Postprint: Feedback Mechanisms in the Star-forming Region G10.32-0.15

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Feedback plays a crucial role in star formation, significantly influencing the formation of stars and planets as well as the evolution of star clusters and their parent molecular clouds. By utilizing multi-band infrared data and submillimeter continuum data, we have determined the positions of star clusters and the distribution of dense dust clumps C1, C2, C3, C4, and C5. The distribution of NH3 velocity-integrated intensity exhibits good correlation with the dense dust distribution traced by 870 µm, indicating that NH3 effectively traces dense molecular gas. Under the assumption of local thermodynamic equilibrium, and combining molecular line data of NH3(1, 1) and NH3(2, 2), we obtained the velocity field, velocity dispersion, rotation temperature, NH3 column density, and beam filling factor distributions of the molecular gas through radiative transfer calculations. Further calculations yielded the kinetic temperature, sound speed, non-thermal velocity dispersion, ratio of thermal to non-thermal pressure, and Mach number of the gas in G10.32-0.15. A comprehensive analysis of these results suggests that the dense gas in G10.32-0.15 may be affected by multiple feedback mechanisms from the star-forming region: gas in region C1 may be influenced by thermal feedback, gas in regions C2 and C3 by explosive feedback, and gas in regions C4 and C5 by momentum feedback. The star-forming region G10.32-0.15 exhibits complex interactions with the surrounding dense gas, with different regions potentially dominated by distinct feedback mechanisms.

Full Text

Preamble

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Study of Feedback Mechanisms in the Star-Forming Region G10.32-0.15

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Abstract

Feedback plays a crucial role in the process of star formation, exerting significant influence on the formation of stars and planets as well as the evolution of star clusters and their parental molecular clouds. Using multi-wavelength infrared data and submillimeter continuum observations, we have identified the location of the infrared star cluster and the distribution of dense dust clumps C1, C2, C3, C4, and C5. The distribution of NH_3 velocity-integrated intensity shows excellent correlation with the dense dust traced by 870 m emission, indicating that NH_3 serves as an excellent tracer of dense molecular gas. Under the assumption of local thermodynamic equilibrium, we have derived the molecular gas velocity field, velocity dispersion, rotational temperature, NH_3 column density, and beam filling factor through radiative transfer calculations using NH_3(1, 1) and NH_3(2, 2) spectral line data. Further calculations yielded the kinetic temperature, sound speed, non-thermal velocity dispersion, ratio of thermal to non-thermal pressure, and Mach number throughout G10.32-0.15. Comprehensive analysis of these results suggests that the dense gas in G10.32-0.15 is likely affected by multiple feedback mechanisms from the star-forming region: gas in the C1 region may be influenced by thermal feedback, gas in C2 and C3 may be subject to explosive feedback, while gas in C4 and C5 may be impacted by momentum feedback. The star-forming region G10.32-0.15 exhibits complex interactions with the surrounding dense gas, with different regions potentially dominated by different feedback mechanisms.

Keywords: molecular cloud; molecular spectral line; star formation

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1 Introduction

Stars typically form in clusters within molecular clouds. During star formation, protostars grow by accreting surrounding material while simultaneously generating various feedback processes such as stellar winds, outflows, and radiation. Through these feedback mechanisms, forming stars continuously inject matter, radiation, energy, and momentum into their parental molecular clouds, thereby influencing star and planet formation as well as the evolution of the parental clouds. Krumholz et al. [?] categorized feedback in star-forming regions into three types: momentum feedback, "explosive" feedback, and thermal feedback. Momentum feedback refers primarily to the injection of momentum into the parental molecular cloud during star formation, which drives gas motion and turbulence within the cloud, with typical manifestations including protostellar outflows and radiation pressure. Explosive feedback involves rapid heating of surrounding gas to very high temperatures while simultaneously driving gas motion, with typical examples including winds from massive stars, photoionization feedback, and supernova explosions. Thermal feedback primarily alters the temperature structure of surrounding gas without changing its dynamical state, mainly originating from non-ionizing radiation. The study of feedback mechanisms in star-forming regions has remained a hot research topic, with world-class telescopes conducting key observational programs dedicated to this subject. Examples include the large-scale FEEDBACK: Radiative and Mechanical Feedback in Regions of Massive Star Formation project using the SOFIA (Stratospheric Observatory for Infrared Astronomy) infrared space telescope [?], and the ongoing PDRs4All: Radiative Feedback from Massive Stars study using JWST (James Webb Space Telescope) [?]. Additionally, numerical simulations of star cluster formation in giant molecular clouds are now incorporating multiple feedback mechanisms, such as STARFORGE (STAR FORmation in Gaseous Environments) [?].

G10.32-0.15 was first discovered in single-dish radio continuum surveys and is located in the northern part of the W31 molecular cloud complex, which contains HII regions [?, ?, ?]. Subsequent multi-wavelength radio continuum and radio recombination line observations were conducted using various telescopes, including 5 GHz continuum observations with the German Effelsberg 100 m telescope [?], 10 GHz continuum observations with the Japanese Nobeyama 45 m telescope [?], and H109α radio recombination line observations with the NRAO (National Radio Astronomy Observatory) 140-foot telescope [?]. Based on VLA (Very Large Array) 21 cm observations, Kim and Koo [?] identified a radio bipolar structure in G10.32-0.15. In terms of interstellar molecular gas detection, Wilson [?] detected OH and H_2CO absorption lines in G10.32-0.15 using the NRAO 42 m radio telescope. Brand et al. [?] discovered 22 GHz water maser emission using the Medicina 32 m radio telescope. Walsh et al. [?] detected 6.7 GHz methanol masers using ATCA (Australia Telescope Compact Array). Beuther et al. [?] investigated the dynamics of large-scale molecular gas and star formation activity in dense clumps within G10.32-0.15 using APEX (Atacama Pathfinder EXperiment) 870 m continuum data and ^{13}CO(2-1) and C^{18}O(2-1) molecular line data, finding that dense dust is distributed at the waist of the bipolar HII region. Dewangan et al. [?] studied triggered star formation mechanisms in the bipolar HII region of G10.32-0.15 based on multi-wavelength continuum and molecular line data.

Based on 2MASS (Two Micron All Sky Survey) data [?], Bica et al. [?] identified an infrared star cluster associated with the radio emission from G10.32-0.15. Bik et al. [?] used near-infrared K-band spectroscopy from VLT (Very Large

Telescope) to study the spectral types of stars in this infrared cluster, discovering an O5V-O6V massive star that dominates the near-infrared radiation of the cluster and provides ionizing radiation for the HII region. Using deep infrared images from UKIDSS (United Kingdom Infra-Red Telescope Infrared Deep Sky Survey), Dewangan et al. [?] identified 14 stars within 10 of this massive star and measured the distance to the cluster, obtaining a precise value of 1.75 kpc. Townsley et al. [?] studied the X-ray emission from this infrared cluster using the Chandra X-ray space observatory, detecting over 50 X-ray point sources as well as extended diffuse X-ray emission.

In summary, G10.32-0.15 is located at a distance of 1.75 kpc and represents a bipolar HII region primarily ionized by an O-type star, containing an infrared star cluster within it, with dense molecular gas undergoing active star formation distributed at the waist of the bipolar HII region. This paper primarily utilizes the latest high-sensitivity, high-resolution NH_3 Galactic plane survey data from the GBT (Green Bank Telescope) 100 m radio telescope, combined with multi-wavelength continuum data, to conduct an observational study of feedback mechanisms in G10.32-0.15. Section 2 describes the multi-wavelength observational data used; Section 3 presents the results obtained from the observational data; Section 4 discusses these results; and Section 5 provides a summary and outlook for future research.

2.1 Molecular Line Data

The NH_3(1, 1) and NH_3(2, 2) spectral line data are part of the GBT NH_3 Galactic plane survey RAMPS (Radio Ammonia Mid-Plane Survey) [?]. The survey covers a Galactic longitude range of l = 10° to 40° and Galactic latitude range of b = -0.4° to 0.4°. The telescope is equipped with a 1.3 cm K-band seven-beam receiver KFPA (K-band Focal Plane Array) at the front end and VEGAS (VErsatile GBT Astronomical Spectrometer) at the back end. The angular resolution of the NH_3 spectral line data is 32 , with a velocity resolution of 0.2 $km \cdot s^{-1}$.

2.2 Continuum Data

This paper analyzes multi-wavelength continuum observations of the star-forming region G10.32-0.15, spanning from centimeter to submillimeter and infrared wavelengths. The 21 cm radio continuum data were obtained from VLA observations with a resolution of 5.4 × 6.2 and a noise level of 3.0 mJy per beam [?]. The submillimeter 870 m continuum data are from the APEX 12 m Galactic plane survey project ATLASGAL (APEX Telescope Large Area Survey of the Galaxy) [?], with an angular resolution of 19.2 and a noise level of approximately 70 $mJy \cdot beam^{-1}$. The infrared data are based on the Spitzer space telescope survey project GLIMPSE (Galactic Legacy Infrared Mid-Plane Survey Extraordinaire) [?], with bands at 3.6 m, 5.8 m, and 8 m used in this study.

3.1 Distribution of the Infrared Star Cluster and Dense Dust Clumps

G10.32-0.15 is a bipolar HII region whose exciting star is a massive O5V-O6V star [?, ?] (marked by the red pentagram in [Figure 1: see original paper]). This massive star provides the ionizing radiation for the entire HII region and dominates the near-infrared radiation of the infrared star cluster [?]. Figure 1a shows a three-color composite image combining 3.6 m, 5.8 m, and 8 m emission. The 3.6 m emission traces the positions of stars in the infrared cluster, while the 8 m emission represents polycyclic aromatic hydrocarbon (PAH) radiation and effectively traces the boundary of the HII region.

As seen in Figure 1b, the 870 m emission is primarily distributed along the boundary of the HII region, showing excellent correlation with the 8 m emission. Based on the 870 m data, Beuther et al. [?] identified dense dust clumps in this region, designated as C1, C2, C3, C4, and C5 [?]. The 20 cm emission originates mainly from free-free radiation of ionized gas and is concentrated near the exciting star (see blue contours in Figure 1b). The 20 cm data used here have relatively high resolution, detecting only the more compact morphology while losing the large-scale diffuse structure observed in previous lower-resolution data [?]. Clump C3 contains very compact 20 cm emission and has been identified as a UCHII (Ultra-compact HII) region [?].

3.2 Distribution of NH_3 Gas

[Figure 2: see original paper] shows typical $NH_3(1, 1)$ and $NH_3(2, 2)$ spectral line profiles toward dense dust clumps C1, C3, and C5. Both $NH_3(1, 1)$ and $NH_3(2, 2)$ exhibit very strong signals, with $NH_3(1, 1)$ showing clear hyperfine structure. The NH_3 profiles are single-velocity-component, similar to the spectral characteristics of CS(2-1) [?], whereas $^{13}CO(2\text{-}1)$ and $C^{18}O(2\text{-}1)$ show multi-velocity-component profiles [?, ?].

[Figure 3: see original paper] presents the velocity-integrated intensity distributions of $NH_3(1, 1)$ and $NH_3(2, 2)$, showing that $NH_3(1, 1)$ is slightly more extended than $NH_3(2, 2)$. NH_3 is primarily distributed along the boundary of the HII region, showing excellent correlation with the dust emission traced by 870 m. The NH_3 emission is strongest at the centers of the dense dust cores where the 870 m emission peaks.

3.3 Fitting of NH_3 Spectral Lines

Under the assumption of local thermodynamic equilibrium, simultaneously fitting the $NH_3(1, 1)$ and $NH_3(2, 2)$ spectral line data using radiative transfer equations (1) and (4) yields the gas velocity, velocity dispersion, NH_3 column density, rotational temperature, and filling factor [?].

The optical depth of NH_3 lines is given by:

$$\tau = \frac{N_{\mathrm{tot}} g A_{ul} c^2}{8\pi\nu^2\sigma\nu_0} \frac{2\pi}{\sqrt{1+\exp(-h\nu_0/(k_B T_{\mathrm{rot}}))}} \frac{1-\exp(-h\nu_0/(k_B T_{\mathrm{rot}}))}{1+\exp(-h\nu_0/(k_B T_{\mathrm{rot}}))}$$

where N_{tot} is the column density, g is the level degeneracy factor, Q is the partition function, A_{ul} is the Einstein A coefficient, c is the speed of light, ν_0 is the rest frequency, σ is the velocity dispersion, h is Planck' s constant, k_B is Boltzmann' s constant, and T_{rot} is the rotational temperature between NH_3(1, 1) and NH_3(2, 2).

The intensity ratio between different hyperfine components of NH_3(1, 1) relates to optical depth as [?]:

$$\frac{\Delta T^*_{\mathrm{m}}(J,K)}{\Delta T^*_{\mathrm{s}}(J,K)} = \frac{1-\exp(-\tau_{\mathrm{m}}(J,K))}{1-\exp(-a\tau_{\mathrm{m}}(J,K))}$$

where subscripts m and s represent the main and satellite hyperfine components, respectively, ΔT^* is the observed line intensity, and a is the intensity ratio between satellite and main lines.

The rotational temperature T_{rot} between NH_3(1, 1) and NH_3(2, 2) is given by [?]:

$$\frac{\tau(J',K')}{\tau(J,K)} = \frac{\nu^2(J',K')}{\nu^2(J,K)} \cdot \frac{\Delta\nu(J,K)}{\Delta\nu(J',K')} \cdot \exp\left(-\frac{\Delta E(J',K';J,K)}{k_B T_{\mathrm{rot}}(J',K';J,K)}\right) \cdot \frac{T_{\mathrm{ex}}(J,K)}{T_{\mathrm{ex}}(J',K')} \cdot \frac{|\mu(J',K')|^2}{|\mu(J,K)|^2} \cdot \frac{g(J',K')}{g(J,K)}$$

where $|\mu(J,K)|^2$ is the dipole matrix element and ΔE is the energy level difference.

Based on equations (1)-(3) and assuming Gaussian line profiles, the line intensity is:

$$I_\nu = f \cdot h\nu \cdot [1-\exp(-\tau(\nu))] \cdot \left[\frac{1}{h\nu/(k_B T_{\mathrm{rot}})} - \frac{1}{h\nu/(k_B T_{\mathrm{CMB}})}\right]$$

where f is the filling factor and T_{CMB} is the cosmic microwave background temperature. Using least-squares fitting to simultaneously model the NH_3(1, 1) and NH_3(2, 2) data yields the spatial distributions of gas velocity, velocity dispersion, NH_3 column density, rotational temperature, and filling factor [?] (see [Figure 4: see original paper]).

From clump C1 to C5, the gas velocity increases from approximately 11 $\mathrm{km \cdot s^{-1}}$ to 15 $\mathrm{km \cdot s^{-1}}$, indicating a velocity gradient (see Figure 4a). The gas velocity dispersion ranges from 0.52 to 2.12 $\mathrm{km \cdot s^{-1}}$, with a mean value of 1.00 $\mathrm{km \cdot s^{-1}}$. Regions with larger velocity dispersion are found in dust clump C3 and the northeast direction of C5 (see Figure 4b). The NH_3 column density ranges from

1.50×10^{15} to 1.10×10^{16} cm^{-2}, with a mean value of 4.79×10^{15} cm^{-2}. The filling factor ranges from 0.06 to 0.45, with a mean value of 0.20; its maximum occurs in the regions of dust clumps C4 and C5, but remains below 0.5. The NH_3 rotational temperature ranges from 14.5 to 31.0 K, with a mean value of 20.1 K, with higher temperatures found in the regions of dust clumps C1, C2, and C3 (see Figure 4e).

4.1 Kinetic Temperature of the Gas

Through Monte Carlo algorithm simulations, Tafalla et al. [?] established the relationship between NH_3 rotational temperature T_{rot} and gas kinetic temperature T_{kin}:

$$T_{\text{kin}} = \frac{1}{\ln\left[1 + 1.1\exp(-16/T_{\text{rot}})\right]} \cdot \frac{T_{\text{rot}}}{42}$$

where T_{kin} is the kinetic temperature and T_{rot} is the rotational temperature between $NH_3(2, 2)$ and $NH_3(1, 1)$. Using equation (5), we converted the NH_3 rotational temperatures in G10.32-0.15 to gas kinetic temperatures (see Figure 4f), which range from 16.2 to 49.3 K with a mean value of 25.3 K.

As shown in Figure 4f, the gas temperature is higher in dust clumps C1, C2, and C3 near the exciting star position, while the temperature is lower in the C4 and C5 regions. This indicates that the exciting star and other stars in the cluster produce thermal feedback that heats the surrounding gas, whereas C4 and C5 experience less thermal feedback. In addition to the high temperature of gas near the exciting star, dust clump C3 itself also exhibits high temperatures due to heating from the UCHII region within it [?].

4.2 Velocity Dispersion and Turbulence

NH_3 spectral line data enable precise measurements of gas temperature, allowing investigation of both thermal and non-thermal components in the gas [?, ?]. The sound speed in the gas can be derived from the kinetic temperature using equation (6):

$$C_s = \sqrt{\frac{k_B T_{\text{kin}}}{\mu m_H}}$$

where μ is the mean molecular weight of the molecular cloud and m_H is the mass of a hydrogen atom. Figure 5a shows the distribution of sound speed in the G10.32-0.15 region, ranging from 0.24 to 0.42 km $\cdot$ s^{-1} with a mean value of 0.30 km $\cdot$ s^{-1}. Since the sound speed is directly related to gas kinetic temperature, its distribution mirrors that of the kinetic temperature, with higher sound speeds in clumps C1, C2, and C3 near the exciting star and lower sound speeds in the C4 and C5 regions.

Molecular line broadening contains both thermal and non-thermal contributions [?]. By subtracting the thermal broadening component from the line profile, the non-thermal component can be obtained. The non-thermal velocity dispersion is given by [?]:

$$\sigma_{\mathrm{NT}} = \sqrt{\sigma_{\mathrm{NH3}}^2 - \frac{k_B T_{\mathrm{kin}}}{m_{\mathrm{NH3}}}}$$

where σ_{NH3} is the velocity dispersion derived from NH_3 lines and m_{NH3} is the mass of NH_3. Figure 5b shows the distribution of non-thermal velocity dispersion in G10.32-0.15, ranging from 0.65 to 1.42 $\mathrm{km \cdot s^{-1}}$ with a mean value of 0.93 $\mathrm{km \cdot s^{-1}}$. Enhanced non-thermal velocity dispersion is observed in clump C3 and the northeast direction of clump C5. C3 is an active star-forming region, and its non-thermal velocity dispersion may be driven by both the external exciting star and internal star formation activity. The northeast region of clump C5 shows large non-thermal velocity dispersion but low kinetic temperature, likely resulting from momentum feedback produced by the exciting star and its host cluster, which alters the gas motion rather than its temperature.

Further analysis of thermal and non-thermal components yields the ratio of thermal to non-thermal pressure [?]: $R_p = C_s^2/\sigma_{\mathrm{NT}}^2$. Figure 5c shows the distribution of R_p in G10.32-0.15, ranging from 0.03 to 0.21 with a mean value of 0.11. Since most R_p values are below 0.2, non-thermal pressure dominates throughout the star-forming region. Regions with relatively higher thermal-to-non-thermal pressure ratios are found in dust clumps C1 and C2, while other regions show lower ratios.

Figure 5d presents the distribution of Mach number $M = \sigma_{\mathrm{NT}}/C_s$ in G10.32-0.15, ranging from 2.16 to 5.36 with a mean value of 3.13. Since the minimum Mach number exceeds 2, the gas is supersonic throughout the entire star-forming region. Furthermore, in the northeast direction of dust clump C5, the Mach number reaches approximately 5, indicating hypersonic gas in this region.

4.3 Feedback Mechanisms

Based on the classification method of feedback mechanisms by Krumholz et al. [?], we can investigate the feedback processes in G10.32-0.15. The gas in dust clump C1 shows relatively high temperature but relatively small velocity dispersion, suggesting it may be affected by thermal feedback. Free-free emission at 20 cm is detected in clumps C2 and C3 near the exciting star position; additionally, this region exhibits high gas temperature and large velocity dispersion, indicating it may be subject to explosive feedback. The gas in dust clumps C4 and C5 shows low kinetic temperature but large velocity dispersion, particularly in the northeast region of C5 where hypersonic gas with Mach numbers around 5 is present. Therefore, C4 and C5 may be influenced by momentum feedback. In summary, different regions within the star cluster forming region G10.32-0.15 appear to be dominated by different feedback mechanisms.

5 Summary

Using NH_3 spectral line and multi-wavelength continuum data, we have conducted a study of the star-forming region G10.32-0.15. The main results are summarized as follows:

(1) The NH_3 velocity-integrated intensity map correlates well with the dense dust distribution traced by 870 m emission, demonstrating that NH_3 is an excellent tracer of dense molecular gas.

(2) Under the assumption of local thermodynamic equilibrium, we simultaneously fitted $NH_3(1, 1)$ and $NH_3(2, 2)$ spectral line data using molecular radiative transfer calculations to obtain the velocity, velocity dispersion, column density, rotational temperature, and filling factor of NH_3.

(3) Based on the fitted parameter distributions, we further derived the kinetic temperature, sound speed, non-thermal velocity dispersion, ratio of thermal to non-thermal pressure, and Mach number of the molecular gas. The gas throughout the star-forming region is dominated by non-thermal components.

(4) Through comprehensive analysis of kinetic temperature, non-thermal velocity dispersion, Mach number, and 20 cm emission data, we find that momentum feedback, explosive feedback (ionization feedback), and thermal feedback may all be present in the G10.32-0.15 star-forming region, with different mechanisms potentially dominating different regions.

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