Postprint of the Study on NH3(1, 1) Hyperfine Structure Intensity Anomalies in the Taurus Molecular Cloud

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Abstract

Using the NH_3 spectral line observation data from the Nanshan 26 m radio telescope, combined with the quantitative calculation method of integrated HIA (hyperfine intensity anomaly), the HIA mapping distribution of the B211/B213 + L1495 region in the Taurus molecular cloud was obtained. The results indicate that HIA is prevalent in the Taurus molecular cloud. The average HIA values for the inner and outer satellite lines of $NH_3(1,1)$ are 1.07 and 1.15, respectively, both of which are greater than 1. Furthermore, the HIA under the systematic contraction or expansion motion (CE) model and the hyperfine selective trapping (HST) model account for 55.7% and 21.7% of the observations, respectively, suggesting that the generation mechanism of HIA in this region is consistent with the predictions of the CE model. Additionally, the HIA quadrant mapping distribution shows that there may be large-scale gas infalling motion along the ridge of the B211/213 filamentary structure. Correlation analysis indicates that in this region, HIA distributed under the CE model is positively correlated with velocity dispersion, while HIA under the HST model is negatively correlated with velocity dispersion.

Full Text

Study of Intensity Anomalies in the $NH_3(1,1)$ Transition in Taurus

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Abstract

By utilizing spectral line observation data from radio telescopes combined with a quantitative calculation method for the integrated Hyperfine Intensity Anomaly (HIA), we have obtained the mapping distribution of the Taurus B211/B213 and L1495 regions. The results indicate that the HIA is prevalent throughout the Taurus molecular cloud. The average HIA values for the inner and outer satellite lines of the $NH_3(1,1)$ transition are found to be 55.7% and 21.7%, respectively. These values were analyzed under models of systematic contraction or expansion (CE) motion as well as the hyperfine selective trapping (HST) model. The findings suggest that the mechanism generating the HIA in this region is consistent with the predictions of the hyperfine selective trapping model. Furthermore, the quadrant mapping distribution reveals that the ridge of the B211/B213 filamentary structure may undergo large-scale gas infalling motion. Correlation analysis demonstrates that the HIA distribution in this region is positively correlated with velocity dispersion in certain areas, while showing a negative correlation with velocity dispersion in others.

Keywords: Molecular clouds; Molecular spectral lines; Star formation; Hyperfine structure anomalies **CLC number:** P155.2 **Document code:** A

1. Introduction

The inversion lines of NH_3 are essential tools for studying molecular clouds. In research focusing on star-forming regions and neighboring galaxies, NH_3 serves as an ideal probe for determining the density, temperature, velocity, and intrinsic linewidth of molecular clouds. Due to the low potential barrier exerted by the hydrogen atoms, the nitrogen atom can "tunnel" through the energy barrier to migrate to an equivalent position. This tunneling motion causes a periodic "inversion," leading to energy level splitting that divides all (J, K) rotational states into inversion doublets. The transition frequency between these doublets lies within the microwave range and can be measured in the radio band.

Within these inversion doublets, the interaction between the electric quadrupole moment of the nitrogen nucleus and the electronic electric field causes each inversion state' s energy level to split into several sublevels. According to selection rules, the $NH_3(1,1)$ line ultimately splits into 18 fine-structure lines of different frequencies, consisting of a main component and symmetric pairs of satellite lines. Under conditions of Local Thermodynamic Equilibrium (LTE), the $NH_3(1,1)$ fine-structure lines include two inner satellite lines (ISL) and two outer satellite lines (OSL).

The intensities of the satellite lines are theoretically assumed to be equal to each other relative to the main line intensity. This assumption of equal intensity is a fundamental prerequisite for calculating critical physical parameters such as density and temperature. However, observations reveal that the intensities of the (1,1) satellite lines are not always equal. This phenomenon, known as the hyperfine intensity anomaly (HIA), is widespread in molecular clouds, particularly in star-forming regions.

Two primary models have been proposed to explain the origin of HIA: hyperfine selective trapping (HST) and systematic contraction or expansion motion (CE). The HST model suggests that during the transition from the (2,1) state to the (1,1) ground state, asymmetric weighting between hyperfine structure lines causes the population of the (1,1) energy levels to deviate from a thermal distribution. The CE model suggests that systematic motions (infall or outflow) induce Doppler shifts that cause photons emitted from one hyperfine level to be absorbed by another, leading to non-thermal populations.

2. Observations and Data Processing

2.1 Nanshan Radio Telescope Spectral line observations were conducted using the 25-meter radio telescope at the Nanshan Observatory of the Xinjiang Astronomical Observatory, Chinese Academy of Sciences, equipped with a K-band dual-polarization cryogenic receiver. At the observed frequency band, the telescope' s angular resolution is $1'$, and the observation terminal provides a bandwidth of 512 MHz. The dispersion system consists of channels with a corresponding velocity resolution of 0.098 km/s. The observations simultaneously covered the NH_3 (1,1) line at 23,694.495 MHz and the (2,2) line at 23,722.633 MHz.

[FIGURE:1]

Figure [FIGURE:1] displays the integrated intensity distribution of the NH_3 (1,1) line in the Taurus B211/B213 L1495 region. Our results show that the (1,1) line was detected in 19.74% of the surveyed area. The Taurus molecular cloud is an ideal target for studying low-mass star formation and serves as one of the premier locations for investigating filamentary structures and dense cores [**?**].

2.2 Data Reduction This study primarily utilizes the GILDAS CLASS data processing tool and Python libraries (Matplotlib, APLpy, Astropy, Pandas, Spectral-cube, and Pyspeckit). We excluded spectral lines where the signal-to-noise ratio (SNR) was below a specified threshold and manually inspected spectra to exclude those where inner satellite lines overlapped with the main component. We performed fitting on the (1, 1) lines using multiple Gaussian functions to derive the centroid velocity and intrinsic velocity dispersion.

The calculation method determines the $\mathcal{R}$ value by taking the ratio of the integrated intensities of the blue-shifted and red-shifted components:

$$A_{IS} = \frac{F_{BISL}}{F_{RISL}}$$

$$A_{OS} = \frac{F_{BOSL}}{F_{ROSL}}$$

The uncertainty σ_{HIA} is calculated based on the noise level of the baseline σ and the number of channels N within the integration range.

3. Analysis of Intensity Anomalies

3.1 Integrated Intensity Distribution Based on our calculations, we obtained the integrated intensities for the detected spectral lines. [FIGURE:1] and [FIGURE:2] display the integrated intensity distributions. It is evident that HIA is ubiquitous throughout the Taurus molecular cloud, particularly within the B211/B213 filamentary structure. The eastern side of the B211/B213 filament ridge mostly exhibits values less than the threshold, whereas the western side shows a more complex distribution pattern.

3.2 Statistical Results The statistical analysis indicates that the distributions of anomalies are spread across the region. The mean HIA values for the inner and outer satellite lines are 1.07 and 1.15, respectively. These findings indicate that within this specific region, the primary mechanism responsible for generating the observed values is consistent with the selective trapping model.

3.3 Quadrant Analysis Quadrant analysis serves as a probe for tracing accretion or expansion motions. Under the HST model, specific transition selection rules lead to $\mathcal{R} > 1$ for inner satellite lines and $\mathcal{R} < 1$ for outer satellite lines. In contrast, under the CE model, expansion motion enhances red-shifted lines ($\mathcal{R} < 1$), while collapse motion enhances blue-shifted lines ($\mathcal{R} > 1$).

Our results indicate that 67.92% of the data points follow specific distribution patterns. According to the quadrant statistics, 55.7% of the points align with the CE model, while 21.7% align with the HST model. This implies that the dominant mechanism for producing these features in the Taurus B211/B213 and L1495 regions is driven by systematic gas motions.

4. Discussion

4.1 Kinematic Implications The quadrant distribution map reveals that data points tracing inward motion (infall) tend to be distributed along the B211/B213 ridge. This is consistent with previous findings [?] that the filament is contracting radially toward its major axis while accreting ambient material. In the L1495 region, we observed data points tracing expansion motions at the center, which may be related to ongoing star formation activities and protostellar feedback.

4.2 Correlation with Physical Parameters Correlation analysis with velocity dispersion shows that as velocity dispersion increases, the ΔT values for the infall model deviate further from zero, indicating more pronounced anomalies. Conversely, for the expansion model, the intensity anomaly phenomenon weakens as velocity dispersion increases. This can be explained by spectral line

Figure 4

Figure 1: Figure 4

overlap at higher dispersions, which tends to reduce the differences between hyperfine intensities, consistent with the findings of Stutzki & Winnewisser [**?**].

5. Summary and Conclusions

In this study, we utilized NH_3 spectral line data from the Nanshan radio telescope to investigate hyperfine intensity anomalies in the Taurus B211/B213 L1495 region. Our conclusions are as follows:

1. NH_3 hyperfine intensity anomalies are prevalent within the Taurus molecular cloud, primarily along the B211/B213 filamentary structure.
2. The average HIA values for both inner and outer satellite lines are greater than 1. The primary mechanism generating these anomalies is consistent with the predictions of the selective trapping and systematic motion models.
3. Quadrant distribution results suggest large-scale inward motion toward the ridge of the B211/B213 filament.
4. Correlation analysis reveals that the HIA of the outer satellite lines becomes more anomalous as velocity dispersion increases, whereas the HIA of the inner satellite lines weakens.

Figures