Examining the Interstellar Medium For The First Stages of Stellar Formation

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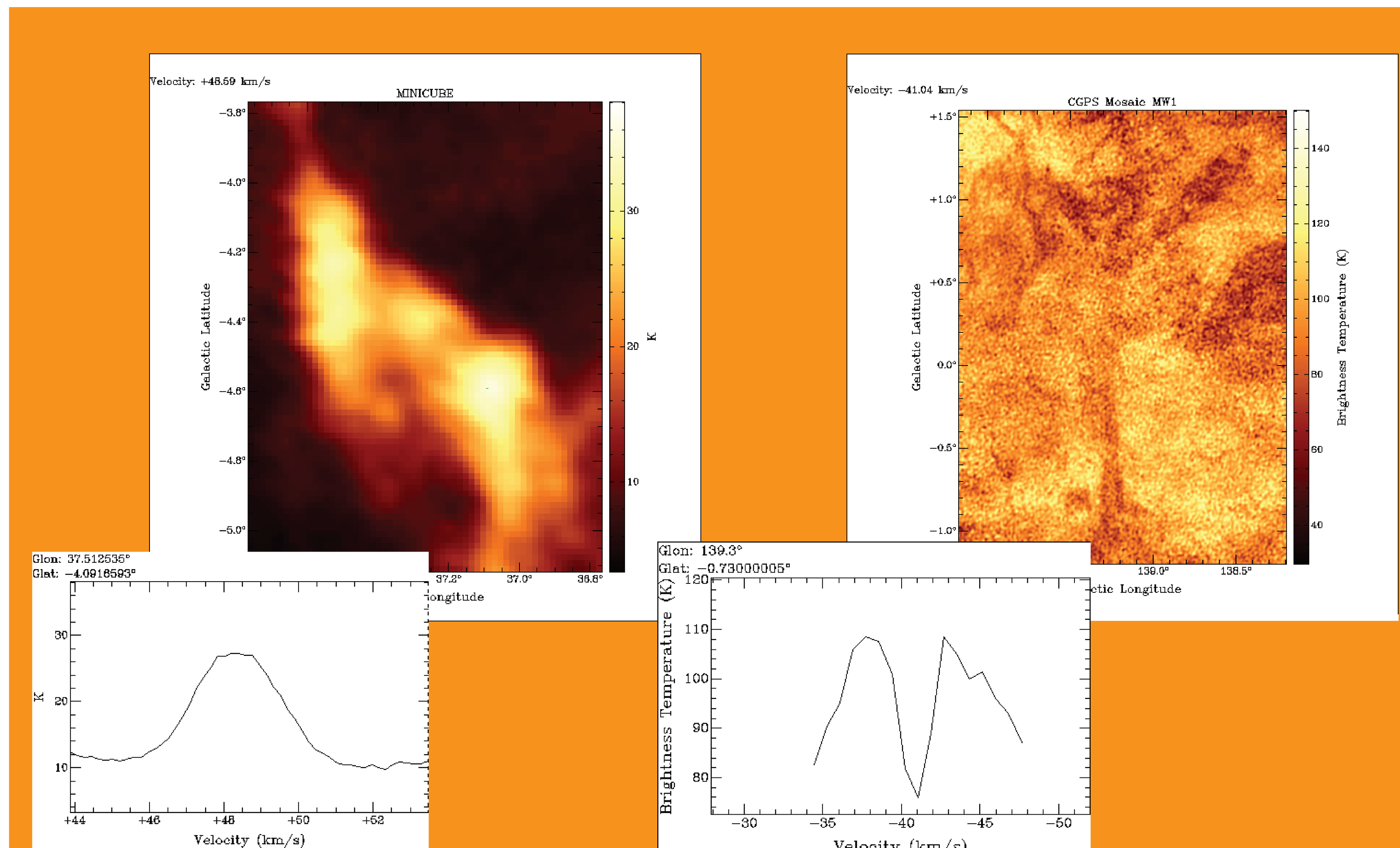
The Interstellar Medium

The space between the stars is not empty: it is filled with an interstellar medium (ISM) of gas and dust. The ISM can be imagined as a galactic ecosystem in which stars live and die, only to provide the material for new stars to be born. Star formation requires interstellar clouds that are cold and dense enough for self-gravity to overcome internal pressure from gas thermal motions and other factors, thus leading to cloud contraction and eventual collapse to stellar densities. These cold and dense conditions are not present in all clouds in the ISM, but they can be identified using observations of neutral atomic hydrogen gas (HI).

Observing Interstellar Hydrogen Clouds

Clouds in the ISM can produce either emission or absorption spectra. Emission lines show a rise in brightness above a background level, while absorption lines show a decrease in brightness. HI clouds are made visible by the 21 cm spin-flip transition (a change of energy in the ground state of HI that emits or absorbs a photon with a wavelength of 21 cm). Observations of this type are made with radio telescopes like the 305-meter Arecibo telescope in Puerto Rico. Once such data are collected, careful analysis is required to determine the properties of a given cloud. This analysis can provide valuable information on what is happening in different parts of our home galaxy. The information gained will also help us understand similar interstellar environments in other nearby galaxies and beyond.



Regions in the ISM can either emit or absorb radiation. In an emission region, the object is brighter than the background in maps of the sky (top left), and the spectrum shows a peak at the cloud velocity (bottom left). An absorption feature arises when the backround brightness is greater than the object being observed (top right). The corresponding spectrum has a decrease in brightness at the cloud velocity, resulting in a trough/valley feature (bottom right).

References

Rohlfs, K., Braunsurth, E., & Mebold, U. (1972). On the Determination of the Optical Depth of the 21-cm Emission Line Profiles. The Astrophysical Journal, 77, 711-725

Analyzing HI Regions

Mapping the properties of HI clouds involves finding the optimal combination of parameters for each part of the cloud. For emission regions, the parameters fitted are: temperature (Ts), optical depth (tau0), line width (FWHM), and average velocity (v0). Absorption has all of these parameters plus one more describing the fraction of the emission (p) that is behind the absorbing cloud. To find an optimal combination of parameter values, we used the Nelder-Mead 'amoeba' method to explore a chi squared space. The 'amoeba' travels through the chi squared space until it finds a minimum that satisfies the given requirements. Equations (1) and (2) are used for both emission and absorption fitting routines, with (3a) for emission and (3b) for absorption. The amoeba method was successfull in fitting emission features, but not absorption, which appears not to have an adequately constrained solution in the scenario we have considered.

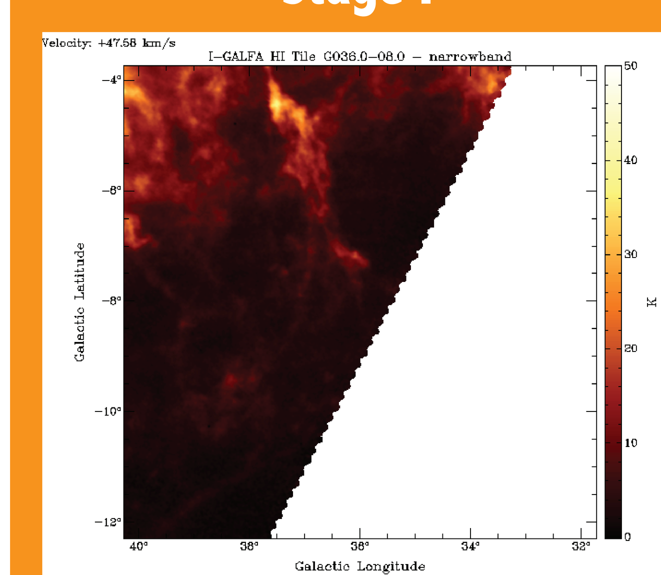
$$\sigma_{line} = \frac{FWHM}{8\sqrt{8\ln 2}} \quad (1)$$

$$\tau = \tau_0 e^{-\frac{1}{2}\left(\frac{v-v_0}{\sigma_{line}}\right)^2} \quad (2)$$

$$T_b = T_s\left(1-e^{-\tau}\right) + T_{bg}e^{-\tau} \quad (3a)$$

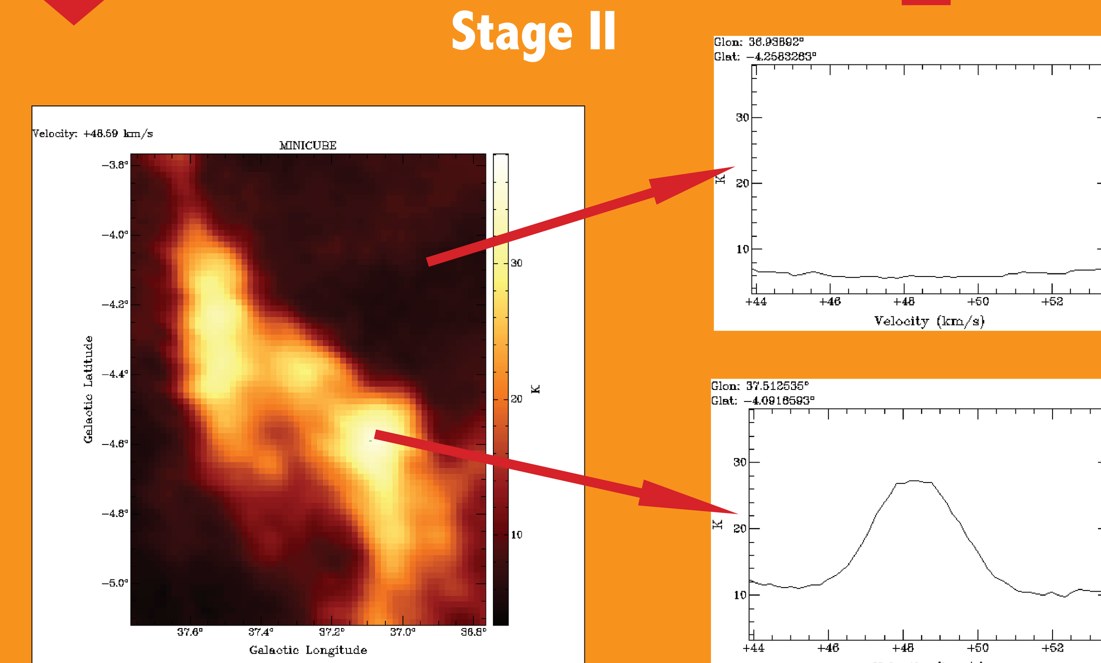
$$T_{on} - T_{off} = \left(T_s - T_c - pT_{off}\right)\left(1-e^{-\tau}\right) \quad (3b)$$

Stage I



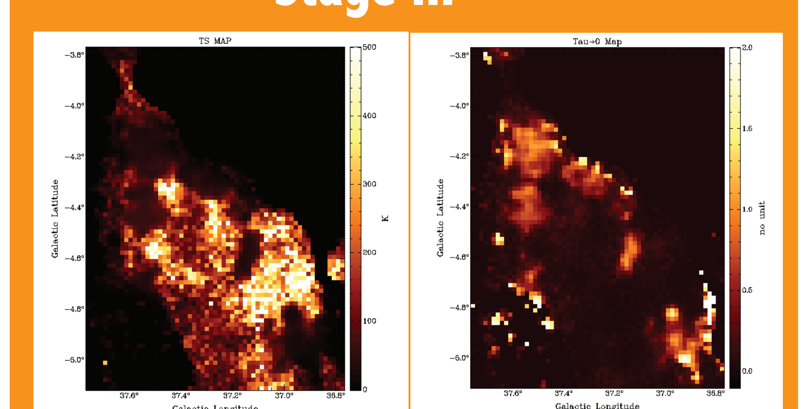
The program selects a subcube of the original data cube that contains the object being analyzed.

Stage II



The program then determines where significant emission is present in the subcube and saves each such spectrum for analysis. A usable emission spectrum is shown on the bottom right, and a spectrum with no real emission is shown on the top right.

Stage III

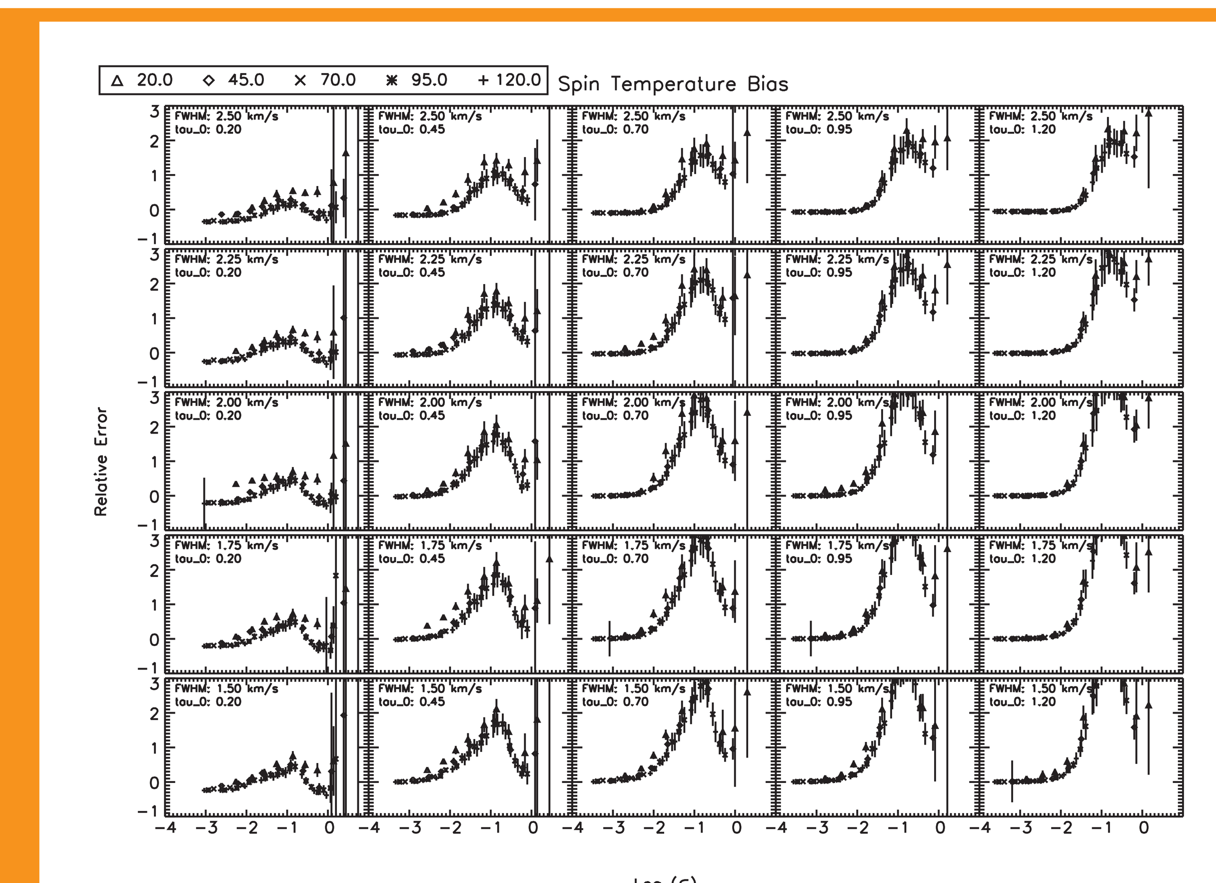


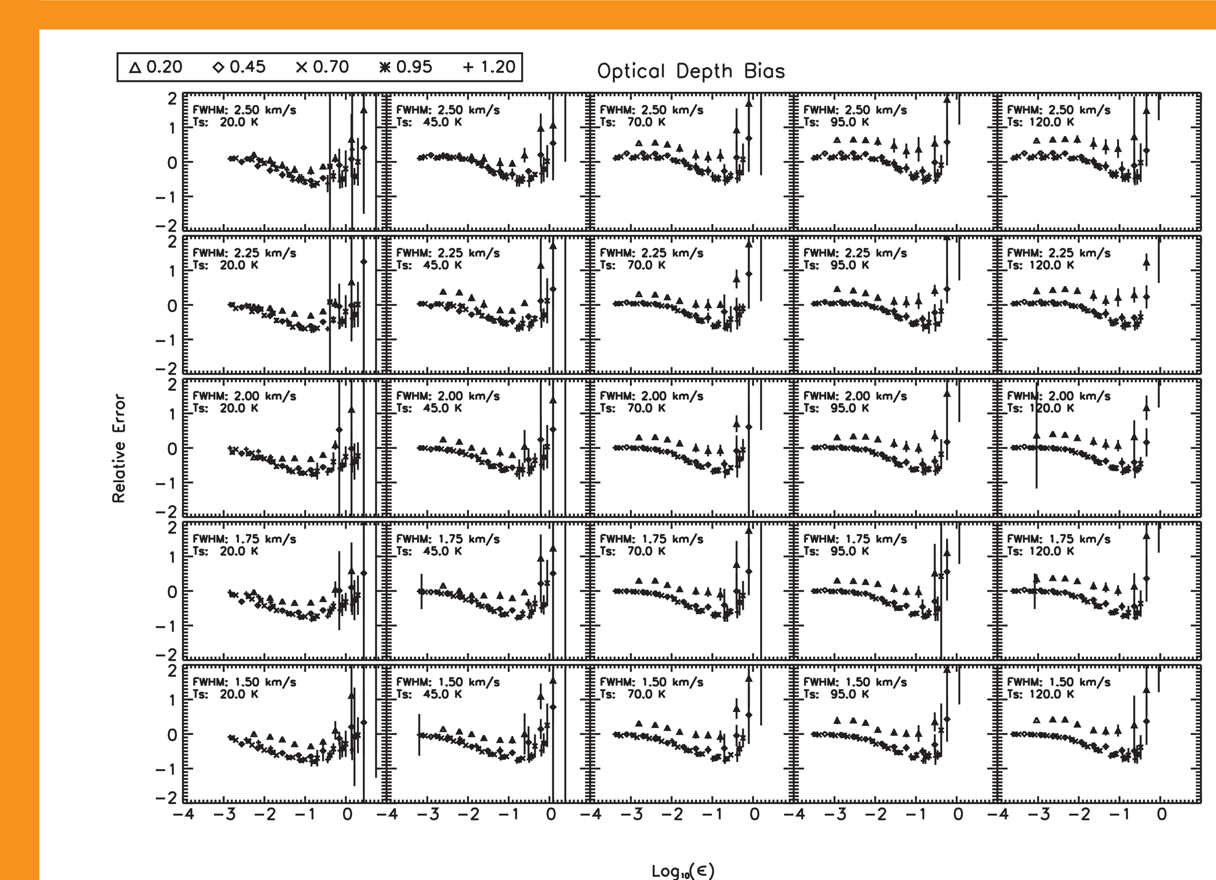
Finally, at every map position where emission was found, the amoeba algorithm is used to determine the cloud parameters that best fit the spectrum at that location. The resulting maps of cloud properties are written to a set of output images as shown above. (Left: temperature map; right: optical depth map)

Quality of the Analysis

A combination of 1250 emission spectra was tested 1000 times in order to determine the effectiveness of the amoeba fitting routine. The simulation was tested over varying line widths, temperatures, and optical depths. We added different levels of noise to each emission spectrum, ranging from 0.02 - 20 K. Our simulation builds on previous work by Rohlfs et al. (1972). Their results determined that the tests are very susceptible to noise, and only very high-quality data can be properly analyzed. Our simulation shows that at noise levels of more than a few percent of signal, the emission fitting routine will give an incorrect answer, including a systematic underestimate of the real temperature value.

$$E_r = \frac{X_{model} - X_{actual}}{X_{actual}} \quad (4)$$





The plots above are results from a Monte Carlo simulation used to determine the reliability of the amoeba fits. The x axis is the log of the noise level divided by the peak brightness. The y axis is the deviation of the results from the expected answer as given by the equation (4). Each of the 25 individual plots represents one combination of parameters.

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