 2015b). Torii et al. (2017a) pointed out that the bridge feature at the intermediate velocity range probes the turbulent motion of the gas enhanced by the collision. They also indicated that the spatially complementary distribution between two clouds is an expected outcome of the CCC and is attributed to identical silhouettes of the smaller cloud and the cavity in the larger cloud projected on the sky (see Figure 1 in Torii et al. 2017a). Based on this argument, we have also examined the channel maps of $^{12}$CO and $^{13}$CO, and have found a possible complementary pair that appears to be seen in the velocity ranges $[-21, -20]$ km s$^{-1}$ and $[-16, -15]$ km s$^{-1}$ (see Figures 1 and 2).

In Figures 7 and 8, we present the $^{12}$CO and $^{13}$CO emission contours overlaid on the *Spitzer* 3.6 μm image, respectively. Figure 7(a) and 8(a) show the *Spitzer* 3.6 μm image overlaid with the $^{12}$CO and $^{13}$CO emission integrated over $-24$ to $-18$ km s$^{-1}$, respectively. Figures 7(b) and 8(b) present the *Spitzer* 3.6 μm image superimposed with the $^{12}$CO and $^{13}$CO emission integrated over $-18$ to $-13.5$ km s$^{-1}$, respectively. In Figures 9(a) and (b), we show the $^{12}$CO and $^{13}$CO emission contours overlaid on the *Spitzer* 3.6 μm image, respectively. These emissions are integrated over $-18.75$ to $-17.75$ km s$^{-1}$, which is an intermediate velocity range between two velocity peaks (see Figure 3(b)). In Figures 7–9, we have highlighted previously known different subregions (i.e., east 1, east 2, north, north–west, Central W, Central E, south–west, S235A, S235B, and S235C) and the positions of the ionizing sources within E-S235.

Based on Figures 3(c), 4(c), and 7–9, the sites “S235ABC,” east 1, and south–west are spatially found at the junction of the molecular clouds within E-S235 (also see Section 4 for more details).

### 3.2 Dust Continuum Clumps and Ionized Emission in E-S235

In this section, we study the dust continuum clumps and the distribution of ionized emission in E-S235. The dust continuum
Figure 7. (a) Spitzer 3.6 μm image overlaid with the 12CO emission integrated over −24 to −18 km s\(^{-1}\). (b) Spitzer 3.6 μm image overlaid with the 12CO emission integrated over −18 to −13.5 km s\(^{-1}\). In both the panels, different subregions are labeled (also see Figure 1 in Dewangan et al. 2016). The scale bar on the bottom left shows a size of 3 pc at a distance of 1.8 kpc in each panel. In each panel, the contours are similar to the one shown in Figure 3(c). In both the panels, the positions of ionizing stars of “S235main,” S235A, S235B, and S235C are also highlighted by open stars (also see Table 1 in Bieging et al. 2016). The positions of ionizing stars of S235A, S235B, and S235C are marked by open stars. In each panel, a solid box shows the area investigated in Paper II.

Figure 8. (a) Spitzer 3.6 μm image overlaid with the 13CO emission integrated over −24 to −18 km s\(^{-1}\). (b) Spitzer 3.6 μm image overlaid with the 13CO emission integrated over −18 to −13.5 km s\(^{-1}\). In both the panels, different subregions are labeled (also see Figure 1 in Dewangan et al. 2016). The scale bar in the bottom left shows a size of 3 pc at a distance of 1.8 kpc in each panel. In each panel, the other marked symbols and labels are similar to those shown in Figure 7(a).
Figure 9. (a) Spitzer 3.6 μm image overlaid with the $^{12}$CO emission integrated over −18.75 to −17.75 km s$^{-1}$. The $^{12}$CO contours are shown with levels of 35.933 K km s$^{-1} \times (0.2, 0.3, 0.45, 0.5, 0.6, 0.7, 0.8, 0.9, \text{and } 0.98)$. (b) Spitzer 3.6 μm image overlaid with the $^{13}$CO emission integrated over −18.75 to −17.75 km s$^{-1}$. The $^{13}$CO contours are shown with levels of 14.402 K km s$^{-1} \times (0.09, 0.15, 0.25, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, \text{and } 0.98)$. In both the panels, different subregions are labeled (also see Figure 1 in Dewangan et al. 2016). The scale bar in the bottom left shows a size of 3 pc at a distance of 1.8 kpc in each panel. In each panel, other marked symbols and labels are similar to those shown in Figure 7(a).

Figure 10. (a) Bolocam 1.1 mm dust continuum contour map (beam size ∼33") of E-S235. The contour levels are 2.5%, 8%, 15%, 20%, 30%, 40%, 55%, 70%, 85%, and 95% of the peak value i.e., 3.39 Jy/beam. The positions of dust clumps at 1.1 mm are highlighted by yellow squares and are also labeled. Clumps 1–15 are distributed toward “S235main” (see also Paper II), while clumps 16–18 are found toward “S235ABC.” The solid magenta box encompasses the area shown in Figure 10(b). (b) IPHAS Hα grayscale image overlaid with the GMRT 610 MHz emission contours. The GMRT 610 MHz dotted-dashed contours (in cyan) are shown with levels of 0.01, 0.024, 0.04, 0.07, 0.12, and 0.15 Jy/beam. In both the panels, the other marked symbols and labels are similar to those shown in Figure 7(a).
Figure 11. (a) Selection of embedded young stellar populations within E-S235. The GPS-2MASS color–magnitude diagram (H−K/K) of the sources is detected in the H and K bands. The identified YSOs are marked by open blue circles, while the dots in gray represent the stars with only photospheric emissions. In the NIR H−K/K plot, we have plotted only 1001 out of 5401 stars with photospheric emissions. Due to large numbers of stars with photospheric emissions, only some of these stars are randomly shown in the NIR H−K/K plot. A dotted-dashed line separates the identified YSOs against the stars with photospheric emissions. (b) The surface density contours (in navy) of all the identified YSOs are overlaid on the 1.1 mm dust continuum map. The background map is similar to the one shown in Figure 10(a). The contours are shown at 5, 10, 25, and 60 YSOs pc$^{-2}$, from the outer to the inner side. A solid box shows the area investigated in Paper II. The other marked symbols and labels are similar to those in Figure 7(a).

Figure 12. Surface density contours (in blue) of all the identified YSOs overlaid on the molecular $^{13}$CO maps. The background maps are similar to the one shown in Figure 4(c). The surface density contours are shown at 5, 10, 25, and 60 YSOs pc$^{-2}$, from the outer to the inner side. The other marked symbols and labels are similar to those shown in Figure 7(a).
map at 1.1 mm allows us to depict the dense and cold regions. Figure 10(a) shows the grayscale Bolocam dust continuum map at 1.1 mm overlaid with the dust continuum clumps at 1.1 mm. These clumps were obtained from the Bolocam source catalog v2.1 (Ginsburg et al. 2013). For our selected target region, we find 18 clumps and 15 of them (1–15; see Figure 10(a)) have also been reported in Paper II. These fifteen clumps (i.e., nos 1–15) are distributed toward “S235main,” while the remaining three clumps (numbers 16, 17, and 18) are seen toward “S235ABC.” In Paper II, the clump masses of the first 15 clumps have been computed to vary between 7 $M_{\odot}$ and 285 $M_{\odot}$ (see Table 1 in Paper II). The most massive dust clump (i.e., no. 15; $M_{\text{clump}} \sim 285 M_{\odot}$) is associated with the east 1 subregion. The mass of a clump seen in the site south–west is reported to be about 60 $M_{\odot}$ (see ID #3 in Table 1 in Paper II). Following Paper II, we have also computed the clump masses of clumps 16, 17, and 18 (see Equation (1) in Paper II for $M_{\text{clump}}$), which are ~635, 70, and 40 $M_{\odot}$, respectively. In the calculation, we have used a dust absorption coefficient ($k_D = 1.14 \text{cm}^2 \text{g}^{-1}$ (e.g., Enoch et al. 2008; Bally et al. 2010)), a distance ($D = 1.8 \text{kpc}$, and a dust temperature ($T_D = 20 \text{K}$ (e.g., Kirsanova et al. 2014)). A dust clump (i.e., no. 16; $M_{\text{clump}} \sim 635 M_{\odot}$) is seen toward the sites S235A and S235B (hereafter “S235AB”). Two clumps (17 and 18; $M_{\text{clump}} \sim 40-70 M_{\odot}$) are found toward the S235C region.

Figure 10(b) shows an Hα image overlaid with the GMRT 610 MHz emission. Both the images trace the distribution of ionized emission in E-S235. Spitzer-IRAC images also show extended bright features in E-S235 and each feature contains the radio continuum emission at its interior (see Figures 7(a) and 10(b)). In Figure 10(b), we find the spatial match between the Hα emission and the radio continuum emission. The ionized emission is found toward sites “S235main,” S235A, S235B, and S235C. “S235main” is powered by a single massive star BD+35°1201 of O9.5V type, while the sites S235A, S235B, and S235C are linked with the compact H II regions, which are mainly excited by B1V–B0.5V stars (see Table 1 in Bieging et al. 2016). The positions of the ionizing sources are marked in Figure 7(a). These results are also in agreement with estimations of Lyman continuum photons using the GMRT 610 MHz data. We have also used the GMRT 610 MHz data to compute the dynamical ages ($t_{\text{dyn}}$) of the H II regions associated with “S235AB” and S235C sites. Adopting a typical value of $n_0$ (as $10^4 (10^5)$ cm$^{-3}$), we estimated the dynamical ages of these H II regions to be $\sim 0.06 (0.22)$ Myr. In Paper II, the dynamical age ($t_{\text{dyn}}$) of the H II region linked with “S235main” was reported to be $\sim 1$ Myr. Based on these results, it appears that the H II regions associated with the “S235AB” and S235C sites are relatively younger than the H II region linked with “S235main.”

### 3.3. Young Stellar Populations and their Clustering

In this section, to probe the star formation activity, we have carried out an investigation of young stellar objects (YSOs) in our selected region. The YSOs are identified using their infrared excess emission, which are produced by the envelope and/or the disk of dust around them. Previously, many authors identified the young stellar populations in our selected target (e.g., Allen et al. 2005; Kirsanova et al. 2008; Camargo et al. 2011; Dewangan & Anandarao 2011; Chavarría et al. 2014; Kirsanova et al. 2014; Bieging et al. 2016; Dewangan et al. 2016). In the present work, we have employed the UKIDSS-GPS NIR data for depicting more deeply embedded and faint young stellar populations. This is possible because the UKIDSS-GPS NIR data are three magnitudes deeper than the data of 2MASS. In Paper II, the GPS NIR data were mainly employed for the “S235main” site. Following the analysis presented in Paper II, we have selected sources that have detections only in the H and K bands. To identify infrared excess sources, we have utilized a color–magnitude (H–K/K) diagram (see Figure 11(a)). The diagram allows us to select embedded sources with H–K $> 1.04$. This color criterion is chosen based on the color–magnitude analysis of a nearby control field (size $\sim 17^6 \times 15^5$; central coordinates: $\alpha_{2000} = 05^h43^m35^s18, \delta_{2000} = +35^\circ20'20''4$). This condition yields 440 deeply embedded infrared excess sources.

To examine the individual groups or clusters of YSOs in E-S235, the surface density map of YSOs is produced using the nearest-neighbor (NN) technique (also see Gutermuth et al. 2009; Bressert et al. 2010, for more details). We have generated the surface density map of all the selected 440 YSOs, in a manner similar to that utilized in Paper I. The map was obtained using a 5″ grid and 6 NN at a distance of 1.8 kpc. Figure 11(b) shows the resultant surface density contours of YSOs overlaid on the dust continuum map at 1.1 mm. The contour levels are shown at 5, 10, 25, and 60 YSOs pc$^{-2}$, increasing from the outer to the inner regions. The figure clearly reveals the spatial correlation between YSOs surface density and dense clumps. The clusters of YSOs are spatially found toward all the subregions/sites: east 1, east 2, north, north–west, Central W, Central E, south–west, S235A, S235B, and S235C (see Figure 11(b)). In E-S235, this outcome appears to be in agreement with the work of Chavarría et al. (2014); see also Figure 21 in Bieging et al. (2016). In Figure 12, we have also overlaid the surface density contours on the molecular CO emission maps of the redshifted and the blueshifted molecular components. This figure helps us to trace the clustering of YSOs at the junction of two molecular clouds, indicating the intense star formation activities.

### 4. Discussion

Our present work expands upon the outcomes of Paper II with a more detailed multi-wavelength analysis of E-S235 containing the “S235main” and “S235AB/C” sites. In Paper II, the analysis was restricted mainly to the “S235main” site and it was suggested that the star formation activities toward the five subregions (i.e., east 2, north, north–west, Central W, and Central E) could be explained by the expanding H II region via “collect and collapse.” It was also reported that the clusters of YSOs in the east 1 subregion might have originated from compression of the pre-existing dense material by the expanding H II region. Furthermore, it was argued that the CCC process might be acting in E-S235. Using the hydrogen radio recombination line observations, Balser et al. (2011) and Anderson et al. (2015) reported the velocity of the ionized gas to be about $-25.6$ and $-15.3$ km s$^{-1}$ in the H II regions linked with “S235main” and “S235ABC,” respectively. Considering the velocities of the molecular and ionized gases in E-S235, it is obvious that the molecular cloud linked with the sites “S235ABC” is redshifted relative to the cloud associated with the site “S235main” (also see Figures 7 and 8). Hence, it appears that the molecular cloud containing “S235ABC” is
located at the rear side with respect to “S235main.” It is in agreement with the CCC scenario. However, a detailed study of the CCC process in E-S235 is still lacking. Hence, considering this interesting possibility, our present analysis has been focused on obtaining more insights into the CCC in E-S235. The CCC process has also been demonstrated in the numerical simulations (see Habe & Ohta 1992; Inoue & Fukui 2013; Takahira et al. 2014; Haworth et al. 2015a, 2015b, and references therein). As mentioned before, the signposts of the CCC are the bridging feature connecting the two clouds in velocity, the complementary distribution of the two colliding clouds, and the broad CO line wing in the intersection of the two clouds. The presence of a broad bridge feature in the velocity space can be interpreted as evidence of a compressed layer of gas due to the collision between the clouds seen along the line of sight (e.g., Haworth et al. 2015a, 2015b; Fukui et al. 2017; Torii et al. 2017a, 2017b). One can also note that the synthetic observations presented in Haworth et al. (2015a, 2015b) were made with an observer viewing angle parallel to the collisional axis, so that the two colliding clouds are spatially coincident along the line of sight. In such a case, two velocity peaks separated by intermediate intensity emissions are found in the velocity space. This is similar to the case in M20 studied by Torii et al. (2017a). If one observes a CCC with a viewing angle inclined relative to the collisional axis, or if a CCC is an offset collision, the observed position–velocity diagrams and line profiles may be different from those presented in Haworth et al. (2015a, 2015b) and Torii et al. (2017a) (also see Fukui et al. 2017). Using the $^{12}$CO ($J = 1$–0) and $^{13}$CO ($J = 1$–0) line data, two molecular clouds are observed in the direction of E-S235 and are interconnected in space as well as in velocity (see Section 3.1). The molecular second momentum map has revealed the colliding interface or the boundaries of the molecular clouds (see Figure 5(c)). A possible complementary molecular pair at [−21, −20] km s$^{-1}$ and [−16, −15] km s$^{-1}$ is also found in E-S235. Furthermore, the existence of the broad bridge feature (see Figures 3(c) and 4(c)) and its flattened molecular profiles (see Figure 6) indicate the onset of the CCC process and the presence of the turbulent gas excited by this mechanism. Taken together, all the observed signatures are in agreement with the outcomes of models of the CCC (e.g., Inoue & Fukui 2013; Takahira et al. 2014; Haworth et al. 2015a, 2015b).

In E-S235, we find sites, east 1, “S235ABC,” and south–west, seen in the spatially overlapped zones of two molecular clouds (see Figures 5–6 and also Section 3.1). In the sites of the CCC, one may expect higher values of the ratio of CO 3–2/1–0 toward the colliding interface of the colliding clouds (Torii et al. 2015). Bieging et al. (2016) studied E-S235 in CO (2–1), $^{13}$CO (2–1), and CO (3–2) and presented velocity channel maps of CO ($J = 3–2$)/($J = 2–1$) intensity ratios, a map of velocity dispersion for $^{13}$CO (2–1), and a distribution of CO and $^{13}$CO (2–1) excitation temperature derived by an LTE model. Using these published results toward the colliding interfaces (i.e., east 1, “S235ABC,” and south–west) in E-S235, the values of CO ($J = 3–2$)/($J = 2–1$) intensity ratios, velocity dispersion for $^{13}$CO (2–1), and excitation temperature are found to be about 0.6–0.9, 2–4 km s$^{-1}$, and 25–40 K, respectively. These values are noticeably high toward the sites east 1, “S235ABC,” and south–west, and may be explained by the CCC (e.g., Torii et al. 2015, 2017a, 2017b; see also Figure 5 for the molecular first and second momentum maps in this paper). All these sites are associated with intense star formation activities. The sites S235A and S235B contain compact H II regions excited by B-type stars. The site east 1 is not associated with any ionized emission and contains many embedded protostars that show outflow activities (see Papers I and II). A massive clump (i.e., $M_{\text{clump}} \sim 285 M_{\odot}$) is found toward east 1. Additionally, this subregion is considered the youngest star-forming site inS235main (see Kirsanova et al. 2014). In E-S235, the most massive clump (i.e., $M_{\text{clump}} \sim 635 M_{\odot}$) is observed toward sites “S235AB” that has significant gas mass within ~2 pc of the clusters. Considering the velocity separation (i.e., ~4 km s$^{-1}$) of the two colliding clouds in the E-S235, a typical collision timescale is computed to be ~0.5 Myr. The dynamical ages of the H II regions associated with sites “S235AB” are found to be 0.06–0.22 Myr. Average ages of the Class I and Class II YSOs are estimated to be ~0.44 Myr and ~1–3 Myr, respectively (Evans et al. 2009). Taking into account these timescales, it seems that the formation of the youngest populations and massive stars in the interface of two clouds (i.e., east 1, “S235ABC,” and south–west) might have been influenced by the CCC about 0.5 Myr ago. However, the stellar populations older than the collision timescale might have formed prior to the collisions of clouds. Hence, we cannot rule out the onset of star formation activities before the collision in E-S235.

Considering the results presented in Paper II and the outcomes of this paper reinforces the idea that the E-S235 is a very promising triggered star formation site where the “collect and collapse” (e.g., Kang et al. 2012; Chavarría et al. 2014; Kirsanova et al. 2014; Bieging et al. 2016) and the CCC processes seem to have influenced the star formation activities.

5. Summary and Conclusions

In this paper, we have carried out an extensive study of E-S235 (harboring the “S235main” and “S235ABC” sites) using the multi-wavelength data. The major results of our multi-wavelength analysis are the following.

1. Using the $^{12}$CO ($J = 1$–0) and $^{13}$CO ($J = 1$–0) line data, the molecular gas emission in the direction of E-S235 reveals two noticeable molecular clouds (having velocity peaks at ~−20.5 and ~−16.5 km s$^{-1}$), which are separated by ~4 km s$^{-1}$ in the velocity space. The boundaries of the two clouds (or the colliding interface) are traced using the molecular momentum maps. The redshifted molecular component (−18 to −13 km s$^{-1}$) is linked with the sites S235A, S235B, and S235C, while the blueshifted one (−24 to −18 km s$^{-1}$) contains the site “S235main.”

2. The position–velocity space of $^{12}$CO and $^{13}$CO depicts a broad bridge feature. In this configuration, the redshifted and the blueshifted molecular components are interconnected by a lower-intensity intermediate velocity emission.

3. In the velocity channel maps of $^{12}$CO and $^{13}$CO, a possible complementary molecular pair at [−21, −20] km s$^{-1}$ and [−16, −15] km s$^{-1}$ is also traced.

4. The sites east 1, “S235ABC,” and south–west are found in the spatially overlapped zones of two molecular clouds.
5. Deep UKIDSS NIR photometric analysis of point-like sources gives a total of 440 YSOs in E-S235 and depicts significant clustering of young stellar populations toward the sites located in the interface, and “S235main.”
6. The sites “S235ABC” harbor young compact H II regions with dynamical ages of ~0.06–0.22 Myr.
7. The sites “S235ABC,” south–west, and east 1 contain dust clumps (having $M_{\text{clump}} \sim 40$ to 635 $M_\odot$).
8. A typical collision timescale in E-S235 is estimated to be ~0.5 Myr.

With the observational outcomes presented in this paper, we conclude that the CCC process might have influenced the star formation activities (including massive stars) at the junction about 0.5 Myr ago.

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**References**

Aguirre, J. E., Ginsburg, A. G., Dunham, M. K., et al. 2011, ApJS, 192, 4
Allen, L. E., Hora, J. L., Megeath, S. T., et al. 2005, in Proc. IAU Symp. 227, Massive Star Birth: A Crossroads of Astrophysics, ed. R. Cesaroni et al. (Cambridge: Cambridge Univ. Press), 352
Anathpindika, S. V. 2010, MNRAS, 405, 1431
Anderson, L. D., Armientroug, W. P., Johnstone, B. M., et al. 2015, ApJS, 221, 26
Bally, J., Aguirre, J., Batterberry, C., et al. 2010, ApJ, 721, 137
Balser, D. S., Rood, R. T., Bania, T. M., & Anderson, L. D. 2011, ApJ, 738, 27
Bieging, J. H., Patel, S., Peters, W. L., et al. 2016, ApJS, 226, 13
Boley, P. A., Sobolev, A. M., Krushinsky, V. V., et al. 2009, MNRAS, 399, 778
Brand, J., & Blitz, L. 1993, A&A, 275, 67
Bressert, E., Bastian, N., Gutermuth, R., et al. 2010, MNRAS, 409, 54
Brown, C. 2004, in Proc. of ASP Conf. 317, Milky Way Surveys: The Structure and Evolution of Our Galaxy, ed. D. Clemens, R. Shah, & T. Brainerd (San Francisco, CA: ASP), 79
Burns, R. A., Handa, T., Hirota, T., et al. 2016, A&A, 586, 34
Burns, R. A., Imai, H., Handa, T., et al. 2015, MNRAS, 453, 1363
Camargo, D., Bonatto, C., & Bica, E. 2011, MNRAS, 416, 1522
Chavarría, L., Allen, L., Brunt, C., et al. 2014, MNRAS, 439, 3719
Dewangan, L. K. 2017, ApJ, 837, 44
Dewangan, L. K., & Anandaraao, B. G. 2011, MNRAS, 414, 1526
Dewangan, L. K., Luna, A., Ojha, D. K., et al. 2015, ApJ, 811, 79
Dewangan, L. K., Ohja, D. K., Luna, A., et al. 2016, ApJ, 819, 66
Drew, J. E., Greimel, R., Irwin, M. J., et al. 2005, MNRAS, 362, 753
Elmegreen, B. G. 1998, in ASP Conf. Ser. 146, Origins, ed. C. E. Woodward, J. M. Shull, & H. A. Thronson, Jr. (San Francisco, CA: ASP), 150
Elmegreen, B. G., & Lada, C. J. 1977, ApJ, 214, 725
Enoch, M. L., Evans, N. J., II, Sargent, A. I., et al. 2008, ApJ, 684, 1240
Evans, N. J., II, Beichman, C., Gatley, I., et al. 1981, ApJ, 246, 409
Evans, N. J., II & Blair, G. N. 1981, ApJ, 246, 394
Evans, N. J., II, Dunham, M. M., Jorgensen, J. K., et al. 2009, ApJS, 181, 321
Felli, M., Massi, F., Navarrini, A., et al. 2004, A&A, 420, 553
Felli, M., Massi, F., Robberto, M., & Cesaroni, R. 2006, A&A, 453, 911
Felli, M., Testi, L., Valdettaro, R., & Wang, J. J. 1997, A&A, 320, 594
Foster, T., & Brunt, C. M. 2015, AJ, 150, 147
Fukui, Y., Kohno, M., Yokoyama, K., et al. 2017, in IAU Symp. 316, Formation, Evolution, and Survival of Massive Star Clusters, ed. C. Charbonnel & A. Nota (Cambridge: Cambridge Univ. Press), 208
Fukui, Y., Ohama, A., Hanaoka, N., et al. 2014, ApJ, 780, 36
Fukui, Y., Torii, K., Ohama, A., et al. 2016, ApJ, 820, 26
Furukawa, N., Dawson, J. R., Ohama, A., et al. 2009, ApJL, 696, L115
Georgelin, Y. M., Georgelin, Y. P., & Roux, S. 1973, A&A, 25, 337
Ginsburg, A., Glenn, J., Rosolowsky, E., et al. 2013, ApJS, 208, 14
Gutermuth, R. A., Megeath, S. T., Myers, P. C., et al. 2009, ApJS, 184, 18
Habe, A., & Obata, K. 1992, PASJ, 44, 203
Haworth, T. J., Shima, K., Tasker, E. J., et al. 2015b, MNRAS, 454, 1634
Haworth, T. J., Tasker, E. J., Fukui, Y., et al. 2015a, MNRAS, 450, 10
Heyer, M., Brunt, C., Snell, R., et al. 1998, ApJ, 115, 241
Heyer, M. H., Carpenter, I. M., & Ladd, E. F. 1996, ApJ, 463, 630
Inoue, T., & Fukui, Y. 2013, ApJL, 774, 31
Israel, F. P., & Felli, M. 1978, A&A, 63, 325
Kang, J., Koo, B., & Salter, C. 2012, AJ, 143, 75
Kirsanova, M. S., Sobolev, A. M., Thomsson, M. S. et al. 2008, MNRAS, 388, 729
Kirsanova, M. S., Wiebe, D. S., Sobolev, A. M., et al. 2014, MNRAS, 437, 1593
Ladefastanov, D. A., Kirsanova, M. S., Tsivilev, A. P., & Sobolev, A. M. 2016, AstBu, 71, 208
Lawrence, A., Warren, S. J., Almaini, O., et al. 2007, MNRAS, 379, 1599
Mallick, K. K., Kumar, M. N. S., Ohja, D. K., et al. 2013, ApJ, 779, 113
Navarete, F., Daninelli, A., Barbosa, C. L., & Blum, R. D. 2015, MNRAS, 450, 4364
North, H. L., van Duinen, R. J., Fridlund, C. V. M., et al. 1984, A&A, 131, 221
Ohama, A., Dawson, J. R., Furukawa, N., et al. 2010, ApJ, 709, 975
Preibisch, T., & Zinnecker, H. 2007, in Proc. IAU Symp. 237, Triggered Star Formation in a Turbulent ISM, ed. B. G. Elmegreen & J. Palous (Cambridge: Cambridge Univ. Press), 279
Skrutskie, M. F., Cutri, R. M., Stiening, R., et al. 2006, AJ, 131, 1163
Takahira, K., Tasker, E. J., & Habe, A. 2014, ApJ, 792, 63
Torii, K., Hasegawa, K., Hattori, Y., et al. 2015, ApJ, 806, 7
Torii, K., Hattori, Y., Hasegawa, K., et al. 2017a, ApJ, 835, 142
Torii, K., Hattori, Y., Matsuo, M., et al. 2017b, arXiv:1706.07164

The Astrophysical Journal, 849:65 (14pp), 2017 November 1