Gas Dynamics in the Star-forming Region G18.148–0.283: Is It a Manifestation of Two Colliding Molecular Clouds?

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Abstract

We report the results obtained from a multiwavelength study of the H II region G18.148−0.283 using the upgraded Giant Metrewave Radio Telescope at 1350 MHz, along with other archival data. In addition to the radio continuum emission, we have detected the H169α and H170α radio recombination lines toward G18.148−0.283 using a correlator bandwidth of 100 MHz. The moment-1 map of the ionized gas reveals a velocity gradient of approximately 10 km s\(^{-1}\) across the radio continuum peaks. The \(^{12}\)CO \((J = 3−2)\) molecular line data from the CO High-Resolution Survey (COHRS) also show the presence of two velocity components that are very close to the velocities detected in the ionized gas. The spectrum and position–velocity diagram from CO emission reveal molecular gas at an intermediate-velocity range bridging the velocity components. We see mid-infrared absorption and far-infrared emission establishing the presence of a filamentary infrared dark cloud, the extent of which includes the targeted H II region. The magnetic field inferred from dust polarization is perpendicular to the filament within the H II region. We have also identified two O9 stars and 30 young stellar objects toward the target using data from the Two Micron All Sky Survey (2MASS), UKIRT Infrared Deep Sky Survey (UKIDSS), and Galactic Legacy Infrared Midplane Survey Extraordinaire (GLIMPSE). Cumulatively, this suggests that the region is the site of a cloud–cloud collision that has triggered massive star formation and subsequent formation of an H II region.

Unified Astronomy Thesaurus concepts: Interstellar medium (847); Molecular clouds (1072); H II regions (694); Massive stars (732); Star-forming regions (1565); Star formation (1569)

1. Introduction

The understanding of the formation processes of massive stars \((M \geq 8−10 \, M_{\odot})\) or star clusters is still far from complete. Observational studies targeting massive star formation are more challenging compared with their low-mass counterparts due to massive stars forming on short timescales and in clustered environments (Kratter & Matzner 2006). Because the massive star-forming regions are on average more distant compared with the areas forming low-mass stars, there are additional limitations of angular resolution and sensitivity of observing facilities (Kurtz et al. 1994; Churchwell 2002). Despite these difficulties, studies of the massive star formation are crucial, as they continuously influence the evolution of galaxies by emitting protostellar jets, ejecting stellar materials, accreting gas, and various other mechanisms.

Although the formation of low- or intermediate-mass stars by accretion of matter is reasonably well understood, one cannot simply scale up this process to form massive stars. The significant number of companions around high-mass stars influences the subsequent accretion onto the massive protostellar cores (Krumholz et al. 2009). The outward radiation pressure can also halt the accretion process before the core reaches its final mass. Thus, the massive core needs to accrete mass with a high accretion rate \((10^{-6}−10^{-3} \, M_{\odot} \, yr^{-1})\); Wolfe & Cassinelli 1987; McKee & Tan 2003) to overcome the radiation pressure.

McKee & Tan (2003) explained that such an accretion rate is possible if the surface density of the clumps \((\Sigma)\) is sufficiently high, with a value of \(~1 \, g \, cm^{-2}\). One of the ways to create a region with such high values of \(\Sigma\) is a cloud–cloud collision (CCC) event. In this process, two supersonic clouds collide into each other to create a shocked and compressed region suitable for fragmentation and further collapse. CCCs are not very rare in the Milky Way. Early observations of CCCs include studies of NGC 133, where the CO spectra revealed two velocity components (Loren 1976, 1977). The first cluster to be identified as a possible collision object was Westerlund 2, which harbors two associated clouds with a velocity difference of approximately 20 km s\(^{-1}\) (Furukawa et al. 2009; Ohama et al. 2010). Other recent observations by Fukui et al. (2014), Torii et al. (2015), Baug et al. (2016), Dewangan & Ojha (2017), Dewangan et al. (2018, 2019), and Issac et al. (2020) have also detected CCCs in the high-mass star-forming regions.

In most cases, the relative velocity between the two colliding clouds leads to two different velocity peaks or components in the resulting molecular spectrum (Loren 1976, 1977; Dickel et al. 1978). Because the mixing of the colliding clouds continues for a long time after the instance of the collision, a collision-front of shocked materials having intermediate velocities also forms in between the colliding clouds. As a result of this event, a “broad-bridge” feature appears in a position–velocity (PV) diagram of the colliding region (Haworth et al. 2015) that connects the velocity peaks detected in the molecular spectrum. Thus, surveys of molecular line emission (especially \(^{12}\)CO) are great tools to identify and verify CCC events. One such survey is the CO High-Resolution Survey (COHRS; Dempsey et al. 2013), which maps the \(^{12}\)CO \((J = 3−2)\) transition in the Galactic plane between \(0°.5 \leq b \leq 0°.5\) and \(10° \leq l \leq 65°\) with a velocity resolution of 1 km s\(^{-1}\).
Based on their magnetohydrodynamic simulations, Inoue & Fukui (2013) also concluded that a collision between two supersonic clouds gives rise to the dense filamentary structures enhancing the surface density and self-gravity inside the colliding clouds. Such a filament may achieve the required high surface density leading to the formation of massive stars. Simulations also show that the collision amplifies the magnetic field in a direction perpendicular to that of the filament. Although the perpendicular alignment of magnetic fields is found to be the general outcome of turbulent magnetohydrodynamic simulations (e.g., Li & Klein 2019 and references therein), detection of such a field geometry using the dust polarization data from the Planck mission 1 can also act as a subsidiary signature of a CCC along with other pieces of evidence.

Massive stars also ionize their surrounding environment by producing enough UV photons, creating H II regions. Observations of the H II regions using radio recombination lines (RRL) help us determine the ionized gas’s kinematics and properties, such as electron temperature. Moreover, in the event of a CCC, one may observe two velocity components in the RRL emission if massive stars form from both clouds around the collision interface.

In this paper, we perform a multiwavelength study of a H II region, G18.148−0.283 (G18.15 henceforth), to understand its gas dynamics and formation. Located at a heliocentric distance of 4.1 kpc (Quireza et al. 2006), G18.15 has a physical diameter of 4.9 pc, which corresponds to an angular diameter of 4′1 for the given distance. G18.15 is located in the first Galactic quadrant (l = 18°148, b = −0°283; α = 15°20′01″01, δ = −13°15′33″55). The Coordinated Radio and Infrared Survey for High-mass Star Formation (CORNISH; Hoare et al. 2012; Purcell et al. 2013) reported a flux density of 856.18 ± 82.85 mJy at 5 GHz, and classified G18.15 as an ultracompact-H II (UC-H II) region. Quireza et al. (2006) used the National Radio Astronomy Observatory (NRAO) 140 ft (43 m) telescope in Green Bank at 8.6 GHz (HPBW = 3′20) to estimate an electron temperature (T_e) of 7180 ± 70 K for the entire region assuming G18.15 to be a homogeneous, isothermal sphere. Lockman (1989) measured the local standard of rest (LSR) velocity of G18.15 using the same 140 ft telescope, and reported V_{LSR} = 53.9 ± 0.4 km s\(^{-1}\). Kurtz et al. (1994) estimated the lower limit of the Lyman-continuum photon rate in the region, based on which they assigned a spectral type of B0.5 to the central ionizing star.

In their multiwavelength-based observation, Zhang et al. (2017) concluded that there are three clump candidates associated with G18.15, and high-mass star formation processes may still be happening within these clumps. According to them, the formation process was triggered by the forward-propagating shock wave, which originated from the expansion of G18.15 itself. In this paper, we present evidence that the star formation activity may be the outcome of a CCC.

The structure of our paper is as follows. In Section 2, we describe our radio observations with the upgraded Giant Metrewave Radio Telescope (uGMRT) and the ancillary data used for our study. In Section 3, we describe the results of our study, including radio continuum, RRL emission, distribution of molecular hydrogen, ionizing stars, and young stellar objects (YSO) in the region. Lastly, in Section 4, we discuss the possibility of a CCC event behind the formation of G18.15.

2. Observations and Archival Data

2.1. uGMRT observations

Our observation of G18.15 was carried out using the upgraded Giant Metrewave Radio Telescope (uGMRT) (Swarup 1990), situated in Pune, India. The observations were carried out with the GMRT Wideband Backend correlator configured to have a bandwidth of 100 MHz centered on 1350 MHz with 8192 channels. uGMRT has a native resolution of 2″ and a largest detectable angular scale of 7″ in this band. The details of the observational run are furnished in Table 1. A total of five hydrogen RRLs, H167\(\alpha\) to H171\(\alpha\) (see Table 2), are present in this frequency range. The radio source 3C48 was used as the flux density calibrator and bandpass calibrator, and 1911–201 was used as the gain calibrator.

The data were reduced using the NRAO Common Astronomy Software Applications (CASA 4.1; McMullin et al. 2007) package. An initial bandpass solution was computed and applied to the data in order to identify and excise radio frequency interference (RFI). The bad data were then flagged successively using the FLAGDATA task. Next, gain solutions were computed and applied to the calibrators, after which another iteration of data examination and editing was carried out. The final bandpass and gain solutions were computed using these data, after which the solutions were applied to the target source.

Although the RFI-affected channels were flagged from the target data before calibration, another careful examination of the data was performed before imaging. After RFI excision, the net bandwidth available for imaging G18.15 was around 50 MHz considering only the line-free channels. The target was then imaged using the CLEAN task, and the continuum image was self-calibrated to improve the dynamic range. The final 1σ noise in the continuum image is 0.06 mJy beam\(^{-1}\).

### Table 1

| Parameter | Value |
|-----------|-------|
| Target name | G18.148-0.283 |
| Observation date | 2019 March 11 |
| System temperature | 73 K |
| On-source time | 210 minutes |
| No. of channels | 8192 |
| Central frequency | 1350 MHz |
| Bandwidth | 100 MHz |
| Primary Beam | 25″ |
| Synthesized Beam | ≈ 2″ |
| Peak continuum flux density | 373.3 mJy beam\(^{-1}\) |
| Theoretical rms | (σ)\(^b\) 0.4 mJy beam\(^{-1}\) |

Note.  
1 In a single channel at 10 km s\(^{-1}\) resolution before stacking.

### Table 2

| RRL Name | Rest Frequency (\(\nu_0\) in MHz) |
|----------|----------------------------------|
| H167\(\alpha\) | 1399.368 |
| H168\(\alpha\) | 1374.601 |
| H169\(\alpha\) | 1350.414 |
| H170\(\alpha\) | 1326.792 |
| H171\(\alpha\) | 1303.718 |

1 https://www.cosmos.esa.int/web/planck
As shown in Table 1, the observations were carried out with 8192 channels, providing a native velocity resolution of \(\sim 2.6 \text{ km s}^{-1}\). The gain calibrated line data were first Hanningsmoothed to a velocity resolution of \(\sim 5 \text{ km s}^{-1}\) in order to get rid of the Gibbs ringing phenomenon caused by the strong RFI sources. Next, we used the UVLSF task of the NRAO Astronomical Image Processing System (AIPS) package to subtract the continuum from the total emission, as UVLSF gave a better result than the UVCNTSUB task of CASA. The self-calibration solutions determined from the radio continuum were then applied to the line data.

After this, the H169\(\alpha\) and H170\(\alpha\) line data were imaged using CLEAN. The H167\(\alpha\) and H171\(\alpha\) could not be imaged because the lines were affected by the edges of the bandpass. The H168\(\alpha\) line was discarded due to poor signal-to-noise ratio. To enhance the signal-to-noise ratio, the images of both RRLs were stacked to the observed frequency of H169\(\alpha\), following smoothing to a velocity resolution of \(1 \text{ km s}^{-1}\). The self-calibration solutions determined from the radio continuum were then applied to the line data. 2.2. Archival Data

The uGMRT observations are complemented by data from The HI/OH/Recombination line survey of the inner Milky Way (THOR; Beuther et al. 2016). THOR was carried out with the Karl G. Jansky Very Large Array (VLA) in the C-configuration using the Wideband Interferometric Digital Architecture correlator covering the HI 21 cm line, four OH, and 19 RRLs in addition to the continuum emission at 1–2 GHz in full polarization. The detected RRLs are also stacked in order to increase the signal-to-noise ratio. The final spectral line map from THOR has a velocity resolution of 10 \(\text{km s}^{-1}\) and an angular resolution of 40\(\arcsec\). There are six different spectral windows to observe the continuum emission at 1–2 GHz. As the angular resolution has a frequency dependence, all continuum images are smoothed to a common resolution of 25\(\arcsec\).

We have used \(^{12}\text{CO}\) \((J = 3–2)\) data from COHRS (Dempsey et al. 2013) to study the molecular emission associated with G18.15. The COHRS data were taken using the Heterodyne Array Receiver Programme (HARP; 325–375 GHz) on the James Clerk Maxwell Telescope (JCMT) in Hawaii. COHRS provides data products at a velocity and angular resolution of 1 \(\text{km s}^{-1}\) and 16\(\arcsec\) respectively, with a typical rms in antenna temperature of \(\sim 1 \text{ K}\).

To determine the orientation of the magnetic field lines around G18.15, we have utilized the Planck 353-GHz (850 \(\mu\text{m}\)) dust continuum polarization data (Planck Collaboration et al. 2015). The polarization data include Stokes I, Q, U maps from the Planck Public Data Release 3 full mission maps with PCCS2 Catalog\(^5\).

To analyze the cold-dust emission, we have used data from the Herschel infrared Galactic Plane (Hi-GAL) survey (Molinari et al. 2010). The Hi-GAL survey provides images of the far-infrared continuum at 500, 350, 250, 160, and 70 \(\mu\text{m}\) using the Spectral and Photometric Imaging Receiver (SPIRE) and Photodetector Array Camera and Spectrometer (PACS) cameras of the Herschel Space Observatory. We used the level

\(^{5}\text{https://github.com/jbjolly/LineStacker/releases}\)

\(^{5}\text{https://irsa.ipac.caltech.edu/applications/planck/}\)

Figure 1. The radio continuum image of G18.15 at 1350 MHz is shown overlaid with the contour levels (in blue) from THOR at 1310 MHz. The color scale depicts the specific intensity or brightness in mJy beam\(^{-1}\). The levels are starting from 3\(\sigma\) and increasing in steps of 75 mJy beam\(^{-1}\), while the rms noise is equal to \(\sim 1.4 \text{ mJy beam}^{-1}\). The respective beam size in the black empty circle is shown at the bottom-left corner of the figure.

2.5 data products from the Herschel Science Archive to analyze the dust emission and estimate the hydrogen column density \((N(\text{H}_2))\) across G18.15.

We have also used the mid-infrared point-source catalog from the Galactic Legacy Infrared Midplane Survey Extraordinary (GLIMPSE; Benjamin et al. 2003), and near-infrared point-source catalogs from the Two Micron All Sky Survey (2MASS; Skrutskie et al. 2006) and UKIRT Infrared Deep Sky Survey (UKIDSS) Galactic Plane Survey (Lawrence et al. 2007) to study the YSO population and main-sequence stars in G18.15.

3. Results

3.1. Radio Emission from the Ionized Gas

3.1.1. Continuum Emission

Figure 1 shows the 1350 MHz radio continuum emission from G18.15 at 10\(\arcsec\) resolution using the uGMRT, with the THOR map at 25\(\arcsec\) resolution being overlaid in contours. Although the native resolution of uGMRT is 2\(\arcsec\), we have restricted the resolution to 10\(\arcsec\) to recover the extended emission. The morphology of radio continuum emission is elongated along the NW–SE direction with an extended envelope of emission along the perpendicular direction of the central elongated structure. At 25\(\arcsec\) resolution, there are two peaks in the radio continuum, which are resolved into multiple peaks at the higher resolution of uGMRT.

The spectral index for the region is obtained from THOR and is seen to be \(\approx 0.1\). This suggests that the emission is thermal and has an optical depth around unity, because one expects the spectral index to be close to 0 as the emission transitions from being optically thick to optically thin. Although the assumption of the radio continuum emission being optically thin is not strictly valid, we can derive a lower limit for the Lyman-continuum photon rate \((N_{\text{Ly}})\) using the following equation
where \( S_\nu \) is the flux density in jansky (Jy), \( \nu \) is the frequency in gigahertz, \( d \) is the distance to the source in parsecs, and \( T_e \) is the electron temperature of the ionized gas. Adopting an electron temperature of 7180 K (Quireza et al. 2006) and a distance of 4.1 kpc, one obtains the Lyman-continuum photon rate to be larger than \( 5.8 \times 10^{48} \) s\(^{-1}\) (log \( N_{Ly} = 48.76 \)). If all the ionizing radiation were to arise from a single star, this would require a main-sequence star of spectral type O6.5–O7 or earlier (Martins et al. 2005).

Our estimate of the Lyman-continuum photon rate is in good agreement with that of Zhang et al. (2017), who found log \( N_{Ly} = 48.68 \) using the radio continuum data from the 1.4 GHz NRAO VLA Sky Survey (NVSS; Condon et al. 1998), but is significantly higher than that of Kurtz et al. (1994), who found log \( N_{Ly} = 48.82 \) using observations of the region at 8.4 GHz with the VLA in the B-configuration. A higher Lyman-continuum photon rate estimated in our study than that of Kurtz et al. (1994) is probably due to the extended emission being resolved out in their high-resolution study. Similarly, the Lyman-continuum photon rate estimated from the high-resolution (~2\(''\)) CORNISH survey is seen to be log \( N_{Ly} = 48.0 \), which suggests that some extended emission is resolved out in the CORNISH maps as well.

### 3.1.2. RRL Emission

Figures 2 and 3 show the channel map and integrated intensity map of the RRL emission at an angular resolution of 25\(''\). It can be seen from the figures that three different emission peaks are aligned with the central elongation of continuum emission. The SE peak is the brightest among the three peaks, followed by the middle and NW peaks. The SE peak is located within 2\(''\) of the continuum SE peak, while the middle and NW peaks are located at opposite sides of the continuum NW peak.

### 3.1.3. Electron Temperature Map

Figure 4 shows the electron temperature \( (T_e) \) distribution across G18.15 using the RRL and continuum data (the
methodology and relevant equations are given in the Appendix). This was done by smoothing the radio continuum map to the same resolution as that of the RRL map—25″ for the uGMRT data.

The electron temperature at the peaks of continuum emission ranges from 5200–9500 K. The electron temperature agrees well with the average electron temperature of 7180 K (Quireza et al. 2006) toward the region, considering that this was measured at a much coarser resolution of 3.2″. It is, however, surprising to see that the electron temperature is much lower at the locations of diffuse emission.

3.2. Kinematics of the Region

Figure 5 shows the velocity field of the ionized gas in the region. The NW continuum peak is observed to have a higher velocity compared with the SE peak. The velocity field (52–65 km s⁻¹) between the NW and SE peaks appears to be smooth, with a linear gradient at 40″ resolution of THOR, while at 25″ resolution, it appears somewhat discontinuous. The presence of two velocity components to the RRL emission separated by 13 km s⁻¹ with a discontinuity in the middle of the HII region suggests that G18.15 is a case of a CCC.

The possibility of G18.15 being a case of a CCC can be tested by examining the kinematics of the molecular gas in the region. We used the COHRS data for this purpose because the J = 3–2 transition of CO is an excellent tracer of the warm gas (10–50 K) at densities around 10⁴ cm⁻³. The CO spectrum toward G18.15 (Figure 6) shows the presence of two velocity components (or peaks) at 53.4 km s⁻¹ and 66.7 km s⁻¹ respectively. It can be seen that the velocity components in CO are close to those observed in the ionized gas. This suggests that the massive stars in the region have formed from the two molecular clouds traced by the CO emission. The spectrum also shows that the velocity components representing two different molecular clouds are connected by a narrow plateau of intermediate velocity and moderate intensity, which may arise from the interaction between the two clouds.

Figure 7 shows the CO integrated intensity map using the velocity range of 39–55 km s⁻¹ covering the low-velocity molecular cloud overlaid with the black contours from the integrated intensity map using the 59–74 km s⁻¹ velocity range of the high-velocity molecular clouds. The radio continuum emission at 1350 MHz is also overlaid with the blue contours. Figure 7 shows that both clouds are obliquely shaped with a NE–SW elongation. The figure also shows the presence of a cavity (diameter ~0.5 pc) toward the west of the radio continuum peaks, with most of the CO line emission occurring from a C-shaped region that is offset to the east of G18.15 from the center.

The presence of two velocity components connected with an intermediate-velocity emission profile in the CO spectrum, a large cavity, a linear gradient, and a C-shaped emission region suggest that G18.15 is the site of a CCC event between two molecular clouds with a relative velocity of 10 km s⁻¹. The features observed are in agreement with the simulations of Habe & Ohta (1992) and Takahira et al. (2018).

In particular, it is interesting to note the presence of a dark filamentary structure connecting the radio continuum peaks in 8.0 μm (Figure 8). Although the filament is not classified as an infrared dark cloud (IRDC) in the catalogs of Simon et al. (2006) and Peretto & Fuller (2009), the extinction at 8.0 μm that has close correspondence with 870 μm emission suggests that the filament is an IRDC. This is consistent with the simulations of Inoue & Fukui (2013), wherein dense filaments are formed in CCC events due to enhancement of the gas surface density.

3.3. FIR Emission from the Cold Dust

The cold-dust emission was analyzed using data from the Hi-GAL survey. We used level 2.5 data from the Herschel Science Archive for this purpose. The data have a plate scale of 3.2″ per pixel at the PACS wavelengths of 70 and 160 μm, and 6, 10, and 14″ per pixel at the SPIRE wavelengths of 250, 350, and 500 μm respectively. Moreover, the data have different units,
with the PACS data having units of Jy pixel\(^{-1}\) and the SPIRE data having units of MJy sr\(^{-1}\). The data were processed in the Herschel Interactive Processing Environment (HIPE)\(^6\) to have the same units and were regridded to a common plate scale using a premade kernel (Aniano et al. 2011). The pixel size of the 500\(\mu\)m image (14\(''\)) is considered the reference pixel size, as the 500\(\mu\)m image has the poorest resolution of 36\(''\). A constant background was then subtracted from the data.

To estimate the column density from the far-infrared images, we have fitted a modified blackbody function on a pixel-to-pixel basis. The modified blackbody function with specific intensity, \(I_v\), has the following form:

\[
I_v = B_v(T_d)(1 - e^{-\tau_v})
\]

where

\[
\tau_v = \frac{\mu m_H \kappa_\nu N(H_2)}{\eta}
\]

Here \(\tau_v\) is the optical depth of the cold medium at frequency \(\nu\); \(B_v(T_d)\) is the blackbody function at the dust temperature \(T_d\); \(\eta\) is the gas-to-dust ratio of the interstellar medium, which is \(\sim 100\); \(\mu\) is the mean weight of the molecular gas; \(\kappa_\nu\) is the dust opacity; \(m_H\) is the mass of a hydrogen atom; and \(N(H_2)\) is the column density of molecular hydrogen. We have taken \(\mu\) to be 2.86 assuming that the cold molecular gas is made up of 70\% molecular hydrogen by mass (Ward-Thompson et al. 2010). Following Ossenkopf & Henning (1994), the dust opacity at frequency \(\nu\) can be expressed by the following equation:

\[
\kappa_\nu = \kappa_0 \left(\frac{\nu}{\nu_0}\right)^\beta
\]

where \(\beta\) is the dust emissivity index. We have assumed \(\beta = 2\) following Russeil et al. (2013), and \(\kappa_0 = 5.04 \text{ cm}^2 \text{ g}^{-1}\) at 500\(\mu\)m for a Mathis–Rumpl–Nordsieck distribution (Mathis et al. 1977) of grain sizes (for the diffuse interstellar medium of gas density \(= 10^6 \text{ cm}^{-3}\)) with thin ice mantles (Ossenkopf & Henning 1994). We have considered \(T_d\) and \(N(H_2)\) as free parameters while fitting the far-infrared data points using the nonlinear least squares Levenberg–Marquardt algorithm. The column density and dust temperature maps are shown in the left and right panels of Figure 9, respectively.

High column densities can be observed across the radio continuum peaks tracing the central filament with a peak value of \(3.1 \times 10^{22} \text{ cm}^{-2}\) located close to the NW continuum peak. The dust temperature also peaks toward the center and remains almost constant overall (\(\sim 33\) K) within the H\(\text{II}\) region. The relatively high value of dust temperature suggests significant heating from the massive stars inside the H\(\text{II}\) region.

### 3.4. Orientation of the Magnetic Field Lines

We have utilized the 353-GHz Planck dust polarization data to determine the mean orientation of the magnetic field lines in the vicinity of G18.15. Following the IAU convention (i.e., the position angle, \(\theta_{\text{GAL}} = 0^\circ\), points Galactic north but increases
toward Galactic east, the $\theta_{\text{GAL}}$ values are derived using the relation

$$\theta_{\text{GAL}} = 0.5 \times \tan^{-1}(-U/V)$$  \hspace{1cm} (5)$$

Adopting the transformation relation of position angles (Corradi et al. 1998), the magnetic field orientation in Equatorial coordinates can be calculated as

$$\theta_{\text{B}} = \theta_{\text{GAL}} + \frac{\pi}{2} - \psi$$ \hspace{1cm} (6)

where $\psi$ is the transformation relation of the position angles in the Equatorial and Galactic systems at the position of each pixel. It is expressed as

$$\psi = \tan^{-1}\left[ \frac{\cos(l - 32\degree 9)}{\cos(b)\cot(62\degree 9) - \sin(b)\sin(l - 32\degree 9)} \right]$$ \hspace{1cm} (7)

The mean orientation of the magnetic field is estimated to be at a position angle of 30\degree 8 ± 2\degree 6, as shown in Figure 10. It can be seen that the mean magnetic field is nearly perpendicular to the underlying central filament within G18.15.

3.5. Identification of the Candidate Ionizing Stars

To identify the candidate ionizing stars and YSOs toward G18.15, we have performed a photometric study of the near-infrared and mid-infrared point sources using data from 2MASS$^7$, UKIDSS GPS$^8$, and GLIMPSE$^9$. We have searched for the candidate ionizing stars in the 2MASS All Sky Catalog of Point Sources and UKIDSS GPS sixth archival data release (UKIDSSDR6plus catalogs using a circle of 2' radius centered on $\alpha = 18h 25m 01s$, $\delta = -13\degree 16\arcmin 02\arcsec$.

Next, two separate color–magnitude diagrams (CMDs; K against H–K) are generated using the Bessell & Brett

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$^7$ http://vizier.u-strasbg.fr/viz-bin/VizieR-3?-source=II/246/out
$^8$ http://wsa.roe.ac.uk:8080/wsa//region_form.jsp
$^9$ https://irsa.ipac.caltech.edu/data/SPITZER/GLIMPSE/
homogenized system (Carpenter 2001) equivalent colors of the point sources, assuming that all the sources are at the distance to G18.15. Although this process will lead to spurious sources that are misclassified as OB-type stars on account of incorrect distances, these can be removed by constructing the color–color diagrams, and only selecting sources whose colors are consistent with that expected from OB-type stars. Thus, we selected the OB-type candidates from the CMD and plotted them separately in respective color–color diagrams (CCDs; $H - K$ against $J - H$). We have also assumed the interstellar reddening law of Rieke & Lebofsky (1985) ($A_J/A_V = 0.282; A_H/A_V = 0.175$ and $A_K/A_V = 0.112$) to draw the reddening vectors, where the crosses are placed at an increasing interval of $A_V = 5$. The CMD and CCD from 2MASS are shown in the left and right panels of Figures 11, and 12 shows the same for UKIDSS.

Following our analysis, we have identified two and five candidate ionizing stars from the UKIDSS and 2MASS surveys respectively. Table 3 lists all seven candidates identified using near-infrared photometry, and they are shown in Figure 13. As an added consistency check, we determined the hydrogen column density ($N(H_2)$) expected at the coordinates of the candidate stars from the visual extinction ($A_V$) measured in the color–color diagram using Bohlin et al. (1978),

$$N(H_2) = \frac{A_V}{5.3 \times 10^{-22} \text{ cm}^{-2}}$$

(8)

The respective $N(H_2)$ values from Equation (8) and locations of the candidate stars in Figure 13 are also listed in Table 3. We find that there is broad consistency between the column density measured from the far-infrared map and that estimated by the visual extinction, with discrepancies attributed to the uncertainty in the dust opacity and other variations in the $N(H_2)$ to $A_V$ ratio (Predehl & Schmitt 1995; Güver & Özel 2009).

This gives confidence that the sources listed in Table 3 are indeed OB-type stars that are associated with the G18.15 region. However, it is to be noted that only two stars are of spectral type earlier than B0. Figure 13 shows that two (2MASS-1 and 2) out of the seven candidate ionizing sources are located near the continuum peaks of G18.15, whereas four out of the remaining five sources are located at the periphery of the central dust filament, with the last source (UKIDSS-2) at a location slightly away from the region showing radio continuum emission. Thus, while 2MASS-2 is the likely source for the southern continuum peak, the ionizing stars for the northern peak are not detected. However, our analysis does not preclude the existence of a population of ionizing stars in the IRDC that is not detected at near-infrared wavelengths on account of significant extinction. This is consistent with the overall ionizing photon flux in the H II region, which is significantly higher than that produced by a single O9 star.

3.6. YSOs Associated with the G18.15

To identify YSO candidates, we have searched the Spitzer-GLIMPSE online database within the same circular region (2' radius centered on $\alpha = 18^h 25^m 01^s, \delta = -13^\circ 16' 02''$) used for searching the candidate ionizing stars and found a total of 369
Figure 11. Left: The K versus (H–K) color–magnitude diagram of the 2MASS near-infrared sources within a circle of radius 2′ centered on G18.15. The reddening vectors of the massive stars (O3–B9) are plotted on the color–magnitude diagram. Right: The (J–H) versus (H–K) color–color diagram of the 2MASS point sources that are of spectral type earlier than B9 in the color–magnitude diagram. The solid black and red lines represent the loci of Class V (main-sequence stars) and Class III (giant stars) objects respectively (Allen 1973; Bessell & Brett 1988). The black long-dashed line represents the locus of the T-Tauri stars (Meyer et al. 1997). Reddening vectors corresponding to the different classes are also shown using dotted lines. The crosses on the reddening vectors are placed at an increasing interval of $A_V = 5$. Sources (main-sequence and giants) that are located within the reddening vectors of M6$_{giant}$ and O9 spectral classes are represented by black triangles, whereas pre-main-sequence sources are denoted by gray stars. Any other objects are denoted by the cyan dots. The candidate ionizing stars are denoted by the red dots with respective error bars.

Figure 12. Same as Figure 11 but for sources detected in the UKIDSS GPS.
mid-infrared sources inside our region of interest. Due to the nebulosity affecting Spitzer’s Infrared Array Camera’s (IRAC) 8.0 μm band, most of the sources are not detected in all four bands of IRAC. Thus, we have adopted IRAC three-band and 2MASS-IRAC five-band classification schemes as described in Gutermuth et al. (2008) to classify the YSOs. These classification schemes are based on the [4.5]–[5.8] color, as it is less contaminated by the dust extinction than the 3.6 μm emission-based colors (Hartmann et al. 2005).

Following the IRAC three-band classification scheme, we have detected 18 protostar candidates within G18.15, of which two are likely to be highly reddened Class II objects. We have also detected an additional YSO using the 2MASS-GLIMPSE five-band classification scheme. The corresponding CCDs are shown in the left and right panel of Figure 14 respectively.

Because UKIDSS is a much deeper survey compared with 2MASS, we have also searched for YSOs using the NIR and MIR colors of UKIDSS and GLIMPSE. We first identified counterparts of the GLIMPSE point sources in the UKIDSS GPS using a 0"/5 matching radius. The UKIDSS colors were then converted to equivalent 2MASS colors, following which the five-band classification scheme was used to identify YSOs. A total of 13 Class I or II objects were detected following this method, out of which 11 were undetected in the IRAC three-band and 2MASS-IRAC five-band classification schemes.

Overall, we have detected 30 YSOs using all aforementioned classification schemes.

The left and right panels of Figure 15 show the dereddened CCD using the GLIMPSE and UKIDSS surveys and locations of detected YSOs toward G18.15. We find most of the YSOs to be located toward the edges of the H II region, including the IRDC extending beyond the radio emission, with only a couple of YSOs toward the central filamentary structure. As with the case of ionizing stars, a significant fraction of YSOs in the central IRDC is likely to be undetected because of high extinction.

### 4. Discussion

#### 4.1. Age of the Region

The age of G18.15 can be estimated using the observed properties of the H II region. Under the assumption that the H II region is expanding into a homogeneous medium, the Stromgren radius \( R_s \) is given by the following expression:

\[
R_s = \left( \frac{3 N_{Ly}}{4 \pi n_b \alpha_b} \right)^{1/3}
\]

where \( \alpha_b \) is the radiative recombination coefficient assumed to be \( 2.6 \times 10^{-13} \text{ cm s}^{-1} \) (Osterbrock 1989), and \( n_b \) is the number density of atomic hydrogen, which can be derived from the column density map following \( n_b = 3N(\text{H}_2)/2R \). Here \( R \) is the radius of the ionized clump. We can estimate the dynamical age, \( t_{dyn} \), of the H II region based on a simple model of an expanding H II region in a homogeneous medium (Dyson & Williams 1980) as

\[
t_{dyn} = \left[ \frac{4}{7} \frac{R_s}{c_s} \right] \left[ \left( \frac{R}{R_s} \right)^{7/4} - 1 \right]
\]

where \( c_s \) is the sound speed in the ionized medium and is assumed to be 10 km s\(^{-1}\). The radius of the H II region \( R \) is estimated to be 1.31 pc considering the radio continuum emission above 3σ level, and the mean value of hydrogen column density calculated using the same area obtained from the radio continuum is equal to \( 1.43 \times 10^{22} \text{ cm}^{-2} \). Consequently, \( n_b \) and \( R_s \) are estimated to be 5.3 \( \times 10^3 \text{ cm}^{-3} \) and 0.186 pc respectively. Because the size of the H II region is larger than that of the Stromgren sphere, the expansion of G18.15 is currently pressure-driven. Using Equation (10), we derive the dynamical age of G18.15 to be 0.31 Myr.
4.2. Signatures of a CCC in G18.15

The characteristic observational features of a CCC are the overlapping distribution of the colliding clouds, the presence of two velocity components in the CO spectra (Habe & Ohta 1992; Takahira et al. 2018), and the “broad-bridge” feature connecting the velocity peaks at the intermediate-velocity range (Haworth et al. 2015). G18.15 manifests many of these characteristics, which suggests that it is a site of a CCC event.

The RRL data show two distinct velocities with a region of intermediate velocity separating them spatially. In addition, the spectrum of $^{12}$CO molecular emission also shows two velocity components connected by a narrow plateau-like emission profile at intermediate velocity (Figure 6). The velocity peaks of the CO emission are seen to be in close correspondence with that of RRLs, indicating that both the CO and RRL emission are tracing the same molecular clouds.

Figure 14. Left: The color–color diagram of the Spitzer-GLIMPSE point sources within the searching radius centered on G18.15. Sources that are detected in the 3.6, 4.5, and 5.8 μm IRAC bands simultaneously are shown in the diagram. Regions belonging to different classes of objects are shown following the color conditions given in Gutermuth et al. (2008). Right: The color–color diagram of the Spitzer-GLIMPSE point sources, which are detected in the J, H, and K bands of 2MASS and 3.6 and 4.5 μm bands of IRAC simultaneously.

Figure 15. Left: The color–color diagram of the Spitzer-GLIMPSE point sources, which are detected in the J, H, and K bands of UKIDSS and 3.6 and 4.5 μm bands of IRAC simultaneously. The JHK colors of UKIDSS are converted to the JHK colors of 2MASS following Carpenter (2001) before constructing the color–color diagram. Right: The panel shows the locations of the YSOs (green crosses) that are detected from the GLIMPSE, 2MASS, and UKIDSS surveys on the 8 μm warm dust emission map toward G18.15.

4.2. Signatures of a CCC in G18.15

The characteristic observational features of a CCC are the overlapping distribution of the colliding clouds, the presence of two velocity components in the CO spectra (Habe & Ohta 1992; Takahira et al. 2018), and the “broad-bridge” feature connecting the velocity peaks at the intermediate-velocity range (Haworth et al. 2015). G18.15 manifests many of these characteristics, which suggests that it is a site of a CCC event.
To further test the CCC hypothesis, we have searched for the presence of a "broad-bridge" like feature connecting the two molecular clouds in the position–velocity (PV) diagram. The right panel of Figure 16 shows the PV diagram from the COHRS data generated across the white line shown in the left panel of the exact figure wherein the bridging features are visible. An approximate position of the feature located at an offset $\approx -50''$ is shown in a yellow ellipse in the left panel.

The white solid line shows the cut along which the position–velocity diagram is extracted. The radio continuum contours in green are identical to those in Figure 3. Right: The position–velocity diagram extracted along the cut shown in the left panel. The "broad-bridge" like features are visible, and are encircled in red.

Figure 17. The figure shows the NH$_3$(1,1) inversion spectrum toward G18.15. The line peaks at $56.8 \pm 0.03$ km s$^{-1}$ matching the velocity of the compressed layer.

To further test the CCC hypothesis, we have searched for the presence of a “broad-bridge” like feature connecting the two molecular clouds in the position–velocity (PV) diagram. The right panel of Figure 16 shows the PV diagram from the COHRS data generated across the white line shown in the left panel of the exact figure wherein the bridging features are visible. An approximate location of these features is shown using a yellow ellipse on the white line. However, the observed "broad-bridge" features in the CO ($J = 3–2$) PV diagram are much weaker than what is observed in the simulations of Haworth et al. (2015). This is surprising because the bridge feature must be strong at a phase where the cloud–cloud interaction has triggered star formation in the colliding clouds. Moreover, the $J = 3–2$ transition of CO is expected to be a better tracer of dense, compressed gas compared with the $(1–0)$ transition in the Haworth et al. (2015) simulations. However, the NH$_3$ spectrum toward the region from the Red MSX Survey (Urquhart et al. 2011) using the Robert C. Byrd Green Bank telescope shows strong emission at the intermediate velocity of $56.8 \pm 0.03$ km s$^{-1}$ (Figure 17). Because NH$_3$ is an excellent tracer of the dense gas, this strongly suggests the presence of a significant amount of dense gas in the collision interface. This agrees with the simulations of Priestley & Whitworth (2021) where molecules tracing dense gas were observed to have strongly enhanced emission in the shock-compressed layer between colliding clouds. The smooth velocity gradient in the RRL emission also suggests that the bridge feature may be visible in a PV diagram constructed from the RRL data. This is indeed the case as seen in Figure 18, wherein the bridge feature is as prominent as the component at high velocity. The
prominent bridge feature in the RRL data along with the presence of dense molecular gas at the intermediate velocity add to the evidence of G18.15 being a possible site of a CCC.

Moreover, the far-infrared emission and mid-infrared absorption reveal a dense filament that passes through the central regions of G18.15, extending farther to the south, and the mean magnetic field orientation is estimated to be perpendicular to the central filament within the HII region. Although the magnetic field geometry by itself cannot be taken to be evidence for a CCC, it adds to the results obtained from the PV diagram, and suggests a CCC hypothesis behind the formation of G18.15.

In addition to the massive stars inhabiting G18.15, the detection of several YSOs suggests that star formation is actively ongoing in the cloud complex. As mentioned earlier, the presence of extended emission at mid-infrared wavelengths and the high extinction as seen by the dark features at 8.0 μm suggest a significant undetected population of YSOs and massive stars.

5. Summary and Conclusions

In this paper, we have performed a multiwavelength analysis of G18.15. Our major findings are listed below:

1. Using high-resolution uGMRT data, we have detected multiple radio continuum peaks within G18.15. The H169α and H170α RRLs are also detected toward G18.15, and are stacked to increase the signal-to-noise ratio of the final map. The RRL data reveal two distinct velocity components in G18.15.

2. The electron temperature is determined using the RRL and radio continuum data and is found to be 5200 − 9500 K at the location of the continuum peaks, which is consistent with the average electron temperature determined by previous studies using single dish telescopes.

3. The COHRS data reveal two molecular clouds with LSR velocities of 53.4 and 66.7 km s⁻¹ respectively. These two clouds are connected by a narrow plateau-like emission at intermediate velocity. The NH₃(1,1) spectrum shows a strong peak at 56.8 km s⁻¹ located within the intermediate-velocity range.

4. The position–velocity diagrams of ¹²CO and RRL reveal the presence of “broad-bridge” features.

5. The Herschel far-infrared emission and GLIMPSE 8.0 μm absorption reveal an IRDC filament with G18.15 located at the northern edge.

6. The mean orientation of the magnetic field lines is found to be perpendicular to the HII region.

7. Using 2MASS and UKIDSS photometric data, star formation activity is investigated, and two O9 stars are identified toward G18.15. Although 30 YSOs have been detected toward this region, the extended emission at mid-infrared wavelengths and high extinction suggest the presence of an undetected population of massive stars and YSOs.

8. The dynamical age of G18.15 is estimated to be 0.3 Myr approximately.

Following the observational evidence presented in this paper, we conclude that G18.15 is very likely to have been formed due to a cloud–cloud collision event roughly 0.3 Myr ago.

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Appendix
Calculation of the Electron Temperature

We derive the electron temperature under the local thermodynamic equilibrium (LTE) conditions. Under LTE and the Rayleigh–Jeans limit, the observed specific intensity takes the following form:

$$I_{\text{cont}}(\nu) = \frac{2 k_B T_e \nu^2}{c^2} \left(1 - e^{-\tau_{\text{cont}}(\nu)}\right)$$  \hspace{1cm} (A1)

where $\nu$ is the frequency, $k_B$ is the Boltzmann constant, $T_e$ is the electron temperature, and $\tau_{\text{cont}}(\nu)$ is the optical depth of the medium for continuum emission. Rearranging the terms, Equation (A1) can also be written as

$$\tau_{\text{cont}}(\nu) = -\ln \left(1 - \frac{c^2 I_{\text{cont}}(\nu)}{2 k_B T_e \nu^2}\right)$$  \hspace{1cm} (A2)

Now, from the definition of brightness temperature, the continuum temperature ($T_{\text{cont}}$) can be estimated as

$$T_{\text{cont}} = \frac{c^2 I_{\text{cont}}(\nu)}{2 k_B \nu^2}$$  \hspace{1cm} (A3)
Similarly, the brightness temperature of the spectral line \( T_{\text{line}} \) is

\[
T_{\text{line}} = \frac{c^2 I_{\text{line}}(\nu)}{2k_B \nu^2} \quad \text{(A4)}
\]

for any given pixel in the image. Thus, the line-to-continuum intensity ratio in a single pixel is

\[
\frac{I_{\text{line}}(\nu)}{I_{\text{cont}}(\nu)} = \frac{I(\nu) - I_{\text{cont}}(\nu)}{I_{\text{cont}}(\nu)} = \frac{I(\nu)}{I_{\text{cont}}(\nu)} - 1 \quad \text{(A5)}
\]

where \( I(\nu) \) is the total intensity. Now, we can rewrite Equation (A5) in terms of \( T_{\text{cont}}, T_{\text{line}}, \tau_{\text{cont}}(\nu), \) and \( \tau_{\text{line}}(\nu) \) as follows:

\[
\frac{T_{\text{line}}}{T_{\text{cont}}} = e^{-\tau_{\text{cont}}(\nu)} \left[ 1 - e^{-\tau_{\text{line}}(\nu)} \right]/\left[ 1 - e^{-\tau_{\text{cont}}(\nu)} \right] \quad \text{(A6)}
\]

From Equation (A6), \( \tau_{\text{line}}(\nu) \) can be expressed as

\[
\tau_{\text{line}}(\nu) = -\ln \left( 1 - \frac{T_{\text{line}}}{T_{\text{cont}}} e^{-\tau_{\text{cont}}(\nu)} \left[ 1 - e^{-\tau_{\text{cont}}(\nu)} \right] \right) \quad \text{(A7)}
\]

Using Equation (A2) and Equation (A7), one can determine \( \tau_{\text{cont}}(\nu) \) and \( \tau_{\text{line}}(\nu) \) for each pixel. The value of \( \tau_{\text{cont}}(\nu) \) along a line of sight (LOS) can also be related to the properties of the H II region using the Altenhoff approximation (Altenhoff et al. 1960; Mezger & Henderson 1967),

\[
\tau_{\text{cont}}(\nu) \approx 8.235 \times 10^{-2} \left( \frac{T_e}{K} \right)^{-1.35} \left( \frac{\nu}{\text{GHz}} \right)^{-2.1} \left( \frac{EM}{\text{pc.cm}^{-6}} \right) \quad \text{(A8)}
\]

where \( EM \) is the emission measure. Similarly, following Wilson et al. (2009), the line optical depth is

\[
\tau_{\text{line}}(\nu) \approx 1.92 \times 10^3 \left( \frac{\nu}{\text{GHz}} \right)^{-2.5} \left( \frac{\Delta \nu}{\text{KHz}} \right)^{-1} \left( \frac{EM}{\text{pc.cm}^{-6}} \right) \quad \text{(A9)}
\]

for the recombination lines in the radio frequency domain. Here \( \Delta \nu \) is the FWHM of the RRLs in KHz. Following Equation (A8) and Equation (A9) we get

\[
\frac{\tau_{\text{line}}(\nu)}{\tau_{\text{cont}}(\nu)} = 23.315 \times 10^3 \left( \frac{T_e}{K} \right)^{-1.15} \left( \frac{\Delta \nu}{\text{KHz}} \right)^{-1} \left( \frac{\nu}{\text{GHz}} \right)^{2.1} \quad \text{(A10)}
\]

Because the optical depth of the line and continuum are measured from the data, we can use Equation (A10) to estimate pixel-to-pixel \( T_e \) values for the entire region under the LTE conditions. It is to be noted that Equation (A2) is not completely independent. We have to provide a \( T_e \) to derive a \( \tau_{\text{cont}}(\nu) \) value. When the continuum is optically thin, the continuum optical depth is inversely proportional to \( T_e \), and one can use Equations (A6) and (A10) to derive \( T_e \). However, because the relation between the continuum optical depth and \( T_e \) is nonlinear for moderate optical depth, we adopt an iterative procedure, wherein an initial guess of the electron temperature is provided in Equation (A2), following which the electron temperature is recomputed using Equation (A10). This is repeated until the value of electron temperature converges.

Goldberg (1966) showed that the intensities of the observed RRLs could only be explained using departures from LTE, similar to the anomalous intensities of optical lines from nebulae and stellar atmospheres. Following Goldberg (1966), the excitation temperature \( T_e \) of an electronic transition is not equal to the \( T_e \) of the ionized gas inside a H II region, and is thus corrected using

\[
e^{-\nu/k_BT_e} = \frac{b_n}{b_{n-1}} e^{-\nu/k_BT_n} \quad \text{(A11)}
\]

where \( b_n \), the departure coefficient, is the ratio of the actual population of atoms in the \( n \)th state to the population that would be there if the ionized gas were in the LTE at the temperature \( T_e \). Under the condition \( \nu \ll k_BT_e \), the corrected or non-LTE value of the line absorption coefficient \( \kappa_{\text{line}} \) for the line \( n \to n-1 \) is found to be (Goldberg 1966; Brocklehurst & Seaton 1972)

\[
\kappa_{\text{line}} = \kappa_{\text{line}}^* b_{n-1}/\beta \quad \text{(A12)}
\]

where \( \kappa_{\text{line}}^* \) is the LTE value of the line absorption coefficient, and the correction factor \( \beta \) is approximated by Brocklehurst & Seaton (1972) for RRL transitions with \( \Delta n \approx 1 \). If the values of \( \tau_{\text{line}} \) and \( \tau_{\text{cont}} \) are less than 1, we can approximate the exponential terms in Equation (A6) to the second order to get

\[
T_{\text{line}} \approx T_{\text{line}}^* b_n \left( 1 - \frac{T_{\text{line}}}{2} \beta \right) \quad \text{(A13)}
\]

under the condition \( \nu \ll k_BT_e \). Again, \( T_{\text{line}} \) is the LTE value of the line temperature. Now, using the non-LTE value, i.e., \( T_{\text{line}} \) in Equation (A7) and following Equation (A10), we can get the non-LTE electron temperature of the ionized gas.

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